Suitability of test methods to characterize the durability of timber products in various exposure situations under particular consideration of their moisture performance

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Preface

This work has mainly been performed at the Institute of Vocational Sciences in the Building Trade (IBW) at the Faculty of Architecture and Landscape Sciences at Leibniz University Hannover during the years 2012 – 2016.

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Summary

The service life of wooden structures exposed outdoors is predominantly affected by wood destroying organisms. Besides the wood material itself, different factors like climate and test design have an indirect effect on degradation processes and therefore need to be considered for testing the durability of wood and wood-based materials. To date, no methodology for testing the performance of wooden components exposed above ground reflecting the variety of different loads has been fully established, but is required for service life prediction.

One focus of this thesis was to identify field test methods which are suitable to improve the current testing procedure. Different factors influencing the performance of wood and wood-based materials exposed above ground were investigated to develop an exposure-related test procedure. In a first step potential test methods were evaluated according to their principle test design and their potential to reflect differently severe exposure situations. Therefore, the relationship between wood moisture content (MC) and decay development within the different set-ups was determined in a quantitative manner.

In most cases moisture performance coincided well with the resulting decay response. However, the results also showed that tests, which were exposed extremely close to the ground (10 cm or less) showed an accelerated decay development. Therefore, microclimatic influences such as wind speed or splash water have to be taken into account. Furthermore, it became evident that due to the wide range of different designs and corresponding loads, one single method cannot sufficiently reflect the full spectrum of moisture conditions possibly occurring in above ground components.

The different test set-ups were classified into three groups with high, medium, and low time of wetness. Within these groups they were evaluated according to the following criteria 1.) moisture induced risk 2.) decay rate and 3.) practicability. The following test methods turned out to be the most promising: “Segmented double layer”, “Bundle test” and the “Façade-decking element”, representing high, medium and low moisture-induced risk for decay above ground.

To enhance the informative value of MC measurements conducted on different wood-based materials and to enable an interpretation in form of moisture induced decay risks, physiological threshold values for different wood degrading fungi were studied using a pile test method. After a moisture gradient developed in the piled wood specimens, growth and decay of different basidiomycetes were analyzed. In general, the pile test set up was found to be suitable to determine moisture thresholds of decay fungi for different wood species and modified timber. It was found that the wood species itself as well as fungal species have an effect on the moisture requirements for fungal decay. Since these results were obtained in a test set up in which the fungi were provided with an external moisture and nutrient source in form of malt agar, the thresholds might be lower compared to those under real-life conditions without external moisture supply. The thresholds can therefore be considered to include a safety margin.

Finally, for the first time a combination of wetting ability and material resistance data was used for modeling the above ground field performance of wood. Results from in- and above-ground field tests as well as from laboratory wetting ability and resistance tests were included in the development and validation of a simple and transparent model for predicting decay rates of wood and wood-based materials. The approach allows including further factors such as ageing effects, the formation of cracks and climate related effects.

A set of above-ground methods representing different levels of moisture-induced decay risks has been identified. In addition, a model that is based on laboratory and in-ground field test data was developed which allows predicting above-ground decay. Both elements can be easily linked for performance prediction in differently severe exposure conditions

Keywords: Wood durability, testing methodology, above ground exposure

Zusammenfassung

Insbesondere bei der Verwendung im Außenbereich bedingen unterschiedliche Faktoren eine Herabsetzung der Widerstandsfähigkeit des Holzes gegen schädliche Organismen, was wiederum zu einer Limitierung der Gebrauchsdauer des jeweiligen Bauteils führt. Diese Faktoren können vom Holz selbst ausgehen, z. B. durch Inhaltsstoffe, die eine erhöhte Resistenz bewirken, oder sie treten abhängig von der vorherrschenden Umgebung auf wie z. B. der konstruktionsbedingten Holzfeuchtebelastung. Da Holzbauteile und Holzprodukte zunehmend bestimmten Aufgaben und Funktionen hinsichtlich ihrer Leistungsfähigkeit zugeordnet werden, ist eine möglichst genaue Bestimmung der zu erwartenden Gebrauchsdauer enorm wichtig. Hierzu ist es notwendig, den Einfluss der jeweiligen Konstruktionsdetails auf das entstehende feuchteinduzierte Befallsrisiko zu ermitteln. Bislang werden diese Aspekte in Standardprüfungen zur Bestimmung der Dauerhaftigkeit von Holz nicht ausreichend berücksichtigt.

In dieser Arbeit sollte der Einfluss verschiedener expositionsbedingter Faktoren auf die Performance von Holz und holzbasierten Materialien in Konstruktionen und Bauteilen außerhalb des Erdkontakts untersucht werden. In einem ersten Schritt wurden hierzu mögliche Prüfverfahren identifiziert und auf Grundlage des Testdesigns bewertet. Weiterhin wurden sie auf ihre Eignung hin überprüft, die unterschiedlich starke feuchtebedingte Belastung von Bauteilen widerzuspiegeln. Hierzu wurde anhand von Holzfeuchtemessungen die Beziehung zwischen Feuchtebelastung (= Time of wetness, ToW) und Fäulnisentwicklung quantitativ untersucht. Darüber hinaus wurden praktische Aspekte wie z. B. Kosten und Zeiteinsatz zur Herstellung der Prüfkörper und des Prüfaufbaus diskutiert und evaluiert.

Umfangreiche Literaturstudien sowie ein vergleichendes Langzeit-Feuchtemonitoring ergaben, dass die Vielzahl möglicher Konstruktionen und entsprechender Feuchtebelastungen mehr als nur eine Prüfmethode erfordern, um alle möglichen Expositionen außerhalb des Erdkontakts widerzuspiegeln. Unter Berücksichtigung des Feuchteverhaltens und der sich daraus ergebenden Fäulnisentwicklung wurden die untersuchten Prüfmethoden in drei Gruppen eingeordnet (hohe, moderate und geringe Feuchtebelastung) und bezüglich der folgenden Faktoren bewertet: 1.) Feuchteinduziertes Befallsrisiko, 2.) Abbaurate und 3.) Praktische Durchführbarkeit der Tests. Basierend auf dieser Bewertung erwiesen sich folgende Methoden als vielversprechend: „Segmented double layer“ (hohe Belastung), „Bundle test“ (moderate Belastung) und „Façade-decking element“ (geringe Belastung).

Um die Aussagekraft von Feuchtemessungen für eine Bestimmung der Gebrauchsdauer von Holzbauteilen zu erhöhen, wurden physiologische Schwellenwerte für den pilzlichen Abbau sowohl an nativem als auch an modifiziertem Holz in Stapelversuchen ermittelt. Wachstum und Holzabbau verschiedener Basidiomyceten wurde quantitativ an gestapelten Hölzern mit einem Feuchtegradienten ermittelt. Die Holzarten selbst, aber auch der verwendete Prüfpilz zeigten eine Wirkung auf die Feuchteanforderungen für den pilzlichen Abbau des Holzes. Da den Prüfpilzen hierbei eine externe Feuchtequelle zur Verfügung stand, darf angenommen werden, dass die erzielten Grenzwerte unter Freilandbedingungen höher sind und die ermittelten Grenzwerte daher mit einer Sicherheitsspanne belegt sind.

Anhand der Ergebnisse aus unterschiedlichen Labor- und Freilandstudien zur Bestimmung der Dauerhaftigkeit wurde ein Modell zur Vorhersage der Abbaugeschwindigkeit von Holz außerhalb des Erdkontakts entwickelt. Zum ersten Mal wurden Kennwerte zum Feuchteverhalten, d. h. zur Aufnahme und Abgabe von Flüssigwasser und Wasserdampf sowie zur inhärenten Resistenz, in ein solches Modell implementiert. Das Modell zur Vorhersage der Abbaugeschwindigkeit von Holz bleibt transparent und bietet die Möglichkeit, weitere Aspekte wie das Klima, Alterungseffekte oder die Neigung zur Rissbildung von Holz einzubeziehen.

Basierend auf den in dieser Arbeit erzielten Ergebnissen ließ sich eine Reihe von Prüfmethoden für die Prüfung der Dauerhaftigkeit außerhalb der Erde empfehlen. Zusätzlich wurde ein auf Freiland- und Labordaten basierendes Modell entwickelt, anhand dessen sich die Abbaugeschwindigkeit außerhalb des Erdkontaktes voraussagen lässt. Zusammenfassend bieten diese Erkenntnisse die Möglichkeit, die Performance in unterschiedlich stark belasteten Expositionen abzuschätzen.

Schlagworte: Dauerhaftigkeit, Testmethodik, Gebrauchsklasse 3

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1 General introduction

1.1 Wood in outdoor use

Wood was always used for all sorts of construction, ranging from simple structures like fences or poles to more complex ones like balconies, bridges or multi-story buildings (Mahapatra and Gustavsson 2009). All these different structures involve a wide range of different loads affecting their service life.

Several studies showed the advantages of wooden building materials regarding greenhouse gas emissions if compared to PVC, concrete, or steel (e.g. Börjesson and Gustavsson 2000, Asif et al. 2002, Petersen and Solberg 2005, Upton et al. 2008, Switala-Elmhurs and Udo-Inyang 2015). Gustavsson et al. (2006) compared the CO_2 emission from concrete- and wood-framed buildings and concluded that the production of wood-framed building materials causes less CO_2 emission than the material production for constructions made from concrete. This effect depends not only on the building material itself, but also on the amount of biomass obtained by processing and demolition residues that can be used as a substitute for fossil fuel. Contrary to this increasing awareness of the ecological benefits of wood, a lot of wooden components are nowadays replaced by products made from aluminum (e. g. windows), wood-polymer compounds (WPC) (e. g. terrace floorings), polyvinyl chloride (PVC) (e. g. facades) or a mixture of steel, plastic and wooden elements (Figure 1).

Figure 1: Left: Playground elements ('Škocjanske jame' national park, Slovenia) provoking huge variety of different exposure conditions from UC 4 (poles) to UC 3.1 or even 2 (gable board, flooring covered by roof). Right: Playground element (Hannover, Germany) mainly consisting of plastic and steel.

A limited or simply unknown durability of wood is often the most crucial factor when it comes to decisions for products used in a certain construction (Foliente et al. 2002, Robichaud et al. 2009). In a survey undertaken in the United States and Canada (O´Connor 2004), architects, structural engineers, builders, and developers were asked about the expected service life of non-residential buildings with regards to different structural materials. Wood was estimated to have an average service life of 51.6 years whereas concrete and steel were rated with 87.2 and 77.3 years respectively. O´Connor (2004) concluded that the majority of buildings are not demolished due to lack of stability or serviceability of the construction, but due to reasons like “area development, lack of maintenance or building no longer suitable for intended use” (O´Connor 2004). Bysheim and Nyrud (2007) conducted a survey on the attitude of Norwegian architects and civil engineers towards the use of wood in constructions. Among others, the “perceived risk of using wood as a construction material” was named as one major factor influencing the decision for or against wood for constructions.

To counter the trend of replacing wood by inorganic or synthetic materials and to strengthen the standing of wood in the building sector, performance data and a reliable service life prediction is needed. This, in return, requires a more detailed knowledge of the influence of different factors like climate and design on the performance of wood and wood-based materials.

1.2 Exposure conditions

According to the European standard EN 335 (2013), the use of timber products can be categorized into different use classes (UC) with respect to their general use situation and the potential occurrence of biological agents as summarized in Table 1.

Table 1: Use classes according to EN 335 (2013)

Use class	General use situation[a]	Occurrence of biological agents [b, c]				
		Disfiguring fungi	**Wood destroying fungi**	**Beetles**	**Termites**	**Marine borers**
1	Internal use, dry	-	-	U	L	-
2	Interior, or under cover, not exposed to the weather; Possibility of water condensation	U	U	U	L	-
3.1	Exterior, above ground, exposed to the weather; Limited wetting conditions	U	U	U	L	-
3.2	Exterior, above ground, exposed to the weather; Prolonged wetting conditions					
4	Exterior, in ground contact and/or fresh water	U	U	U	L	-
5	Permanently or regularly submerged in salt water	U[d]	U[d]	U[d]	L[d]	U

U = ubiquitous in Europe and EU territories
L = locally present in Europe and EU territories

[a] Border line and extreme cases of use of wood and wood-based products exist. This can cause the assignment of a use class that differs from that defined in the standard EN 335 (2013), Annex B.

[b] It may not be necessary to protect against all biological agents listed as they may not be present or economically significant in all service conditions in all geographic regions, or may not be able to attack some wood-based products due to the specific constitution of the product.

[c] See EN 335 (2013), Annex C.

[d] The above water portion of certain components can be exposed to all of the above biological agents.

The different use situations result in conditions that advance or constrain the potential degradation by different agents, i.e. the accessibility for termites and beetles or a certain wood moisture content (MC) necessary for fungal degradation processes. If wooden components are exposed in ground (UC 4), they are exposed to an existing fungal flora and are easily accessible for beetles and termites. Furthermore, in ground contact a constant wetting is usually given (e. g. Wakeling 2006, Augusta 2007, Brischke et al. 2011). In contrast, above ground exposure (UC 2, 3.1 and 3.2) involves a wide range of different conditions influencing the accessibility as well as moisture loads (Figure 2 to Figure 5).

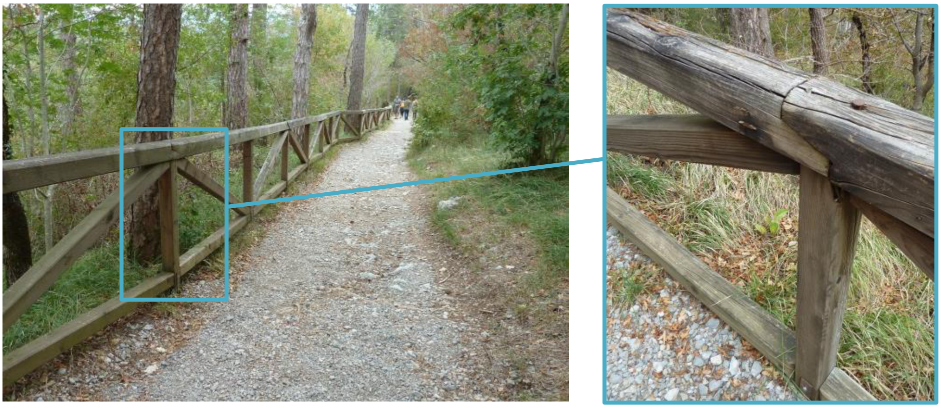

Figure 2: Handrail in 'Škocjanske jame' national park, Slovenia. Different exposures, varying from UC 4 (posts) to UC 3.1 (stabilizer and handrail). In addition, water trapping is caused by lap-joint-construction of segmented handrail (UC 3.2).

Figure 3: Wooden window with poorly maintained coating on a building in Kristineberg, Sweden. Defects in coating can cause enhanced water uptake due to capillary effects.

Figure 4: Bench in the city of Kaunas, Lithuania. Exposure in UC 3.2, close to the ground. Left: Newly installed bench. Middle: Bench after exposure. Right: Detail of bench severely decayed after exposure for several years.

Figure 5: Bridge in Sävsjö, Sweden. Different design details causing water trapping and accumulation of moisture.

1.3 Durability and performance

1.3.1 Wood destroying organisms

Wood is potentially attacked and degraded by termites, beetle larvae, marine borers and several wood-destroying fungi and bacteria. All these groups need to be considered when determining the overall performance of a wooden material exposed outdoors. Besides the exposure conditions (*cf.* chapter 1.2), the geographical position influences the occurrence of different wood degrading agents so that some organisms can be neglected in particular regions. The conditions in northern and central Europe are for instance not favorable for termites (Brischke and Thelandersson 2014). Therefore, in this region in particular brown and white rot causing basidiomycetes are responsible for damage on wood exposed in and above ground (Huckfeldt and Schmidt 2006, Schmidt 2006). In all studies presented and discussed in this thesis the focus was on wood-destroying fungi.

Besides the digestible material itself, air oxygen, wood MC and temperature directly influence decay fungi and their ability to metabolize and degrade wood cell wall substance (Brischke et al. 2006, Gobakken and Lebow 2010, Viitanen et al. 2010, Morris and Wang 2011). Different studies on wood destroying fungi showed the considerable impact of MC and temperature, whereby a wood MC around 25 to 30 % (fibre saturation) and temperatures between 20 to 30 °C were found to advance the conditions for fungal degradation (Boddy 1983, Viitanen and Ritschkoff 1991, Carll and Highley 1999, Nofal and Kumaran 1999, Morris and Winandy 2002).

1.3.2 Material-inherent resistance

The European standard EN 350-2 (1994) provides information on the resistance of different wood species against decay fungi, marine borers, wood boring beetles and termites. With respect to degradation by decay fungi, durability classes (DC) are defined based on the inherent resistance determined in in-ground field tests and laboratory resistance tests performed with basidiomycete monocultures (Råberg et al. 2005, Kutnik 2013). However, since most of the wooden components in exterior use are exposed without ground contact in UC 2, 3.1 or 3.2 (Blom and Bergström 2006, Pfeffer et al. 2008, Friese et al. 2009), not only the inherent resistance is decisive for the performance of a material but also its wetting ability (Kutnik et al. 2014, Suttie et al. 2013, Brischke et al. 2014a, b). The ability of wood to take up and release water is influenced by hydrophobic ingredients and various anatomic features and can be improved by cell wall modification or impregnation with water repellents (Hill 2007, Thybring 2013).

Therefore, in addition to material inherent resistance, the wetting ability in terms of for example resins or susceptibility to ageing and crack formation needs to be taken into account for a realistic durability classification.

1.3.3 Exogenous factors

While the material-inherent resistance and wetting ability are endogenous factors and vary between different wood species and wood-based materials, exogenous factors are a result of the exposure, defined for instance by the local climate, varying shelter, distance to ground, and water trapping (Fredriksson et al. 2013, Fredriksson and Lindgren 2013, Isaksson and Thelandersson 2013, Brischke et al. 2013) (Table 2).

Table 2: Examples of factors potentially influencing the performance of wood exposed outdoors including material inherent factors on one hand and exposure dependent factors on the other hand

Material inherent resistance (endogenous factors)	**Exposure (exogenous factors)**
Resistance: · extractives · preservatives · cell wall modification	*Local climate*: · temperature · rain fall sum · relative humidity *Design*: · distance to ground · roof overhang · water traps · shading · coatings · shelter *Other*: · presence of organisms · maintenance · use-conditions
Wetting ability: · resins · thylosis · water repellents · cell wall modification	

The influence of climatic differences on the resulting decay risk has been subject of several studies (e. g. Francis and Norton 2005, Lebow et al. 2008). Preston et al. (1996) carried out comparative tests at two test sites (UK and Hawaii, USA) and Morris et al. (2015) conducted decking tests according to AWPA E25 (2013) at four climatically different test sites. Both studies resulted in significant differences in climatic load and corresponding decay development.

The effect of design details was analyzed in different studies in which test set-ups reflecting different real life exposure situations for wooden components were supplemented with acceleration measures like defect coatings or shading (Fougerousse 1981, Zahora et al. 2013, Militz and Bloom 2000, Francis and

Norton 2005, Clausen et al. 2006, Brischke and Rapp 2008, Meyer et al. 2013, Cookson et al. 2014). Zahora (2008) as well as Cookson et al. (2014) concluded that the distance to ground can have a significant influence on decay processes. Commodity tests were conducted by Brischke et al. (2010) who performed MC measurements at seven different heights on a cladding and detected the highest MC close to ground. The decay promoting effect of hindered re-drying when specimens are exposed under trees was shown by Augusta (2007), Brischke and Rapp (2007), and Meyer et al. (2012). Here, organic litter and therewith nutrients play an important role. A further decay influencing factor are coatings which were examined by Meyer et al. (2013) as well as Militz and Bloom (2000) who conducted MC measurements on coated and uncoated specimens and found faster decay development in the coated sets of specimens. These results show that exogenous factors have a remarkable influence on the durability of wood and wood-based products exposed outdoors. To be able to quantify the influence of different design details suitable tests methods need to be identified.

1.4 Testing the performance of wood

1.4.1 Durability tests

In general, the number of available field tests shows a significant imbalance if related to the different use classes. For testing wood in ground contact (UC 4) usually only one method is used: the so called ‘graveyard test’, e. g. according to EN 252 (2015). In contrast, a huge number of above ground test methods was reported in literature (e. g. Fougerousse 1976, De Groot 1992, Råberg et al. 2005, Fredriksson 2010, Brischke et al. 2012a). However, durability according to EN 350-2 (1994) (*cf.* chapter 1.3.2) is determined exclusively in laboratory and in-ground field tests, and consequently assumed to be identical in different use classes.

Along with this, no methodology for testing the durability of wood in exterior above ground use is fully established so far (Brischke et al. 2011). In contrast, most of the existing methods were designed to determine the effectiveness of wood preservatives (Fredriksson 2010, Suttie et al. 2013). Furthermore, the variety of different acceleration measures and test protocols as well as the fact that the results are often presented in an encoded way, e. g. in terms of durability classes, results in a limited comparability of existing test data (Brischke et al. 2013).

Since wood exposed in UC 3.1 and 3.2 faces varying loads (*cf.* chapter 1.2) a set of tests could finally be used for testing wood and wood-based materials in above ground exposure more efficiently rather than only one single method. Therefore, the existing above ground methods as well as new approaches need to be examined with respect to the exposure conditions they are creating. Furthermore, the test design needs to ensure practicability and adequate time and effort. To attain this, influences of different design details on the performance of wood and wood-based materials need to be examined in a quantitative manner in terms of moisture and temperature loads and the resulting decay response.

Moisture loads can be expressed as “time of wetness”, e. g. by counting the days above certain moisture content critical for the onset of decay (e. g. Van Acker et al. 2014). Therefore, continuous MC measurements can be included in above ground field tests to serve as a time-saving alternative to long-term decay tests.

1.4.2 Moisture content measurements

Measurement methods to determine MC in field trials and components in service can generally be divided into direct and indirect methods. Furthermore, distinctions can be made between continuous and periodical measurements as well as measuring local (= MC at a single location) or global MC (= MC of the whole specimen) (Figure 6).

In recent years more and more experiments have been conducted to quantify the effect of wood moisture on decay (e. g. Augusta 2007, Van den Bulcke et al. 2009, Meyer et al. 2013). Furthermore, the significant role of wood MC and temperature has nowadays been frequently addressed for decay modelling (Brischke and Thelandersson 2014). However, interpretation of MC data requires detailed information on a minimum threshold for fungal decay. Since critical moisture levels as well as optimum and maximum MC for fungal growth are material-specific characteristics they need to be considered when estimating the resulting moisture and temperature induced risk for decay of different materials.

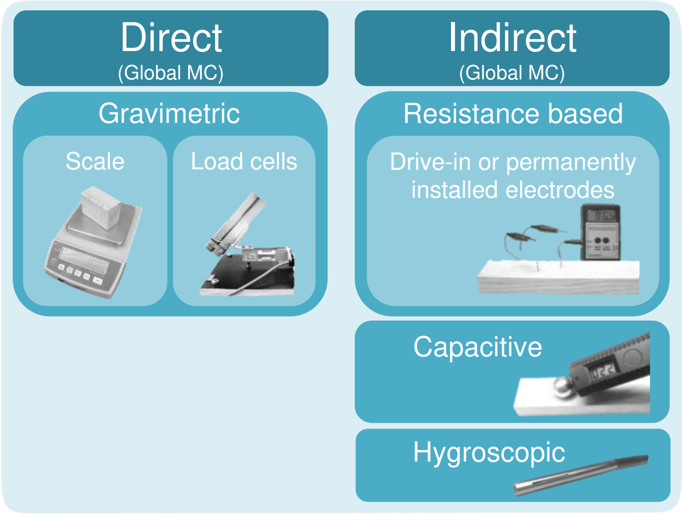

Figure 6: Measurement principles of frequently used methods used to determine wood moisture content (MC) in durability field test methods

1.4.3 Moisture thresholds for fungal decay

It is widely accepted that wood MC above fibre saturation is favorable for most decay fungi in order to metabolize wood substrates (*cf.* 1.3.1). Keeping water away from wood is, therefore, a key aspect for wood protection by design (Ibach and Rowell 2000, Brischke et al. 2008, Isaksson and Thelandersson 2013, Thybring 2013, Ringman et al. 2014) as well as different wood modifications and treatments which have been developed to reduce the accessibility of wood cell walls for water (Williams and Feist 1999, Rowell 2006, Hill 2007, Esteves and Pereira 2008, Thybring 2013). Some modified materials like acetylated wood showed, however, increased water uptake in field tests (Figure 7).

This seems to be contradictory on first sight, but can be explained by the fact that for example the acetylation process is on the one hand decreasing the hygroscopicity of wood (Rowell 2006b), but on the other hand increases its capillary water uptake (Larsson and Simonson 1994). Similar changes in water uptake behavior were reported for thermally modified wood (Metsä-Kortelainen et al. 2006). However, it is still controversially discussed to which extent the presence of liquid water in cell lumens influences decay processes in modified wood (Thygesen et al. 2010, Ringman et al. 2014). It is therefore indispensable to determine material specific physiological threshold values for all kinds of wood-based materials to implement MC data into performance modelling.

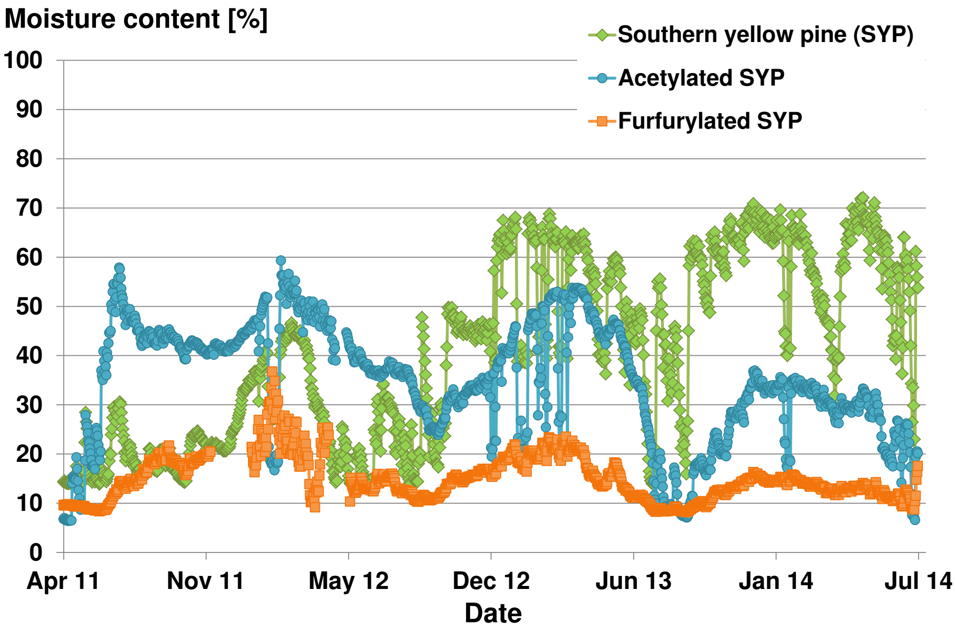

Figure 7: Moisture course of untreated Southern Yellow Pine (SYP) as well as acetylated and furfurylated SYP exposed in double layer tests in Hannover, Germany

1.5 Performance classification

1.5.1 Standards and classification procedures

To date results from durability tests are translated into durability classes (DC) according to the European standard EN 350-2 (1994) (*cf.* chapter 1.3.2). In combination with the use classes as defined in EN 335 (2013) (*cf.* chapter 1.2), the standard EN 460 (1994) gives information about whether the natural durability of a material is sufficient for use in a particular use class or requires treatment with wood preservatives (Table 3).

Hence, the current procedure, illustrated in Figure 8, is a non -continuous process which simply results in the conclusion whether a material is suitable for a certain exposure or not and gives no information about the service life or performance of a material in a quantitative manner (Suttie et al. 2014). Furthermore, by determining the DCs exclusively in laboratory and in-ground field tests it is assumed that the durability of a material is independent of the UC, what might be doubted as shown by Rapp et al. 2010 and Brischke et al. 2013.

Table 3: Guidance on the durability classes of wood species for use in use classes, according to EN 460 (1994)

Use class	Durability class				
	1 very durable	2 durable	3 moderately durable	4 slightly durable	5 not durable
1	O	O	O	O	O
2	O	O	O	(O)	(O)
3	O	O	(O)	(O) – (X)	(O) – (X)
4	O	(O)	(X)	X	X
5	O	(X)	(X)	X	X

O = natural durability sufficient.

(O) = natural durability is normally sufficient, but for certain end uses treatment may be advisable.

(O) – (X) = natural durability may be sufficient, but depending on the wood species, its permeability, and end use, preservative treatment may be necessary.

(X) = preservative treatment is normally advisable, but for certain end uses natural durability may be sufficient.

X = preservative treatment necessary.

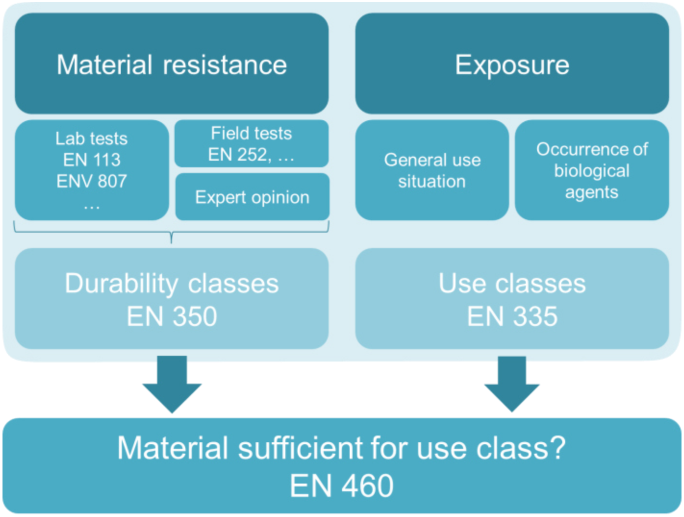

Figure 8: Current procedure to identify whether a wood material is sufficient for a certain exposure or needs to be treated with preservatives

In contrast to this procedure, performance prediction is required by European regulations, e. g. the construction products regulation (CPR) (European Commision 2011) and the biocidal products regulation (BPR) (European Commision 2012) (Kutnik et al. 2014). Furthermore, different researchers and standardization committees (e. g. Kutnik 2013, Suttie et al. 2013) pointed out the need to gain information about the expected service life of a material in a particular exposure.

Figure 9 suggests components that need to be implemented into performance modelling to achieve a reliable base for service life prediction of wood and wood-based products in different exposure situations. Here, the durability is assumed to be the product of a resistance dose in terms of inherent resistance and wetting ability and an exposure dose whereby the two factors form a continuum independent of classes or stepwise defined exposure conditions.

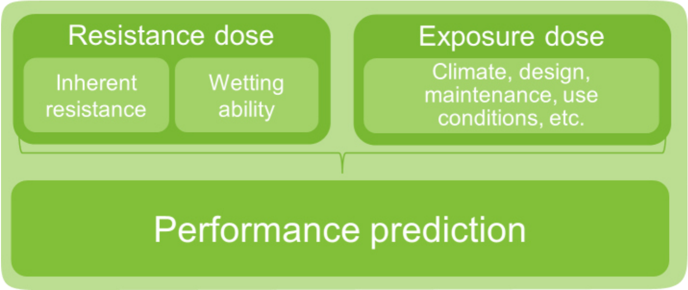

Figure 9: Components that need to be implemented to achieve a performance prediction for wood and wood-based materials taking into account different exposures

1.5.2 Performance modelling

The performance of wood and wood-based materials is an essential parameter for the prediction of service life. It has, however, so far mainly been based on expert judgment (e. g. Brischke et al. 2012b, Kutnik 2013). Several approaches to predict the service life of wood products are based on a dose-response relationship (Brischke and Rapp 2010, Viitanen et al. 2010, Isaksson et al. 2013, Niklewski et al. 2016). Here, the dose is given as a function of different climate related factors (e. g. MC, temperature, relative humidity) and response is understood as a certain level of decay.

A comprehensive overview of existing modelling approaches and model types is given by Brischke and Thelandersson (2014). None of the previously reported models considers material resistance as the combined effect of inherent resistance and wetting ability.

A first approach to implement wetting ability as part of the material resistance into a design concept has been made by Isaksson et al. (2014). Here, an exposure dose (D_{Ed}) and resistance dose (D_{Rd}) are used to define the following design condition:

$$\text{Exposure } (D_{Ed}) \leq \text{Resistance } (D_{Rd})$$

The resistance dose D_{Rd} can be considered to be the product of a critical dose D_{crit} and two factors describing the wetting ability of wood (k_{wa}) and its inherent durability (k_{inh}):

$$D_{Rd} = D_{crit} \cdot k_{wa} \cdot k_{inh} \text{ [d]}$$

where

D_{crit} = critical dose corresponding to decay rating 1 (EN 252, 2015) [d]

k_{wa} = factor accounting for the wetting ability of the material

k_{inh} = factor accounting for the inherent protective properties of the material against decay

This procedure allows to directly including data from durability tests in prediction models. Furthermore, it considers the specifics of modified materials, like thermally modified timber (TMT), which suffer from low inherent resistance but enhanced wetting ability. Therefore, including material resistance composed of inherent resistance and wetting ability in addition to the exposure will further improve the reliability of performance models.

Additional improvements could be achieved by including further aspects to the exposure dose, for instance climatic measures or crack formation.

2 Objectives

The overall objective of this thesis was to identify test methods which are suitable for a revision and improvement of the current testing methodology. Therefore different factors influencing the performance of wood and wood-based materials exposed above ground were investigated with respect to the following:

- Evaluation of suitable test methods according to their principle test design as well as practical aspects like decay assessment, practicability, costs and time efforts (Paper 1)
- Investigation of potential measurement methods to determine the relationship between moisture content and decay development (Paper 2)
- Assessing the potential of different field test methods to reflect variously severe exposure situations (Paper 3 and 4)
- Determination of physiological threshold values for different wood degrading fungi and wood-based materials to enhance the informative value of MC measurements by a more precise interpretation of MC test data (Paper 5 and 6)
- Developing an approach to implement the combined effect of wetting ability and durability data into performance prediction in differently severe exposure conditions (Paper 7)

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4 Publications

This thesis is based on the following publications:

1. Meyer L, Brischke C, Preston AF (2014) Testing the natural durability of timber exposed above ground – a review. *Wood Material Science and Engineering*. doi: 10.1080/17480272.2014.983163 [1, 2, 4]
2. Meyer L, Brischke C, Kasselmann M (2015) Holzfeuchte-Monitoring im Rahmen von Dauerhaftigkeitsprüfungen - Praktische Erfahrungen aus Freilandversuchen. *Holztechnologie* 56: 11-19 [1, 2, 3, 4]
3. Meyer-Veltrup L, Brischke C (2016) Bundle tests – Simple alternatives to standard above ground durability field test methods. *Holztechnologie* 57: 26-30 [1, 2, 3, 4]
4. Meyer-Veltrup L, Brischke C, Källander B (2016) Testing the durability of timber above ground - Evaluation of different test methods after 3 years of exposure. *European Journal of Wood and Wood Products*. doi: 10.1007/s00107-016-1137-8 [1, 2, 3, 4]
5. Meyer L, Brischke C (2015) Fungal decay at different moisture levels of selected European-grown wood species. *International Biodeterioration and Biodegradation* 103: 23-29 [1, 2, 3, 4]
6. Meyer L, Brischke C, Treu A, Larsson-Brelid P (2015) Critical moisture conditions for fungal decay of modified wood by basidiomycetes. *Holzforschung* 70: 331–339 [1, 2, 3, 4]
7. Meyer-Veltrup L, Brischke C, Alfredsen G, Humar M, Flæte P-O, Isaksson T, Larsson Brelid P, Jermer J (2016) The combined effect of wetting ability and durability on field performance – verification of a new prediction approach. *Wood Science and Technology*. Submitted for publication [2, 3, 4]

Contribution of the author of this thesis was as follows and indicated for every publication:

[1] literature review

[2] evaluation of findings and writing of the paper

[3] planning and execution of trials (partly together with co-authors)

[4] comments that were discussed with the co-authors were included

Paper 1

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REVIEW ARTICLE

Testing the durability of timber above ground: A review on methodology

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Abstract

The majority of timber products in outdoor use are exposed above ground, e.g. façades, terrace decking, playground equipment, garden furniture, windows, balconies or carports. In contrast, the durability of wood and wood products is most often determined in laboratory against Basidiomycete monocultures or in-ground field tests, where wood samples are submitted to permanent wetting. Worldwide, only a few above ground field test methods evaluating durability against fungal decay have been standardized. Wood used in above ground situations can be exposed to a wide range of moisture loads reflecting different design details such as varying shelter, distance to ground, ventilation and water trapping, whereas temperature and rainfall variations are overall influences on service life performance. The aim of this review was to gather information about standardized and non-standardized above ground field test methods used to determine the durability of wood and wood-based products. In total, more than 60 methods have been evaluated according to different criteria, such as principle set-up and design, severity of exposure and distance to ground. Their suitability to reflect a certain exposure under real-life conditions is discussed as well as practical aspects regarding acceleration measures, decay assessment and practicability, costs and time efforts.

Keywords: *Field tests, use class 3, test methodology, wood durability*

Introduction

In the building sector, wood competes with other building materials such as concrete, composites and steel. Besides the well-known advantages regarding greenhouse gas emissions and less waste production (Petersen and Solberg 2005), design and processing options speak for the use of wood. However, the durability of building materials can be a crucial factor when it comes to product decisions in the design process (Foliente *et al.* 2002). Therefore, reliable durability data are needed to predict the expected performance of building components (Thelandersson *et al.* 2011).

The durability of wooden constructions and components used outdoors is affected by several factors, such as temperature, surrounding moisture regime and fungal flora. In different exposure situations, these factors need to be weighted differently. When wood is exposed in ground contact [Use Class (UC) 4, EN 335 2013], for example, in poles, fencing or palisades, constant wetting conditions are usually assumed (e.g. Wakeling 2006, Augusta 2007, Brischke *et al.* 2011). Therefore, decay is predominantly influenced by temperature, soil moisture and the fungal colonization potential at the given site.

However, most applications for wood in exterior use are without ground contact (UC 3.1 or UC 3.2), e.g. façades, terrace decking, playground equipment, garden furniture, windows, balconies or carports (Blom and Bergström 2006, Pfeffer *et al.* 2008, Friese *et al.* 2009). These components are exposed to a wide range of moisture loads reflecting different design details such as varying shelter, distance to ground, ventilation and water trapping (Fredriksson *et al.* 2013, Fredriksson and Lindgren 2013, Isaksson and Thelandersson 2013, Brischke *et al.* 2013b). Consequently, the number of test methods related to the different UCs shows a significant imbalance, whereas testing wood in ground contact is almost exclusively conducted in so-called ‘graveyard tests’, e.g. according to EN 252 (1989), testing of wood in above ground situations is based on a wide range of

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different standardized and non-standardized test methods (e.g. Fougerousse 1976, De Groot 1992, Råberg *et al.* 2005, Fredriksson 2010, Brischke *et al.* 2012). Most of the above ground test methods were designed to determine the effectiveness against decay fungi of wood preservatives or to compare different wood species or treatments (Fredriksson 2010). Due to different restrictions in the use of preservatives (Schultz *et al.* 2007) naturally durable or modified timber are also used frequently nowadays. However, till now in many countries durability classification is still exclusively based on laboratory decay tests and in-ground field test results (Råberg *et al.* 2005, Kutnik *et al.* 2014) and a comparative test methodology for wood in exterior above ground use is still not fully established (Brischke *et al.* 2013a). Although a high number of studies on above ground performance of wood have been conducted in the past, the variety of existing test methods and test protocols as well as the fact that they were modified in different ways makes it difficult to obtain comparable results and a UC-related testing methodology (Brischke *et al.* 2011). In addition, the documentation of above ground studies is sparse (Lindegaard and Morsing 2003) and often the results are presented in a condensed and cryptic format (Brischke *et al.* 2013a).

The aim of this review was to gather information about standardized and non-standardized above ground field test methods to determine the durability of wood and wood-based products against decay fungi. Therefore, methods applied worldwide have been evaluated according to different criteria, such as principle set-up and design, severity of exposure or distance to ground. Their suitability to reflect a certain exposure under real-life conditions was discussed as well as practical aspects regarding acceleration measures, decay assessment and practicability, costs and time efforts.

Field test methods

Table I shows in summary 54 different above ground test methods which were identified in literature and used in various field test studies. Among all listed test procedures, only eight methods are standardized: two European standards (EN 330 1993, CEN/TS 12037 2003), five US standards (AWPA E9 2013, AWPA E16 2013, AWPA E18 2013, AWPA E25 2013, AWPA E27 2013) and one Australian standard (AWPC 2007). All these methods were initially developed to assess the relative effectiveness of wood preservatives used for above ground applications. All tests were evaluated according to their principle design and severity of exposure in form of distance to ground, moisture trapping as well as acceleration measures. Furthermore, the initial test purpose and current status are indicated in Table I.

Design principles

Generally, the test methods listed in Table I can be differentiated by their design principles. Test methods consisting of a single layer are found most often in literature, followed by methods with two or more (specimen) members creating a joint. While single layer specimens (Figure 1a) promote fast re-drying after rain events (horizontal exposure) or enable water draining (vertical/inclined exposure), segmented specimens creating a water trapping joint (Figure 1b), provoke moisture accumulation.

Principle designs will be discussed in the following section.

Joints

L-joint and Lap-joint tests have been compared by Clausen and Lindner (2011) as well as Meyer *et al.* (2013), who found that moisture content (MC) within these two test set-ups can be significantly different. In both studies, Lap-joint (Figure 2.3) specimens showed more fluctuations in MC over time compared with L-joint (Figure 2.1) specimens. This might be a reason for a more consistent decay rating among the L-joint specimens (Clausen and Lindner 2011). Sailer *et al.* (1999), Grinda *et al.* (2001) as well as Westin *et al.* (2002) found a relatively low decay activity within Lap-joint tests especially when they are performed in the Northern European countries with cold climates. This was also proved by Preston *et al.* (2011) who found similar results even for test sites with a higher decay promoting climate compared with Northern Europe. Furthermore, Terziev and Edlund (2000) stated that although the Lap-joint exposure reflects real-life conditions, decay process is too slow.

Looking on material costs as well as time and effort required for sample preparation, one drawback of the Lap-joint method is its sample size. Specimens, particularly references which have to be prepared from pine sapwood are difficult to produce free of heartwood and knots (Sailer *et al.* 1999). However, Zahora *et al.* (2013) stated that due to the wide surface the Lap-joint test conforms to the dimensions of wooden components to a large extent. On the other hand, preparation of smaller test samples consisting of two or more segments building a tenon and mortise member [L-joint, Bundesanstalt für Materialforschung und Prüfung (BAM) test unit (Figure 2.11), Hickinsons T-joint (Figure 2.6) or Housed window joint (Figure 2.8)] are comparatively time intensive, and thus cost consuming.

Table I. Above ground field test methods.

		Distance to ground			Moisture trapping			Acceleration measure						Status		Initial test purpose			
#	Name/principle design	Close (≲300 mm)	Medium (310–500 mm)	Distant (≳510 mm)	Severe	Moderate	Slight/No	Water reservoir	Shading	Coating	External infestation	Feeder elements	None	Non-standard	Standard	Efficacy testing[a]	Durability testing	MC measurements	Reference
	Joints																		
1	L-joint			x	x					x					x	x			EN 330 (1993), AWPA E9 (2013)
2	Accelerated L-joint			x	x			x				x		x			x		Van Acker and Stevens (2003)
3	Lap-joint			x	x								x		x	x			CEN/TS 12037 (2003), AWPA E16 (2013)
4	Y-joint		x		x					x				x		x			Hedley *et al.* (1995)
5	T-joint			x	x					x				x		x		x	Sell (1982)
6	Hickson's T-joint			x	x								x	x		x			Fougerousse (1976)
7	Unglued T-joints			x	x								x	x		x			Fougerousse (1976)
8	Housed window joint		x		x								x	x		x			Fougerousse (1976)
9	Sash unit			x	x					x				x		x			Fougerousse (1976)
10	Post and rail			x	x					x				x		x			Highley and Scheffer (1993)
11	BAM test unit			x	x					x		x		x		x			Fougerousse (1976)
12	Miter block unit			x	x								x	x		x			Fougerousse (1976)
13	Rail and newel			x	x								x	x			x		De Groot (1992)
14	Embedded test			x	x					x	x	x		x		x			Cookson and Carr (2009)

Table I. (Continued)

#	Name/principle design	Distance to ground			Moisture trapping			Acceleration measure						Status		Initial test purpose			Reference
		Close (≲300 mm)	Medium (310–500 mm)	Distant (≳510 mm)	Severe	Moderate	Slight/No	Water reservoir	Shading	Coating	External infestation	Feeder elements	None	Non-standard	Standard	Efficacy testing	Durability testing	MC measurements	
	Single elements																		
15	Flat panel test		x	x	x							x			x	x			AWPC (2007)
16	Vertical stakes			x			x						x	x			x		Augusta (2007)
17	Wood panel test			x			x			x				x			x	x	Öqvist (1988)
18	Board test (30°)			x			x						x	x		x			Fougerousse (1976)
19	Painted panel test	x								x				x		x			Creffield *et al.* (1992)
20	Façade element			x		x						x		x			x	x	Bornemann *et al.* (2013)
21	Decking element			x			x					x		x			x	x	Bornemann *et al.* (2013)
22	Deck-on-ground	x			x							x		x		x			Cookson and Carr (2009)
23	Raised deck			x	x							x		x		x			Cookson and Carr (2009)
24	Exposed decking		x			x										x			Fougerousse (1976)
25	Decking test		x			x				x					x		x		AWPA E25 (2013)
26	Mini-deck test	x				x							x	x		x			Westin *et al.* (2010)
27	Decking test	x					x					x		x		x			Hedley *et al.* (1995)
28	Xylophone test			x			x						x	x			x		Larkin and Laks (2008)
29	Weatherboard panel			x			x					x		x					Fougerousse (1976)
30	Above ground bars	x				x							x	x		x			Zahora (2008)
31	Gutter test	x			x			x						x		x			Fougerousse (1976)

Table I. (Continued)

		Distance to ground			Moisture trapping			Acceleration measure						Status		Initial test purpose			
#	Name/principle design	Close (≲300 mm)	Medium (310–500 mm)	Distant (≳510 mm)	Severe	Moderate	Slight/No	Water reservoir	Shading	Coating	External infestation	Feeder elements	None	Non-standard	Standard	Efficacy testing	Durability testing	MC measurements	Reference
	Blocks and stacks																		
32	Double layer	x			x							x		x			x		Rapp and Augusta (2004)
33	Double layer PE	x			x								x	x			x	x	Meyer *et al.* (2013)
34	Block test	x			x				x			x					x		Pfeffer *et al.* (2008)
35	Solid stack			x	x								x	x			x		De Groot (1992)
36	Block			x	x								x	x			x		De Groot (1992)
37	Five board stack			x		x							x	x			x		De Groot (1992)
38	Pyramid			x		x							x	x			x		De Groot (1992)
39	Stacked board units			x		x							x	x		x			Fougerousse (1976)
40	A-frame test	x	x	x		x		x	x					x		x			Williams *et al.* (1995)
41	Rot box	x			x							x		x		x			Cookson and Carr (2009)
42	Staple bed	x			x				x					x			x		Råberg *et al.* (2009)
	Bundles																		
43	Sandwich	x			x				x			x		x		x			Zahora (2008)
44	Bundle test			x	x								x	x			x		Brischke *et al.* (2012)
45	Johansson method			x		x							x	x		x			Johansson *et al.* (2001)
46	Cross brace test			x		x							x	x			x		Highley (1995)
47	Acc. Lap-joint test		x		x								x		x	x			AWPA E27 (2013)
48	Cross configuration			x		x							x	x			x		De Groot (1992)

Table I. (Continued)

		Distance to ground			Moisture trapping			Acceleration measure						Status		Initial test purpose			
#	Name/principle design	Close (≤300 mm)	Medium (310–500 mm)	Distant (≥510 mm)	Severe	Moderate	Slight/No	Water reservoir	Shading	Coating	External infestation	Feeder elements	None	Non-standard	Standard	Efficacy testing	Durability testing	MC measurements	Reference
	Concrete bearings																		
49	4-Block test	x			x						x			x		x			Behr (1978)
50	Ground proximity	x				x			x						x	x			AWPA E18 (2013)
51	Mini-stake	x				x			x					x			x		Westin *et al.* (2004)
52	Verandah post-unit	x				x							x	x		x			Fougerousse (1976)
53	Japanese Test B	x			x								x	x		x	x		Fougerousse (1976)
	Others																		
54	Peg test			x		x							x	x		x			Cookson and Carr (2009)

[a] Determination of relative effectiveness of preservatives and durability of preservative treated wood.

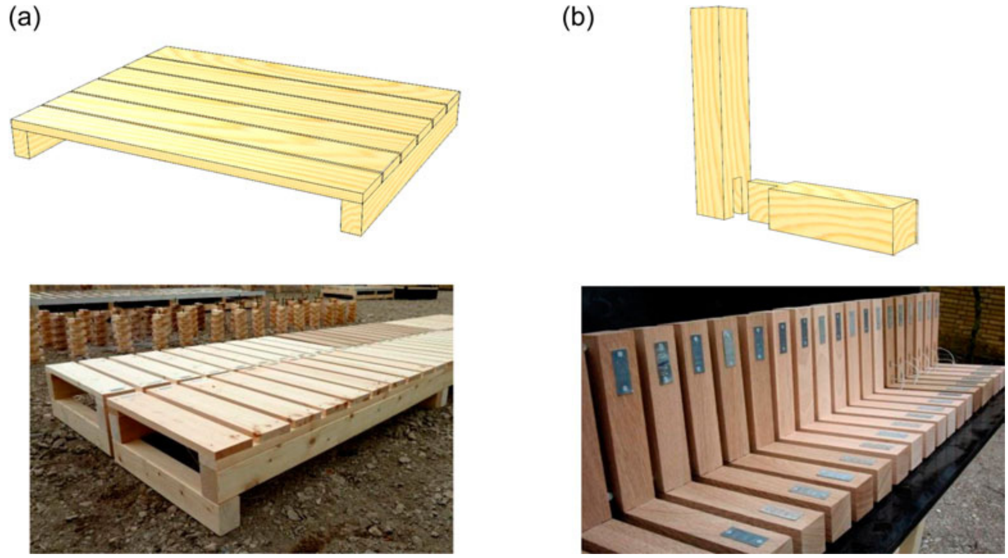

Figure 1. Examples of (a) single layer test method and (b) segmented specimen creating a joint.

Single elements

Test methods using single elements (Figure 2.15–2.31) mainly differ in orientation of the individual components. Most common are different decking tests (Figure 2.21–2.27) followed by tests that mimic facades (Figure 2.16, Figure 2.20 and Figure 2.29) whereby the decking tests provide the more severe conditions. While a vertical or inclined board promotes rapid water draining, horizontally exposed test boards enable accumulation of water on the surface and thus longer absorption periods. However, Fougerousse (1976) pointed out that single test elements are designed without any help to the fungus for rapid initial settlement. Although this is a drawback in terms of slow decay development decking tests as well as vertically exposed single specimens reflect actual construction situations to a high extent. Another advantage of single element tests is the simple specimen preparation. However, this might be restricted when it comes to large dimensioned boards, which need to be prepared from pine sapwood, for example.

Blocks and stacks

Block and stack tests (Figure 2.32–2.42) consist of several specimen layers creating water traps providing high potential for moisture accumulation. The different layers can be arranged in a parallel order (Pfeffer *et al.* 2008, Figure 2.34), displaced to each other (Rapp and Augusta 2004, Figure 2.32) or piled with ascending size (De Groot 1992, Figure 2.38). With all such arrangements, a large contact surface provides water entrapment areas in the test samples. Since the individual layers consist of single bars, boards or panels, respectively, all set-ups require minor effort for sample preparation. Larnøy *et al.* (2014) referred to the high potential of fungal colonization as one further advantage of the block test (Figure 2.34). This is mostly due to the short distance to the ground and fast spread of decay within the test set-up once fungal attack has started. However, the latter can also turn out to be a drawback of test set-ups with stacked specimens: the single replicates within the Double layer test (Figure 2.32) or block set-ups are arranged alongside one to another exposed to varying conditions depending on their individual position. Therefore, the whole set-up practically acts as one single replicate (Zahora 2008, Brischke *et al.* 2011). Alternatively, one can include inert spacers (Meyer *et al.* 2013, Figure 2.33) or arrange a certain number of individual specimens as a bundle (e.g. Figure 2.44). However, one open question for all these test designs is how to handle failure of specimens within a test set-up because both replacing and removing will change the test conditions.

Bundles

Bundle tests (Figure 2.43–2.47) consist of two or more segments held together by clamps (Zahora 2008, Figure 2.43), cable straps (Brischke *et al.* 2012, Figure 2.44) or screws (Johansson *et al.* 2001, Figure 2.45). Accordingly, the Lap-joint test might be considered either as bundle or as a joint test.

Bundle tests combine the advantages of joint and block tests by creating water traps, providing a large contact area, but consisting of separated, individual replicates.

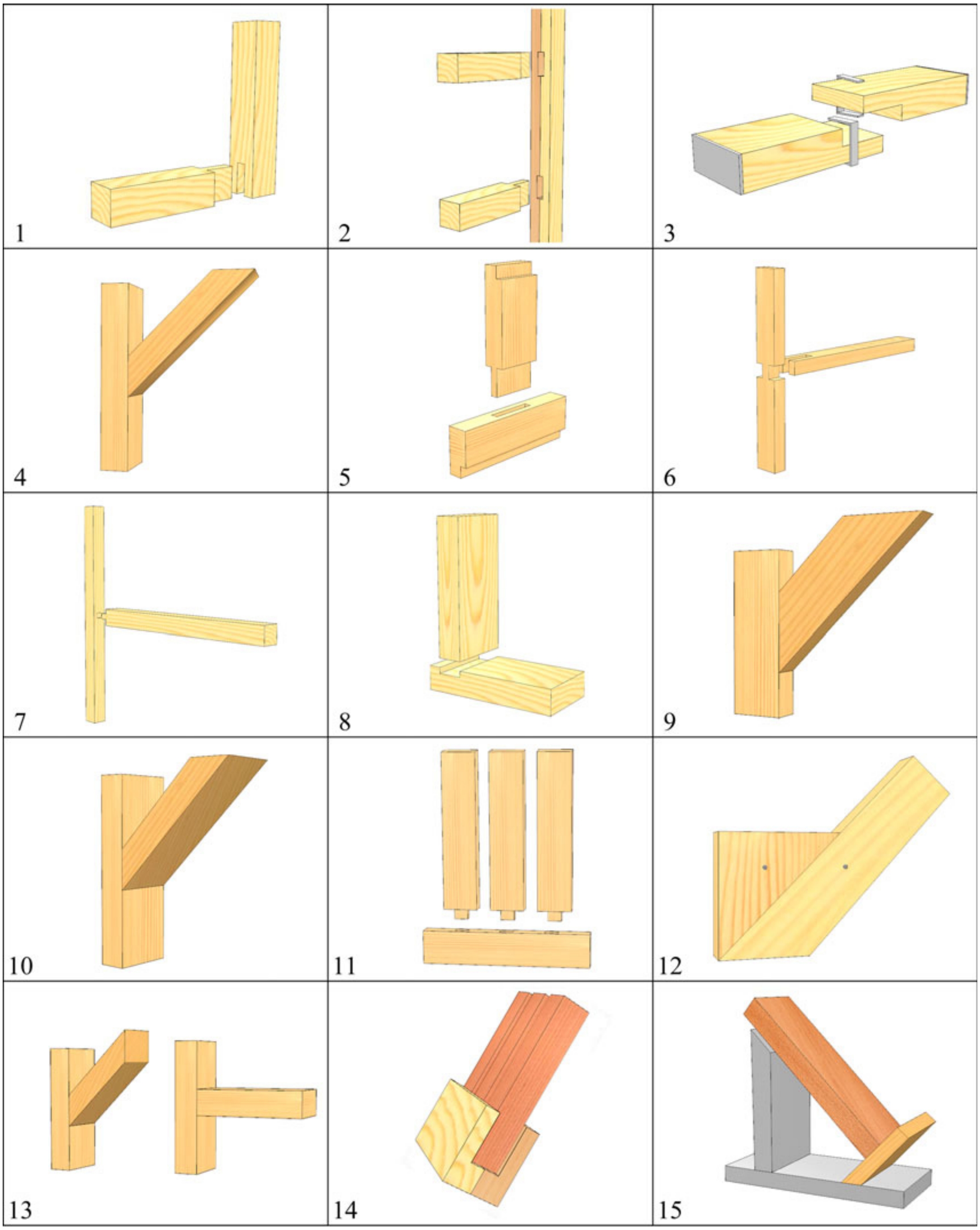

Figure 2. Principle design of test methods (*cf.* Table I). Drawings are not to scale.

Concrete bearings

Tests which were categorized as ‘concrete bearing tests’ (Figure 2.48–2.52) consist of a single specimen exposed on or under a concrete block. The Ground proximity test (Figure 2.49) is standardized in AWPA E18 (2013). The specimens are exposed close to the ground which leads to severe moisture conditions due to hindered re-drying and additional splash water. However, Zahora (2008) concluded that the ground proximity test might reflect too severe conditions when looking at common above ground applications.

Acceleration measures

Some of the 54 methods again have been applied in differently modified ways (e.g. different specimen size/orientation of specimens, external infestation, shading or additional coating) why at least in some

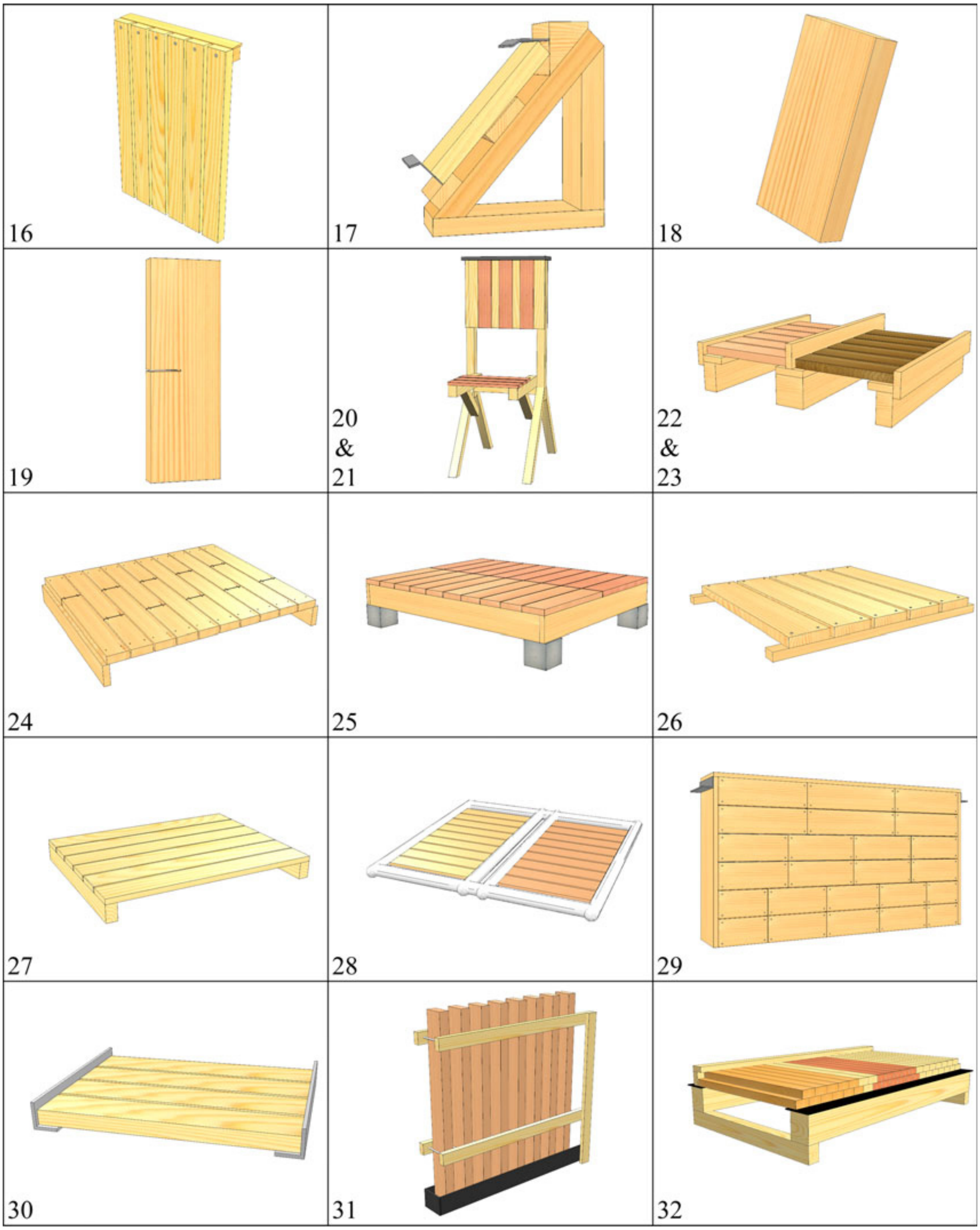

Figure 2. (Continued)

cases they could be interpreted as different or actually new methods. This would make an even higher number of above ground test methods that have been or are still in use. In most cases, they were modified to accelerate the decay process what consequently leads to shorter test durations. This, on the other hand, is favourable when it comes to acquisition of data for new wood protection systems to enable approval to the market (e.g. Clausen and Lindner 2011). CEN/TS 12037 (2003), for instance, suggests placing test rigs at a 'slightly shaded' test site to decelerate drying. According to their impact on test methods, the acceleration measures can be allocated to different climate levels as described by Brischke et al. (2006) (Table II).

External infestation and provision of water reservoir

Several studies on the effect of direct contact of test specimens with decay promoting components like

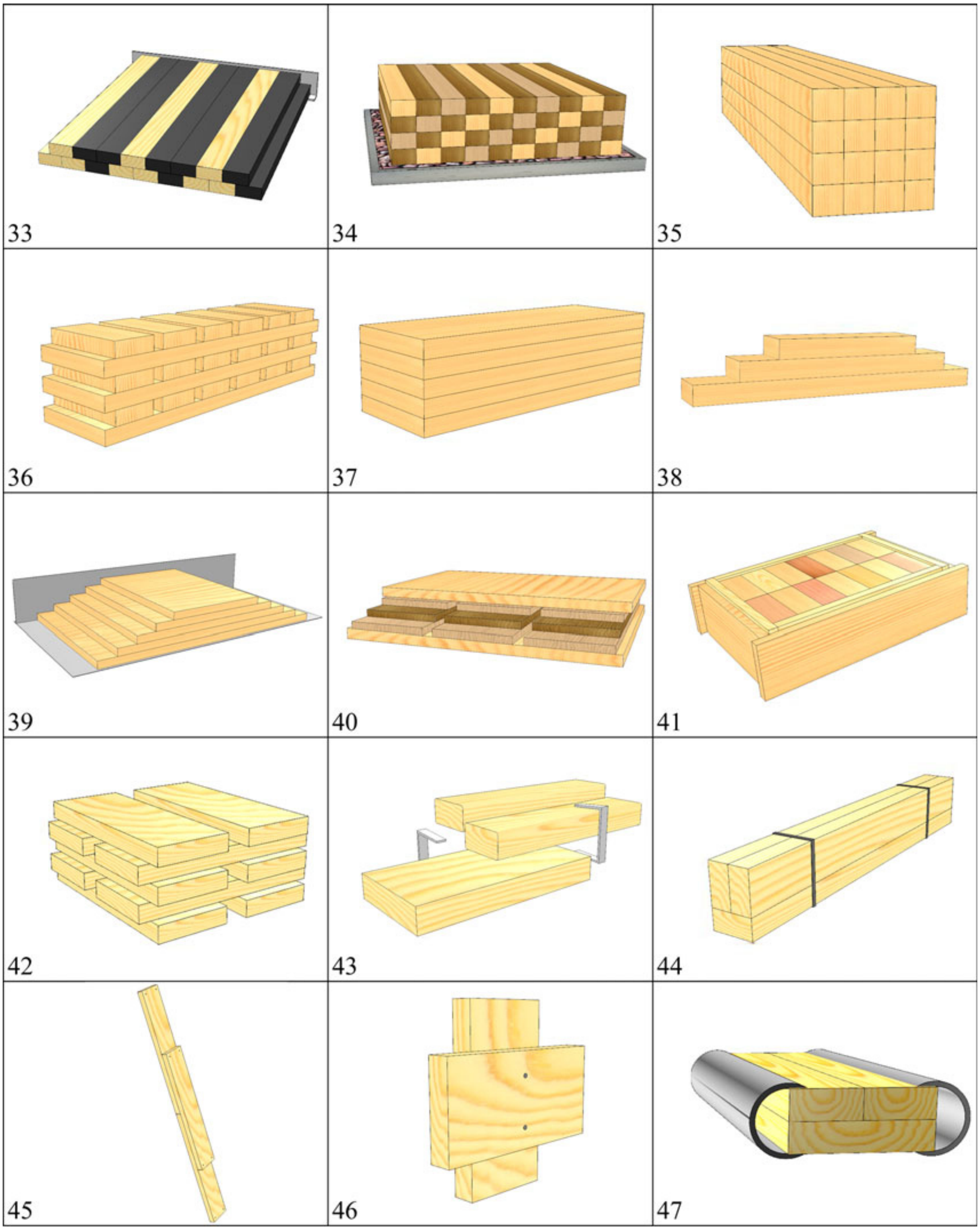

Figure 2. (Continued)

non-durable wood (feeder boards), pre-inoculated wood pieces or water reservoirs were carried out. Vidović (1981) used water reservoirs as well as pre-infected Scots pine sapwood (*Pinus sylvestris* L.) blocks to accelerate infestation of L-joint specimens. All pre-infected and watered L-joints showed severe attack already after 6 months of exposure, while only 34% of L-joints without infestation blocks exposed for the same time showed signs of decay after 3 years of exposure. Water reservoirs were also used in an accelerated L-joint test (Figure 2.2) by Van Acker and Stevens (1997). Rock wool sponges were placed at the point where tenon and mortise were connected. This sponge was moistened twice a day using an automated pipe system. In addition, the mortise member served as feeder element since it was composed of Scots pine sapwood and beech (*Fagus sylvatica* L.) to ensure colonization of brown and white rot fungi. Van Acker and Stevens (2003) reported that already after 18 months of exposure

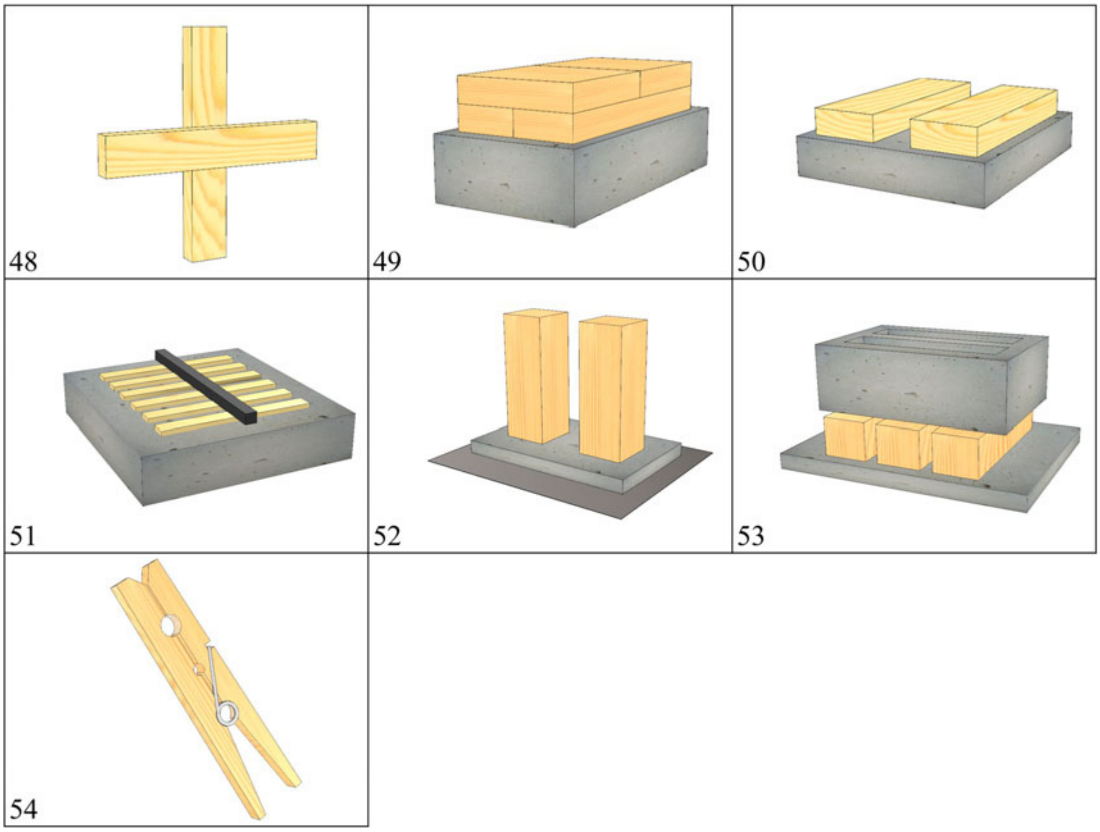

Figure 2. (Continued)

wood species under test could be differentiated in terms of decay resistance. A similar approach was made by Cookson and Carr (2009) who 'embedded' test specimens into two bolted L-shaped feeder boards, made from a non-durable hardwood and softwood (Figure 2.14). The specimens were separated by untreated wood blocks. In a second version, these separators were pre-inoculated with two different fungi and positioned in a way that all samples were in contact with both fungi. Over the test period of 4 years, several types of fruiting bodies were found on specimens and test frames (Cookson *et al*. 2014). It was concluded that this might be due to the high portion of untreated wood provided by feeder boards and separators in combination with a high moisture accumulation caused by the test design. Five out of the seven tested materials showed a higher fungal degradation in the pre-inoculated tests compared with the embedded test without pre-inoculated spacers.

Another example of including wood with low durability in test set-ups was reported by Zahora *et al*. (2013). Sandwich specimens were prepared from an untreated middle piece and two treated top/bottom layers of the same size. However, test results showed that the untreated feeder board had no detectable effect on decay development. Therefore, it seems that a combination of moisture promoting components and feeder elements is the more effective measure.

Feeder boards might, however, also be provided unintentionally. Brischke and Rapp (2008b) exposed Scots pine sapwood and Douglas fir heartwood in a Double layer test (Figure 2.32) for 7 years. Figure 3

Table II. Acceleration measures allocated to different climate levels.

Climate level	Micro climate	Meso climate	Macro climate
Acceleration measure	External infestation Water reservoir Feeder elements Coating Specimen size	Shading Distance to ground Trees/canopy Greenhouse	Climatic zone

Figure 3. Scots pine sapwood (left) and Douglas fir heartwood (right) exposed in a Double layer test for 7 years.

shows a test rig exposed in Freiburg (Germany). On both sides, the end grains of the specimens were in contact with untreated spruce boards which were installed to keep the specimens in place. As can be seen especially on the bottom board, the fungus was able to grow from one wood species to the other using the spruce board.

Coating

L-joint specimens according to EN 330 (1993) are poorly constructed and maintained components tested under above ground conditions. A coating is applied and impaired by purpose to simulate a practical application and to accelerate the decay process. Defective coating is an often included acceleration measure. Fougerousse (1981) exposed painted and unpainted Y-joints (Figure 2.4) and found higher decay rates for the painted set of specimens. This was explained by the fact that water was not able to evaporate what finally led to favourable conditions for fungal degradation. This effect was approved by Militz and Bloom (2000) as well as Francis and Norton (2005) who conducted MC measurements on coated and uncoated Lap-joint specimens. They found that the coated specimens showed high MC over a long period, whereas measurements in uncoated specimens showed long periods with low MC ($\leq$25% MC). Additionally, they included painted and unpainted specimens without lap and found a reversed effect: the painted specimens showed lower MC compared with the unpainted samples. This is confirmed by results from Meyer *et al.* (2013), who performed MC measurements on various test set-ups. MC was measured on painted and unpainted accelerated L-Joint tests (Figure 2.2). For the painted specimens, an almost 4 times higher number of days above 25% MC was found compared with the unpainted test specimens.

Specimen size

An acceleration measure which is in most cases achieved by the test method itself is the specimen size. The effect of faster re-drying with decreasing specimen size was approved by several studies (e.g. Fougerousse 1976, Sell 1980, Lebow *et al.* 2008, Zahora 2008). De Groot and Highley (1995) found differences in estimated service lives for the same wood species between different board sizes. They stated that the fact that larger samples where estimated to have a shorter service life might be explained by the ability of moisture uptake especially after cracks have developed. Mehlich (2009) conducted MC measurements on specimens made from spruce and Scots pine sapwood. In total, 10 different cross-sections were examined with respect to development of cracks and influence of dimension on moisture performance. The results showed that the number and size of cracks increased with increasing specimen volume. Furthermore, small dimensioned specimens showed faster water uptake but also faster water release. Cookson *et al.* (2014) conducted above ground tests with commercial clothes pegs made from pine (Figure 2.53). Under a number of 12 tests, they brought out in comparison the peg test with the smallest dimension showed the lowest decay activity. These findings underline the assumption of faster re-drying; consequently, lower MC and thus lower decay activity. Meyer *et al.* (2013) found differences in MC course for similarly exposed samples [Mini stake test (Figure 2.50) and Ground proximity test (Figure 2.49)]. Since the mini stakes had an almost 5 times lower volume (32 mm^3) compared with the Ground proximity test samples (150 mm^3) higher MCs were measured after rain events. A very fast re-drying led only to peaks of high MC compared with a moderately high, but more continuous moisture course for the Ground proximity test. This was also confirmed by findings of Meyer *et al.* (2014) who conducted moisture uptake tests under laboratory conditions using downscaled test specimens. The results showed that by tendency the capillary as well as the water vapour uptake decreased with increasing volume of the test specimen. Furthermore, a proportionally higher surface/volume ratio led to an increased moisture uptake. Augusta (2007) conducted decking tests comparing nine different specimen dimensions. These tests showed that not only the volume is decisive in terms of fungal degradation but also the surface–volume ratio. Specimens with a high surface–volume ratio showed faster re-drying, thus lower decay attack compared with specimens with the same volume, but a lower surface–volume ratio.

Shading

The impact of shading on the severity of test conditions has been subject of several studies. Brischke and Rapp (2008a), Clausen *et al.* (2006), Råberg *et al.* (2009) and Meyer *et al.* (2013) conducted comparative studies with shaded and unshaded specimens. However, the findings are inconsistent in some cases. Brischke and Rapp (2008b) stated that the decay process was accelerated in Double layer set-ups (Figure 2.32) placed in a shade box. Clausen *et al.* (2006) found lower MCs and a decreased decay progress in shaded Lap-joints compared with unshaded ones (Figure 2.3). These divergent findings might be explained by the material used to shade the specimens as well as by the test set-up itself. While Brischke and Rapp (2008b) used a 'water permeable textile', Clausen *et al.* (2006) covered the specimens with a tarp provided with slits. Meyer *et al.* (2013) also used a water permeable textile for shade boxes, but found a reduced MC in shaded Sandwich tests (Figure 2.43) with 30 days above 25% MC compared with 39 days in unshaded Sandwich tests for a period of 8 weeks. Råberg *et al.* (2009) conducted staple bed tests (Figure 2.42) in natural shade by placing them under trees what did not lead to remarkable acceleration of the decay process. In contrast, Preston *et al.* (2011) and Zahora *et al.* (2013) stated that Sandwich specimens exposed under a canopy decayed faster compared with those exposed at a test site with a higher climate index. This points on an additional acceleration measure when testing wood durability under trees: Falling leaves and other organic litter hinder re-drying of the specimens and can lead to accumulation of decomposing biomass (Brischke and Rapp 2007, Augusta 2007, Meyer *et al.* 2012).

Distance to ground

The distance between the test specimens and the ground can indirectly influence the decay development. Direct factors caused by minor exposure heights are for example: splash water, less wind speed, damped temperatures and a higher humidity. Zahora (2008) concluded that the distance to ground as well as the distance between bearing and end grain can influence decay. Cookson *et al.* (2014) found that decay in the embedded test (Figure 2.14) and a decking test could be faster when placing the rigs closer to ground. Commodity tests were conducted by Brischke *et al.* (2010) who calculated decay risks for a wooden cladding by using dose–response functions. Therefore, MC measurements were performed at seven different heights of a cladding and showed that for most wood species decay risk was the highest close to ground. Meyer *et al.* (2012) reported on differences in moisture performance between Double layer tests (Figure 2.32) exposed in Hannover, Germany, and Borås, Sweden. In total, three different test set-ups were compared: Double layer, Lap-joint (Figure 2.3) and Sandwich tests (Figure 2.43). Although there was no clear difference in moisture performance between the two test sites for the Lap-joint and Sandwich tests, the Double layer tests showed higher MC in Borås. On the one hand, this might be explained by the test method itself, but on the other hand the tests were exposed differently. Although the test rigs in Borås were placed under trees approximately 150 mm above ground, the Double layer set-up in Hannover was exposed on a roof test site on a grid floor which might have supported a very fast re-drying after rain events.

Test site/climate

In addition to construction details, the test-site specific climate has a major influence on decay risk (Francis and Norton 2005, Lebow *et al.* 2008). The relationship of climate indices and resulting decay risk has been subject of several studies. However, none of them resulted in a sufficiently strong correlation (Brischke and Rapp 2008a). Preston *et al.* (1996) carried out comparative L-joint tests (Figure 2.1) at Garston, UK, and Hilo, USA. The two test sites differed significantly in climatic load and thus in decay risk. This was confirmed by Morris *et al.* (2011) who conducted Decking tests according to AWPA E25 (2013) (Figure 2.25) at four climatically different test sites and Wong *et al.* (2004) who brought out comparative Lap-joint trials (Figure 2.3) at a Danish and a Malaysian test site. Furthermore, Brischke and Rapp (2008a) who conducted Double layer tests (Figure 2.32) at 23 different test sites within Europe found drastic differences in decay risk between the test sites. This again confirms earlier findings by Augusta and Rapp (2003) and Grinda *et al.* (2001).

However, studies performed by Cookson *et al.* (2014) and Meyer *et al.* (2012) showed that differences in the test set-up (e.g. distance to ground or shading) can be greater than the effect of climatic differences. This points to the impact of interactions between climate and test set-up specific characteristics resulting in a certain material climate (Brischke and Rapp 2008b, Brischke *et al.* 2013a). On the other hand, the effect of different details (e.g. moisture traps, feeder elements) can be superseded by climatic conditions (Brischke *et al.* 2013b). This was shown by De Groot (1992), who exposed 18 different test set-ups in comparison at two test sites located in Panama and Mississippi, USA. Influences of test design became apparent at the Mississippi site (temperate climate), whereas no effect was found for the Panama site (tropical climate).

As an alternative to exposure at tropical test sites, specimens might be exposed in greenhouses with tropical or subtropical climate conditions to accelerate decay as, for instance, shown by Evans *et al.* (1991), Polman *et al.* (1991) and Brischke and Rapp (2008b).

Evaluation methods and assessment schemes

The best known and most frequently used evaluation method for field tests is the so-called pick test. With this method, a pointed knife is pricked into the specimen and backed out again. The fracture characteristics of the splinters are assessed visually to identify the different decay types (Figure 4). In a second step, depth and distribution of decay are evaluated e.g. according to the European standard prEN 252 (2012, Table III) or the US standard AWPA E7 (2013, Table IV). However, this evaluation method was developed and is mainly used for evaluating decay on test specimens exposed in ground.

In the USA, the same rating scheme is recommended for different above ground test methods, such as Lap-joint (AWPA E16 2013), L-joint (AWPA E9 2013), Ground proximity (AWPA E18 2013) and Decking tests (AWPA E25 2013) referring to the in-ground test method according to AWPA E7 (2013). This eight-step rating scheme (between 10 ‘sound’ and 0 ‘failure’, Table IV), is based on the remaining cross-section of the specimen. In contrast, in Europe a five-step rating scheme is used for in-ground tests according to prEN 252 (2012), but the grading is based on depth and distribution of decay. With respect to above ground exposure, there are only two methods standardized in Europe, i.e. the Lap-joint method (CEN/TS 12037 2003, Table VI) and the L-joint method (EN 330 1993, Table V) using rating schemes which are similar, but not identical with the in-ground test assessment. While the Lap-joint rating scheme is at least referring to depth and spread of decay which can be related to the specimens’ cross-section, the rating scheme for L-joints is neglecting depth of decay. This makes it difficult to draw interferences from remaining cross-section to remaining strength. However, the preliminary draft, prEN 330 (2012), is now adapted to the rating scheme for Lap-joints and might therefore give an indication on resulting strength loss as well.

Based on the respective description of grading levels in the different standards, a quantitative comparison has been attempted as illustrated in Figure 5 referring to the minimum remaining cross-section that can be reached at the different rating steps. In comparison, the American system is more sensitive at earlier stages of decay (remaining cross-section >90%), but can be directly linked to each of the European systems. In contrast, even though the two European schemes both consist of a

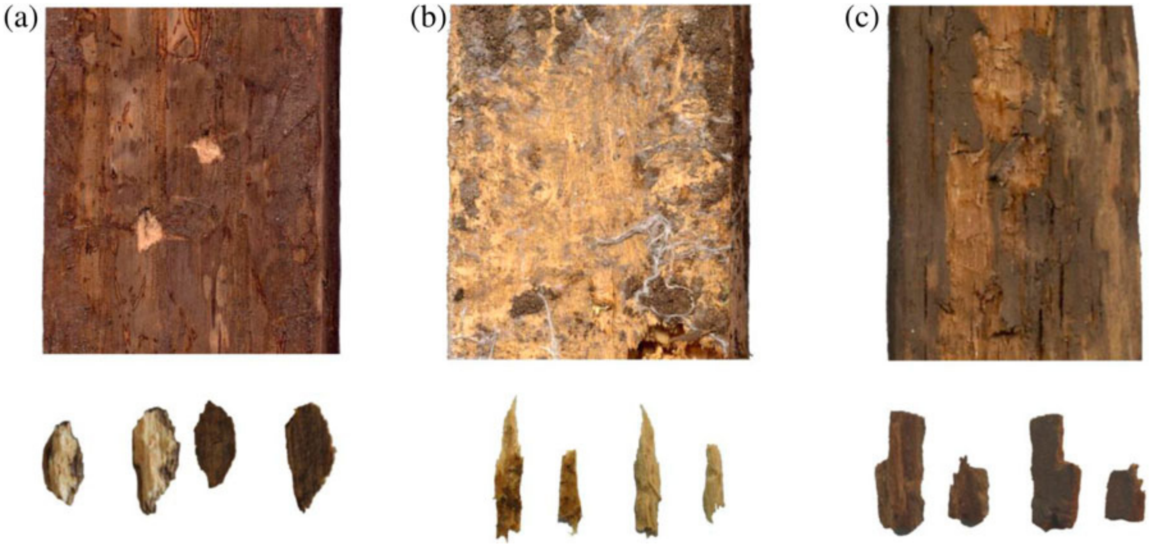

Figure 4. Splinter characteristics: (a) soft rot: shell-shaped splinter, attack on the outer wood shell, clean fracture; (b) white rot: whitish discolouration, long-fibred splinter, fibred fracture; (c) brown rot: brownish discolouration, brittle/cubical splinter, cross-checking texture.

Table III. Rating scale according to prEN 252 (2012).

Rating	Description	Definition
0	Sound	No change perceptible by the means at the disposal of the inspector in the field. If only a change of colour is observed, it shall be rated 0.
1	Slight attack	Perceptible changes, but very limited in their intensity and their position or distribution: changes which only reveal themselves externally by superficial degradation, softening of the wood being the most common symptom.
2	Moderate attack	Clear changes: softening of the wood to a depth of at least 2 mm over a wide surface (covering at least 10 cm^2) or by softening to a depth of at least 5 mm over a limited surface area (covering less than 1 cm^2).
3	Severe attack	Severe changes: marked decay in the wood to a depth of at least 3 mm over a wider surface (covering at least 25 cm^2) or by softening to a depth of at least 10 mm over a more limited surface area.
4	Failure	Impact failure of the stake in the field.

five-step rating scale, there are considerable differences between them. The remaining cross-section varies drastically for the same nominal decay ratings between in-ground and Lap-joint assessments. Practically, this means that for a rating 3 (severe attack), there can be a difference in minimum remaining cross-section of approximately 25% points.

Table IV. Decay rating scheme according to AWPA E7 (2013), AWPA E16 (2013) and AWPA E9 (2013).

Rating	Description	Definition
10	Sound	No sign or evidence of decay, wood softening or discolouration caused by microorganism attack.
9.5	Trace-suspect	Some areas of discolouration and/or softening associated with superficial microorganism attack.
9	Slight attack	Decay and wood softening is present. Up to 3% of the cross-sectional area is affected.
8	Moderate attack	Similar to '9' but more extensive attack with 3–10% of cross-sectional area affected.
7	Moderate/ severe attack	Sample has between 10% and 30% of cross-sectional area decayed.
6	Severe attack	Sample has between 30% and 50% of cross-sectional area decayed.
4	Very severe attack	Sample has between 50% and 75% of cross-sectional area decayed.
0	Failure	Sample has functionally failed. It can either be broken by hand due to decay or the evaluation probe can penetrate through the sample.

Table V. Rating scale according to EN 330 (1993) – L-joint method.

Rating	Description	Definition
0	Sound	No evidence of deterioration.
1	Slight attack	Slight discolouration, often dark and in streaks: no significant softening or weakening of the wood.
2	Moderate attack	Distinct discolourations, but in discrete patches and streaks, with small areas of decay (softened, weakened wood); typically no more than 25% of the visible area affected.
3	Severe attack	Marked softening and weakening of the wood typical of fungal decay and in extensive patches or streaks; distinctly more than 25% of the visible area affected
4	Failure	Very severe and extensive rot; tenon often capable of being easily broken.

Note: Observations made on specimens for non-destructive inspection will often yield a lower rating than when surfaces created by sawing are available for evaluation.

In particular, with respect to service life planning of timber structures and other wooden components, a rating system providing more information on

Table VI. Rating scale according to CEN/TS 12037 (2003) – Lap-joint method.

Rating	Description	Definition
0	Sound	No evidence of decay.
1	Slight attack	Visible signs of decay, but no significant softening or weakening of the wood.
2	Moderate attack	Areas of decay (softened, weakened wood); typically not more than 3 cm^2 and to a depth of 2–3 mm
2+	Moderate attack	Approaching 3, severe attack
3	Severe attack	Marked softening and weakening of the wood typical of fungal decay; distinctly more than 3 cm² affected and to a depth of 3 or 5 mm or 5–10 mm over a few cm²
3+	Severe attack	Approaching 4, failure
4	Failure	Very severe and extensive rot, joint member(s) often capable of being easily broken.

Note: (1) Discolouration obviously due to the attack of wood destroying Basidiomycetes and/or soft rot fungi shall be recorded and mentioned in the test report. If recommended by the sponsor of the test discolouration due to staining fungi should be rated according to Annex C, Table C.1. (2) Due to physico-chemical lignin degradation defibration of the wood cells may occur at the upper surface of the Lap-joints. Together with checks originating from differing wood moisture contents in different layers of the specimens, their upper surface may be softened, especially when the Lap-joints are wet. This has to be distinguished carefully from fungal decay. (3) In certain climatic areas with predominantly high relative humidity and frequent precipitation, soft rot may occur in a thin layer of the upper surface, leading to softening of this layer.

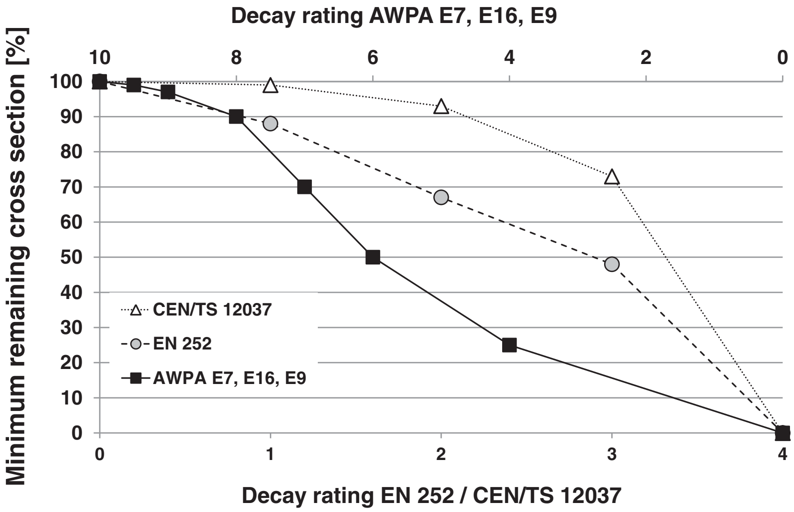

Figure 5. Comparison of different rating schemes.

resulting strength properties would be needed. In this respect, it becomes evident that the majority of established field test methods were rather designed for efficacy or durability testing than for service life prediction (e.g. Suttie *et al.* 2014).

Although the pick test is the best known and most widely used decay assessment method, it is criticized as being subjective and therefore highly sensitive to the interpretation of the respective evaluating person (Larkin and Laks 2008, Friese *et al.* 2009, Preston *et al.* 2011, Klamer *et al.* 2013). Furthermore, it is difficult to apply on modified wood due to changed surface strength properties (Pfeffer *et al.* 2008) and is less sensitive to early stages of decay (Wilcox 1983, Grinda and Göller 2005). However, in contrast to other evaluation methods that have been reported (e.g. Råberg *et al.* 2005, 2013, Francis and McGavin 2008, Friese *et al.* 2009), the pick test is less time- and cost-consuming and therefore preferential when high numbers of test specimens need to be evaluated.

Besides the pick test, numerous more advanced and partly significantly more objective assessment methods have been developed, such as different dynamic and static strength tests (Wilcox 1978, Curling *et al.* 2002), sounding and ultrasonic methods (Machek *et al.* 2001, Sivertsen *et al.* 2009, Reinprecht and Pánek 2012), different tomography techniques (Van den Bulcke *et al.* 2011) as well as molecular and immunodiagnostic techniques (Clausen 1997, Råberg *et al.* 2013). Since the majority of these assessment techniques have been developed for building diagnostics comprehensive reviews are available in this sector (e.g. Kasal and Tannert 2010). One aspect that most methods have in common is that clear evaluation criteria are missing (Lebow *et al.* 2008, Van den Bulcke *et al.* 2008). Therefore, it is important to determine the decay process as precise as possible to enable reliable service life estimations (Brischke and Rapp 2007).

Consequently, the following aspects should be considered important as the sensitivity of the respective assessment technique itself: decay does not always occur where it is expected or supposed to do (Brischke and Melcher 2014, Meyer *et al.* 2014). For instance, the contact face between specimen and bearing often turns out to be the most critical position in terms of wetting and fungal infestation even when the specimen itself provides a moisture trap forming a critical detail. Furthermore, decay sometimes develops on unexpected positions which are either difficult to detect or difficult to rate because of their poor accessibility with the respective inspection instrument. In some cases, the effect of measures intended to protect the specimen from severe exposure can turn into the opposite and promote decay. As shown in Figure 6, the end-grain sealant on Lap-joint specimens can have several effects apart from the intended protection of water intake – simulating a long timber member typical for construction purposes. At the same time, it serves as moisture barrier and hinders re-drying, it furthermore prevents high uptake of preservative solution close to the end grain. This in combination can lead to severe brown rot decay inside the specimen, where it is most difficult to detect. In contrast, the joint area is usually well protected because of high preservative retentions and to some extent the possibility to re-dry after wetting. As shown in Figure 7 also for untreated wood, the most critical part can be the contact face to the bearing or the small metal clamps keeping the two members together.

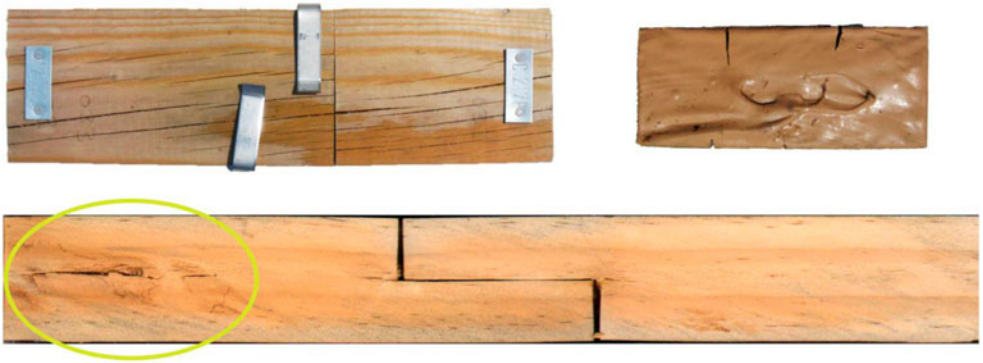

Figure 6. Top left: Lap-joint specimen after 3 months of exposure; top right: cracks have already led to damages in the end-grain sealing. Bottom: slide cut from Lap-joint specimen exposed for 3 years, showing heavy decay inside the specimen close to the end grain.

Finally, one has to decide which part or component of a segmented test specimen is decisive for its overall decay rating. Following the 'worst case rule' might in this case lead to a generally more severe test situation than it was initially intended to be. On the other hand, onset and progress of decay cannot be neglected although it is, for instance, limited to the bearing contact faces. Clear definitions and test protocols are needed to assure reproducibility of tests, but are in many cases lacking in the respective standards.

Practical aspects

Besides evaluating the individual test methods with respect to the principles of their set-up and resulting severity of exposure, one needs to consider time and effort required for conducting the test as well as its practicability (Meyer *et al.* 2013). Material costs, costs for additional components and the need to replace components should not be underestimated. Insufficient stability and permanency of test rigs and other details of the set-up can cause unexpected costs. Figure 8 shows specimens of L-joint and embedded tests, both consisting of a tenon and a mortise member made from two different wood species (feeder components made from non-durable species). In both set-ups, severe cracking occurred after a short time of exposure. While this leads to increased capillary water uptake (which is not necessarily negative), it also means that the tenon members are no longer tightly fixed to the feeder mortise. Besides cost aspects, the test conditions change over time thus reducing the reproducibility of test results.

Replacement of non-reusable components such as cable straps used for bundle or Lap-joint tests can cause additional costs and efforts. Also the assessment can become more difficult when the fitting of test components is not assured after swelling and deformation. Therefore, tolerances need to be considered, e.g. when using metal clamps to connect specimen members.

Even more important than the costs for replacements might be potential changes of the respective set-up. In particular, the removal of failed control or reference specimens, which have the potential to infect and moisten other test specimens, is critical.

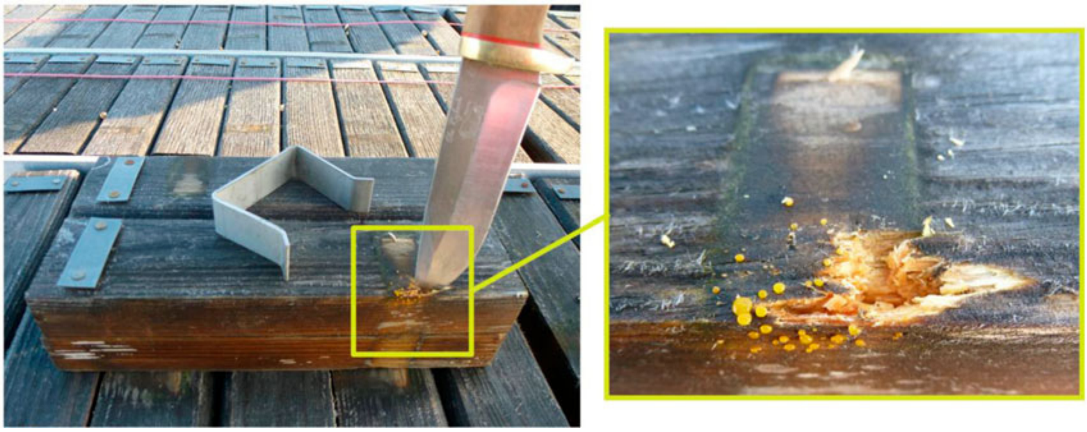

Figure 7. Sandwich specimen showing decay under a metal clamp.

Figure 8. Left: accelerated L-joint test. Mortise shows cracks. Right: embedded test with open mortise.

For some test methods such as Decking or Double layer tests also the size of the entire set-up can have significant effects on the moisture conditions (Saladis and Rapp 2004). Reducing the size of a given set-up during a running test might consequently change the severity of exposure and should be avoided.

Conclusions

Various criteria can be applied to above ground test methods strongly depending on the study objectives. The suitability of a certain test protocol may vary, but is generally dominated by its ability to reflect real-life use conditions and the potential to deliver reliable results in an acceptable time span. In particular for industry purposes (e.g. approval of wood preservatives or timber products) costs for performing above ground tests play an important role.

The time needed to obtain reliable results depends mainly on the severity of exposure (location, moisture trapping, test set-up) and the limit state defined for the test (e.g. onset of decay, failure). Since the severity of exposure is always a product of the climatic conditions and the test set-up itself both parameters can be considered control quantity. Various studies showed that more humid and warm climates can accelerate decay progress considerably, but directly transferring test results e.g. from the tropics to temperate zones is not necessarily possible. Climatic effects might be neglected for durability studies by factorization, i.e. relating test results to reference materials. In contrary, field test data for service life prediction must be carefully related to the respective climatic conditions.

In contrast to in-ground tests, where permanent wetting can be assumed, wood above ground can be exposed to a wide range of moisture regimes. This is to a large extent also reflected by the high number of above ground test methods providing very different moisture loads. The number of studies that systematically quantified the ‘severity of exposure’ is still rare and more data on the climate and moisture conditions in field tests would be needed for a better estimate. However, without controversy it can be concluded that a single method cannot reflect the full spectrum of moisture conditions possibly occurring above ground. Within this review, at least five groups of test methods were identified that can be related to different structure details and thus to different moistening regimes: single elements, joints, blocks and stacks, bundles, and components with contact to concrete.

At this stage, it seems inappropriate to define an ‘ideal above ground test method’, firstly because they need to be adapted to the respective purpose, and secondly because a single method cannot fulfil requirements for all above ground situations. In particular, with respect to service life prediction of wooden components, a compromise is required between acceptably long test durations and representativeness of the respective real-life use conditions. Nevertheless, the following might be useful and recommended for future test protocols:

- simple specimen preparation and test set-up;
- specimen dimension enabling preparation from regular sapwood portions;
- specimens forming separate units (no unintended contact to other materials);
- decay progress easy to detect and to quantify;
- unintended influence of additional components (fasteners, clamps, bearing, etc.) prevented;
- stable and durable test rigs;
- low sensitivity to wind loads, animals and vandalism.

To further promote above ground field testing and to improve the usability of test results, their comparability shall be improved. In particular, the use of divergent grading schemes and assessment techniques hamper their utilization, in particular for service life prediction and performance classification purposes.

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Paper 2

Holzfeuchtemonitoring im Rahmen von Dauerhaftigkeitsprüfungen

Praktische Erfahrungen aus Freilandversuchen

Linda Meyer, Christian Brischke, Martin Kasselmann

Unterschiedliche Methoden lassen sich zur Charakterisierung der Feuchteperformance von Holz einsetzen. Es werden direkte und indirekte Messmethoden unterschieden. Einige erlauben die Bestimmung der globalen, andere die Bestimmung der lokalen Holzfeuchte. Jede Messmethode hat Besonderheiten, die bereits beim Design des Prüfaufbaus und beim Einsatz im Freiland berücksichtigt werden sollten. In diesem Beitrag sind praktische Erfahrungen aus unterschiedlichen Studien, die in den vergangenen vier Jahren durchgeführt wurden, zusammengefasst. Ziel des Beitrages ist es, Faktoren, die die gravimetrische und die elektrische Holzfeuchtebestimmung beeinflussen, zu identifizieren. Die Ergebnisse aus den unterschiedlichen Studien belegen das Potenzial eines Feuchtemonitorings für eine verbesserte Interpretation von Freilandprüfergebnissen. Es werden Einflussfaktoren, die für eine zielgerichtete Holzfeuchtemessung im Freiland zu beachten sind, beschrieben. Insbesondere der Einfluss von Messposition, Messtiefe, Bewitterung und die Identifizierung der kritischsten Position innerhalb eines Prüfaufbaus werden hervorgehoben.

Schlüsselwörter: Holzfeuchtemessung, Lap-joint-Methode, Performance, Widerstandsverfahren

Einleitung

Holzprodukte im Außenbereich werden mehrheitlich außerhalb der Erde verbaut. Die Dauerhaftigkeit von Fassaden, Terrassen, Decks, Spielgeräten, Gartenmöbeln oder Carports wird dabei von der Menge und der Art der im Holz enthaltenen Inhaltstoffe mit biozider oder hemmender Wirkung bestimmt. Darüber hinaus ist die Dauerhaftigkeit des Holzes aber auch die Folge seiner Feuchteperformance (*Kutnik et al.,* 2014). Pilzlicher Holzabbau erfordert Wasser, um den dafür notwendigen Enzymtransport in die Zellwände zu ermöglichen. Folglich steigt das Risiko für einen Pilzbefall bei Holzfeuchten oberhalb Fasersättigung. Des Weiteren hat die Temperatur des Holzes einen maßgeblichen Einfluss auf einen Abbau durch Pilze, da sie nahezu alle biochemischen Reaktionen bestimmt. Um das Feuchteverhalten von Holz zu charakterisieren und den Effekt einer Feuchtebelastung auf die sich ergebende Dauerhaftigkeit zu quantifizieren, sind verschiedene Methoden entwickelt und auch bereits angewendet worden. Dennoch ist ihr Einsatz im Rahmen von Labor- und Freilandprüfungen zur Bestimmung der Dauerhaftigkeit noch immer selten (*Brischke et al.,* 2014).

Grundsätzlich lassen sich direkte und indirekte Methoden zur Bestimmung der Holzfeuchte einsetzen (u. a. *Glass und TenWolde,* 2007). Direkte gravimetrische Messungen lassen sich automatisiert und rechnergestützt mit Wägezellen durchführen (*Van den Bulcke et al.,* 2009). Diese Methode ist für ihre hohe Genauigkeit bekannt und ermöglicht die Bestimmung der globalen Holzfeuchte (Global Moisture Content – GMC) eines Holzprüfkörpers, aber nicht die Holzfeuchte an einer bestimmten Position, wie beispielsweise einem kritischen Konstruktionsdetail. Außerdem ist die Methode anfällig für Wind und Regenereignisse, weshalb eine inerte Referenz mitgeprüft werden muss. Abmessungen und Gewicht der Prüfkörper sind ebenfalls begrenzt.

Im Gegensatz dazu erlauben indirekte Methoden wie das kapa-

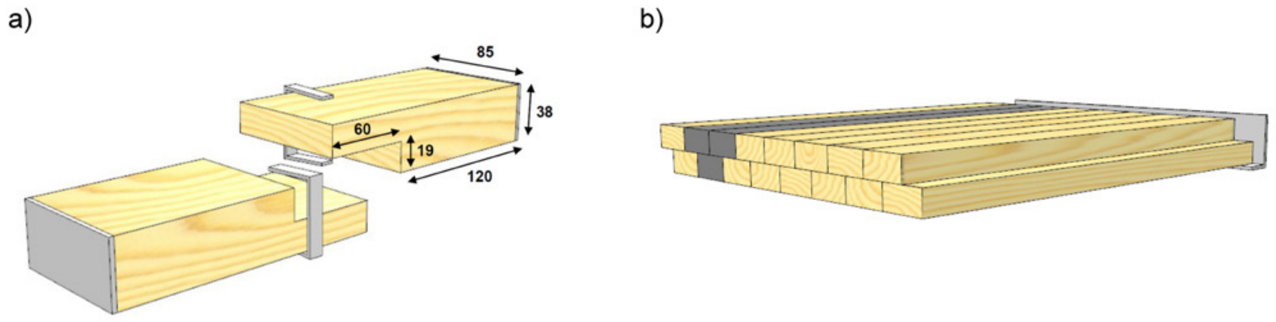

Abb. 1: Aufbau der Freilandprüfungen: a) Lap-joint-Verfahren, b) Doppellagenverfahren
Fig. 1: Set up of field tests: a) Lap-joint method, b) Double layer method

zitive Verfahren oder hygroskopische Messgeräte die Bestimmung der lokalen Feuchte (Local Moisture Content – LMC). Kapazitive Messungen sind stark abhängig von der Rohdichte des Holzes, die aber oft unbekannt ist und innerhalb eines Untersuchungsobjektes variiert. Hygroskopische Messungen basieren auf dem Zusammenhang zwischen relativer Luftfeuchte, Temperatur und Holzausgleichsfeuchte. Ausgehend von der Temperatur und der relativen Luftfeuchte in einem Bohrloch, lässt sich auf die Holzfeuchte schließen (u. a. *Evans,* 2004; *Dyken und Klepp,* 2010). Die Methode ist aber auf den Feuchtebereich unterhalb Fasersättigung beschränkt, der für pilzlichen Holzabbau nahezu unbedeutend ist.

Eine weitere indirekte Messmethode, die häufig eingesetzt wird, ist das elektrische Widerstandsverfahren (*Du,* 1991; *Glass und TenWolde,* 2007). Es ermöglicht ebenfalls die Bestimmung der lokalen Holzfeuchte zwischen zwei Messelektroden, so dass sich kritische Konstruktionsdetails untersuchen lassen. Die elektrische Leitfähigkeit des Holzes hängt allerdings u. a. von der Holzart und der Holztemperatur ab, so dass holzartspezifische Kennlinien benötigt werden und eine Temperaturkompensation durchgeführt werden muss. Vorangegangene Untersuchungen haben gezeigt, dass Messungen mit ausreichend hoher Genauigkeit zwischen 15 % und 50 % Holzfeuchte möglich sind (*Brischke et al.,* 2008). Elektrische Widerstandsmessungen an modifiziertem und mit Holzschutzmitteln behandeltem Holz ergaben ebenfalls plausible Messwerte weit über Fasersättigung (*Brischke und Lampen,* 2014).

In verschiedenen Studien zeigte sich, dass zahlreiche Aspekte in Abhängigkeit von der eingesetzten Methodik (Prüfmethode zur Bestimmung der Dauerhaftigkeit und Methode zur Holzfeuchtebestimmung) berücksichtigt werden müssen. In diesem Beitrag sollen praktische Erfahrungen mit dem Monitoring der Holzfeuchte im Rahmen von Dauerhaftigkeitsprüfungen im Freiland und im Labor zusammengestellt werden. Deshalb beinhaltet der Beitrag Ergebnisse aus unterschiedlichen Studien, die von den Autoren während der letzten vier Jahre durchgeführt wurden. Ziel des Beitrages ist es somit, Faktoren, die die gravimetrische und elektrische Holzfeuchtebestimmung beeinflussen, zu identifizieren, und sie bei der Interpretation von Freilandversuchsergebnissen besser einschätzen zu können.

Material und Methoden

Bestimmung globaler und lokaler Holzfeuchte

Ziel der Messungen war ein Vergleich zwischen globaler und lokaler Holzfeuchte an unterschiedlichen Prüfaufbauten. Prüfkörper aus Kiefernkern- und Kiefernsplintholz (*Pinus sylvestris* L.) wurden im schwedischen Borås in horizontaler Doppellage 20 cm und als Lap-joint-Prüfkörper (Lap-joint – Überblattung) ca. 1 m oberhalb des Bodens exponiert (Abb. 1a). Die Prüfkörper für den Doppellagentest (25 mm x 50 mm x 500 mm) wurden in Anlehnung an das von *Rapp und Augusta* (2004) beschriebene Doppellagenverfahren auf Aluminium-L-Profilen exponiert (Abb. 1b). Hierbei lagen die Prüfkörper unbefestigt in den L-Profilen und die untere Lage war um 25 mm seitlich gegenüber der oberen Lage verschoben. Die Lap-joint-Prüfkörper wurden entsprechend den Maßgaben nach *CEN/TS 12037* (2003) hergestellt und ebenfalls auf Aluminiumprofilen horizontal exponiert. Die Ausgangsfeuchte der Prüfkörper wurde anhand zugeordneter Referenzprüfkörper ermittelt, die hierzu bis zur Gewichtskonstanz gedarrt wurden.

An den bereits zuvor exponierten Prüfkörpern wurde während eines Zeitraums von sechs Wochen die Holzfeuchte nach drei unterschiedlichen Verfahren in regelmäßigen Abständen bestimmt:

1. Periodisch – gravimetrisch: Die Bestimmung der Masse der Prüfkörper erfolgte auf 0,01 g durch Wägung im Feld.
2. Periodisch – elektrisch: Die elektrischen Holzfeuchtemessungen erfolgten in Anlehnung an das entwickelte Messsystem von *Brischke et al.* (2008). Der elektrische Widerstand des Holzes wurde hierzu zwischen zwei mit Polytetrafluorethylen isolierten Einschlagelektroden (Länge: 50 mm; Messtiefe: ca. 25 mm; Abstand zwischen Elektroden: 30 mm) mit Hilfe eines resistiven Materialfox-Messgerätes (Fa. Scanntronik Mugrauer GmbH) bestimmt. Die Holzfeuchte wurde anhand holzartspezifischer Widerstandskennlinien (vgl. *Brischke und Lampen,* 2014) errechnet.
3. Kontinuierlich – elektrisch: Holzfeuchte und -temperatur wurden analog zur periodisch-elektrischen Messung täglich bestimmt und aufgezeichnet. Hierzu wurden Miniaturdaten-

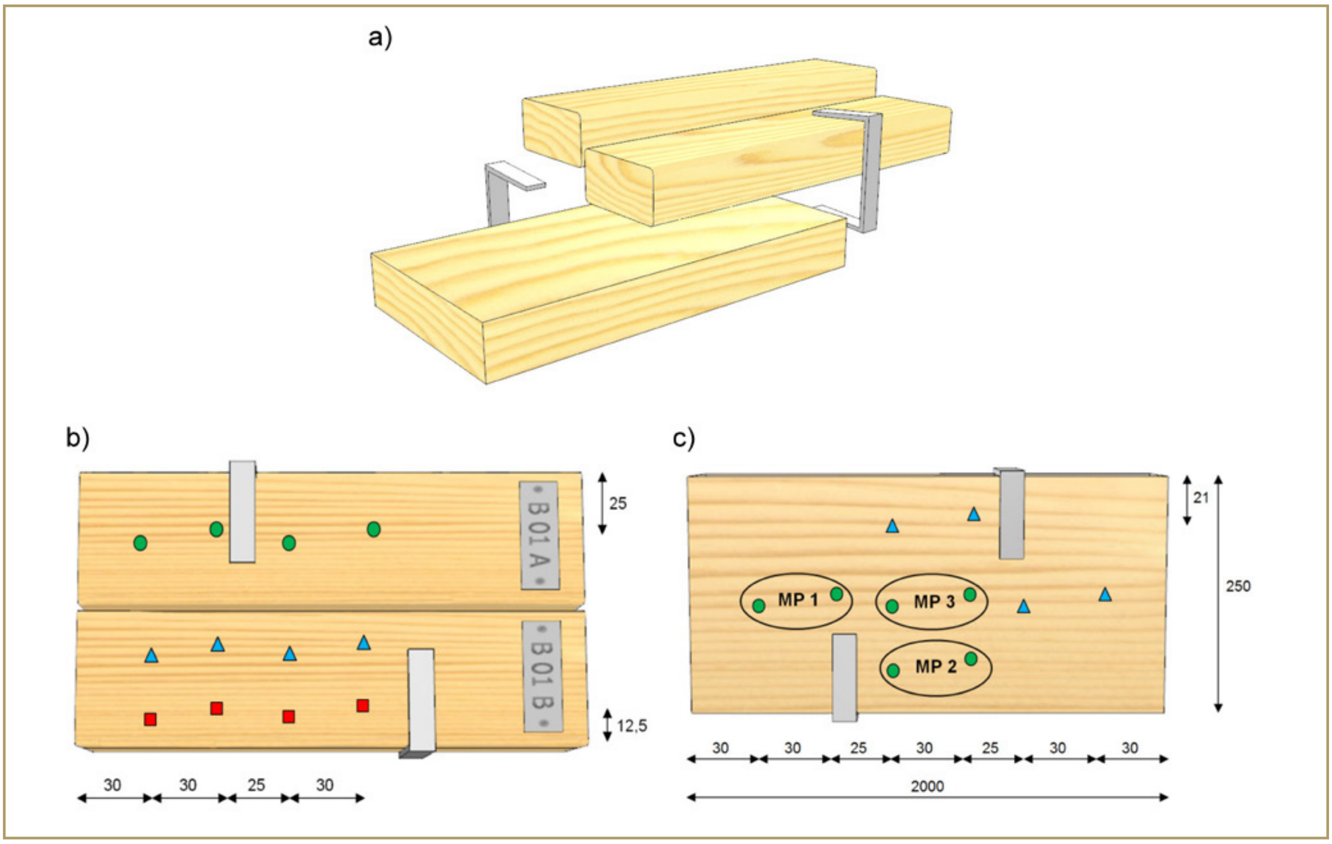

Abb. 2: Holzfeuchtemessungen an Sandwichprüfkörpern: a) Explosionszeichnung, b) Draufsicht obere Elemente, c) Unterseite des unteren Elementes mit unterschiedlichen Messpositionen (MP 1-3) – Messtiefen b) und c): rotes Quadrat 6 mm, grüner Kreis 15 mm, blaues Dreieck 23 mm, alle Maße in mm

Fig. 2: Wood moisture content measurements on sandwich specimens: a) Explosion view, b) Top view upper members, c) Bottom view lower member with different measuring positions (MP 1-3) – measuring depths b) and c): red square 6 mm, green circle 15 mm, blue triangle 23 mm, all dimensions in mm

logger Materialfox Mini und Thermofox Mini (Fa. Scanntronik Mugrauer GmbH) verwendet.

Untersuchung der Feuchteverteilung in Prüfkörpern

Ziel der Untersuchung war es, den Effekt der Messposition auf die Ergebnisse bei einem vorgegebenen Prüfaufbau zu quantifizieren. Hierzu wurde die lokale Holzfeuchte an unterschiedlichen Positionen und in unterschiedlichen Tiefen von Sandwichprüfkörpern im Freiland vergleichend bestimmt. Sandwichprüfkörper wurden nach dem von *Zahora* (2008) beschriebenen Verfahren wie in Abb. 2 dargestellt in modifizierter Weise hergestellt und auf dem Versuchsstand der Leibniz Universität in Hannover exponiert. Jeweils drei Parallelprüfkörper wurden aus den Holzarten Buche (*Fagus sylvatica* L.), Stieleiche (*Quercus robur* L.), Douglasiensplint- und Douglasienkernholz (*Pseudotsuga menziesii* Franco) hergestellt. Die Sandwichprüfkörper bestanden aus einem unteren Element (200 mm (ax.) x 25 mm x 100 mm) und zwei oberen Elementen (200 mm (ax.) x 25 mm x 49 mm) mit abgerundeten Kanten (r = 5 mm). Die drei Elemente wurden durch Stahlklammern miteinander verbunden. Die Prüfkörper wurden 1 m über dem Boden auf Aluminium-L-Profilen exponiert. Jeder Prüfkörper war mit insgesamt 18 Elektroden versehen, so dass sich wie in Abb. 2b und 2c dargestellt die Holzfeuchte an neun Positionen mit Hilfe des in Abschnitt „Bestimmung globaler und lokaler Holzfeuchte“ beschriebenen Hand-Holzfeuchtemessgerätes periodisch bestimmen ließ.

Untersuchung zum Einfluss einer Bewitterung auf die Holzfeuchte im Freiland

Ziel dieser Untersuchung war es, mögliche Einflüsse einer oberflächlichen Degradation sowie weiterer Witterungseinflüsse auf das Feuchteverhalten von Holz zu detektieren und ggf. zu quantifizieren. Hierzu wurden Prüfkörper mit den Abmessungen 5 mm x 10 mm x 100 mm (ax.), die verkleinert im Maßstab 1:5 Freilandprüfkörpern nachempfunden waren, unter Laborbedingungen einer 24-stündigen Befeuchtung bzw. Trocknung ausgesetzt. Es wurden Prüfkörper aus insgesamt 40 verschiedenen Materialien hergestellt (Tab. 1), deren Dauerhaftigkeit parallel im Freiland geprüft wurde (*cf. Meyer et al.*, 2012). Je Material wurden acht Parallelen (n = 8) geprüft. Die Prüfkörper wurden bei 103 ± 2 °C bis zur Massenkonstanz gedarrt und auf 0,001 g genau gewogen. Ein Prüfkörpersatz wurde zur Bestimmung der Flüssigwasseraufnahme während 24 h in demineralisiertes Wasser getaucht. Ein zweiter Satz

Tab. 1: Native, chemisch und thermisch modifizierte sowie mit Schutzmitteln behandelte Hölzer für Wasseraufnahmeversuche
Tab. 1: Untreated timbers, chemically and thermally modified timbers and preservative treated timbers for water uptake tests

Native Hölzer	Botanischer Name
Kiefer-Splintholz I	*Pinus sylvestris* L.
Kiefer-Splintholz II	
Kiefer-Kernholz I	
Kiefer-Kernholz II	
Kiefer harzreich	
Southern Yellow Pine (SYP)	*Pinus* spp.
Radiata-Kiefer	*Pinus radiata* D. Don
Fichte I	*Picea abies* Karst.
Fichte II	
Lärche I	*Larix decidua* L.
Lärche II	
Buche I	*Fagus sylvatica* L.
Buche II	
Ahorn	*Acer* spp.
Stieleiche	*Quercus robur* L.
Esche	*Fraxinus excelsior* L.
Robinie I	*Robinia pseudoacacia* L.
Robinie II	
Douglasie I	*Pseudotsuga menziesii* Franco
Douglasie II	
Chemisch und thermisch modifizierte Hölzer	
Furfurylierte SYP	
Furfurylierte Kiefer	
Furfurylierter Ahorn	
Furfurylierte Radiata-Kiefer	
Furfurylierte Buche	
Acetylierte SYP	
Acetylierte Radiata-Kiefer	
Thermisch modifizierte Kiefer	
Öl-Hitze-behandelte Fichte	
Öl-Hitze-behandelte Esche	
Schutzmittelbehandelte Hölzer	
Kiefer CCA 2 kg/m³	
Kiefer CCA 4 kg/m³	
Kiefer CCA 9 kg/m³	
Kiefer ACQ (AC 800)	
Kiefer Mikro-Kupfer	
Kiefer – Schwermetallfrei	
Kiefer – Organic I	
Kiefer – Organic II	

wurde während 24 h in einer Miniaturklimakammer einer Temperatur von 20 °C und einer relativen Luftfeuchte von 100 % ausgesetzt. Nach einer erneuten Wägung wurde die Feuchteaufnahme bzw. Holzfeuchte u nach Gl. 1 bestimmt. Anschließend wurde derselbe Prüfkörpersatz auf dem Versuchsstand der Leibniz Universität in Hannover exponiert. Nach einer 6-monatigen Bewitterung im Freiland wurden alle Tests wiederholt.

$$u = \frac{m_{24} - m_0}{m_0} \qquad (1)$$

Dabei ist
u = Holzfeuchte [%],
m_{24} = Masse nach 24 h Exposition [g],
m_0 = Darrmasse [g].

Ergebnisse und Diskussion

Unterschiede zwischen globaler und lokaler Holzfeuchte

Die Feuchteverläufe von Kiefernsplint- und Kiefernkernholz sind für die drei eingesetzten Messmethoden vergleichend in Abb. 3 dargestellt. Die Doppellagenprüfkörper wiesen generell höhere Holzfeuchten als die Lap-joints auf. Des Weiteren ergaben die beiden Widerstand-basierten Messmethoden in der Doppellage weitgehend übereinstimmende Feuchteverläufe. Die gravimetrische Feuchtebestimmung ergab einen Feuchteanstieg nach etwa der Hälfte der Expositionszeit für Splint- und Kernholz in der Doppellage und Splintholz in den Lap-joints. Hier zeigte sich deutlich der Einfluss der Messmethode. Während bei der gravimetrischen Bestimmung die globale Holzfeuchte (Global Moisture Content – GMC), also die mittlere Holzfeuchte des gesamten Prüfkörpers, erfasst wurde, ließ sich mit der elektrischen Widerstandsmessung nur die lokale Holzfeuchte (Local Moisture Content – LMC) in einem etwa 30 mm langen Bereich im Zentrum des Prüfkörpers bestimmen.

Folglich spiegeln die hier ermittelten Unterschiede zwischen GMC und LMC variierende Feuchtebedingungen zwischen Prüfmethoden oder Versuchsmaterialien wieder und lassen sich durch den kapillaren bzw. diffusiven Feuchtetransport in den Prüfkörpern erklären (*Meijer und Militz,* 2000 und 2001): Für die kapillare Wasseraufnahme vom Hirnende zur Prüfkörpermitte wurde eine gewisse Zeit benötigt (*Wagenführ und Scholz,* 2008). Das so aufgenommene flüssige Wasser wurde zunächst als GMC erfasst, aber es bedurfte einer deutlichen Zeitspanne, bis es auch in Form von LMC nachweisbar wurde.

Einfluss der Messposition

Die Holzfeuchte von Buche und Eiche unterschied sich deutlich in den unterschiedlichen Tiefen der im Freiland exponierten Sandwichprüfkörper. Die Feuchte von Douglasiensplint- und Douglasienkernholz wies hingegen nur geringe Unterschiede auf. Wie in Abb. 4 dargestellt war die Holzfeuchte für alle Holzarten in 23 mm Tiefe, also nahe der durch die drei Prüfkörperelemente gebildeten Wasserfalle, am höchsten, gefolgt von 15 mm und 6 mm Tiefe. Für Buchenholz wurden Unterschiede von über 20 %-Punkten festgestellt. Eine weitere Ursache für die vergleichsweise hohen Holzfeuchten in 23 mm Tiefe könnte neben der Wasserfalle, welche zu einer erhöhten Feuchteansammlung führt, die verringerte Ab-

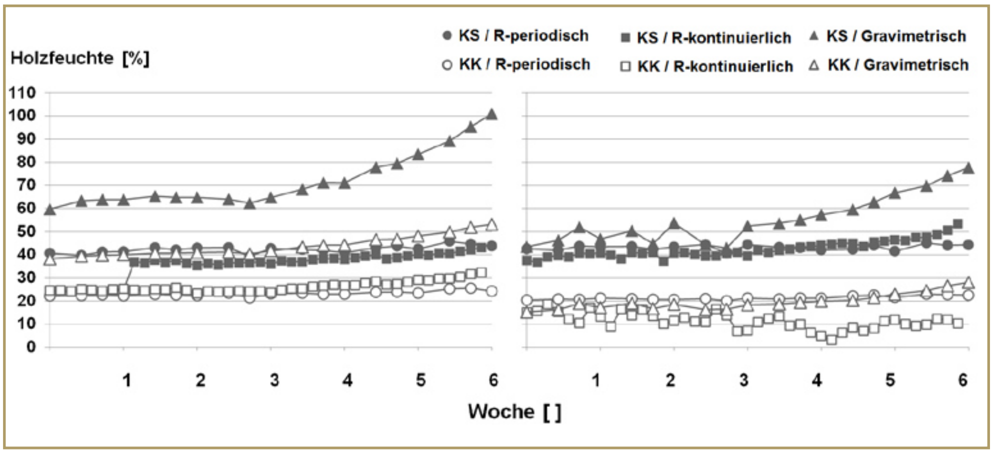

Abb. 3: Verlauf der Holzfeuchte von im Freiland exponiertem Kiefernsplintholz (KS) und Kiefernkernholz (KK) – links: Doppellage, rechts: Lap-joint

Fig. 3: Moisture course of Scots pine sapwood (KS) and Scots pine heartwood (KK) exposed outdoors – left: double layer test, right: lap-joint test

trocknungsmöglichkeit an dieser Stelle sein. In Abb. 5 sind die Holzfeuchteverläufe der vier Hölzer für unterschiedliche Messpositionen (MP 1-3) im unteren Prüfkörperelement dargestellt. Wiederum unterschied sich die Holzfeuchte von Buche und Eiche deutlich zwischen den Messpositionen, wobei die höchste Feuchte wie erwartet nahe des Hirnholzes auftrat (MP 1), gefolgt von den nahe der Seitenflächen gelegenen Messstellen (MP 2). Da die Holzfeuchte der Douglasie während der gesamten Messperiode nahe der unteren Grenze des Messbereiches (ca. 15 %) lag, ließen sich keine Unterschiede zwischen den Messstellen ermitteln.

Einfluss der Bewitterung

Der Zusammenhang zwischen kapillarer Feuchteaufnahme (nach 24 h Tauchen) und der Wasserdampfaufnahme (nach 24 h Exposition in 100 % relativer Luftfeuchte) ist in Abb. 6 vor der Bewitterung und in Abb. 7 nach sechs Monaten Bewitterung im Freiland für folgende drei Materialgruppen dargestellt: native Hölzer, modifizierte Hölzer und mit Schutzmitteln behandelte Hölzer. Generell stieg die Flüssigwasseraufnahme mit zunehmender Dampfaufnahme zwar für alle Materialien an, die hohe Variation zeugte aber von holzart- und materialspezifischen Besonderheiten (*Stamm,* 1929; *Wadsö,* 1994; *Engelund et al.,* 2013). So ließ sich beispielsweise die hohe kapillare Wasseraufnahme von thermisch modifizierter Kiefer (TMT-Kiefer) nicht aus deren Wasserdampfaufnahmevermögen ableiten, deckte sich aber mit Beobachtungen von *Johansson* (2008) und *Welzbacher* (2007). Des Weiteren stimmen die hohen Flüssigwasseraufnahmen der modifizierten Hölzer verglichen mit deren Wasserdampfaufnahmen mit Beobachtungen von *Meyer et al.* (2012) in Freilandversuchen überein. Insbesondere für acetyliertes Holz lässt sich die erhöhte kapillare Wasseraufnahme durch den dauerhaft gequollenen Zustand des Holzes nach der Acetylierung erklären (*Larsson und Simonson,* 1994).

In Abb. 7 ist der Zusammenhang zwischen der Feuchteaufnah-

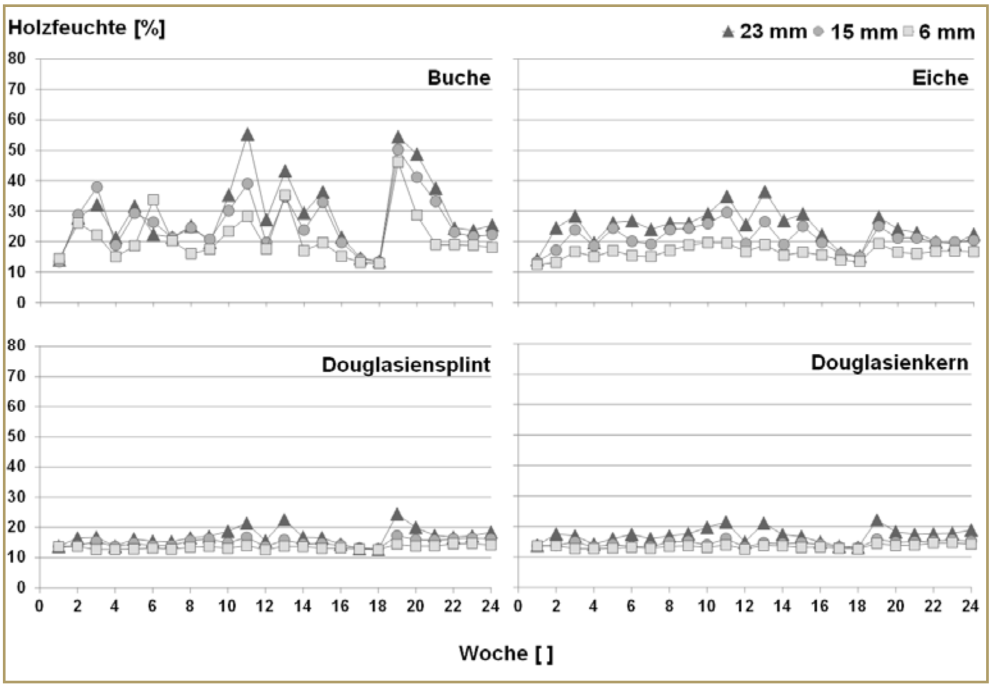

Abb. 4: Verlauf der Holzfeuchte in unterschiedlichen Messtiefen in den oberen Elementen im Freiland exponierter Sandwichprüfkörper

Fig. 4: Moisture course for different measuring depths in the upper two members of a sandwich specimen

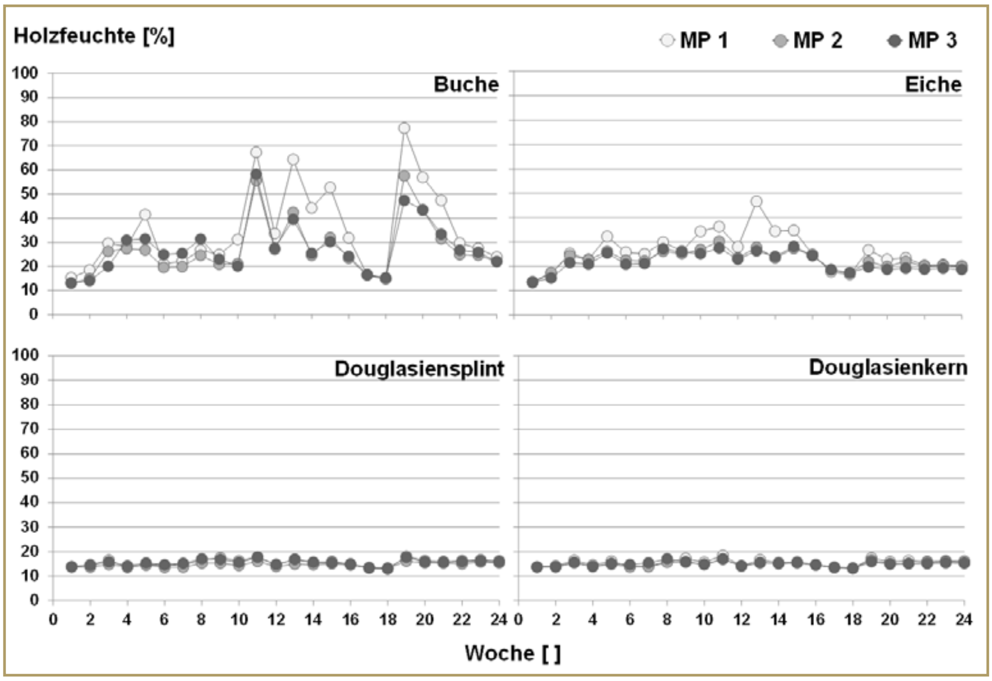

Abb. 5: Verlauf der Holzfeuchte im unteren Element im Freiland exponierter Sandwichprüfkörper

Fig. 5: Moisture course for different measuring points in the bottom member of a sandwich specimen

me vor und nach Bewitterung dargestellt. Insgesamt betrachtet ergab sich kein einheitlicher Effekt der Bewitterung auf das Feuchteaufnahmeverhalten der unterschiedlichen Materialien. Für eine Bewertung des sich hier augenscheinlich als vernachlässigbar gering darstellenden Einflusses einer Bewitterung auf das Feuchteaufnahmeverhalten von Holz muss aber berücksichtigt werden, dass letzteres an kleinen fehlerfreien Proben bestimmt wurde. Der Effekt von Rissen, wie sie an Prüfkörpern in Realdimensionen mit größeren tangential orientierten Abschnitten zu erwarten wären, ließ sich hier nicht berücksichtigen.

Die Entstehung von Rissen und deren möglicher Effekt auf einen bestehenden Versuchsaufbau ist in Abb. 8 dargestellt. Mehrere Holzarten zeigten im Lap-joint-Versuch (cf. Abschnitt „Bestimmung globaler und lokaler Holzfeuchte") eine starke Rissbildung nach nur drei Monaten Exposition. Durch die Risse wurde die Polyurethanabdichtung der Hirnenden beschädigt, was wiederum eine erhöhte kapillare Wasseraufnahme der Prüfkörper zur Folge hatte. Eine Wiederabtrocknung in gleichem Maße war aber durch die verbliebene Abdichtung ausgeschlossen, wodurch sich für einen Pilzbefall günstige Bedingungen in den Prüfkörpern einstellten.

Die mit andauernder Bewitterung zunehmende Befeuchtungsneigung des Holzes, wie sie beispielsweise durch Hirnrisse

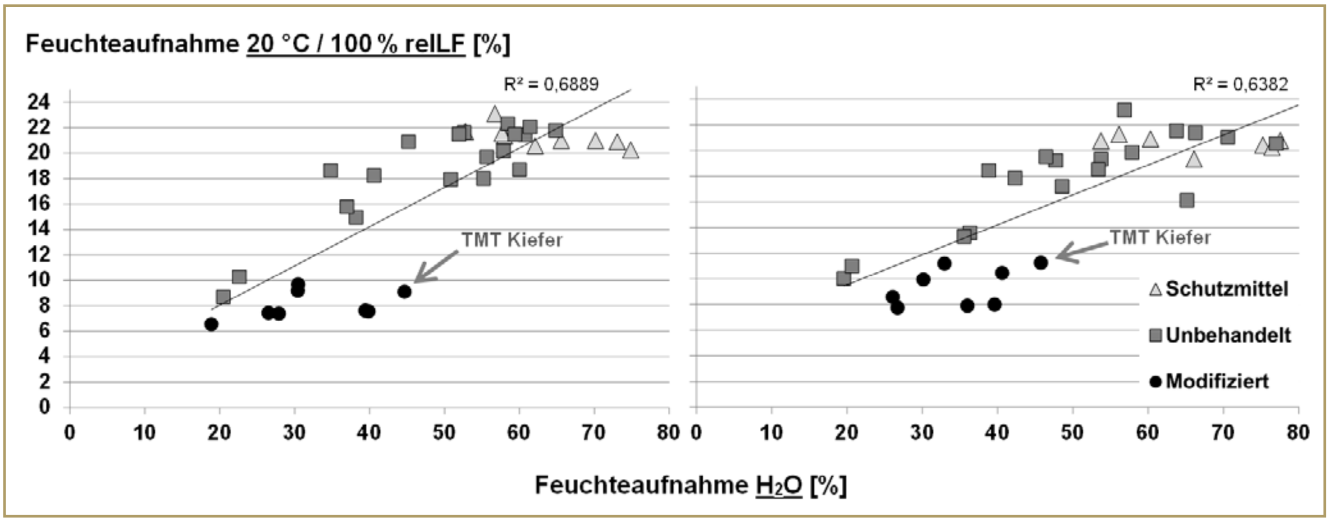

Abb. 6: Zusammenhang zwischen Feuchteaufnahme während 24 h Tauchen bei 20 °C und 24 h Lagerung im Klima 20 °C/ 100 % relative Luftfeuchte (jeder Datenpunkt repräsentiert Mittelwert eines Materials (Tab. 1) – links: vor Bewitterung, rechts: nach Bewitterung)

Fig. 6: Relationship between moisture uptake after 24 h water submersion at 20 °C and after 24 h storage at 20 °C/ 100 % relative humidity (each dot representing mean value of one material (Tab. 1) – left: before weathering, right: after weathering)

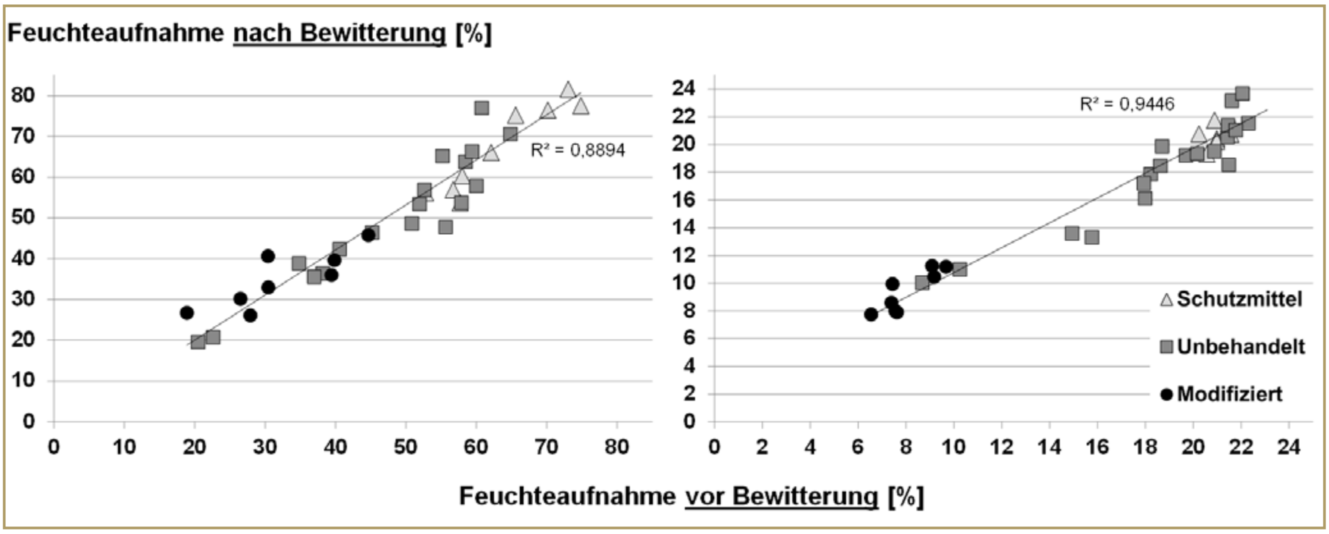

Abb. 7: Zusammenhang zwischen Feuchteaufnahme während 24 h Tauchen bei 20 °C (links) und 24 h Lagerung im Klima 20 °C/ 100 % relative Luftfeuchte (rechts) vor und nach Bewitterung (jeder Datenpunkt repräsentiert Mittelwert eines Materials (Tab. 1))
Fig. 7: Relationship between moisture uptake after 24 h water submersion at 20 °C (left) and after 24 h storage at 20 °C/ 100 % relative humidity (right) before and after weathering (each dot representing mean value of one material (Tab. 1))

herbeigeführt werden kann, ist exemplarisch für einige Nadelhölzer in Abb. 9 dargestellt. Die über einen Zeitraum von einem Jahr aufgezeichneten Feuchten, beginnend mit dem Tag der Exposition, lassen für alle Materialien einen langsamen Anstieg erkennen, der unabhängig von den jahreszeitlichen Schwankungen besteht.

Folgerungen

Aus den Ergebnissen der unterschiedlichen Studien ließen sich ausschlaggebende Aspekte ableiten, die es für ein Feuchtemonitoring im Rahmen von Dauerhaftigkeitsprüfungen im Freiland zu berücksichtigen gilt. Unterschiede zwischen lo-

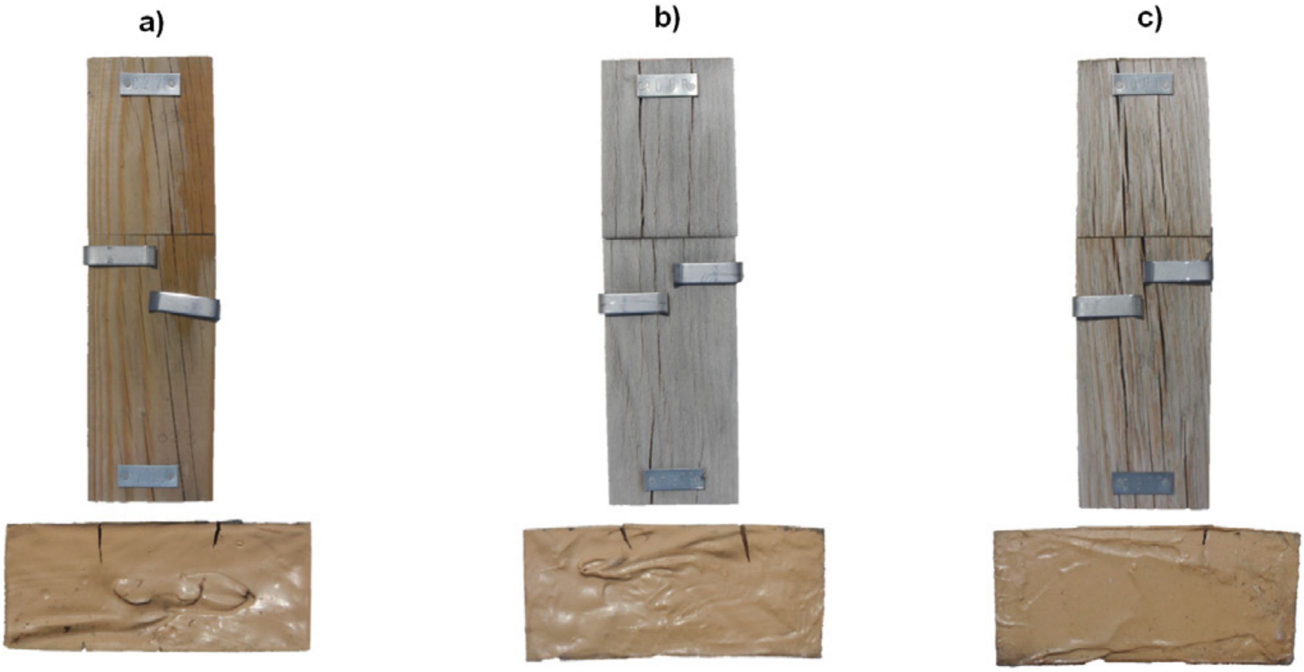

Abb. 8: Draufsicht und Hirnfläche (versiegelt mit Polyurethandichtmasse) von Lap-joints nach drei Monaten Freilandexposition (April-Juli): a) Kupfer-Chrom-Arsen-imprägnierte Kiefer, b) Buche, c) Eiche
Fig. 8: Top view and respective end grain (sealed with polyurethane) of lap-joint specimens after three month of exposure (April-July): a) Chromated copper arsenate impregnated pine, b) Beech, c) European oak

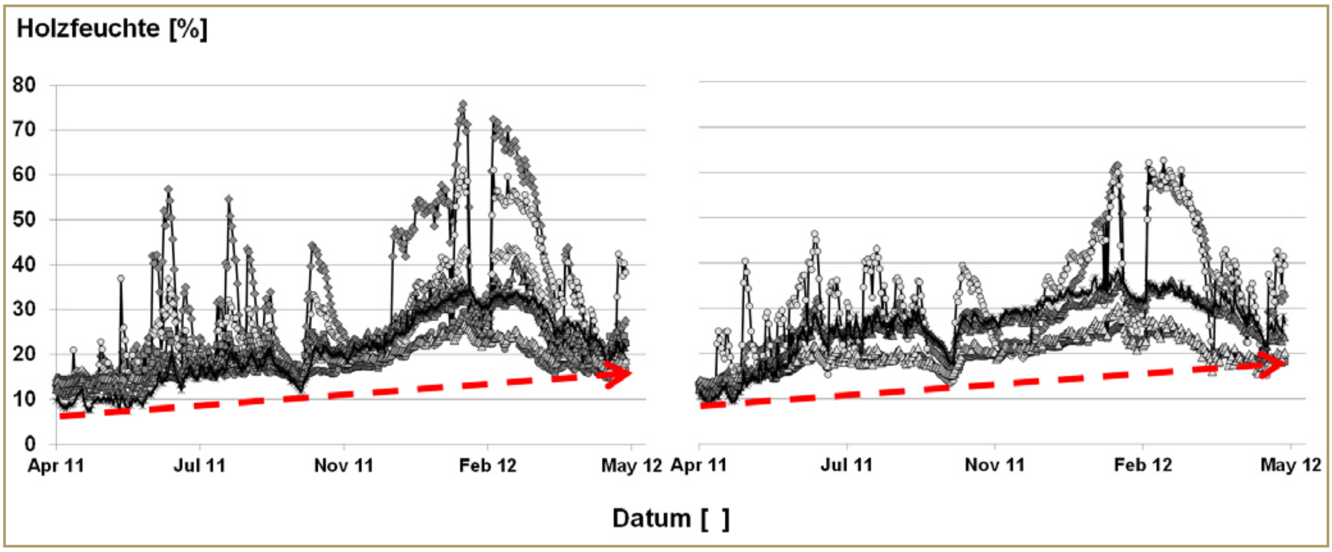

Abb. 9: Feuchteverlauf von Sandwichprüfkörpern (links) und Lap-joints (rechts) aus unterschiedlichen Nadelhölzern (gestrichelte Linie indiziert Feuchteanstieg durch Bewitterung)

Fig. 9: Moisture course for various soft woods exposed in a sandwich test (left) and lap-joint test (right) (dashed line indicates moisture increase due to weathering effects)

kaler und globaler Feuchte sowie der Effekt von Messtiefe und Messposition wurden deutlich. Die Notwendigkeit, die kritischste Stelle eines Versuchsaufbaus vorab abzuschätzen und genau dort Messelektroden zu positionieren, wurde ersichtlich und stellt gleichzeitig die größte Schwierigkeit dar.
Der Einfluss einer Bewitterung auf das Feuchteaufnahmeverhalten von Holz ließ sich anhand der verwendeten Prüfverfahren nachweisen. Folglich ist für die Bewertung und Interpretation von Monitoringergebnissen die Historie (z. B. die bisherige Expositionszeit) bedeutsam.
Des Weiteren kann die witterungsbedingte Ausbildung von Rissen zu Beschädigungen führen, die nicht nur Einfluss auf die Holzfeuchte haben, sondern auch den gesamten Prüfaufbau hinsichtlich seines Befallsrisikos verändern können.
Schließlich zeigten die Ergebnisse deutlich das Potenzial von Monitoringmaßnahmen für eine Bestimmung des feuchteinduzierten Befallsrisikos an unterschiedlich im Freiland exponierten Holzprodukten. Sie können dazu begleitend oder als Zielmessungen durchgeführt werden. Insbesondere für Prüfungen außerhalb der Erde stellen Feuchteaufzeichnungen einen Mehrwert dar, wenn sie parallel zu den klassischen Befallsbestimmungen durchgeführt werden. Vor allem für die sogenannten „alternativ“ behandelten Hölzer, wie thermisch und chemisch modifizierte sowie hydrophobierte Hölzer, liefert ein Feuchtemonitoring wesentliche Informationen über ihre Performance.

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ABSTRACT

Moisture performance testing of wood
Practical experience in the field

Different methods are used to characterize the moisture performance of wood. These methods can be divided into direct and indirect methods. Furthermore they can be distinguished by characteristics like continuous or periodical measurements and measuring local or global moisture content (MC). Each measuring method has certain peculiarities that need consideration when designing a test set-up and conducting MC measurements in the field. Therefore reports are given on practical experience with measuring and monitoring wood MC to determine the moisture performance of wood under lab and field conditions. Results from different studies that have been conducted during the last four years are presented. The aim was to enhance the understanding of factors influencing gravimetric and resistance based MC measurements. The results of the different studies pointed on the potential of moisture monitoring to serve for an improved interpretation of field test data. However, they also highlighted the need for considering several significant factors such as measuring depth and position, the effect of weathering and the identification of the most critical conditions within a given set up.

***Keywords:** Moisture content measurements, Lap-joint-test, performance, resistance*

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B.Sc. Martin Kasselmann studierte Technical Education mit dem Schwerpunkt Wood Technology an der Leibniz Universität Hannover und hat sich im Rahmen seiner Bachelorarbeit mit dem Feuchteverhalten von holzbasierten Materialien in unterschiedlichen Expositionsbedingungen beschäftigt.

Paper 3

Bundle tests

Simple alternatives to standard above ground testing of wood durability

Linda Meyer-Veltrup, Christian Brischke

Within this study different new above ground test set ups to untreated Norway spruce (*Picea abies* Karst.) and Scots pine sapwood (*Pinus sylvestris* L.) which are frequently used as reference or control species in wood durability field tests were applied. The overall aim of this study was to find a simple alternative method to the few standardized above ground field test methods, such as the L-joint and the lap-joint methods, and to overcome some of their shortcomings (e. g. costly and time-consuming specimen preparation, occurrence of hardly detectable interior rot behind sealants or coatings). Therefore, different bundle type specimens were exposed above ground and monitored in terms of moisture content (MC) for one year and fungal decay for up to eight years. Both wood species decayed rather fast and all four different bundle compositions accelerated decay compared to single stake shaped specimens. Brown rot was the dominating rot type independent of the set up and the wood species. The global MC of the specimens was not extremely high, but obviously wetting close to the contact faces was sufficient to allow fungal infestation and decay. Also from a practical point of view the set ups performed in a promising way: specimen preparation was simple and inexpensive, decay assessments were easy, and decay progress sufficiently fast, partly faster than expected from a moderate moisture induced risk as determined for all four bundle type specimens.

Keywords: Decay, durability, field testing, moisture monitoring, service life prediction

Introduction

The majority of wooden components used outdoors are exposed above ground (*Blom and Bergström,* 2006; *Friese et al.,* 2009). However, the severity of exposure above ground varies drastically, which is not adequately reflected by the small number of standardized methods for testing wood durability in the field today. Among more than 60 different test procedures that can be found for testing the performance of wood above ground (e. g. *De Groot,* 1992; *Fougerousse,* 1976; *Råberg et al.,* 2005; *Brischke et al.,* 2012) only eight methods are standardized: two European standards (*EN 330,* 1993; *CEN/TS 12037,* 2003), five US standards (*AWPA E9,* 2013; *AWPA E16,* 2013; *AWPA E18,* 2013; *AWPA E25,* 2013; *AWPA E27,* 2013) and one Australian standard (*AWPC,* 2007). Furthermore, most of the few standardized methods were designed for determining the efficacy of wood preservatives (*Fredriksson,* 2010). The peculiarities of untreated or thermally and chemically modified wood are frequently not considered. Some methods suffer from complicated, costly and time-consuming manufacture (*Meyer et al.,* 2014). Additional criteria have to be taken into account such as slow decay progress as found for the lap-joint test (*CEN/TS 12037,* 2003; *AWPA E16,* 2013) in several studies (e. g. *Westin et al.,* 2002; *Preston et al.,* 2011; *Terziev and Edlund,* 2000) or mutual infestation within horizontal double layer (*Rapp and Augusta,* 2004) or block tests (*Pfeffer et al.,* 2008) where the whole set-up practically acts as one single replicate (*Zahora,* 2008; *Brischke et al.,* 2011). This study aimed therefore on screening simple test set-ups reflecting differently severe exposure situations above ground, which combine the advantages of joint and block tests by creating water traps, providing a large contact area, but consisting of separated, individual replicates. The basic specimen elements were identical with the *EN 252* (2015) standard stake used for in ground testing, but details and composition in bundles varied with the aim to provoke water traps. Specimens were monitored in terms of moisture content (MC) for one year and fungal decay for up to eight years.

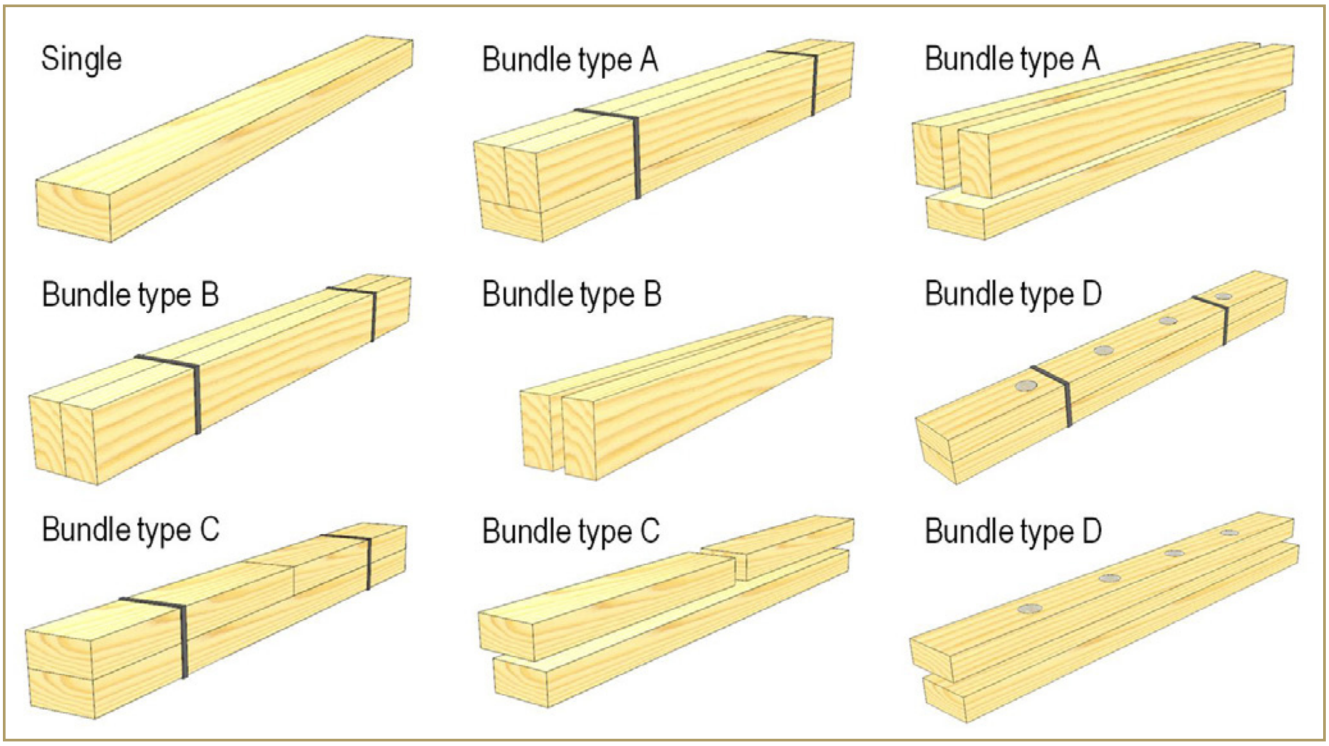

Fig. 1: Schematic drawing of bundle and single specimens showing configuration and potential water traps
Abb. 1: Anordnung und Zusammensetzung der unterschiedlichen Bündelvarianten bzw. der Einzelprüfkörper sowie der potenziellen Wasserfallen

Experimental

Specimens (n = 3) were prepared from Norway spruce (*Picea abies* Karst.) and Scots pine sapwood (*Pinus sylvestris* L.) with a cross section of 25 x 50 mm² and a length of 500 mm according to *EN 252* (2015). Single element specimens and four different types of bundle specimens were prepared as illustrated in Fig. 1. Bundle type A and C consisted of three elements, where type C had two upper elements of only 250 mm length. Bundle type B and D consisted of only two elements, where type D had an upper element with four holes of 20 mm diameter. The elements of each bundle were fixed with cable strips. Specimens were exposed on aluminum L-profiles mounted on test rigs one meter above ground in Hamburg (1st year) and Hannover (2nd to 8th year), both Germany. Fungal decay was assessed every year according to the five-step rating scheme according to *EN 252* (2015), i. e. sound (0), slight attack (1), moderate attack (2), severe attack (3), and failure (4). Furthermore, wood moisture content (MC) of the specimen elements was determined gravimetrically in intervals during the first year of exposure.

Results and discussion

Bundle specimens decayed rapidly after a time lag between exposure and onset of decay of two to three years (Fig. 2). The time lag was one to two years longer for single specimens. Bundle types A and B decayed fastest so that spruce specimens completely failed after four years and pine sapwood after five years (Fig. 2). In contrast, *Brischke and Melcher* (2015)

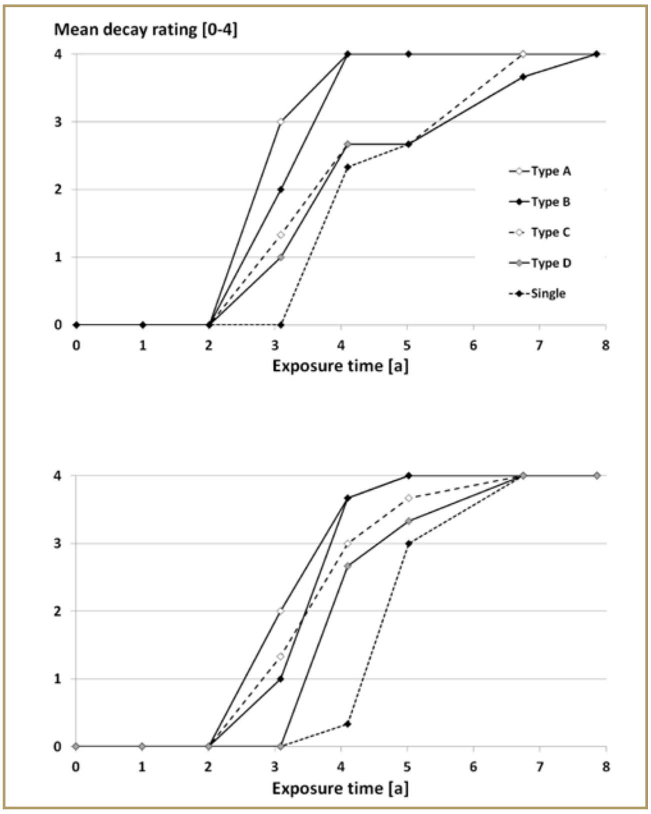

Fig. 2: Mean decay rating of Norway spruce (top) and Scots pine sapwood (bottom) specimens according to *EN 252* (2015)
Abb. 2: Mittlere Abbaubewertung von Fichten- (oben) und Kiefernsplintprüfkörpern (unten) nach EN 252 (2015)

Fig. 3: Brown rot decay starting from water traps at contact faces between end grain and end grain (left) and between side-grain and side grain (right)

Abb. 3: Braunfäule ausgehend von Wasserfallen an den Kontaktflächen zwischen Hirnholz und Hirnholz (links) und zwischen zwei Längsflächen der Prüfkörper (rechts)

exposed pine sapwood in lap-joint and double layer tests and even after eight years of exposure the lap-joint specimens did not fail. In the double layer set-up a mean decay rating of two was reached after five years of exposure. Similar results were reported by *Palanti et al.* (2011) who detected a median decay rating of three in pine sapwood lap-joints after five years. Bundles type C and D as well as the single specimens did not fail for three to four years (spruce) and one to two years more (pine sapwood). Compared to horizontal double layer specimens, which are considered to mimic an extremely severe above ground exposure, decay proceeded as fast or even faster (*Stirling et al.,* 2016).

All specimens were infected exclusively by brown rot and decay was either starting from water traps at contact faces between the different bundle members or the centred end-grain areas of upper bundle members type C (Fig. 3). This stands in contrast to results from lap-joint and sandwich tests when metal clamps were used and decay occurred beneath clamps or water proof end-grain sealants (*Meyer et al.,* 2014). The MC of the specimens during outdoor exposure differed between both, spruce and pine sapwood, and between the different specimen compositions (Fig. 4). As expected, pine sapwood showed always higher MC compared to spruce and reached in maximum almost 70 % in the winter season. This coincides with results reported by *Meyer-Veltrup et al.* (2016) who conducted MC measurements on bundle types A and C for three years and found 58 % (pine sapwood) and 45 % (spruce) of the days to be above a MC of 25 %.

During the first year of exposure highest MC was observed in the upper members of bundles type D, which might be caused through the increased end-grain areas of the four drilling holes. Interestingly, the spruce specimens showed MC significantly above 25 % (i. e. approx. above fibre saturation) only during the winter half year. Nevertheless, wetting was obviously sufficient to provoke onset of brown rot decay after the second year of exposure on spruce.

Apart from the bundle type D (including holes) manufacturing of all specimens turned out be very easy and so was the inspection with respect to fungal decay. Plastic cable strips turned out to be more practicable compared to metal clamps, because the latter have the potential to create new water traps and thus starting points for fungal decay (*Meyer et al.,* 2014).

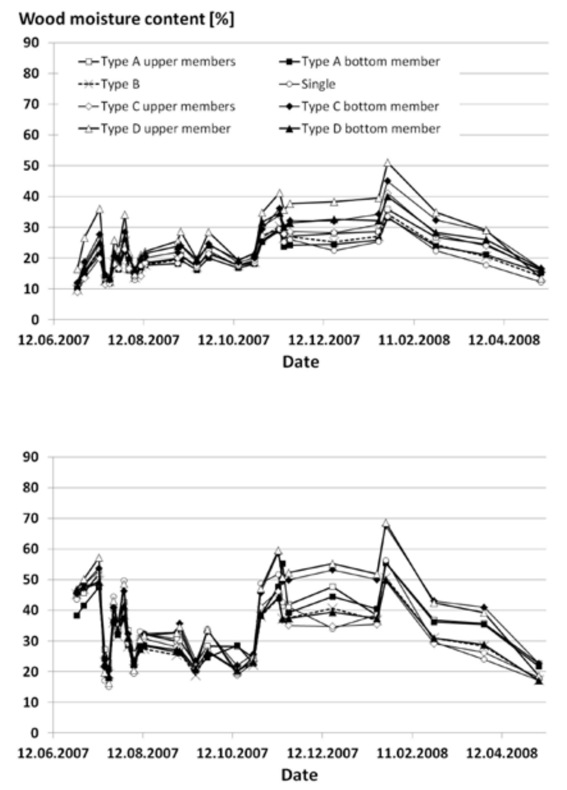

Fig. 4: Course of wood moisture content during first year of exposure of different bundle type specimens (top: Norway spruce, bottom: Scots pine sapwood)

Abb. 4: Holzfeuchteverlauf während des ersten Jahres der Freilandexposition von unterschiedlichen Bündelprüfkörpern (oben: Fichte, unten: Kiefernsplint)

Conclusions and outlook

The different bundle test set-ups provoked rather fast decay starting from water traps created by assembling two or three wooden elements. Specimen preparation was easy and inexpensive due to the use of simple stake shaped wood members without complicated joints and additional sealants. Ongoing tests with more durable species, modified and preservative treated wood at different sites will show if the promising findings of this screening study can be verified (e. g. *Meyer-Veltrup and Brischke,* 2016).

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ABSTRACT

Bündeltests
Einfache Alternativen zu standardisierten Freilandverfahren zur Prüfung der Dauerhaftigkeit von Holz

Im Rahmen dieser Studie wurden insgesamt vier neue Prüfmethoden als einfache Alternativen zu standardisierten Freilandverfahren zur Prüfung der Dauerhaftigkeit von Holz außerhalb der Erde angewendet. Hierzu wurden Prüfkörper aus unbehandelter Fichte (Picea abies Karst.) und Kiefernsplint (Pinus sylvestris L.), die in den meisten Freilandversuchen als Referenz verwendet werden, hergestellt. Übergeordnetes Ziel dieser Studie war es, eine einfache Alternative zu den wenigen standardisierten Prüfmethoden für Expositionen außerhalb der Erde, wie zum Beispiel der L-Joint- und der Lap-Joint-Methode zu finden, und einige ihrer Mängel (kostenintensive und zeitaufwendige Prüfkörperherstellung, Auftreten von kaum nachweisbarer Innenfäule hinter Dichtstoffen oder Beschichtungen) zu reduzieren. Aus diesem Grund wurden verschiedene Bündelprüfkörper außerhalb der Erde exponiert und über ein Jahr im Hinblick auf ihr Feuchtigkeitsverhalten und für bis zu acht Jahre hinsichtlich der Entstehung von Fäulnis untersucht. Für beide Holzarten ließ sich eine schnelle Fäulnisentwicklung nachweisen, wobei alle vier Bündeltypen zu einer beschleunigten Fäulnisentwicklung im Vergleich zu Einzelprüfkörpern führten. Unabhängig vom Prüfkörpertyp und der Holzart war Braunfäule der dominierende Fäuletyp. Die Gesamtfeuchte der Proben über den gemessenen Zeitraum war nicht sehr hoch, die Feuchte in der Nähe der Kontaktflächen aber ausreichend, um einen Pilzbefall und somit Fäulnis zu ermöglichen. Auch im Hinblick auf die praktische Umsetzung erwiesen sich die Bündel als geeignet, sehr kostengünstig und ließen sich mit geringem Aufwand herstellen. Weiterhin ließ sich der Fäulnisfortschritt einfach und sicher bestimmen.

Schlüsselwörter: *Dauerhaftigkeit, Freilandprüfverfahren, Holzfeuchte-Monitoring, Gebrauchsdauervorhersage, pilzlicher Holzabbau*

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Testing the durability of timber above ground: evaluation of different test methods

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Abstract A large number of studies on the decay performance of wood in outdoor exposure have been conducted in the past. However, no test methodology for wooden components exposed above ground reflecting the variety of different loads has been established so far. Many test protocols were modified in different ways throughout the years and results were often published only in an encoded or incomplete way. This makes it difficult to obtain comparable results to work on a comprehensive above-ground test methodology. Therefore, a comparative study on moisture performance and the resulting decay response was conducted. Five different wood species were exposed according to 24 different test methods representing a wide range of different exposure situations including in- and on-ground exposure. After three years of exposure the moisture load as well as decay development differed between the test methods and tested materials. Different parameters were identified influencing the moisture performance of wood in the respective test set-ups and finally an attempt was made to set up a test methodology providing sets of test methods for differently severe applications within use class 3.1 and 3.2 as defined in the European standard EN 335 (2013).

1 Introduction

The complexity of testing the biological durability of wood results from the different areas and exposure situations wood is used in. Wood was always used for constructions in the building sector where the areas of application are ranging from simple structures like range land fences to more complex ones like balconies, studwork, bridges or nowadays also roller coasters (Seidel and Wiegand 2001). All these different constructions and their specific details are exposed to a wide range of different agents and combinations and intensities of their actions. With respect to the service life of wooden components exposed outdoors the decisive loads responsible for the risk of damage can mainly be reduced to moisture, temperature and the presence of wood destroying organisms. The first step to classify a wooden component with respect to an expected load is to distinguish between in-ground (use class 4) and above-ground exposure (use class 3.1 and 3.2 according to EN 335 (2013)). In the past numerous test methods were conducted all over the world and have been described in literature referring to both of these exposure conditions (e.g. Fougerousse 1976; De Groot 1992; Francis and Norton 2005; Fredriksson 2010; Brischke et al. 2012).

Among these tests the ones reflecting above-ground exposure are not regularly used to determine durability and only eight methods are standardized: two European standards (EN 330 2014; CEN/TS 12037 2003), five US standards (AWPA E9 2013; AWPA E16 2013; AWPA E18 2013; AWPA E25, 2013; AWPA E27 2013) and one Australian standard (AWPC 2007). The reason for this can be found in the long testing periods needed for above-ground tests compared to testing in ground contact. While tests in ground contact can lead to final results after one to five years, depending on wood species, modification or

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Table 1 Wood species used for field trials

Material	Botanical name
Beech	*Fagus sylvatica* L.
English oak	*Quercus robur* L.
Norway spruce	*Picea abies* Karst.
Scots pine	*Pinus sylvestris* L.
Scots pine sapwood	*Pinus sylvestris* L.

treatment (Larsson Brelid et al. 2011), failure due to decay in above-ground tests can take many more years or even decades (Wang et al. 2008; Augusta 2007). However, testing wood durability exclusively in ground stands in contrast to the fact that the majority of timber products in outdoor use with different requirements according to dimensional accuracy as well as load bearing capacity are exposed above ground, for example façades, terrace decking, windows, balconies or carports (Blom and Bergström 2006; Friese et al. 2009). Furthermore, results from in-ground tests cannot be transferred to the performance of timber products used in above-ground situations (Kutnik et al. 2014).

For most of the test protocols decay progress is determined regularly every 6–12 months, but since the moisture and temperature load is usually not recorded, reliable information about their ability to reflect different exposure situations is lacking. Furthermore, the influence of different acceleration measures (i.e. methods to intensify decay) like defect coatings, feeder boards or artificial shading is not fully understood. The high variation of test methods which are conducted under varying conditions including different evaluators, different test sites and different accelerations or modifications makes it difficult to get comparable results which are strongly needed for service life prediction of timber structures (Brischke et al. 2011, 2013b).

To overcome this drawback a comparative study on moisture performance and the resulting decay response was conducted. Five different wood species were exposed according to 24 different test methods representing a wide range of different exposure situations. The test set-up covered established and standardized test methods (e.g. L-joint test, decking test, ground proximity test) as well as some new alternative test methods.

2 Materials and methods

2.1 Wood materials

In this study, the moisture performance and natural durability of five wood species (Table 1) were tested using 24 different field test methods. All specimens were free of cracks, decay and other obvious defects.

2.2 Test set-up

Ten replicates of each test material were exposed to a field test site in Hannover, Germany, in 2012 (Fig. 1) (coordinates: 52.395067°N, 9.701913°E, elevation: 54 m, mean temperature: 9.2 °C, precipitation sum: 642 mm, climate: temperate zone). The ground of the test site was covered with gravel.

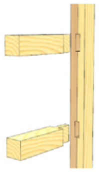
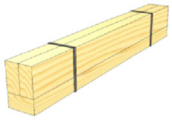
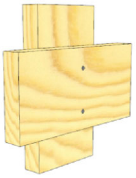
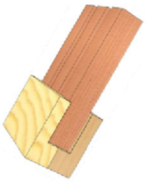
In Table 2, schematic drawings of all tests including dimensions and details of exposure and specimen composition are shown. All tests were carried out according to the named references. A detailed analysis of design details and acceleration measures is given by Meyer et al. (2016). In addition to decay assessment, moisture content and temperature were determined once a day.

2.3 Decay assessment

Decay was assessed every six months and evaluated according to EN 252 (2015). A pick-test was used, where a pointed knife is pricked into the specimens and backed out again. The fracture characteristics of the splinters as well as depth and appearance of decay were assessed visually, and referred to the evaluation scheme according to EN 252

Fig. 1 Field test site in Hannover-Herrenhausen, Germany. Overview of above ground tests

Table 2 Test set-up

Test	Name (Reference)	Set-up	Specimen size [mm³] Distance to ground [cm]	Details
1 + 2	Accelerated L- joint test; (Van Acker and Stevens 2003)		195 x 38 x 38 100	– Mortise assembled of beech and pine sapwood – Painted version(2): Defect coating (alkyd resin based, dry film thickness: 50 ± 5 µm) at the joint – Supported at 10°
3	Bundle test I (Meyer-Veltrup and Brischke 2016)		500 x 50 x 25 100	– Bottom segment with two upper segments; edges faced upwards – Segments held together with cable straps
4	Bundle test II (Meyer-Veltrup and Brischke 2016)		500 x 50 x 25 250 x 50 x 25 100	– Bottom segment with two half-length upper segments; edges faced sidewards – Segments held together with cable straps
5	Close to ground mini-stake test (Westin et al. 2004)		200 x 20 x 8 15	– Placed on concrete and weight down with PE stick
6	Cross brace test (Highley 1995)		152 x 76 x 19 15	– Boards screwed together at mid-length
7	Decking test (Laks et al. 2008)		500 x 100 x 20 16	– Decking boards fixed to supports from the same wood species – Distance between boards: 20 mm
8	Embedded test (Cookson and Carr 2009)		200 x 35 x 35 100	– Specimens embedded in feeder supports (beech and pine sapwood) – Supported at 45°

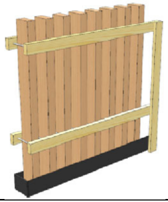
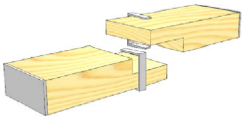
(2015). For test set-ups with cross sections deviating from the cross section given in the standard (50 × 25 mm^2) the rating scheme was adapted to the respective dimensions (Table 3). Therefore, the maximum decay depth [mm] was approximated in 0.5 mm steps to reach the minimum intact cross section [%] given for the ratings according to EN 252 (2015) specimen dimensions.

2.4 Durability classification

Since the mean lifetime of the specimens was not yet obtained for all materials tested after three years of exposure, the mean decay rate v_{mean} was calculated (Eq. 1) as previously reported by Brischke et al. (2013a).

Equation 1: Mean decay rate v_{mean} after certain time:

Table 2 continued

9	Combined façade and decking element (Bornemann et al. 2012)		500 x 100 x 20 100	– Board on board cladding – Upper end-grains protected by tin roof – South oriented
10			500 x 100 x 20 57	– Single layer screwed to beam supports – Distance between boards: 20 mm
11+ 12	Ground proximity test (AWPA E18, 2013)		150 x 50 x 20 15	– Exposed on concrete blocks – Shaded version (12): Set up placed under a shade box
13	Gutter test (Modified after Fougerousse 1976)		500 x 50 x 25 100	– Vertically exposed in a gutter – Gutter size: 1000 x 50 x 65 mm³ – Laterally draining of water not possible
14	Horizontal double layer test (Modified after Augusta 2007)		500 x 50 x 25 20	– Upper layers displaced laterally by 25 mm – Supports made from aluminum profiles – PE spacers for segmentation – Three specimens serve as one replicate
15	Lap-joint test (CEN/TS 12037, 2003)		180 x 85 x 40 100	– Two segments with lap-joint held together by metal clamp – Supports made from aluminum profiles – End-grains sealed with PU

$$v_{mean} = \frac{\sum_i^n v_i}{n} = \frac{\sum_i^n \frac{R}{t}}{n} [a^{-1}]$$

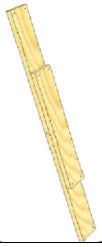
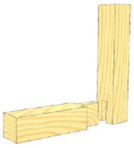
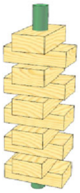
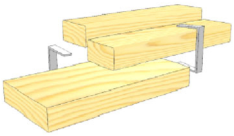
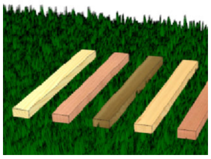
where v_{mean} is mean decay rate of specimens [a^{-1}], v_i is decay rate of single specimen [a^{-1}], R is decay rating, e.g. according to EN 252 (2015), t is exposure time [a], n is number of replicate specimens

2.5 Moisture content and temperature measurements

MC and wood temperature were recorded on three of ten replicates per material in all tests once a day. The moisture and temperature recording was performed with data logging devices “Materialfox Mini” and “Thermofox Mini” (Scanntronik Mugrauer GmbH, Zorneding, Germany). The memory capacity was 16,000. The data loggers were equipped with three ports. The measuring ranged from 2×10^4 to 5×10^8 Ω. The measuring principle was based on the discharge–time–measurement method. First, a capacitor was charged through a very small ohmic resistance and then discharged through the material to be measured. Based on the time needed for discharging, the resistance of the material can be calculated.

Resistance characteristic curves were established for every single material under test by determining the

Table 2 continued

16	Johansson test (Johansson et al. 2001)		500 x 95 x 22 100	– Three specimens overlapping each other and screwed together – Supported at 60°
17+ 18	L-joint test (EN 330, 2014)		203 x 38 x 38 100	– Tenon-mortise bond – Supported at 10° – Painted version (18): Defect coating (alkyd resin based, dry film thickness: 50 ± 5 μm) at joint
19	Rod test (Meyer et al. 2013)		100 x 50 x 25 0	– Specimens turned by 90° to each other and piled up on a plastic coated rod
20- 22	Sandwich test (Modified after: Zahora 2008)		200 x 49 x 25 200 x 100 x 25 100 / 20	– Three segments held together by a steel clamp – Three different versions: – Far above ground (20) (100 cm) – Close to ground (21) (20 cm) – Shaded (22) (20 cm); placed under a shade box
23	On-ground test (Meyer et al. 2013)		500 x 50 x 25 0	– Specimens directly placed on ground
24	In-ground test (EN 252, 2015)		500 x 50 x 25 0	– Stakes buried half to their length

relationship between the gravimetric MC and the electric MC at different temperatures (Brischke and Lampen 2014). Gravimetric and electric MC measurements were carried out in comparison at four target MCs (MC = 15, 18, 25 and 50%) and three target temperatures (T = 4, 20, and 36 °C).

The measuring points were installed from the bottom side of the specimens and located in their center. The electrodes were installed at half of the depth of each specimen. The distance between the centers of the two measuring points was 30 mm parallel and 6 mm orthogonal to the grain. The electrodes were made from polyamide coated stainless steel cables with a core diameter of 1 mm. The electrodes were glued into predrilled holes of 4 mm diameter with an epoxy resin. The bottom part of the holes was filled with 0.1 ml of an epoxy-graphite mixture to provide conductivity. The first 5 mm of the plastic coating of the electrode was removed before putting it into the glue. After 24 h hardening the remaining volume of the hole was filled up with an isolating epoxy resin. After hardening the electrodes were connected to the data logger.

Table 3 Adapted maximum decay depth [mm] and minimum intact cross section [%] (given in brackets) according to the rating scale given in EN 252 (2015)

Rating	Maximum decay depth [mm] (minimum intact cross section [%])				
	0 (Sound)	1 (Slight attack)	2 (Moderate attack)	3 (Severe attack)	4 (Failure)
Test method					
Bundle Test I; Bundle Test II; Gutter test; Double layer test; In ground test; On ground test; Rod test	0 (100)	1 (88)	3 (67)	5 (48)	50 (0)
Accelerated L-joint test, painted and unpainted; L-joint test painted and unpainted	0 (100)	0.5 (89)	1.5 (69)	2.5 (51)	38 (0)
Close to ground mini-stake test	0 (100)	0.5 (83)	1 (68)	1.5 (53)	20 (0)
Cross brace test	0 (100)	1 (87)	2.5 (68)	4.5 (46)	76 (0)
Decking test, combined façade and decking element	0 (100)	1 (88)	3 (66)	5 (45)	100 (0)
Embedded test	0 (100)	1.5 (84)	3.5 (64)	5 (51)	35 (0)
Ground proximity test, shaded and unshaded	0 (100)	1 (86)	2.5 (68)	4.5 (45)	50 (0)
Johansson test	0 (100)	1 (89)	3 (68)	5 (49)	95 (0)
Lap-joint test	0 (100)	2 (86)	5 (66)	7.5 (51)	85 (0)
Sandwich test, far above ground, close to ground, shaded (upper segments)	0 (100)	1.5 (83)	3 (67)	5 (48)	49 (0)
Sandwich test, far above ground, close to ground, shaded (bottom segment)	0 (100)	1.5 (85)	3.5 (67)	5.5 (50)	100 (0)

3 Results and discussion

3.1 Moisture performance and durability

Both MC and decay development differed significantly between wood species as well as between the different test methods. In Fig. 2a and b, moisture courses and the corresponding decay development are exemplary shown for beech and Norway spruce heartwood for six different test set-ups. For all tests, high MC over longer periods led to fast decay development (e.g. horizontal double layer, Fig. 2a-3). However, some tests with similarly high MC showed differences in decay development, such as sandwich tests exposed close to the ground under a shade-box (Fig. 2a-2) and the in-ground test (Fig. 2a-1). In contrast to the in-ground test, the sandwich test seems to cause a time lag of one year between exposure and onset of decay. This might on the one hand be explained by the fungal flora in soil, which is able to immediately infest the wood in ground contact, whereas the elevated set-up needed longer intervals prior to air-borne infestation. Furthermore, the negative peaks in the moisture courses especially for beech show a higher potential to re-dry for the elevated sandwich test samples right after heavy rain events. Time lags were also observed for Norway spruce exposed to the Bundle II test (Fig. 2b-4), the Decking test (Fig. 2b-5) and the Façade element test (Fig. 2b-6).

3.2 Time of wetness

For quantifying the differences in moisture loads between the different test methods the time of wetness (ToW) was calculated and expressed as the number of days with MC $\geq$25% (Table 4). After an exposure period of three years, ToW differed significantly between test methods as well as between tested materials. The ToW for all wood species was summed up for every test and finally the percentage was calculated to give an indication of differences in moisture loads between all 24 tests. Therefore, different test set-ups were ranked with respect to their ToW and grouped accordingly (cf. Table 5).

It became clear that high moisture loads were caused by shade boxes, exposure close to the ground and defect coatings. Medium moisture loads occurred in tests that consisted of segmented specimens but were exposed far above ground (>1 m) or single layer specimens. Low moisture loads were found in test set-ups that were exposed vertically or enabled a fast re-drying like the façade element or the Johansson test.

As expected, the highest number of wet days was determined for the in-ground test specimens that were wet at 91% of the exposure time. This can of course be explained by the fact that the specimens had been in contact with wet soil almost all the time. The second highest ToW was determined for those methods providing a defect of the coating. Here, the effect of high

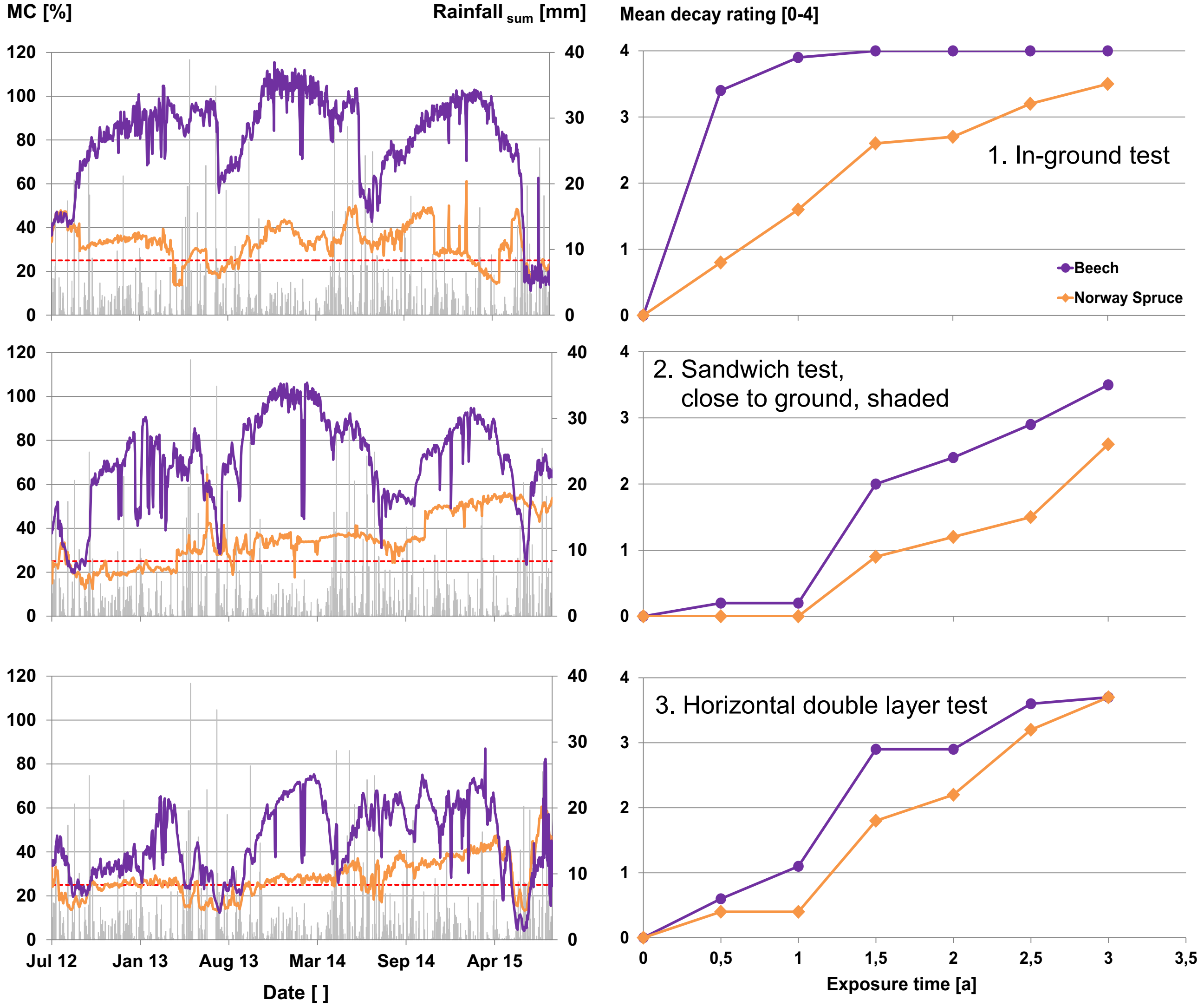


Fig. 2 *Left* moisture courses of beech and Norway spruce exposed to different test set-ups. *Dashed line* critical moisture content of MC = 25%. *Grey columns* daily rainfall sum. *Right* mean decay rating of beech and Norway spruce exposed to different test set-ups

capillary water uptake through cracks and a hindered re-drying due to areas with still intact coating became obvious. Similar observations were made by Francis and Norton (2005) who compared coated and uncoated Lap-joint specimens at several climatically different locations in Australia.

Segmented specimens creating a water trapping joint like in the horizontal double layer test or the sandwich test also showed high MC on 75 and 82% of the days of exposure. A further detail which showed the effect on the moisture load was artificial shading. The sandwich test exposed close to ground as well as the ground proximity test, both exposed under a shade box, showed higher ToW compared to exposure without shading.

The test set-ups that caused the lowest ToW were either composed of two to three members exposed vertically or consisted of single members. Vertical exposure (e.g. cross brace test or Johansson test) allowed fast water draining, whereby single members re-dried faster after rain events compared to segmented specimens with joints.

3.3 Decay resistance

Although moisture, more specifically the time of wetness, is considered to be the key factor for decay, other parameters such as temperature and the presence of decay causing organisms have an effect on decay progress. To identify the decay potential of the 24 different test set-ups the decay

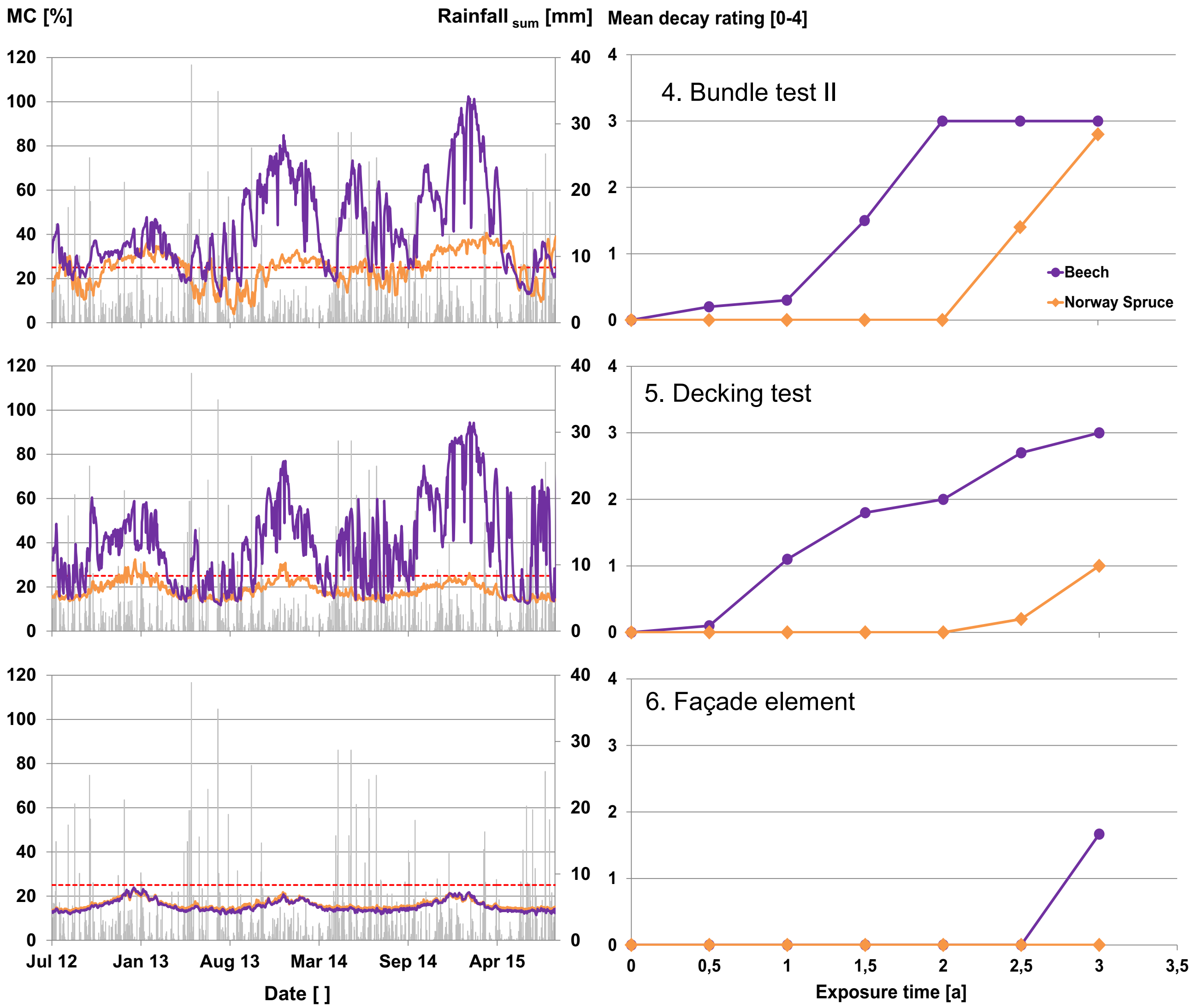


Fig. 2 continued

rate v of the material exposed to the different test set-ups was calculated and summed up for all materials under test (Table 6).

A correlation between the two test factors (1) number of days with MC ≥25% and (2) decay rate is given in Fig. 3. Here, the mean of all wood species was used to minimize the influence of outliers as observed for example for Scots pine exposed to the sandwich test, close to ground (cf. Table 4). The three ToW-groups marked by three different shades of grey and defined in Table 5 were added to the graph.

Except for a few outliers, the two measures correlated fairly well. In some cases deviations might be caused by (1) the distance to ground, (2) the position of the MC measuring points or (3) the decay assessment procedure. All outliers which showed a high decay rate with comparably low number of days above 25% MC (Decking test, Rod test, On-ground test, Horizontal double layer test, in-ground test) were either exposed in or on the ground or extremely close to the ground (10 cm or less). Therefore, bacteria and other microorganisms which accelerate decay development have to be taken into account additionally (Clausen 1996).

In the Johansson test (Fig. 4a) decay developed almost exclusively close to the end grains (Fig. 4b). In contrast, the measuring points were installed at the bottom part of the upper members (Fig. 4c). Such influence of the measuring position was previously indicated by Meyer et al. (2014). Similar difficulties to detect decay occurred in the L-joint (Fig. 5a) and Lap-joint tests (Fig. 5c). Here, decay often developed either behind the coating or the end-grain sealing and was therefore not detected over a long period (Fig. 5b, d). The end-grain sealant of Lap-joint specimens is intended to protect them from water uptake to simulate a

Table 4 Number of days with MC ≥25% for all tests and materials, (based on in total 1156 days and ranked according to number of wet days)

Test Method		**Days with MC ≥ 25 % (=ToW)**						
		Beech	**Oak**	**Spruce**	**Scots pine**	**Scots pine sap**	**Sum ∑**	**ToW %**
24	In-ground test	1075	1116	914	1089	1087	5281	**91**
2	Accelerated L-joint test, painted	1094	1116	985	758	1044	4997	**86**
18	L-joint test, painted	1156	1009	939	597	1146	4847	**84**
22	Sandwich test, close to ground, shaded	1119	1120	904	478	1100	4721	**82**
14	Horizontal double layer test	995	973	775	507	1092	4342	**75**
21	Sandwich test, close to ground	1121	984	1011	18	1107	4241	**73**
12	Ground proximity test, shaded	963	1003	631	616	953	4166	**72**
23	On-ground test	874	1146	501	596	910	4027	**70**
20	Sandwich test, far above ground	1105	840	790	229	1026	3990	**69**
15	Lap-joint test	1074	715	626	181	1092	3688	**64**
8	Embedded test	808	754	732	400	879	3573	**62**
4	Bundle test II	941	774	673	107	852	3347	**58**
11	Ground proximity test	922	576	669	303	837	3307	**57**
13	Gutter test	554	599	368	569	756	2846	**49**
19	Rod test	610	721	476	219	626	2651	**46**
3	Bundle test I	963	892	78	0	666	2599	**45**
17	L-joint test, unpainted	683	653	143	138	878	2495	**43**
5	Close to ground mini-stake test	631	661	239	177	783	2491	**43**
7	Decking test	829	504	62	13	540	1948	**34**
16	Johansson test	540	488	0	0	344	1372	**24**
1	Accelerated L-joint test, unpainted	336	631	43	6	303	1319	**23**
6	Cross brace test	480	397	10	7	384	1278	**22**
10	Decking element	154	314	38	6	348	860	**15**
9	Façade element	0	77	0	0	8	85	**1**

long timber member typical for construction purposes. At the same time it serves as moisture barrier, hinders re-drying, and promotes decay inside the specimen, where it is most difficult to be detected. In contrast to the end grain area, in the joint area the wood has, to some extent, the possibility to re-dry after wetting.

3.4 Evaluation

Besides the moisture induced risk and the development of decay further aspects have to be taken into account to identify suitable test methods. Therefore, all test methods have been evaluated previously with respect to practicability, time and effort required for preparing and conducting the test as well as material and component costs (Meyer et al. 2013). The three crucial factors (1) moisture induced risk, (2) decay rate and (3) practicability issues have been assessed as summarized in Table 7.

Within the group of methods with high moisture load, the horizontal double layer provided a combination of high moisture loads, fast and severe decay, and a low rating for costs and efforts. Methods where specimens are in direct contact with the ground need to be considered separately and were not regarded as potential test methods for above ground situations.

Within the group of test methods resulting in a medium moisture induced risk the Bundle test type II turned out to be one of the most promising tests with very inexpensive sample preparation but high moisture load within this group. Specimens in the rod test, which showed a high decay development, decayed almost exclusively on the bottom which was in direct contact with the ground. In addition, this method turned out to be very time consuming with respect to sample preparation as well as evaluation, because all ten specimens serve as one replicate and need to be disassembled.

Table 5 Groups of all tests and materials according to time of wetness (ToW)

Group (Marker)	ToW [%]	Moisture load
Dark grey	66.7 – 100	High
Medium grey	33.4 – 66.6	Medium
Light grey	0 – 33.3	Low

Table 6 Mean decay rate v_{mean} [a^{-1}] after three years of exposure (based on in total 1156 days and ranked according to the decay rate sum)

Test method		Decay rate v_{mean} [a^{-1}]					
		Beech	Oak	Spruce	Scots pine	Scots pine sap	Sum $\sum$
24	In-ground test	5.47	1.20	2.53	1.56	2.19	12.95
14	Horizontal double layer test	1.50	0.63	1.37	0.80	1.33	5.63
19	Rod test	1.30	0.77	1.30	0.93	0.90	5.20
23	On-ground test	1.93	0.67	0.87	0.97	0.97	4.87
18	L-joint test, painted	1.62	1.00	0.37	0.47	0.87	4.32
2	Accelerated L-joint test, painted	1.45	0.47	1.09	0.77	0.33	4.11
15	Lap-joint test	1.27	0.33	1.26	0.03	0.17	3.06
21	Sandwich test, close to ground	1.09	0.53	0.90	0.27	0.10	2.89
7	Decking test	1.00	1.37	0.33	0.00	0.13	2.84
22	Sandwich test, close to ground, shaded	1.22	0.10	0.87	0.50	0.10	2.79
13	Gutter test	0.93	0.47	0.47	0.00	0.53	2.40
20	Sandwich test, far above ground	0.99	0.40	0.83	0.00	0.13	2.36
16	Johansson test	1.00	0.00	0.70	0.00	0.30	2.00
5	Close to ground mini-stake test	1.60	0.00	0.03	0.23	0.10	1.97
4	Bundle test II	1.00	0.00	0.93	0.00	0.00	1.93
3	Bundle test I	1.07	0.00	0.67	0.03	0.13	1.90
12	Ground proximity test, shaded	1.43	0.00	0.23	0.07	0.13	1.86
11	Ground proximity test	1.18	0.00	0.00	0.00	0.13	1.31
17	L-joint test, unpainted	0.00	0.13	0.50	0.07	0.27	0.97
9	Façade element	0.56	0.00	0.00	0.11	0.22	0.89
8	Embedded test	0.43	0.13	0.10	0.10	0.00	0.77
6	Cross brace test	0.63	0.00	0.00	0.00	0.00	0.63
10	Decking element	0.33	0.00	0.00	0.00	0.00	0.33
1	Accelerated L-joint test, unpainted	0.13	0.00	0.10	0.00	0.00	0.23

All tests within the group providing low moisture induced risk showed, as expected, low decay rates except the Johansson method, where specimens decayed mainly at the steel screws, not in the overlap area where MC measurements were performed and decay was intended to occur first. Consequently, all tests within this group require long exposure periods before first signs of decay can be detected. To allow achieving test results within this group in an acceptable long time span, moisture monitoring appears to be the only feasible alternative to usual decay assessments. The potential of such alternative measurements was previously reported by Brischke et al. (2013a). Façade elements can consequently serve as relevant test set-ups within this group representing the lowest moisture-induced decay risk.

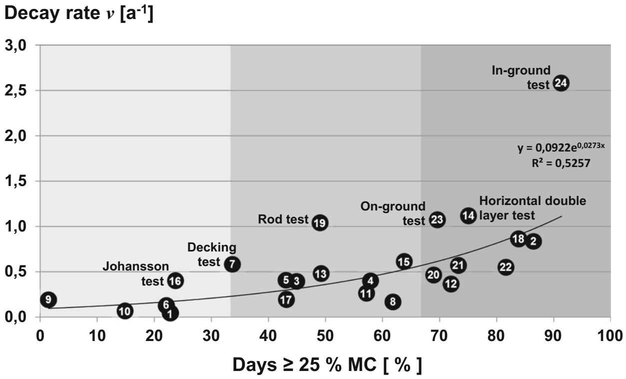


Fig. 3 Relationship between days with MC ≥25% and decay rate *v* for all wood materials and test set-ups after 3 years of exposure

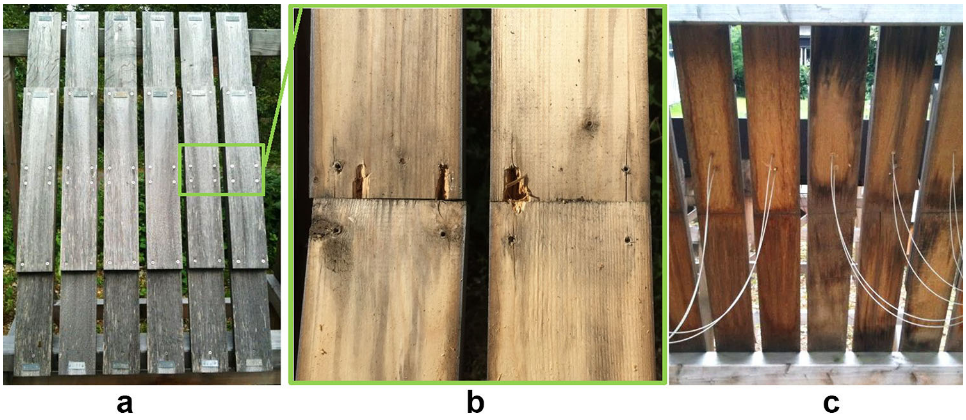


Fig. 4 **a** Johansson test set-up. **b** Decay close to the end grains behind the middle member which is screwed onto the upper and bottom member. **c** MC measurement points in Johansson test

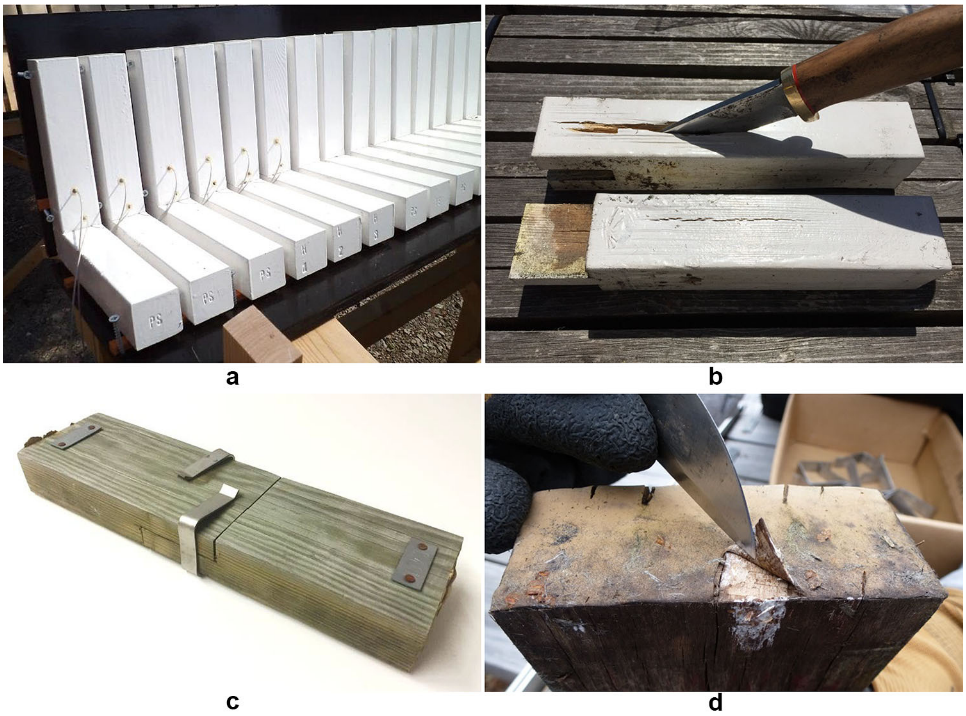


Fig. 5 **a** L-joint test, painted. **b** Tenon and mortise member showing severe decay under the coating. **c** Lap-joint test. **d** End grain of Lap-joint specimen with decay under sealing

4 Conclusion

The evaluation of the 24 test methods with respect to moisture performance and decay development resulted in considerable differences between test methods as well as between the response of different wood species to the method-specific moisture induced risk. In most of the cases the time of wetness coincided well with the resulting decay response. However, especially if the wooden component is exposed close to, on, or in the ground additional factors influencing the degradation need to be considered, for example the fungal flora which is permanently present in soil. Further influencing factors are the position of measuring and the detection of decay progress. In addition, one has to keep in mind that due to the huge range of different exposure situations of wooden components in real life, one test method cannot sufficiently reflect the decay behaviour of a wooden material in all these different exposures. Therefore, a set of test methods for different applications is needed rather than one universal method. Based on this study, the suitability of the various in and above ground test methods to serve as elements of a comprehensive test methodology was investigated. The methods were ranked according to different criteria and the most feasible

Table 7 Evaluation of test methods

Test method		Criteria*														
		Effort for specimen production	Effort for assembling	Material costs	Requirements for wood quality	Costs for add. components	Availability of components	Required space on test site	Need to replace components	Time and effort for assessment	Liability to damages by animals	Liability to wind loads etc.	Detectability of decay	Sum Σ – Criteria	Sum Σ – ToW [%]	Sum Σ - Decay rate $[a^{-1}]$
24	In-ground test	1	3	2	2	1	1	3	1	1	3	1	1	20	91	12.95
2	Accelerated L-joint test, painted	5	5	2	2	2	1	2	5	3	1	3	4	35	86	4.11
18	L-joint test, painted	5	3	2	2	2	2	3	2	3	2	3	4	33	84	4.32
22	Sandwich test, close to ground, shaded	3	2	2	2	4	4	3	2	3	4	1	1	31	82	2.79
14	Horizontal double layer test	2	1	3	2	3	4	3	1	1	2	1	1	**24**	**75**	**5.63**
21	Sandwich test, close to ground	3	2	2	2	3	3	3	1	3	2	1	1	26	73	2.89
12	Ground proximity test, shaded	3	1	1	1	3	4	2	2	1	4	3	1	26	72	1.86
23	On-ground test	1	1	2	2	1	1	3	1	1	4	1	1	19	70	4.87
20	Sandwich test, far above ground	3	2	2	2	3	3	3	1	3	2	2	1	27	69	2.36
15	Lap-joint test	4	2	3	5	3	3	3	1	3	2	2	3	34	64	3.06
8	Embedded test	2	3	1	1	2	2	2	5	2	2	2	1	25	62	0.77
4	Bundle test II	2	2	3	2	3	2	3	2	3	1	2	1	**26**	**58**	**1.93**
11	Ground proximity test	1	1	1	1	1	2	2	1	1	3	3	1	18	57	1.31
13	Gutter test	4	1	2	2	3	2	2	2	1	1	2	1	23	49	2.40
19	Rod test	2	2	1	1	2	2	3	1	4	4	2	1	25	46	5.20
3	Bundle test I	2	2	3	2	3	2	3	2	3	1	2	1	26	45	1.90
17	L-joint test, unpainted	4	3	2	2	1	1	3	2	3	2	3	3	29	43	0.97
5	Close to ground mini-stake test	1	1	1	1	2	2	1	1	1	4	3	1	19	43	1.97
7	Decking test	2	3	2	3	1	1	3	2	3	2	1	1	24	34	2.84
16	Johansson test	3	4	3	3	2	1	5	2	5	1	5	1	35	24	2.00
1	Accelerated L-joint test, unpainted	5	5	2	2	1	1	2	5	3	1	3	3	33	23	0.23
6	Cross brace test	2	2	1	1	1	1	2	2	2	1	2	1	18	22	0.63
10	Decking Element	3	2	3	3	2	1	4	1	2	2	2	1	26	15	0.33
9	Façade Element	4	4	3	3	3	4	4	1	3	2	4	1	36	1	0.89

* 1 = very low, 2 = low, 3 = moderate, 4 = high, 5 = very high

methods were identified in a quantitative manner to represent at least three groups of differently severe moisture induced risk. With respect to the time of wetness, the different test set-ups were classified into three groups (high, medium, and low). Within these groups they were evaluated by the following factors (1) moisture induced risk, (2) decay rate and (3) practicability. The following test methods turned out to be the most promising: horizontal double layer, bundle test and the Façade-decking element.

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Paper 5

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Fungal decay at different moisture levels of selected European-grown wood species

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ABSTRACT

Several factors such as local climate, design details, exposure conditions and coatings have an indirect effect on decay in outdoor conditions. Besides all these factors, in particular the wood temperature and moisture content (MC) directly impact on the fungus and its ability to metabolize and degrade wood cell wall substance over time. Therefore the significant role of MC has been addressed in a wide range of field experiments and approaches to establish decay models. However, all these approaches have one crucial aspect in common, i.e. the need for defining a minimum threshold for wood MC that is necessary for the onset of decay and its subsequent progression.

The aim of this study was therefore to examine the moisture requirements of different brown and white rot causing basidiomycetes for growth and decay of a wider range of European-grown wood species including moderately durable, durable and even very durable species. Remarkably, the majority of the material/fungus combinations under test it was observed that the minimum MC for fungal decay was more or less distinct below fiber saturation, whereby the highest deviations from MC threshold to FSP were found for beech and Scots pine sapwood, i.e. the wood species with the lowest inherent resistance.

Introduction

The service life of wooden structures exposed outdoors is predominantly affected by wood destroying fungi. In particular brown and white rot causing basidiomycetes are responsible for substantial damage on wood exposed above ground (Bech-Andersen, 1995, Carll and Highley, 1999; Huckfeldt and Schmidt, 2006; Schmidt, 2007). The risk for infestation by rot fungi is hereby primarily determined by the temperature and moisture conditions of the wood substrate (Bavendamm and Reichelt, 1938; Griffin, 1977; Huckfeldt et al., 2005; Schmidt, 2006), which can be described as its 'material climate' (Brischke et al., 2008; Isaksson and Thelandersson, 2013). While many indirect factors such as local climate, design details, exposure conditions and coatings have an indirect effect on decay, it is in first instance the wood temperature and wood moisture content (MC) which directly impact on the fungus and its ability to metabolize and degrade wood cell wall substance over time (Viitanen, 1997; Brischke et al., 2006; Gobakken and Lebow, 2010; Viitanen et al., 2010; Morris and Wang, 2011).

Besides air oxygen, slightly acidic conditions and favourable temperatures decay fungi need water for their metabolism (Rayner and Boddy, 1988; Viitanen, 1997). Controlling and reducing wood MC is therefore a key instrument for wood protection by design (Isaksson and Thelandersson, 2013) as well as for wood modification and treating wood with water repellents (Williams and Feist, 1999; Hill, 2007). This can be achieved by keeping water away from wood or by reducing the accessibility of the wood cell walls for water (Ibach and Rowell, 2000; Brischke et al., 2008; Thybring, 2013; Ringman et al., 2014).

The prominent role of wood moisture content for wood decay has therefore been addressed by many approaches to predict the service life of wooden structures. Decay models frequently use wood MC as input variable and dose–response relationships have been established between material-climatic conditions and the resulting risk for onset and progress of decay (Brischke and Thelandersson, 2014). Alternatively, models have been based on relative air humidity which is in equilibrium with wood MC (e. g. Viitanen, 1997; Viitanen et al., 2010).

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A wide range of field experiments have been undertaken by various researchers to quantify the effect of wood moisture on decay under varying climatic conditions (e.g. Scheffer, 1971; Augusta, 2007; Van den Bulcke et al., 2009; Meyer et al., 2013). As a result very different models have been developed describing the effect of temperature, RH and partly also rain events on decay (Brischke and Thelandersson, 2014). However, all these approaches have one crucial aspect in common, i.e. the need for defining a minimum threshold for wood MC that is necessary for the onset of decay and its subsequent progression. Furthermore, optimum and maximum MC values are requested for completely defining growth and decay conditions for basidiomycetes.

Many attempts have been made to determine the physiological thresholds of decay fungi more precisely under laboratory conditions. Bavendamm and Reichelt (1938) conducted growth tests on agar and determined mass loss of small wood samples infected by basidiomycetes and incubated on moistened saw dust at different relative humidity (RH). Theden (1941) examined the MC requirements of various rot fungi and conducted different experiments to determine the minimum MC for new infection through mycelium, progress of decay in already infested samples, and reactivation of decay in infected, dried, and remoistened samples.

Ammer (1963) used pre-infected specimens and stored them in screw-top jars above different saturated salt solutions. Within these experiments drastic differences were observed between the target wood equilibrium MC (EMC) and the actual wood MC after incubation of samples that showed significant mass loss (ML). This difference was explained by the author through the amount of water that originates from fungal metabolism, i.e. the respiration of wood cellulose.

Huckfeldt et al. (2005), Huckfeldt and Schmidt (2006) and Stienen et al. (2014) performed experiments with small piled wood samples in Erlenmeyer flasks. The bottoms of the piles were exposed to malt agar inoculated with fungal mycelium serving as nutrition and water source at the same time. The set up provided a MC gradient pile upwards and limit values for fungal growth and for decay were obtained from the experiments without additional conditioning. In contrast, Saito et al. (2012) ran experiments with inoculated samples incubated in dishes at different temperatures and RH controlled by saturated salt solutions.

All approaches described above are using more or less well established fungal mycelium, but can be distinguished with respect to the availability of an external moisture source, for instance in form of malt agar or wetted wood saw dust. New infection through fungal spores was not considered and might need to be addressed separately.

It is commonly agreed that the moisture conditions for decay fungi become critical when free water is available exclusively in the cell walls, but not in the cell lumens anymore (e.g. Schmidt, 2006; Stienen et al., 2014). This so called fibre saturation point (FSP) lies in average at 30% MC for European-grown wood species as reported by Popper and Niemz (2009). However, the water vapour sorption behaviour varies between wood species over the entire hygroscopic range (Trendelenburg, 1939; Keylwerth, 1969; Popper and Niemz, 2009) and so does the FSP (Krpan, 1954; Griffin, 1977). Furthermore FSP is affected by wood treatments such as chemical and thermal modification, which generally lead to reduced equilibrium MC (EMC) (Hill, 2008; Meyer et al., 2014), and impregnation with preservative salt solutions, which increase the sorption capacity of wood (e.g. Brischke and Lampen, 2014). Furthermore, some basidiomycetes are able to degrade wood even below fiber saturation if a moisture source is available nearby as demonstrated by Huckfeldt and Schmidt (2006) and Stienen et al. (2014).

In contrary, physiological threshold values for growth and decay by basidiomycetes have been investigated for a little group of wood species only. In particular less or non-durable softwood species were used, such as Norway spruce (*Picea abies* Karst.), Scots pine sapwood (*Pinus sylvestris* L.), and Japanese red pine sapwood (*Pinus densiflora* Siebold et Zucc.) (Bavendamm and Reichelt, 1938; Theden, 1941; Ammer, 1963, 1964; Viitanen, 1997; Huckfeldt et al., 2005; Huckfeldt and Schmidt, 2006; Saito et al., 2012; Stienen et al., 2014). Only a few experiments have been performed with European beech (*Fagus sylvatica* L.) wood (Bavendamm and Reichelt, 1938; Liese and Ammer, 1964).

The aim of this study was therefore to examine the moisture requirements of different brown and white rot causing basidiomycetes for growth and decay of a wider range of European-grown wood species including moderately durable, durable and even very durable species. Furthermore, we followed the question whether there is a wood-species dependent effect on the minimum MC thresholds besides the species-specific FSP that should be considered for future modelling of wood decay and service life.

Materials and methods

Wood specimens

Specimens of 5 (long.) × 40 × 40 mm^3 were made from the wood species shown in Table 1. In total, 4.800 specimens were prepared whereby always 50 replicate specimens were axially matched.

Determination of fiber saturation point

Wood MC at the fiber saturation point (FSP) was determined for every material using n = 9 replicates. Therefore the specimens were oven-dried at 103 °C till constant mass (m_0), weighed to the nearest 0.001 g and exposed at 20 °C/100% RH in a closed but ventilated small-scale climate chamber over deionized water. After constant mass was achieved the specimens were weighed again (m_{FSP}) to determine FSP according to the following equation (Eq. (1)):

$$FSP = 100 \times (m_{FSP} - m_0)/m_0 \quad (1)$$

FSP = Fiber saturation point in %
m_0 = oven dry mass before incubation in g
m_{FSP} = mass after storage in water saturated atmosphere in g

Pile test

Test set up

To determine the cardinal points of wood MC for different fungi and wood species in terms of mycelial growth and decay activity a piling method was used. The tests were performed according to Ammer (1964), Schmidt et al. (1996) and Stienen et al. (2014). In this study the pile direction was identical with the longitudinal direction of the wood specimens allowing easy water transport and mycelial growth through the wood pile upwards (Fig. 1a).

Table 1
Wood species used for pile tests.

Wood species	Botanical name
Scots pine sapwood	*Pinus sylvestris* L.
Scots pine heartwood	*Pinus sylvestris* L.
Norway spruce	*Picea abies* Karst.
European larch	*Larix decidua* Mill.
Douglas fir	*Pseudotsuga menziesii* Franco
European beech	*Fagus sylvatica* L.
English oak	*Quercus robur* L.
Black locust	*Robinia pseudoacacia* L.

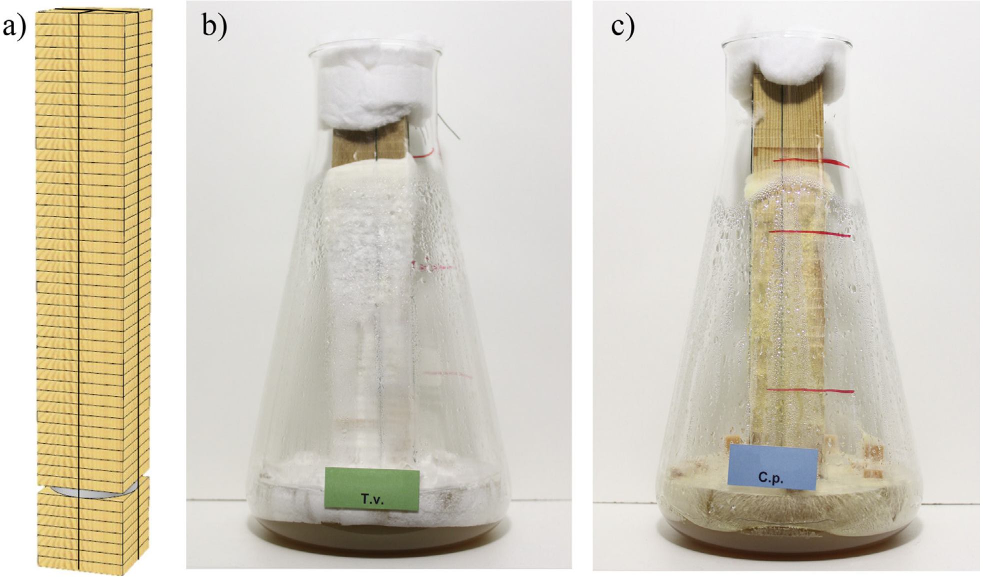

Fig. 1. a) Pile test set up: 50 specimens (5 (long.) × 40 × 40 mm^3) piled up with a metal ring between specimen number 7 and 8. Longitudinal direction of the wood was identical with pile direction. b) Mycelium growth after 3 weeks of incubation with *T. versicolor* (*T.v.*) on beech and c) *C. puteana* (*C.p.*) on Scots pine sapwood.

The decay tests were performed with n = 3 piles (150 specimens) per material and test fungus (in total: 8 materials, 4 test fungi; 4800 specimens, 96 piles). For each material/fungus combination 3 × 50 specimens were piled and a metal ring (ø 30 mm, h = 25 mm) was placed between sample number 7 and 8 to avoid direct contact between malt agar and test specimens. Afterwards, the piles were tied up with thin wires, dipped in tap water for 45 s and put into wide-necked 2l-Erlenmeyer flasks, filled with 500 ml freshly cooked and still liquid malt agar. The flasks were then covered with a cotton plug and aluminum foil and sterilized in a steam oven at 120 °C for 30 min. The flasks were then stored in 20 °C/65% RH to generate a moisture gradient within the piles.

After two weeks of storage 10 inoculated wood samples (10 × 10 × 5 mm^3) were placed on the agar next to the pile. The inoculation samples were pre-incubated in small Petri-dishes for 2 weeks. In total 4 different fungi were used for the decay tests (Table 2).

Incubation and harvest of piled samples

During incubation the mycelium growth height was measured and marked on the flasks once a week (Fig. 1b and c). After 16 weeks of incubation at 20 °C/65% RH all specimens were cleaned from adhering mycelium, weighed, oven dried and weighed again to determine MC (Eq. (2)) and mass loss (ML) by fungal decay (Eq. (3)). In addition, the maximum growth height of mycelium was determined. Therefore it was distinguished between internal mycelium growth through the wood specimens and growth on the pile outer surface.

$$MC = \frac{m_1 - m_{0,1}}{m_{0,1}} \times 100 \qquad (2)$$

MC = moisture content in %

Table 2
Fungal species used for pile tests.

Fungal species	Strain	Abbreviation
Coniophora puteana	Schumacher ex Fries, Karsten DSM 3085	*C.p.*
Gleophyllum trabeum	Murill DSM 3087	*G.t.*
Trametes versicolor	Linnaeus Quélet DSM 2086	*T.v.*
Donkioporia expansa	Kotlaba & Pouzar DSM 5107	*D.e.*

m_1 = mass after incubation in g
$m_{0,1}$ = oven dry mass after incubation in g

$$ML = \frac{m_0 - m_{0,1}}{m_0} \times 100 \qquad (3)$$

ML = mass loss in %
$m_{0,1}$ = oven dry mass after incubation in g
m_0 = oven dry mass before incubation in g

Results and discussion

Softwoods

The relationship between MC and ML was determined for every single pile. For all piles a moisture gradient, increasing from bottom to top, was found. This coincides with findings from Schmidt et al. (1996) who performed tests with crosswise stacked piles of Scots pine sapwood. In the following, peculiarities as well as regularities are exemplarily shown for selected piles.

Fig. 2 shows the results for a Scots pine sapwood pile exposed to *Gleophyllum trabeum*. Within the 16 weeks of exposure a continuous moisture gradient developed and mass loss (ML) decreased with decreasing moisture content (MC). As expected the highest ML and MC were found close to the bottom of the pile on sample no. 8. The moisture threshold for decay (ML ≥ 2%) was surprisingly low; a ML of 2.0% was obtained at a MC of only 16.3%. Consequently, the fungus was able to degrade wood clearly below FSP (34.6%). Stienen et al. (2014) reported similar findings from tests with *Antrodia xantha* which caused more than 2% ML below fiber saturation, i.e. 24.6% on *P. sylvestris*.

In contrast, for Douglas fir piles after 16 weeks of incubation with *Coniophora puteana* (Fig. 2) no MC gradient developed within the exposure time. The highest ML (37.8%) as well as the highest MC (46.5%) were not determined on the bottom samples, but in the middle of the pile. A similar observation was made by Schmidt et al. (1996) who found that the fungus *Antrodia vaillantii* provoked the highest decay on specimens in the middle of a crosswise stacked pile. Furthermore, *C. puteana* showed negative mass loss on the upper samples (no. 38–42). Since the internal mycelium growth border was determined on the 43rd specimen this can be explained

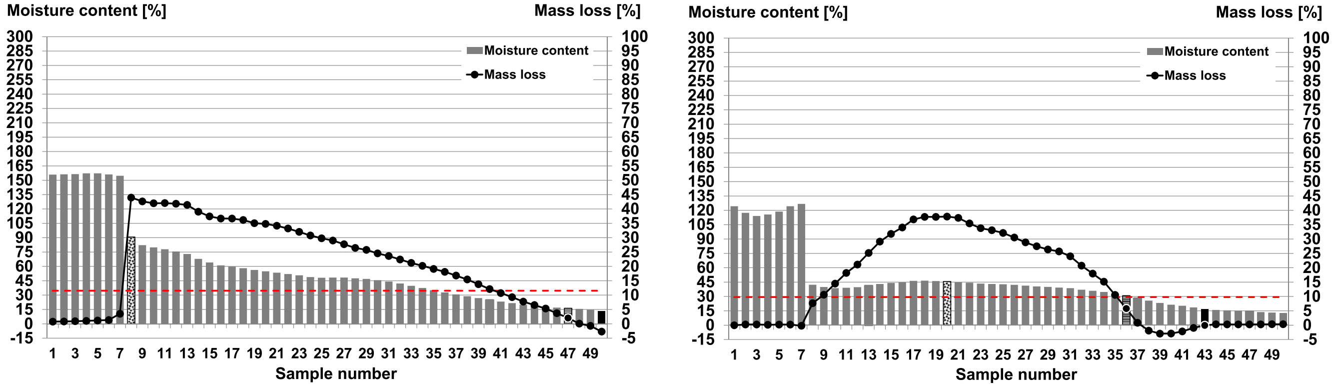

Fig. 2. Moisture content (MC) and mass loss (ML) of **Scots pine sapwood caused by *G. trabeum* (left) and Douglas fir caused by *C. puteana* (right)**, both after 16 weeks of incubation at 20 °C. (No.1 = bottom, No.50 = top, metal ring spacer between No.7 and No.8). Dashed red line is indicating the fiber saturation point. Spotted column: MC optimum where highest ML was achieved; Striped column: minimum MC with ML ≥ 2%; Black column: interior growth border. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

by ingrown mycelium but only little metabolization of the wood substance, as earlier described by Huckfeldt and Schmidt (2006). A high-energy multiple impact (HEMI)-test was conducted by Brischke et al. (2008) using specimens, which were exposed to different fungi in a pile tests. They found a remarkable decrease in structural integrity for specimens showing an increase in mass due to ingrown mycelium. These results led to the question whether the actual threshold might be even lower and pointed out that setting a threshold of only 2% ML can be considered rather conservative.

Larch samples exposed to *Donkioporia expansa* (Fig. 3) showed remarkably high MC in the bottom half of the pile. This coincides with findings from Stienen et al. (2014) who found a higher ability to transport water of *D. expansa* compared to *C. puteana*. Furthermore, the results of this study showed that in contrast to the low moisture threshold found for Douglas fir exposed to *C. puteana* (*cf.* Fig. 2, 16.3%) a comparably high MC of 69.3% was needed to obtain a ML ≥ 2%. However, due to the limited incubation time one might assume that with a longer test period degradation at lower MCs could be possible. Additional exposure times could give more insight into the development of MC and ML. This also applies for results obtained for a spruce pile incubated with *Trametes versicolor*. As shown in Fig. 3 neither a moisture nor a ML gradient developed within the 16 weeks of incubation. Both, MC as well as ML showed stagnation in form of a moisture plateau, starting at sample no. 18 until sample no. 31, after which ML and MC starts to decrease.

Hardwoods

Beech exposed to *T. versicolor* showed a decrease in ML with decreasing MC (Fig. 4) which coincides with findings from Huckfeldt and Schmidt (2006). As expected, highest ML and highest MC were determined for the lowest sample directly above the malt agar. In contrast, the moisture threshold for decay (ML ≥ 2%) was surprisingly low; a ML of 2.2% was obtained at a MC of only 15.4% (FSP = 33.8%). In analogy to Scots pine sapwood exposed to *G. trabeum* (*cf.* Fig. 2), the fungus was able to degrade wood clearly below FSP.

In contrast to *T. versicolor*, the brown rotter *C. puteana* caused relatively low ML on oak (Fig. 4) and the maximum ML (10.7%) was found in the upper part of the pile. In addition, all specimens showed relatively low MC, and in accordance with the results for spruce incubated with *T. versicolor* (*cf.* Fig. 3), no MC gradient was found. This again leads to the assumption that an increased incubation time could give additional information on the development of MC and ML. As can be seen from sample no. 45 a ML of ≥2% (ML = 3.3%) was achieved at a MC of only 23.3%, which is clearly below FSP (39.8%).

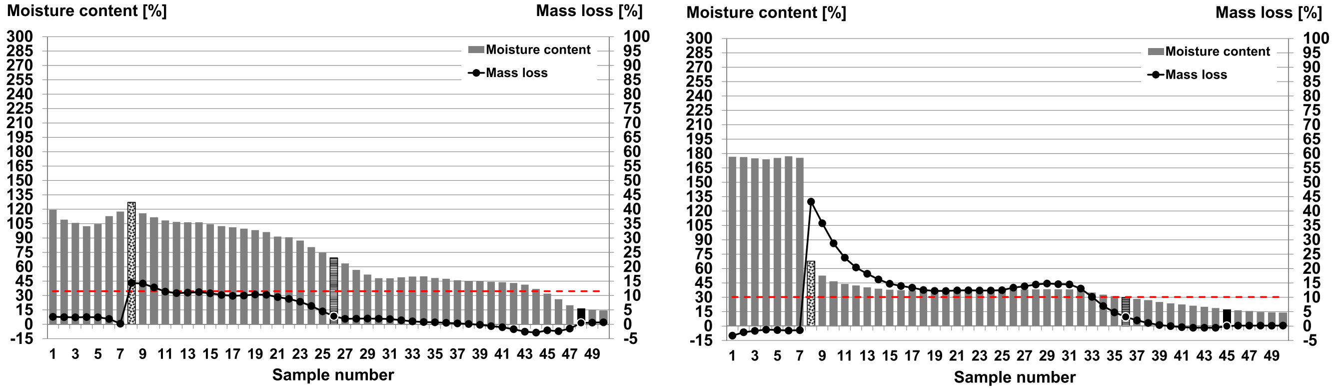

Fig. 3. Moisture content (MC) and mass loss (ML) of **larch caused by *D. expansa* (left) and spruce caused by *T. versicolor* (right)**, both after 16 weeks of incubation at 20 °C. (No.1 = bottom, No.50 = top, metal ring spacer between No.7 and No.8). Dashed red line is indicating the fiber saturation point. Spotted column: MC optimum where highest ML was achieved; Striped column: minimum MC with ML ≥ 2%; Black column: interior growth border. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

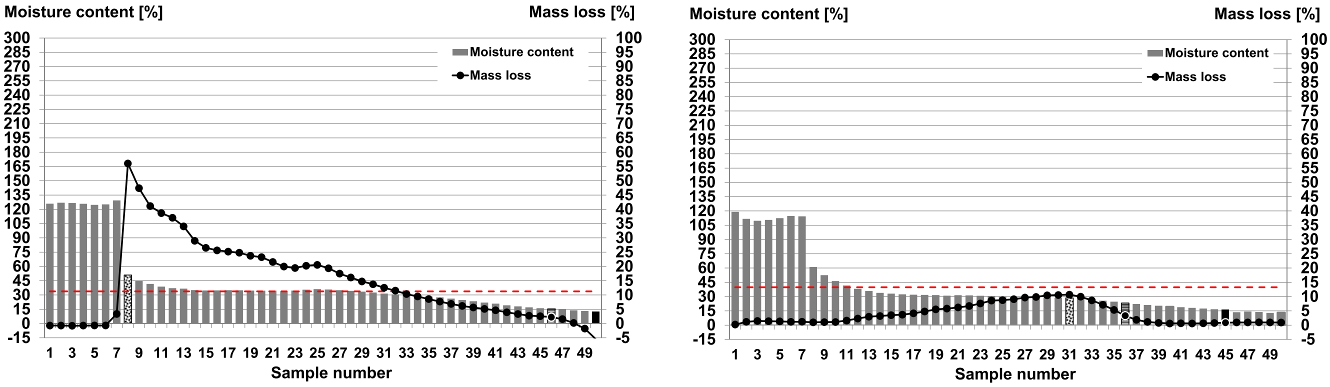

Fig. 4. Moisture content (MC) and mass loss (ML) of **beech caused by *T. versicolor* (left) and oak caused by *C. puteana* (right)**, both after 16 weeks of incubation at 20 °C. (No.1 = bottom, No.50 = top, metal ring spacer between No.7 and No.8). Dashed red line is indicating the fiber saturation point. Spotted column: MC optimum where highest ML was achieved; Striped column: minimum MC with ML ≥ 2%; Black column: interior growth border. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

An example for black locust exposed to *D. expansa* is given in Fig. 5. Here it becomes obvious that although the fungus was able to grow up to the top of the pile (sample no. 40) no ML ≥ 2% occurred. These findings might again point on the need to increase the test duration in order to enable wood species with reduced sorption properties and/or a high natural durability to develop a higher MC and therewith better conditions for fungal decay.

Moisture thresholds

The results of all material/fungus combinations are summarized in Table 3. and moisture thresholds for fungal growth and ML are given. Internal and external growth borders were distinguished and refer to mycelium growing on the outer surface of the pile and through the wood samples inside the pile. Since the fungi generally grew higher inside the pile the internal border was considered for defining the threshold.

Highest ML were found for Scots pine sapwood (60.1%, *C. puteana*), spruce (56.0%, *G. trabeum*), and Beech (57.1%, *T. versicolor* and 55.3%, *D. expansa*). These results coincide with the preference of white-rotters for hardwoods (Schmidt, 2007). For all materials the fungi were able to colonize the piled wood specimens clearly below fiber saturation. The MC limit for fungal growth was found to be in a range between 12.3% (*T. versicolor*, beech) and 24.5% (*D. expansa*, beech). In 22 out of 32 cases the fungi caused ML on the tested materials below the respective FSP. When looking at the difference between FSP and the minimum MC for a ML ≥ 2% it becomes clear that, with the exception of *C. puteana*, the highest deviations were found for beech and Scots pine sapwood, i.e. the wood species with the lowest inherent resistance. *G. trabeum* was able to degrade Scots pine sapwood with a ML of 2.0% at a MC of only 16.3%, *T. versicolor* caused ML of 2.2% at a MC of only 15.4% and exposure to *D. expansa* led to a ML of 3.5% at a MC of 18.9%. However, also for the more durable species like English oak, *C. puteana* was able to degrade at a MC of 23.0% with a ML of 2.9%. These observations coincide with results from Stienen et al. (2014) who found mass loss of ≥2% on Scots pine sapwood caused by *Anthrodia xantha*, *C. puteana* and *Gloeophyllum abietinum* at MC below FSP, which they assumed to be at MC = 30%. In contrast, Zabel and Morrell (1992) concluded that fungi are not able to grow in wood without free water, i.e. below fiber saturation. However, in both studies, the present as well as Stienen et al. (2014), the test set up provided a moisture source (malt agar) from which the fungus is able to transport water (Schmidt, 2006). Hence, one might assume that fungal degradation was merely possible below fiber saturation, because of the test set up. Ammer (1963), however, conducted studies using pre-infected specimens stored above different saturated salt solutions, without a direct moisture source, and observed MLs of 6.1% (*Polyporus stipticus*) and 4.1% (*Polyporus caesius*) on Norway spruce with a MC of 25.5%.

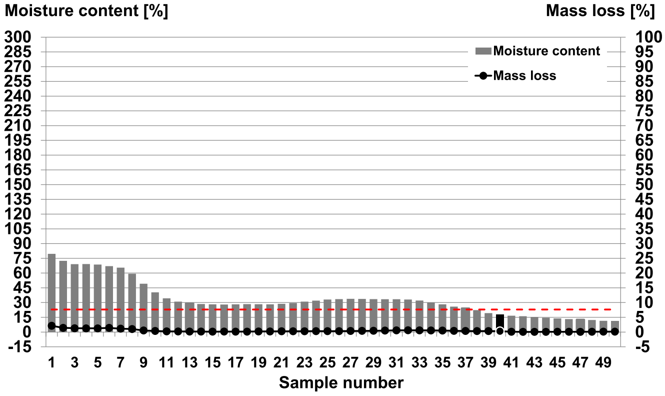

Fig. 5. Moisture content (MC) and mass loss (ML) of **black locust caused by *D. expansa*** after 16 weeks of incubation at 20 °C. (No.1 = bottom, No.50 = top, metal ring spacer between No.7 and No.8). Dashed red line is indicating the fiber saturation point. Black column: interior growth border. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Nevertheless, a test set up including an external moisture source, as well as the fact that the fungi itself consists of approx. 90% water (Schmidt, 2006) only allows limited conclusions on moisture thresholds for fungal decay. Theden (1941) concluded that neither the initial MC nor the MC at the moment decay starts nor MC at test termination alone can give an exact information on moisture requirements. However, since all fungi were active and the MC in the piles was most likely lower at the beginning of degradation, all threshold values determined in this study can be considered as conservative values.

Conclusions

The pile test method turned out to be a useful tool for determining moisture thresholds of decay fungi for the different wood species under test. Considering the fact that, compared to other biological tests, the pile test set up is quite susceptible to several

Table 3
Wood degradation by basidiomycetes at different moisture after 16 weeks of incubation. Note: For interpretation of the results, it should be considered that an external moisture source was available for the fungus.

Fungus	Wood species	Mean MC_{opt}[a]	Mean ML_{max}[a]	Minimum $MC_{growth\ border}$[a]	Minimum $MC_{\geq 2\%\ ML}$[a]	Mean MC_{FSP}[b]	Difference $MC_{\geq 2\%\ ML}$ to MC_{FSP}
		[%]	[%]	[%]	[%]	[%]	[% − points]
C. puteana	Scots pine sapwood	76.1	60.1	13.8	28.5	34.6	6.1
	Scots pine heartwood	45.4	30.8	13.4	24.1	27.2	3.1
	Spruce	55.1	51.8	12.7	25.9	30.3	4.4
	Larch	68.2	43.6	13.6	26.1	34.5	8.4
	Douglas fir	48.4	40.3	14.4	27.4	29.3	1.9
	Beech	73.4	56.0	13.5	29.7	33.8	4.1
	English oak	29.0	10.8	15.1	23.0	39.8	16.8
	Black locust	70.4	15.1	15.9	22.3	22.9	0.6
G. trabeum	Scots pine sapwood	108.6	47.6	13.3	16.3	34.6	18.3
	Scots pine heartwood	64.4	21.9	17.8	37.1	27.2	−9.9
	Spruce	172.8	56.0	14.5	26.4	30.3	3.9
	Larch	47.3	19.0	18.2	31.1	34.5	3.4
	Douglas fir	56.4	10.7	21.3	28.8	29.3	0.5
	Beech	94.6	33.6	14.6	29.2	33.8	4.6
	English oak	n.a.	n.a.	20.1	n.a.	39.8	n.a.
	Black locust	n.a.	n.a.	18.1	n.a.	22.9	n.a.
T. versicolor	Scots pine sapwood	53.2	37.6	12.9	21.4	34.6	13.2
	Scots pine heartwood	113.1	30.7	19.5	30.3	27.2	−3.1
	Spruce	65.2	40.8	17.5	28.4	30.3	1.9
	Larch	81.9	23.7	23.0	31.0	34.5	3.5
	Douglas fir	99.1	10.6	21.2	42.2	29.3	−12.9
	Beech	46.6	57.1	12.3	14.6	33.8	19.2
	English oak	65.3	41.3	18.7	33.8	39.8	6.0
	Black locust	48.2	6.3	16.3	39.4	22.9	−16.5
D. expansa	Scots pine sapwood	63.3	19.3	13.5	18.9	34.6	15.7
	Scots pine heartwood	n.a.	n.a.	24.5	n.a.	27.2	n.a.
	Spruce	119.2	47.2	13.8	21.6	30.3	8.7
	Larch	120.0	14.2	13.8	49.6	34.5	−15.1
	Douglas fir	74.6	5.7	21.6	52.3	29.3	−23.0
	Beech	57.6	55.3	13.7	22.5	33.8	11.3
	English oak	97.5	32.6	16.0	32.2	39.8	7.6
	Black locust	n.a.	n.a.	17.3	n.a.	22.9	n.a.

n.a. = not available; i.e. ML was <2% for all specimens in the pile.

[a] Mean and minimum values have been calculated based on n = 3 replicate piles.

[b] Mean value of n = 9 replicate samples per wood species.

disturbing or irritating factors like the fact that the set up entails an 'open system' in terms of direct air contact of the specimens or that the fungi need to grow upwards, the results were surprisingly consistent. Another aggravating factor is the need to establish a MC gradient within the pile before incubation. This is difficult to monitor without infecting the set-up, e.g. with molds.

For the majority of the material/fungus combinations under test it was observed that the minimum MC for fungal decay was more or less distinct below fiber saturation up to 19.2 %-points. Hereby a wood-species dependent effect on the minimum MC thresholds was found so that the wood species itself, as well as fungal species and the test set up showed an effect on the determined moisture requirements. The highest deviations from MC threshold to FSP were found for beech and Scots pine sapwood, i.e. the wood species with the lowest inherent resistance.

For interpretation of the results, it should be considered that an external moisture source was available for the fungus. Therefore growth and decay limits might differ and are worth to get examined separately, without an external moisture source. Furthermore new infection through fungal spores, i.e. conditions for spore germination need to be addressed separately. These two factors are of great importance when looking at the interpretation of decay related field test results obtained by moisture monitoring. The physiological thresholds obtained in this study can be used for a more accurate modeling of decay and service life of timber structures. However, additional studies on requirements for onset of mycelium growth and subsequent decay without an external moisture source might be needed and are therefore in progress.

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Paper 6

DE GRUYTER Holzforschung 2016; 70(4): 331–339

Linda Meyer*, Christian Brischke, Andreas Treu and Pia Larsson-Brelid

Critical moisture conditions for fungal decay of modified wood by basidiomycetes as detected by pile tests

Abstract: The aim of cell wall modification is to keep wood moisture content (MC) below favorable conditions for decay organisms. However, thermally modified, furfurylated, and acetylated woods partly show higher MCs than untreated wood in outdoor exposure. The open question is to which extent decay is influenced by the presence of liquid water in cell lumens. The present paper contributes to this topic and reports on physiological threshold values for wood decay fungi with respect to modified wood. In total, 4200 specimens made from acetylated, furfurylated, and thermally modified beech wood (*Fagus sylvatica* L.) and Scots pine sapwood (sW) (*Pinus sylvestris* L.) were exposed to *Coniophora puteana* and *Trametes versicolor*. Piles consisting of 50 small specimens were incubated above malt agar in Erlenmeyer flasks for 16 weeks. In general, pile upward mass loss (ML) and MC decreased. Threshold values for fungal growth and decay (ML≥2%) were determined. In summary, the minimum MC for fungal decay was slightly below fiber saturation point of the majority of the untreated and differently modified materials. Surprisingly, *T. versicolor* was able to degrade untreated beech wood at a minimum of 15% MC, and growth was possible at 13% MC. By contrast, untreated pine sW was not decayed by *C. puteana* at less than 29% MC.

Keywords: acetylated wood, critical moisture content, decay resistance, furfurylated wood, mass loss, moisture performance, moisture content, pile test, thermally modified wood, wood degradation by basidiomycetes

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Introduction

The protective mechanism of modified timber is based on its hydrophobic character and improved moisture performance (Hill 2007; Ringman et al. 2014). Different physiological studies on wood destroying fungi (Viitanen and Ritschkoff 1991; Huckfeldt and Schmidt 2006) showed considerable impact of moisture content (MC) on fungal decay. By keeping the MC below conditions favorable for decay organisms, the wood is sufficiently durable for many outdoor applications (Ibach and Rowell 2000; Hill 2007; Welzbacher 2007). The hydrophobicity and the durability of chemically or thermally modified timber (TMT) are strongly dependent on the treatment intensity (TI) (Epmeier et al. 2004; Esteves and Pereira 2008; Thybring 2013).

The TI of TMT is usually expressed by the percentage of mass loss (ML) during heat treatment (HT) (Welzbacher et al. 2007). ML is frequently correlated with TMT intensity and other properties such as durability, moisture behavior, and strength properties (Metsä-Kortelainen et al. 2006; Brischke et al. 2007; Paul et al. 2007; Welzbacher et al. 2007; Meyer et al. 2011). By contrast, for chemical modification (CM) processes, the uptake of solid agents remaining after drying (weight percent gain [WPG]) is considered as a measure of modification intensity (Li et al. 2000; Lande et al. 2004; Mai and Militz 2004; Hill 2007). However, the parts of the modification agent left in the cell lumens do not contribute to cell wall modification. In addition, it is not known to which extent the modification agents react/polymerize within the cell wall after impregnation, and this parameter can have a significant effect on the resulting wood properties. Although the acetylation process decreases the hygroscopicity of wood (Rowell 2006), it might also increase its capillary water uptake (Larsson and Simonson 1994). Similar changes in water uptake behavior were reported for TMT (Metsä-Kortelainen et al. 2006). Information is scarce in terms of the changed water uptake behavior and the critical MC for onset of fungal growth (Meyer et al. 2012). Furthermore, it is still controversially discussed to which extent decay is influenced by the presence of liquid water in cell lumens (Thygesen et al. 2010; Ringman et al. 2014).

Therefore, it seems necessary to determine physiological threshold values for wood decay fungi with respect to modified timber. Critical moisture levels are material-specific characteristics and need to be considered when estimating the resulting moisture and temperature-induced risk for decay of wood-based materials. Hence, this study focused on determining moisture threshold values for wood decay fungi with respect to the three currently most widely commercialized modified wood products, i.e., acetylated, furfurylated, and TMT. In focus was the relationship between treatment-induced mass changes (ML or WPG) and equilibrium moisture content (EMC) as these parameters indicate the TI. The pile test approach, previously described by Schmidt et al. (1996), was applied to determine the minimum MC needed for fungal growth and decay as a function of the type and intensity level of modification.

Materials and methods

Specimens, 5 (long.)×40×40 mm^3, were made from Scots pine sW (*Pinus sylvestris* L.) and European beech (*Fagus sylvatica* L.). In total, 10 000 specimens were prepared, whereby always 50 replicate specimens were axially matched and used together for (1) acetylation, (2) furfurylation, and (3) thermal modification. Each specimen was modified with high and low TI.

Acetylation was performed at SP Technical Research Institute of Sweden in Borås, Sweden, in a pilot plant reactor and consisted of an initial vacuum-pressure impregnation step with acetic anhydride. The excess anhydride was drained off, and the impregnated wood was reacted at elevated temperature for different length of times to achieve two different TIs. The by-product acetic acid was removed by the evacuation of the reactor during heating.

Furfurylation was performed at the Norwegian Forest and Landscape Institute in Ås, Norway, with two different aqueous furfuryl alcohol (FA) solutions: (1) 62% water, 35% FA, and 3% additives (FA55) (low TI); and (2) 57% water, 40% FA, and 3% additives (FA70, Kebony AS, Skien, Norway) (high TI). The impregnation schedule for both solutions was 30 min at 0.004 MPa and 60 min at 0.9 MPa.

HT was performed at Leibniz University Hannover, Germany, at 220°C in a drying oven for beech: 1.5 h (low TI) and 4.0 h (high TI). Pine sW specimens were modified for 4.0 h (low TI) and 8.0 h (high TI). All specimens were tightly wrapped in aluminum foil to reduce access of oxygen.

Change in mass due to modification: The mass change was determined as one of the important parameters. All modified specimens were oven-dried at 103°C until constant mass and weighed to the nearest 0.001 g before (m_0) and after ($m_{0,1}$) the treatments. The WPG of acetylated and furfurylated wood was calculated according to Eq. (1), and the ML by heat treatment (ML_{TMT}) was calculated according to Eq. (2).

$$\text{WPG\%}=100\ \ (m_{0,1}\text{-}m_0)\,/\,m_0 \tag{1}$$

$$\text{ML}_{\text{TMT}}\,\%=100\ \ (m_0\text{-}m_{0,1})\,/\,m_0 \tag{2}$$

Afterward, piles for the fungal tests were selected according to the WPG and ML_{TMT} values. For every pile, the highest possible similarity between specimens was decisive. Hereby, every pile consisted of axially matched specimens exclusively.

Equilibrium moisture content: EMC was also determined as a crucial parameter before the fungal tests. The specimens were placed in a closed but ventilated small-scale climate chamber over a saturated solution of KCl (85% RH, 20°C). After a constant mass was achieved, the specimens were weighed again (m_{EMC}) to determine EMC according to Eq. (3):

$$\text{EMC\%}=100\ \ (m_{EMC}\text{-}m_{0,1})\,/\,m_{0,1} \tag{3}$$

Fiber saturation point: Wood MC at fiber saturation point (FSP) was determined for every material based on n=6 specimens. The specimens were exposed at 20°C/100% RH in water-saturated atmosphere in a closed but ventilated small-scale climate chamber over deionized water. After a constant mass was achieved, the specimens were weighed again (m_{FSP}) to determine FSP according to Eq. (4):

$$\text{FSP\%}=100\ \ (m_{\text{FSP}}\text{-}m_{0,1})\,/\,m_{0,1} \tag{4}$$

Pile tests: The decay test with piled wood specimens was described by Ammer (1964), Schmidt et al. (1996, 1997), and Stienen et al. (2014). This method (Figure 1a) allowed for determining the cardinal points of wood MC for different fungal species and wood-based substrates in terms of mycelial growth and decay activity (Huckfeldt et al. 2005; Huckfeldt and Schmidt 2006). Here, the pile direction was identical with the longitudinal direction of the wood specimens, allowing easy capillary water transport and mycelial growth through the wood pile upward. The brown rot fungus *Coniophora puteana* (Schumacher) P. Karsten (DSM 3085) and the white rot fungus *Trametes versicolor* (L) Lloyd (DSM 2086) were inoculated on malt agar (approximate formula in grams per liter: malt extract, 12.75; glycerin, 2.35; dextrin, 2.75; gelatin peptone, 0.78; and agar, 15.00; pH 4.7±0.2). The decay tests were performed with n=3 piles (i.e., 150 specimens) per material, TI, and test fungus (in total: 6 materials, 2 TIs, 2 test fungi; 3600 specimens, 72 piles). In addition, n=3 piles of untreated controls were included (2 materials, 2 test fungi; 600 specimens, 12 piles). For each material/fungus combination, 3×50 specimens were labeled and piled. A metal ring (ø 30 mm, h=25 mm) was placed between the seventh and the eighth specimens to avoid direct moisture flow between the agar and the test specimens. The piles were tied up with thin, synthetically covered binding wires, dipped in tap water for 45 s, and put into wide-necked 2-l Erlenmeyer flasks, filled with 500 ml, freshly cooked malt agar. The flasks were then covered with a cotton plug and aluminum foil and sterilized in a steam oven at 120°C for 30 min. The flasks were stored in 20°C/65% RH to generate a moisture gradient within the piles. After 2 weeks of storage, 10 inoculated wood samples (10×10×5 mm^3) were placed on the agar next to the pile (Figure 1a). The inoculation samples were preincubated in small Petri dishes for 2 weeks. During incubation, the mycelium growth height was measured visually by marking the maximum height to which the mycelium has grown on the outside of the flasks once a week. After 16 weeks of incubation at a room condition (20°C/65% RH), all specimens were cleaned from adhering mycelium, weighed, oven dried, and weighed again to determine MC and ML. The maximum growth height of mycelium was determined. Therefore, it was

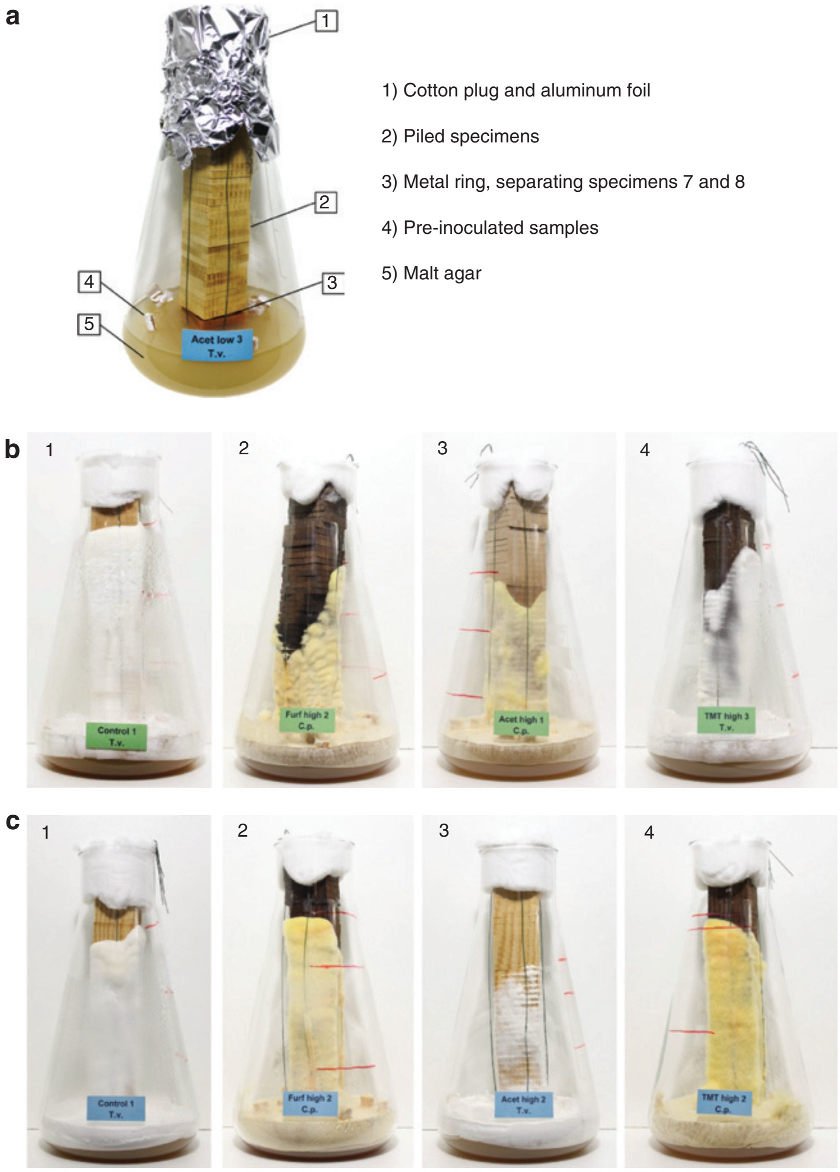

Figure 1: (a) Erlenmeyer flask with piled specimens. (b) Beech and (c) Scots pine sW piles. Mycelium growth after 3 weeks of incubation with *Coniophora puteana* and *Trametes versicolor* on (1) control, (2) furfurylated, (3) acetylated, and (4) thermally modified specimens. Modification level was high.

distinguished between internal mycelium growth through the wood specimens and growth on the pile's outer surface.

Results and discussion

Mass changes as a function of modification

The mass changes (ML_{TMT} as well as WPG) summarized in Table 1 reflect expectedly the TIs. Although the treatment time for TMT was less for the beech specimens, the ML_{TMT} data are higher than those of pine specimens. This can be explained by the higher content of pentosans of hardwoods, which are less thermally stable than the hexosans of softwoods (Tjeerdsma et al. 2002; Weiland and Guyonnet 2003; Hill 2007). The ML_{TMT} of beech (high TI) was more than three times higher than that of pine after the same treatment time (4 h).

Equilibrium moisture content

The EMC of all modified materials was significantly reduced in a range between 31% and 64%. TMT pine sW

Table 1: Mean±standard deviation of ML due to thermal modification (ML_{TMT}) and weight percent gain for acetylated (WPG_{ac}) and furfurylated (WPG_{furf}) samples for n=150 replicate specimens.

Material	ML_{TM} (%)	WPG_{ac} (%)	WPG_{furf} (%)
Beech, TI_{low}	8.2±0.7	13.8±1.3	29.5±8.2
Beech, TI_{high}	15.3±0.5	18.2±0.5	38.0±5.7
Pine sW, TI_{low}	4.9±0.3	15.1±2.6	35.5±8.2
Pine sW, TI_{high}	8.6±0.4	22.3±0.6	55.5±5.1

(low TI) showed the lowest and acetylated pine (high TI) the highest sorption reduction (Table 2). For all materials, EMC reduction corresponds to higher WPG or ML_{TMT}. The reduced water sorption is explained by the reduced number of hydroxyl groups in the cell wall that is accessible or available for water (Hill 2007; Esteves et al. 2011; Thybring 2013; Ringman et al. 2014).

Mycelium growth

The setup allowed fast mycelium growth upward the pile, especially in the first 3 weeks. An example for this is presented in Figure 1b and c for the different materials with high TI. After only 3 weeks of incubation with *C. puteana* and *T. versicolor*, almost all piles were covered with mycelium to half of their height or more. For most materials, mycelium growth remained static after approximately 5 weeks. However, none of the fungi suffered from dry conditions due to the high amount of malt agar serving also as nutrient source. Consequently, results from all 84 piles can be considered valid.

ML and MC of untreated wood

The relationship between MC and ML was determined for every single pile. Figure 2a shows the results for untreated beech exposed to *T. versicolor*. In general, ML decreased with decreasing MC, which coincides with findings of Huckfeldt and Schmidt (2006). As expected, the highest ML and the highest MC were determined for the lowest sample directly above the malt agar. By contrast, the moisture threshold for decay (ML≥2%) was surprisingly low; an ML of 2.2% was obtained at an MC of only 15.4%. Consequently, the fungus was able to degrade wood clearly below FSP.

Figure 2b shows the results for a pine sW pile exposed to *C. puteana*. In analogy to beech wood (Figure 2a), a continuous moisture gradient developed in the piles within the 16 weeks of incubation and ML decreased with decreasing MC. Hereby, water might be transported from the malt agar by fungal mycelium and strands (Schmidt 2006). In addition, water might be derived from fungal metabolism, as suggested, e.g., by Ammer (1964). The highest ML and the highest MC were again determined on sample no. 8. In contrast to *T. versicolor*, the brown rotter *C. puteana* caused mass increase instead of ML on the upper samples (nos. 41–48). Because the internal mycelium growth border was determined on the 48th specimen, this observation might be explained to some extent by ingrown mycelium with little metabolizing effect of wood substance, as earlier described by Huckfeldt and Schmidt (2006). Brischke et al. (2008) conducted a high-energy multiple impact test with specimens previously exposed to different fungi in pile tests. The tests revealed that a remarkable decrease in structural integrity is detectable for specimens with mass increment due to ingrown mycelium. However, as *C. puteana* caused mass increment up to 5–10%, the argument of ingrown mycelium is not enough. It is also possible that nutrients were transported from the malt agar to the growth front at the upper part of the piles. When modeling decay as a function of MC and TI, setting a threshold of only ≥2% ML, might be considered for determining the lower moisture limit as nonconservative because the actual threshold might be even lower.

ML and MC of modified wood

In many cases, a continuous moisture gradient developed in the piles of modified wood similar to the untreated

Table 2: Mean±standard deviation of equilibrium moisture content (EMC) for modified materials and controls as well as reduction in EMC ($EMC_{red.}$) for modified materials; n=150 replicate specimens.

	Control	Thermal modification		Acetylation		Furfurylation	
Material	EMC (%)	EMC (%)	ΔEMC (%)	EMC (%)	ΔEMC (%)	EMC (%)	ΔEMC (%)
Beech, TI_{low}	15.83±0.59	8.51±0.15	46.24	9.00±0.50	43.15	9.36±0.77	40.87
Beech, TI_{high}		7.71±0.24	51.30	6.60±0.14	58.31	9.00±0.32	43.15
Pine sW, TI_{low}	15.15±0.61	10.44±0.43	31.09	8.22±0.88	45.74	8.79±0.55	41.98
Pine sW, TI_{high}		8.45±0.15	44.22	5.36±0.14	64.62	8.41±0.32	44.49

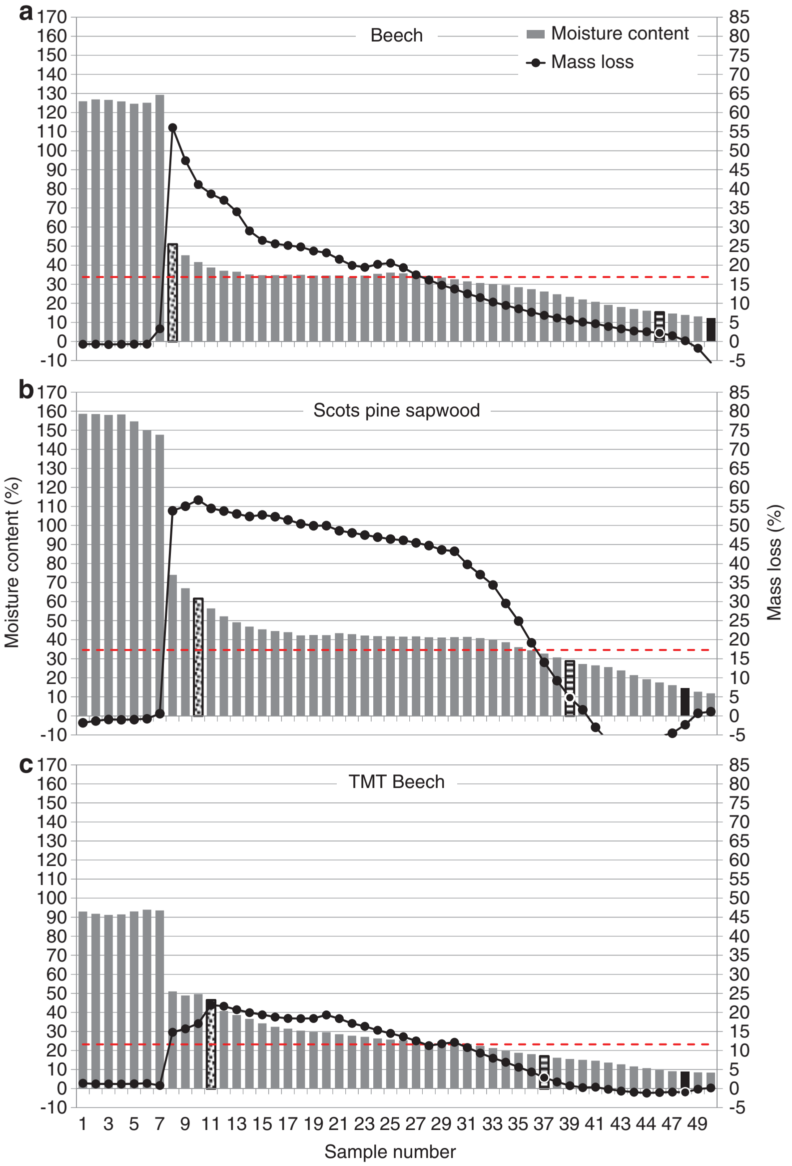

Figure 2: MC and ML for every single sample in (a) untreated beech, (b) untreated Scots pine sW, and (c) thermally modified “low” beech piles exposed to *Trametes versicolor* (a, c) and *Coniophora puteana* (b) for 16 weeks (No. 1=bottom, No. 50=top, metal ring spacer between No. 7 and No. 8). MC at maximum ML (dotted column), MC minimum for ML (≥2%) (striped column), and mycelium growth border (black column). Dotted red line shows FSP.

controls and ML decreased with decreasing MC, although FSP was significantly reduced compared with the untreated wood. This is exemplarily shown in Figure 2c for TMT beech exposed to *T. versicolor*.

The highest ML was found for sample no. 11. The threshold for decay (ML≥2%) was determined below fiber saturation with an ML of 2.9% obtained at an MC of 17.0%. This also demonstrates that TMT was degradable below FSP.

The relationship between MC and ML for acetylated beech is presented in Figure 3. In general, MC and ML decreased upward the pile up to sample no. 16. A new increase of MC and ML was observed at the samples no. 24 and 34. The question arises whether the MC was increased through moisture transport by high fungal activity or the increased ML was caused by a high MC. Additional exposure times could give more insight into the development of MC and ML. Looking at the corresponding WPG and EMC, it can be stated that for every specimen with a remarkably higher ML and MC, the WPG was comparably low. The slight drops in TI within one pile became also evident based on the EMC. Hereby, it becomes clear that a small change in TI can have an enormous effect on fungal degradation. The same effect was found for the furfurylated piles.

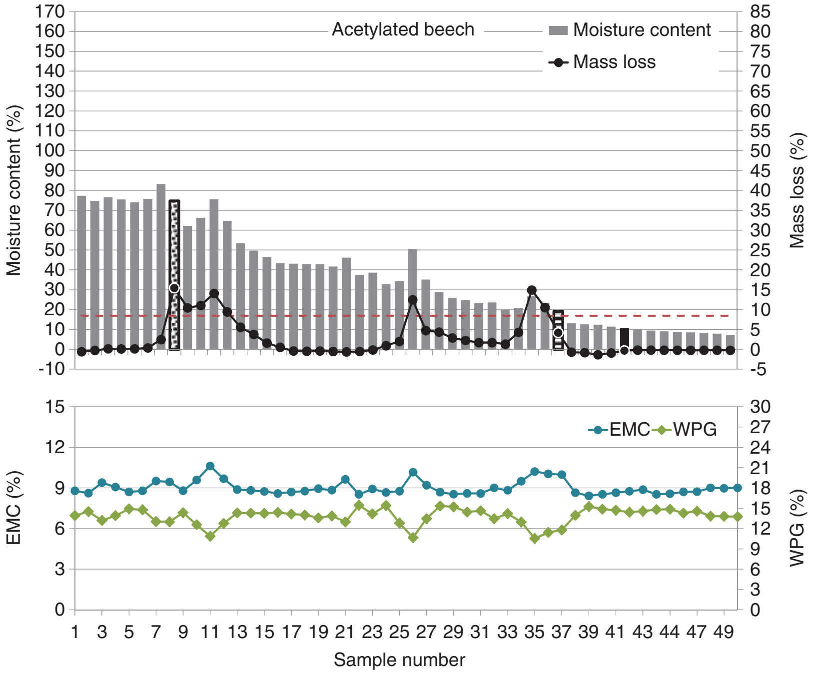

Figure 3: MC and ML as well as equilibrium moisture content (EMC) and weight percent gain (WPG) for every single sample in an acetylated "low" beech pile exposed to *Coniophora puteana* for 16 weeks (No. 1=bottom, No. 50=top, metal ring spacer between No. 7 and No. 8). MC at maximum ML (dotted column), MC minimum for ML (≥2%) (striped column), and mycelium growth border (black column). Dotted red line shows FSP.

Wood moisture thresholds

In Tables 3 and 4, the results concerning moisture thresholds for mycelium growth and ML obtained from untreated and modified beech and pine sW exposed to *T. versicolor* and *C. puteana* are presented, respectively. Internal and external growth borders were distinguished and refer to mycelium growing on the outer surface of the pile and

Table 3: Wood moisture content, fiber saturation, and growth heights (growth b.) of *Trametes versicolor* after 16 weeks of incubation for acetylated (Acet.), furfurylated (Furf.), and thermally modified (TMT) materials.

		MC_{opt}: MC at ML_{max}[a]	$MC_{growth\ b.}$[a]	MC_{min} for ML≥2%[a]	FSP[b]	Mean max growth b.[a,c]
Material	Treatment	(%)	(%)	(%)	(%)	(n)
Beech	Control	46.6	12.3	15.4	33.8±2.6	50
Pine sW	Control	53.2	12.9	21.4	34.6±3.3	48
Beech	Acet. TI_{low}	43.6	8.7	25.0	16.9±1.1	46
	Acet. TI_{high}	n.a.	8.7	n.a.	14.8±1.1	39
Pine sW	Acet. TI_{low}	n.a.	7.9	n.a.	17.1±1.9	43
	Acet. TI_{high}	n.a.	6.1	n.a.	14.4±0.8	45
Beech	Furf. TI_{low}	82.1	12.1	17.9	24.6±2.4	41
	Furf. TI_{high}	60.7	14.4	20.7	25.5±1.4	37
Pine sW	Furf. TI_{low}	62.5	17.0	28.3	30.0±3.7	33
	Furf. TI_{high}	69.1	21.3	37.4	29.4±1.7	23
Beech	TMT TI_{low}	45.5	8.2	16.0	23.2±3.7	49
	TMT TI_{high}	35.2	7.7	15.9	22.3±3.4	48
Pine sW	TMT TI_{low}	34.8	13.1	23.6	21.4±1.7	36
	TMT TI_{high}	n.a.	11.2	n.a.	20.0±2.3	35

Data are presented as mean±standard deviation. n.a., not available; i.e., ML was <2% for all specimens in the pile.
[a]Mean and minimum/maximum values have been calculated based on $n=3$ replicate piles.
[b]Mean value of $n=6$ replicate samples per material.
[c]Maximum height=30 cm.

Table 4: Wood moisture content, fiber saturation, and growth heights (growth b.) of *Coniophora puteana* after 16 weeks of incubation for acetylated (Acet.), furfurylated (Furf.), and thermally modified (TMT) materials.

Material	Treatment	MC$_{opt}$: MC at ML$_{max}$^{a} (%)	MC$_{growth\ b.}$^{a} (%)	MC$_{min}$ for ML≥2%^{a} (%)	FSP^{b} (%)	Mean max. growth b.^{a,c} (n)
Beech	Control	73.4	13.5	29.7	33.8±2.6	49
Pine sW	Control	76.1	13.8	28.5	34.6±3.3	47
Beech	Acet. TI$_{low}$	73.9	10.0	19.2	16.9±1.1	44
	Acet. TI$_{high}$	n.a.	7.1	n.a.	14.8±1.1	45
Pine sW	Acet. TI$_{low}$	49.4	8.5	14.2	17.1±1.9	42
	Acet. TI$_{high}$	n.a.	7.7	n.a.	14.4±0.8	40
Beech	Furf. TI$_{low}$	41.6	12.1	17.5	24.6±2.4	42
	Furf. TI$_{high}$	82.0	12.7	30.6	25.5±1.4	40
Pine sW	Furf. TI$_{low}$	31.1	10.8	17.5	30.0±3.7	40
	Furf. TI$_{high}$	46.6	7.9	44.1	29.4±1.7	40
Beech	TMT TI$_{low}$	49.1	8.5	21.3	23.2±3.7	46
	TMT TI$_{high}$	n.a.	9.3	n.a.	22.3±3.4	42
Pine sW	TMT TI$_{low}$	39.2	12.1	24.4	21.4±1.7	41
	TMT TI$_{high}$	n.a.	10.6	n.a.	20.0±2.3	41

Data are presented as mean±standard deviation. n.a., not available; i.e., ML was <2% for all specimens in the pile.
[a]Mean and minimum/maximum values have been calculated based on $n=3$ replicate piles.
[b]Mean value of $n=6$ replicate samples per wood species.
[c]Maximum height=30 cm.

through the wood samples inside the pile. Because the fungi generally grew higher inside the pile, the internal border was considered for the threshold definition.

The lowest growth height (mean maximum growth border) was found for *T. versicolor* on furfurylated pine sW. This is in agreement with findings reported by Alfredsen et al. (2008), who investigated fungal colonization on furfurylated, acetylated, and TMT and found that furfurylated pine sW showed the lowest amount of *T. versicolor* DNA. They assumed that this might be explained by wood cell wall blocking due to polymerization and reduced accessibility of wood polymers, which hinder the enzymatic degradation of the cell wall and therewith growth of *T. versicolor*. For all other materials, the piles were overgrown by mycelium to at least one half of their height.

In many cases, the fungi were both able to colonize and decay the untreated and the modified materials at MCs below the respective FSP. This coincides with findings from Stienen et al. (2014), who reported that also *Antrodia xantha*, *C. puteana*, and *Gloeophyllum abietinum* were able to grow and subsequently decay pine sW at MCs below FSP, if a moisture source (malt agar) was neighboring. However, Stienen et al. (2014) did not observe ML≥2% at less than 24.6% MC. For *C. puteana*, an MC$_{min}$ of 21.5% for a degradation >2% was determined by Huckfeldt and Schmidt (2006). Ammer (1963) conducted test with *C. puteana* on spruce and observed an ML of 2.4% at an MC of only 18.5%. Schmidt (2006), however, concluded that data on cardinal points for MC can vary depending on the wood species, test parameters, and fungal isolate. The lower threshold MC for fungal decay determined in this study for *T. versicolor* on beech wood can indicate that there is a relationship between fungus and material combinations and the respective moisture thresholds.

Similarly, in this study, the thresholds for all three modification types were partly below their respective FSP, e.g., *T. versicolor* on furfurylated beech and TMT pine sW (6.7% and 6.4% below FSP) and *C. puteana* on acetylated and furfurylated pine sW (2.9% and 12.5% below FSP, respectively). However, as shown in Figure 2, ML was depending on weak points, e.g., reduced TI of the more durable modified materials. Low modification levels in combination with increased MC – even below FSP – might therefore lead to fungal colonization and subsequent decay.

For some materials in this study, in particular the high modification levels, no ML≥2% occurred. Therefore, thresholds could not be determined for the most durable materials.

Conclusions

The pile test method could be confirmed as a useful tool for determining moisture thresholds of decay fungi also for thermally and chemically modified timbers. For interpretation of the thresholds obtained, it has to be considered that an external moisture source was available for the fungus. For future studies, it might be worth investigating growth and decay conditions also without external moisture source as well as the conditions for spore germination. The latter is to reflect the most relevant exposure situations, such as in the building envelope of timber frame houses. The interpretation of the results of moisture monitoring and modeling of the moisture-induced risk for decay requires exact knowledge about MC thresholds for fungal decay and corresponding limit states. The pile test setup lacks information on (1) whether moisture is evenly distributed within one sample or gradually decreasing from decayed to nondecayed areas and (2) whether water is located in the cell lumen or bound in the cell wall. More sophisticated techniques, such as NMR, in combination with the pile test may further contribute to answering these questions.

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Paper 7

Submitted for publication - Wood Science and Technology

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):

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

$W24_{submersion}$ 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):

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

$W24_{100\,\%\,RH}$ 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):.

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

$W24_{0\,\%\,RH}$ 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):

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

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):

$$ML = \frac{m_0 - m_{0,i}}{m_0} \tag{5}$$

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.

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 **[%]**	$\mathbf{k_{wa}}$ **[-]**	**mean** **[%]**	$\mathbf{k_{wa}}$ **[-]**	**mean** **[%]**	$\mathbf{k_{wa}}$ **[-]**	**mean** **[g/cm^2]**	$\mathbf{k_{wa}}$ **[-]**
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

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).

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}** **[a^{-1}]**	**k_{inh}** **[ ]**
	ML **[%]**	**k_{inh}** **[ ]**	**ML** **[%]**	**k_{inh}** **[ ]**	**ML** **[%]**	**k_{inh}** **[ ]**		
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

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.

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.	-	-	-	-

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).

$$v_{rel.} = \frac{v_{species\ x}}{v_{reference}} \tag{10}$$

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

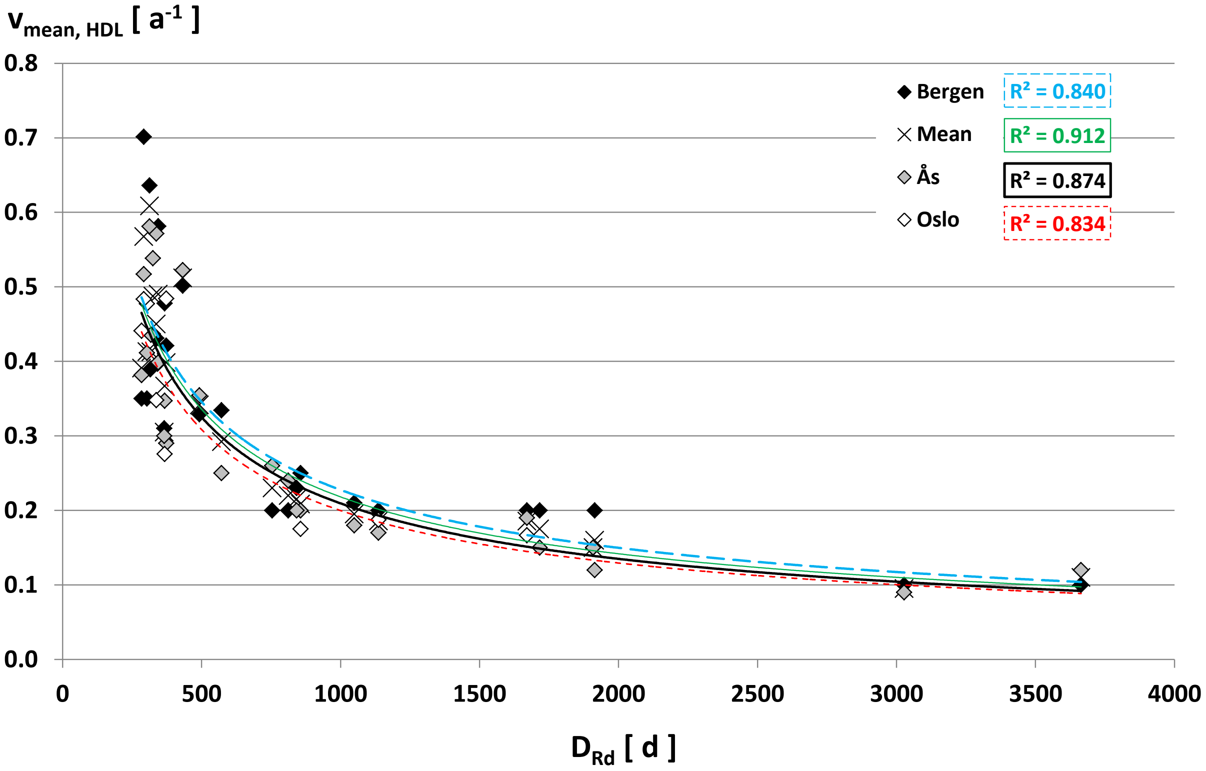

Figure 1: Relationship between calculated D_{Rd} and mean decay rate of horizontal double layer ($v_{mean,\ HDL}$) specimens exposed at three Norwegian test sites. In addition, the average mean value for all three test sites is given (k_{inh} factors based on soil contact tests and k_{inh} factors based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

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 R² 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.

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*****
	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
k_{inh}	**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

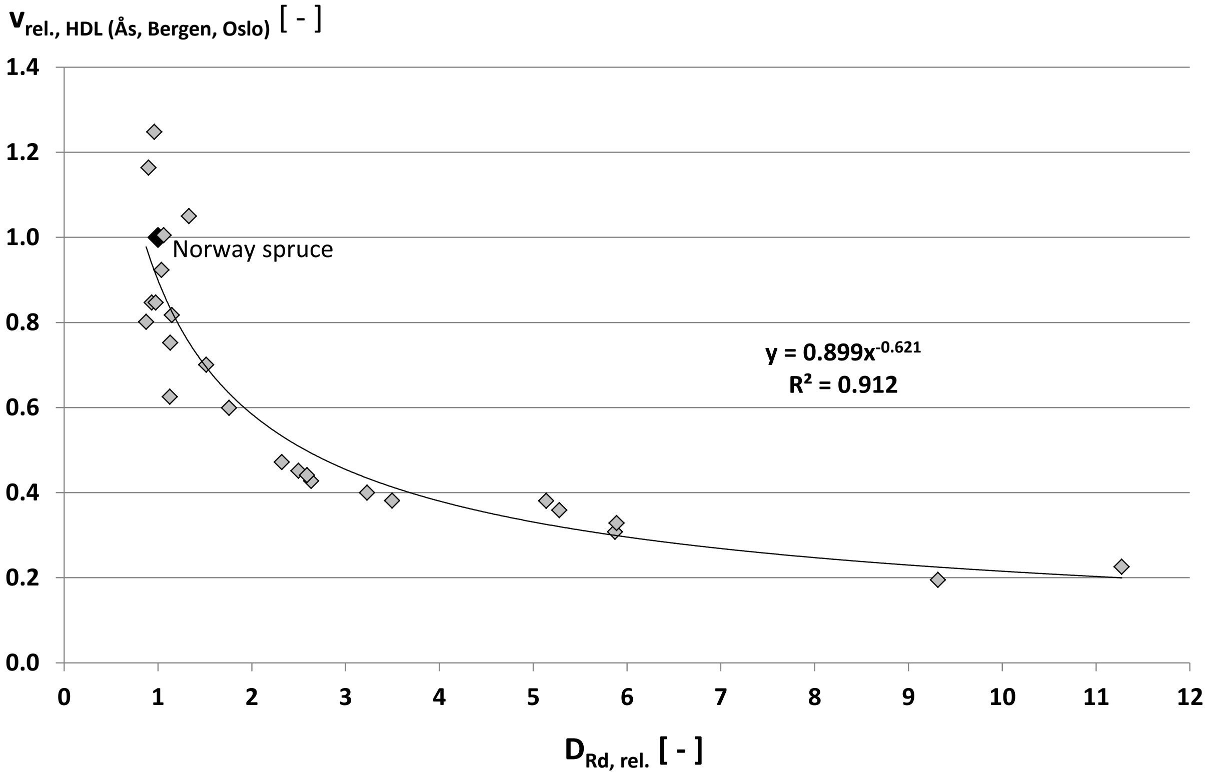

Figure 2: Relationship between mean relative decay rate of horizontal double layer specimens averaged for three Norwegian test sites ($v_{rel., HDL (Ås, Bergen, Oslo)}$) and relative calculated resistance dose $D_{Rd, rel.}$. Reference species Norway spruce is marked.

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.

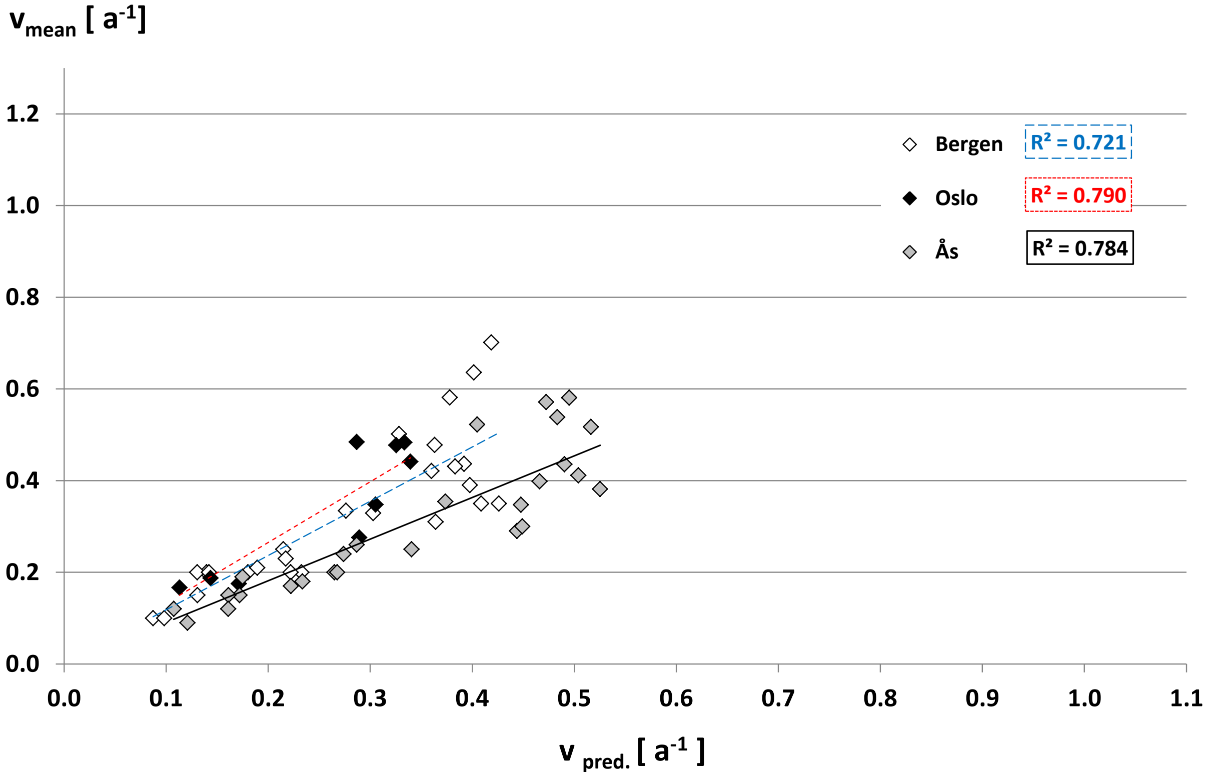

Figure 3: Relationship between decay rates predicted on the basis of the relative material resistance D_{Rd} ($v_{pred.}$) according to the function shown in Figure 2 and the determined decay rate of horizontal double layer specimens for three Norwegian test sites (v_{mean}).

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.

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** $_{\textbf{submersion}}$		**W24** $_{\textbf{100 \% RH}}$		**W24** $_{\textbf{0 \% RH}}$		**CWU**	
	mean [%]	$\mathbf{k_{wa}}$ **[ ]**	**mean [%]**	$\mathbf{k_{wa}}$ **[ ]**	**mean [%]**	$\mathbf{k_{wa}}$ **[ ]**	**mean [g/cm^2]**	$\mathbf{k_{wa}}$ **[ ]**
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

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.

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

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).

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

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).

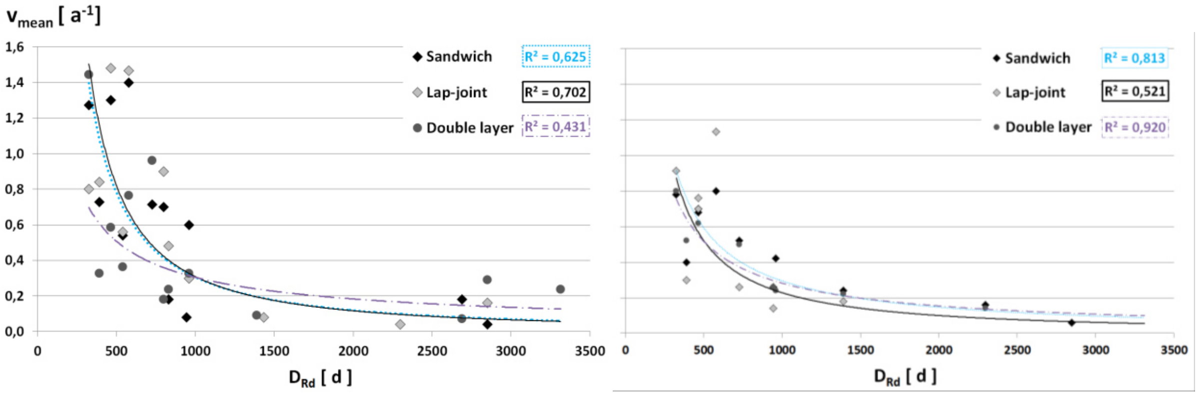

Figure 4: Relationship between v_{mean} of sandwich, lap-joint and horizontal double layer specimens exposed at Hannover, Germany (left) and Borås, Sweden (right), and calculated resistance dose D_{Rd}.

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 ($R^2 = 0.613$).

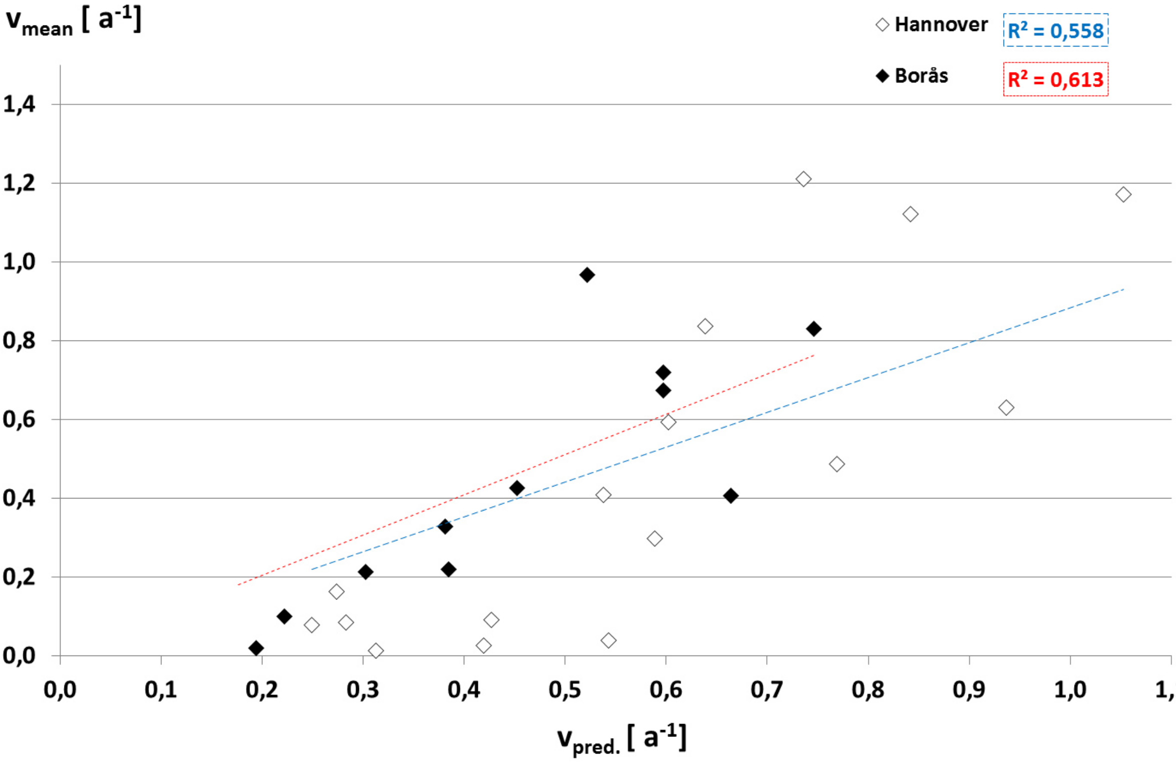

Figure 5: Relationship between decay rates predicted on the basis of the relative material resistance D_{Rd} ($v_{pred.}$) according to the function shown in Figure 2 and the determined decay rate v_{mean} of horizontal double layer, sandwich and lap-joint specimens for the Hannover and Borås test sites.

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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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

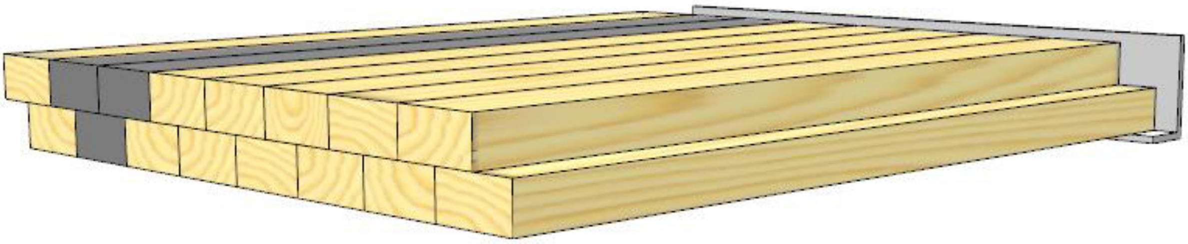

Figure 1: Horizontal double layer test

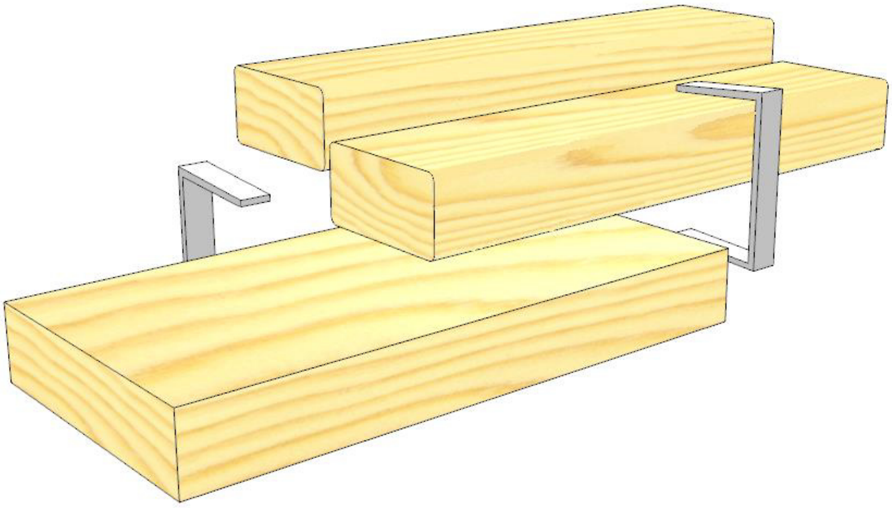

Figure 2: Sandwich test, lap-joint test

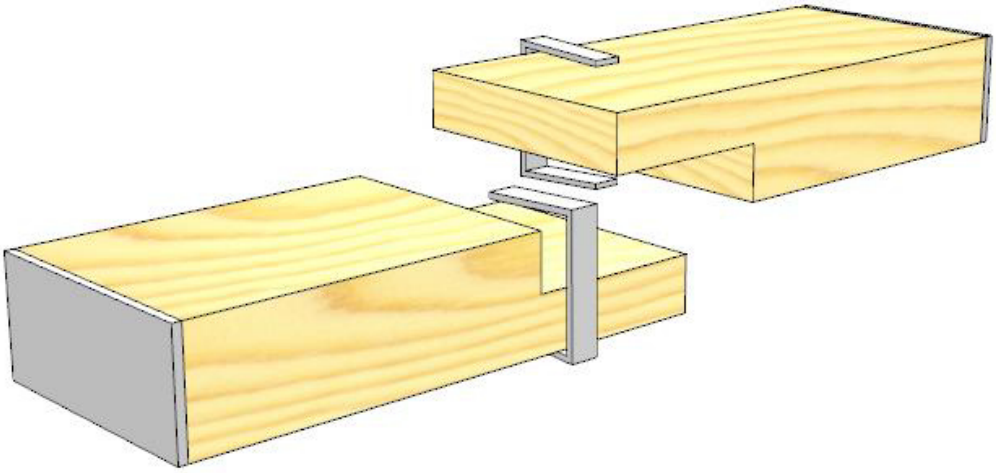

Figure 3: Lap-joint test

4 Conclusions

Wood exposed above ground faces a wider range of decay influencing loads than can be reflected by a single field test method. Relating the different structural details (1. single elements, 2. joints, 3. blocks and stacks, 4. bundles, and 5. components with contact to concrete) to real life exposure it can be concluded that one single method cannot sufficiently reflect the full spectrum of moisture conditions possibly occurring in above ground components.

Including moisture monitoring in different field tests allowed to quantify the moisture induced risk for decay for differently severe above ground methods. The MC measurements conducted within several studies enabled an improved interpretation of field test data and are therefore suggested as an essential tool for testing wood and wood-based materials above ground. The need to consider significant factors such as the measuring position and the identification of the most critical conditions within a given design became evident. The region of interest (ROI) in a certain test design is not always equal to the most critical part when it comes to decay development. Hence, the ROI needs to be carefully selected and has to be considered when MC data are examined with respect to decay risk. The comparative evaluation of 24 different durability field test methods clearly showed that the moisture performance coincided well with the resulting decay response. However, the most severe ‘close to ground’ exposures showed high decay rates after a comparably short time of wetness.

Exact knowledge about MC thresholds for fungal decay and corresponding limit states is needed to implement MC data into service life prediction in particular because those turned out to be material-specific. The pile test studies conducted within this thesis included numerous untreated as well as differently modified materials and showed that the thresholds were frequently below their respective fiber saturation point (FSP) and consequently less than expected. However, these results were obtained in a test set up, in which the fungi were provided with an external moisture and nutrient source in form of malt agar. Since this is rarely the case under real-life conditions and the thresholds might therefore be higher, the results can be considered to include a safety margin for modelling their outdoor performance. Nevertheless, further studies without external moisture sources should quantify their effect. In this regard, also the conditions for spore germination are important and need to be addressed in future research.

The comprehensive evaluation of different above ground test methods with regard to time of wetness resulted in a classification of all methods into three groups (high, medium and low moisture induced risk for decay). Within these groups all tests were ranked by the following factors 1.) moisture induced risk 2.) decay rate and 3.) practicability issues. The most suitable methods for each group are shown in Figure 10.

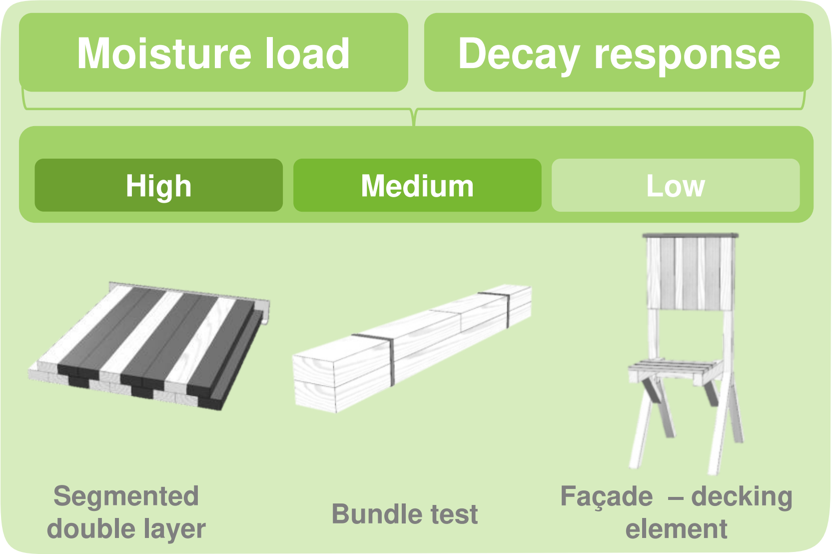

Figure 10: Suggestions for test methods within differently severe exposures

Within the group of methods with high moisture load, the segmented double layer provided a combination of high moisture loads, fast and severe decay, and a low rating for costs and efforts. The Bundle test type II turned out to be one of the most promising tests reflecting medium moisture-induced decay risk. In addition, this test assures inexpensive sample preparation. All tests within the group providing low moisture induced risk showed low decay rates. Consequently, the tests within this group require long exposure periods before first signs of decay can be detected. To allow achieving test results in an acceptable long time span, moisture monitoring appears to be the only feasible alternative to traditional decay assessments. Façade elements can consequently serve as relevant test set-ups within this group representing the lowest moisture-induced decay risk, but can provide results within a few years based on automated MC measurements. However, the presented test methods need to be seen as a recommendation and can be adapted in dependence of the objective of the respective study. For future work verifications of MC field test data with in-service components are suggested to further improve the significance of the obtained test data.

The approach to predict above ground field performance presented in this thesis used field test data from different test sites and tests. For the first time results from in- and above-ground field tests, as well as from laboratory wetting ability and resistance tests were included in the development and validation of a prediction model. The attempt resulted in a simple and transparent model for predicting decay rates of wood and wood-based materials. Furthermore, the model can be directly implemented into existing engineering design guidelines and might be used for implementing wetting ability data into performance classification as requested by European standardization bodies.

The model structure allows including further factors such as ageing effects, the formation of cracks and climate related effects and stands out due to its applicability to engineering design concepts as well as into biological dosimeter models. For a future performance-related test methodology that goes beyond “pass or failure”-criteria, the findings from this thesis provide relevant instruments. On one hand a set of above-ground methods representing different levels of moisture-induced decay risks has been identified. On the other hand, a model that is based on laboratory and in-ground field test data allows predicting above-ground decay. Both elements can be easily linked for performance prediction in differently severe exposure conditions.

Additional publications by the author

(not included in this thesis)

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