ONLINE ISSN 2069-7430
ISSN-L 1841-4737

PRO LIGNO
www.proligno.ro

Vol. 13 N° 4 2017
pp. 8-26

MOISTURE DYNAMICS DEFINING SERVICE LIFE PERFORMANCE OF WOOD PRODUCTS

Joris VAN ACKER
Ghent University (UGent), Laboratory of Wood Technology (Woodlab)
Coupure links 653, 9000 Ghent, Belgium
Tel: 0032 9 2646120, Fax: 0032 9 2646233, E-mail: Joris.VanAcker@UGent.be

Abstract:

Material resistance of wood products against fungal decay has long been considered as a direct derivative of the biological durability, merely the biocidal protection against organisms able to degrade wood. When targeting those applications where moisture content can be controlled by the mere composition or structure of the wood products the service life of a commodity can be significantly impacted. This allows to expect a considerable service life even for so-called non durable wood material.The service life of wood products in exterior applications and in particular in ground contact has since long been defined by a durability class. This durability class is defined mainly by the impact of decaying organisms on the mechanical integrity over time. In ground contact the wood moisture content is nearly always sufficient to sustain both Basidiomycetes induced decay (white rot and/or brown rot) as well as soft rot. However, when exposing wood products outdoors without direct interaction with water or soil, the so-called use class 3 according to EN 335, moisture dynamics become relevant in addition to the inherent biological durability based on biocidal components. Time of wetness can be regarded as a tool to illustrate the possibility to degrade or not by fungi. This is valid for the properties of a wood species, but also for the different wood protecting methods to enhance the service life. Not only the introduction of biocidal actives as done by means of wood preservation technology, but also different wood modifying techniques as well hydrophobation and the application of coatings can be considered valid to prolong service life of wood products.

The role of inherent wood durability of wood species and their origin as well as options to enhance both durability as moisture dynamics allow the wood industry to provide a range of product types and performance levels. This variability in properties from biological origin in combination with man-made transformations allows the end user to select from a range of alternatives to accomplish fit for purpose criteria defined by limit states. These have been identified as simple classification systems in the past but are now evolving toward model based approaches combining resistance to biological degradation and moisture dynamics. European standardization within CEN TC 38 on wood durability is working on this topic and test methodology as well as decision support mechanisms are under discussion. Meanwhile also the forum on how to enhance wood properties is working on this renewed concept, e.g. the International Research Group on Wood Protection (IRGWP) and the European Conference on Wood Modification (ECWM). Although the approach to match performance of wood products with material characteristics seems straightforward several additional parameters seem to interact and require additional stochastic modelling related to different commodities, overall and local climate, design, biological hazard, presence and probability of decay organisms, time of wetness, etc. Extra tools are being developed to understand such parameters. State of the art assessment of moisture content (e.g. continuous moisture measurements), structural impact at microscale using CT scanning, NIR tools to verify presence of active components, advanced methods to detect wood rot are all part of a new methodology to predict service life of wood based products in general and in particular as construction component, e.g. new engineered wood products like CLT.

At the Ghent University the Laboratory of Wood Technology has developed a continuous moisture measurement (CMM) set up to assess by means of simulated field testing the time of wetness based on material characteristics. This CMM was first used to check the outstanding performance of plywood in exterior applications often based on non-durable wood species and often without the need to incorporate additional biocides. Also different wood species as well as modified and hydrophobated solid wood have been assessed. Additional laboratory testing was introduced to check moisture dynamics by means of methods including floating or submersion in combination with drying, all in search for correlation with the time of wetness recorded with the CMM equipment.

Key words: *wood products; durability; service life; moisture dynamics; material resistance.*

INTRODUCTION

Wood and wood based products are similarly to the mainly man-made alternatives limited in their ability to remain functional over time. They are inherently prone to biodegradation under natural conditions of the ecosystem cycle and as such all end uses are impacted to some extent. The risk of wood degradation mainly depends on the application conditions. For example, decay fungi are ubiquitous and can grow everywhere as long as the environmental conditions are suitable. The growth of fungi requires wood substances as nutrient source – so they will decrease the strength of wood materials – and a moisture source.

The risk or hazard of a wooden product regarding fungal degradation depends on typical organisms thriving under dry up to continuous wet circumstances, identified as use classes defined as such in EN 335 (2013). Performance related to service life is depending on the durability or material resistance against degrading fungi. Wood or timber species have been classified for natural durability using a service life approach by means of graveyard type field testing. As mentioned before, high variability is a concern and predicting service life for applications out of ground contact leads often to substantial debate (Kutnik 2013, Suttie et al. 2013). To ensure minimum requirements are met, often highly durable species, mainly tropical hardwoods, are selected while adequate performance is feasible with less durable species. Focusing on softwoods it can be stated that the intrinsic or inherent durability is often insufficient and different treating methods (wood preservation, wood protection, wood modification) are used to enhance the material resistance when the products are intended to be used under harsher circumstances. In addition, new wood based products have been developed as well to answer to this need.

To allow the end user to select from a range of alternatives enabling to accomplish fit for purpose criteria defined by limit states, simple classification systems have been developed in the past that are now evolving toward model based approaches combining resistance to biological degradation and moisture dynamics, allowing to aim for an integrated service life assessment approach. Especially in the construction or building sector an improved assessment of service life is certainly welcomed. European standardization within CEN TC 38 on wood durability is working on this topic and test methodology as well as decision support mechanisms are under discussion. Meanwhile also the forum on how to enhance wood properties is working on this renewed concept, e.g. the International Research Group on Wood Protection (IRGWP) and the European Conference on Wood Modification (ECWM). Although the approach to match performance of wood products with material characteristics seems straightforward several additional parameters seem to interact and require additional stochastic modelling related to different commodities, overall and local climate, design, biological hazard, presence and probability of decay organisms, time of wetness, etc.

In this introduction, some elements are provided related to a fit for purpose flow chart for decision making related to parameters defining material characteristics of these wood based products, a selection of state-of-the-art tools available to assist in assessing parameters during exposure and related reliability analysis. Hereafter a short description is given of different use classes, an overview of different wood treatments and innovative wood products that are intended to be assessed within a service life prediction framework. Finally some details are included on the toolbox for non-destructive monitoring of samples exposed in the laboratory or outdoors. Also a brief snapshot of statistical processing of mass loss data from lab testing and time-to-failure analysis of field data, and some specific aspects of service life prediction like benchmarking are presented.

Use classes

The 5 use classes are defined in the EN 335 and ISO 21887 (Suttie et al. 2013) as:

UC1: Situation in which the wood-based product is inside a construction, not exposed to the weather and wetting. Interior, dry.

UC2: Situation in which the wood-based product is under cover and not exposed to the weather (particularly rain and driven rain) but not persistent, wetting can occur. Interior, or under cover, not exposed to the weather. Possibility of water condensation.

UC3: Situation in which the wood-based product is above ground and exposed to the weather (particularly rain). Exterior, above ground, exposed to the weather.

UC4: Situation in which the wood-based product is in direct contact with ground and/or fresh water; Exterior in ground contact and/or fresh water.

UC5: Situation in which the wood-based product is permanently or regularly submerged (i.e. sea water and brackish water). Permanently or regularly submerged in salt water.

Wood preservation

Especially heavy duty applications like transmission poles and railway sleepers have triggered wood preservation. In many countries wood preservation is still considered mainly for use class 4 applications. The assessment of toxic threshold levels for the biocides used is still defined accordingly. Field testing in ground contact combined with a so-called 'no risk' approach is the basis to continue using heavy duty preservatives like creosote, CCA, PCP, etc. However, wood preservation evolved and exterior out of ground applications have become more apparent. When soft rot is of no concern the assessment of wood preservatives in ground contact may lead to excessive requirements for biocides or overkill of recommended or required retentions. Furthermore, in ground contact (or water contact) a continuous supply of water guarantees the development of fungi. Above ground the climatic conditions are far more dominant and can allow to ensure longer service life by means of protection by design and are also impacted by e.g. coatings. Dealing with the interior climate, e.g. use class 2, the risk of getting higher moisture content in wood for a longer period depends not only on the interior climate. Moisture is linked to dampness and is increased when condensation and/or leakage are involved. A critical parameter here is to lower the risk. In practice wood preservation is linked to industry involved in producing, formulating and applying biocides and hence often related to other application areas of such active components.

Wood modification

Over the last decades, additional actors have been coming to the field of enhanced durability. Technologies working under the denominator wood modification claim to enable this without using biocides. The product brand names often are referred to as 'new' wood species and the main focus might well be on increasing other properties like dimensional stability or weathering performance. Besides thermally modified timber (TMT), chemical modification systems are present especially on the European market. These include acetylation and furfurylation. The so-called non-biocidal systems also cover several methodologies to lower the impact of moisture and are known as oil treatments and hydrophobation like the use of organo-silicon compounds. Clearly these methods come close to the role of exterior wood coatings. Currently the industry involved in these technologies seems to be hardly linked to the producers of wood preservatives.

Innovative wood products

On the scene of service life of wood products not only different treatments to enhance durability are of importance. Mainly since mid of last century many innovative wood products have been developed all having an impact on the moisture dynamics and hence on the rate of fungal degradation or service life. For construction, end uses commodities have been developed often intended for protected interior use. Especially under use class 2 the processing of wood into different engineered wood products (EWP) lowers the risk of high humidity over longer periods. Products like glulam (glued laminated timber), CLT (cross-laminated timber), LVL (laminated veneer lumber), LSL (laminated strand lumber), PSL (parallel strand lumber) and other structural composite lumber (SCL) all have different moisture dynamics than solid timber. Furthermore, I-joists and wood I-beams combine several of these and link with the wood based panels (WBP) like plywood and OSB (oriented strand board). Both are often considered for exterior applications and again a major impact of coatings is part of such applications. Coated plywood is an eminent product in this respect. In the group of innovative wood products one should not forget several composite products being developed next to the more traditional ones. With focus on decking and cladding WPC (wood polymer/plastic composites) are clearly stating argumentation of moisture control as one of the main features (Defoirdt et al. 2009). Similarly, natural fibre composites (NFC) based on other 'non-wood' lignocellulosics have similar issues on moisture control to ensure service life in exterior applications (Defoirdt et al. 2017). Unfortunately, often the industries involved in these products have limited links to the companies involved in wood preservation or wood modification.

A framework for service life prediction

The importance of service life prediction for wood and wood based materials is beyond questioning. If proper test methods, monitoring tools and analysis software are tailored to one another, taking into account the specificities of wood, proper service life prediction is at hand. This is not merely a scientific question, the Construction Products Regulation (CPR) on a European level requires reliable information about product performance and is laying down harmonized conditions for the marketing of construction products. Specifically, we aim here at an integrated approach related to service life predication for natural durability, wood preservation, wood modification and innovative wood products with focus on use classes 2 and 3.

The exposure dosage is a measure for the degree of exposure indicating the potential of decay. Fig. 1 shows the macroclimate as defined by the geographical location and climate data for the region together with local impact identified as microclimate will lead to specific time of wetness of the wooden product (Brischke et al. 2010, Rapp et al. 2000). Design will act as an additional parameter lowering or sometimes increasing (e.g. water trapping) the impact of the climate factors. Clearly the climate and especially the microclimate is not or less relevant when considering applications interior dry (UC1) and in soil and (sea) water contact (UC4/5).

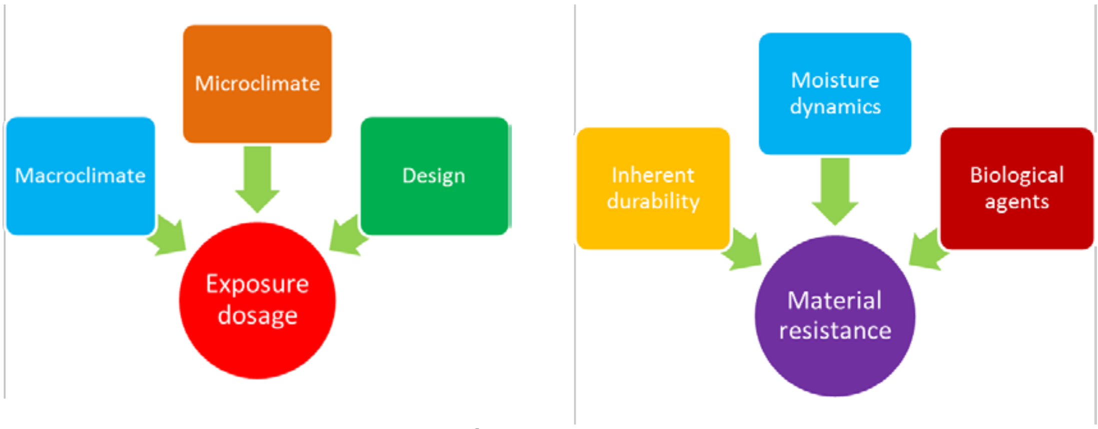

Fig. 1.
(left) Exposure dosage is a combined parameter including macro- and microclimate and design components. (right) Material resistance of wood products is a combination of inherent durability (toxicity), moisture dynamics and these are relevant for the different biological agents.

Any wood species, wood product - treated or not - will have a material resistance against biological agents. Material resistance can be expressed as parameters to assess the degree of resistance related to a biological hazard (Fig. 1). The biological agents of concern differ depending on the use classes and even more to the earlier definition of biological hazard classes. When focusing on fungal decay, the inherent durability can be linked to the presence of biocidal components and hence the level of toxicity towards the fungi of concern. Additionally, it is relevant that the substrate contains a sufficient level of moisture over time. The resistance of any substrate to get wet and the ease or difficulty to dry fast when the wetting stopped can be expressed under the term moisture dynamics (Van den Bulcke et al. 2013, Brischke et al. 2014, Van Acker et al. 2014) and translated into time of wetness (ToW). This parameter is inevitably less relevant when discussing biological agents like drywood insects (HC1) and soft rot / termites / sea organisms (HC4/5).

The parameter interaction defining exposure dosage as presented in Fig. 1 can be presented using 3 axes in a 3D plot for each of them. In Fig. 2 the macroclimate is simply presented as ranging from dry cold to wet warm passing dry warm, continental, maritime and wet cold as intermediate levels. Although this presentation might assume some linear scale the presentation is just to show what components could be considered. Any climate model that can depict the impact on the time of wetness could be used here. When adding the microclimatic impact also some components are listed and the increased impact is not always fully assured. Exposure to the south or north, whether forest cover is present or the exposure is fully open and probably a full sea shore exposure will all have impact mainly on the drying component and limit or increase the time of wetness considerably. Finally, also design qualification will help in identifying different use class levels: (interior) dry, presence of condensation/leakage, out of ground contact without or with water trap and finally contact with soils/water and even sea water. Fig. 2 uses a quasi-continuous approach with outcome levels 0 (blue) up to 5 (red) linked to the harshness of the exposure or simply exposure dosage. The levels 2-3 will probably be most impacted by all variables and need careful concern on how to measure. The different exposure scenarios developed for field testing can be used to verify the parameter time of wetness (ToW). A common approach is actually to work with simulation exposure using semi-field testing (cf. CMM below). This hybrid in service testing also requires adequate statistical approaches as explained further on [8]. When using this approach for a construction commodity, failure can be assessed based on the detection/occurrence and impact of the decay/degradation, but can also be registered based on time of wetness (ToW) determination (Van Acker et al. 2014, Van den Bulcke et al. 2011).

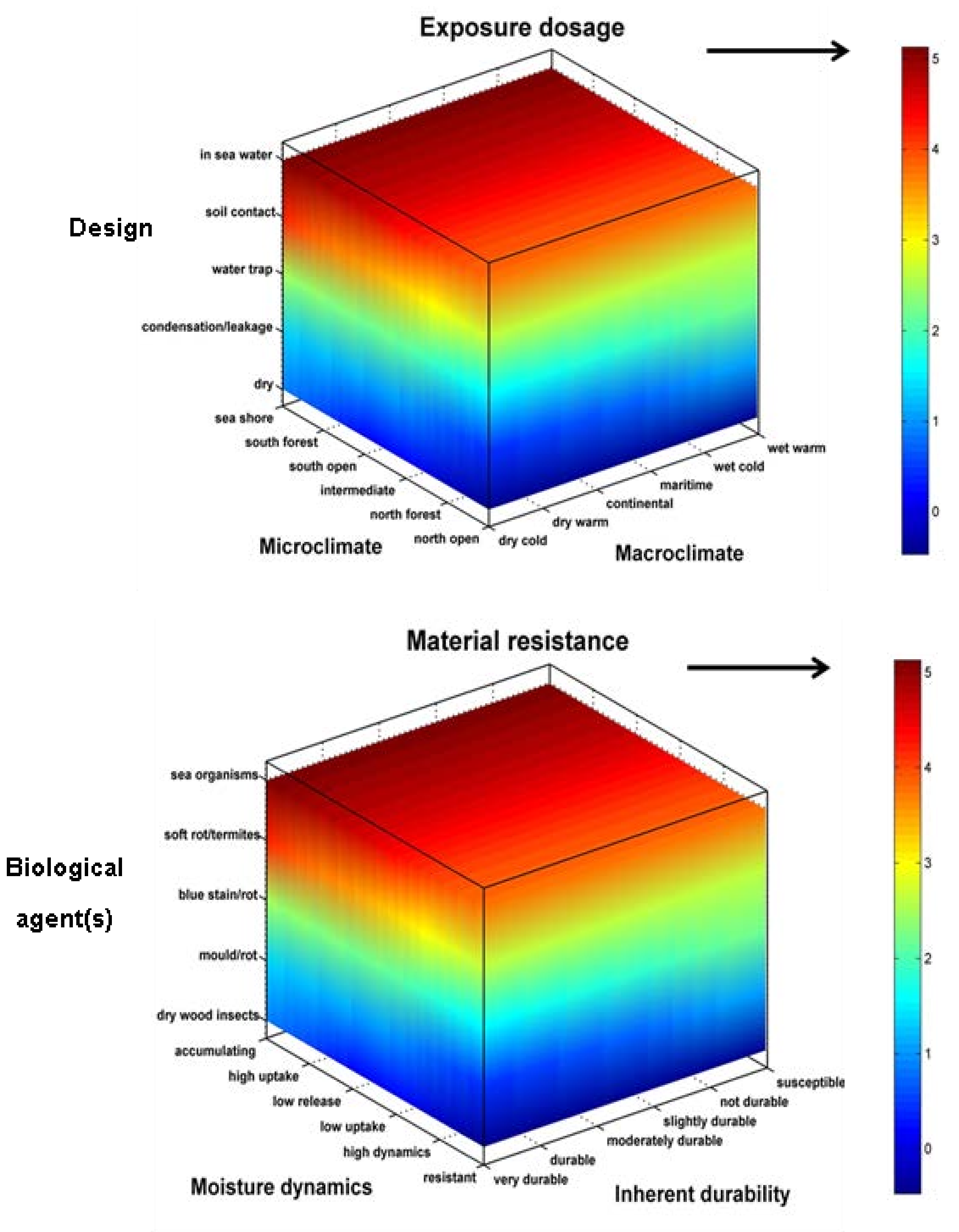

Fig. 2.
(top) Quasi-continuous outline of the exposure dosage (cfr. use classes) in relation to macroclimate, microclimate and design. (bottom) Quasi-continuous outline of the material resistance in relation to inherent durability and moisture dynamics and interacting with biological agents (hazard approach).

Contrary to exposure dosage which is basically independent of the wood product one should assess each commodity intended to perform for a certain time period (service life prediction, SLP). The material resistance is a set of characteristics that determines to what extent one can expect the material to withstand specific biological degradation or even all types of degradation (e.g. weathering). In Fig. 2 the parameters inherent durability, merely due to the presence of active biocidal ingredients, and moisture dynamics are presented in combination with different biological hazards again as a quasi-continuous 3D plot. The material resistance can be checked solely using laboratory testing. Since different biological agents are acting differently it is necessary to have a multi-agent assessment installed considering that different combinations will be relevant depending on the maximum exposure dosage focusing on. As indicated earlier, when dealing with fungal decay, it is relevant to assess via organism related testing the 'nutritional value' or intrinsic nutritional quality / toxicity. Here again it is important to assess variability and reliability using e.g. life distributions (De Windt et al. 2013). Clearly material using only aspects of moisture control will have some limitations but should anyhow be taken into account when considering increased service life. Here is also an option to link with the performance of coatings.

Linking the in-service assessment of exposure dosage and the lab testing based assessment of material resistance allows to combine both integration and interaction. Integration is mainly linked to the fact that any exposure is somewhere located in the 3D plot as presented in Fig. 2 and that any wooden commodity will have an intrinsic or enhanced material resistance that can be positioned on the 3D plot in Fig. 2. The interaction however is based on what level of material resistance is required for a specific exposure dosage. This many-to-many link requires a (quasi-) discrete approach. For the exposure a dosage range could be determined. Hence a probability or priority of risk could be selected, e.g. the most probable or number one (priority) biological agent. Based on selected laboratory testing one could prioritize results and/or use weighing schemes. Adding input on reliability-based durability for each agent the data on material resistance from lab testing should be used to predict in-service field data. Any qualification of performance of a wood product could use such an early predictor method, but will need to be followed up using full field exposure and assessment of end use performance. This approach has been integrated in the book on Performance of Bio-based Building Materials by Jones and Brischke (2017).

Within the framework to assess the risk of performance failure of wood in outdoor exposures the Time of Wetness (ToW) can be regarded as a tool to illustrate the possibility to degrade or not by fungi (Van den Bulcke et al. 2013). ToW is defined as the time during which a specimen reached a minimal wood moisture content of 20% or 25%. These limits were chosen based on the fact that Hunt and Garatt (1938) considered 20% wood moisture content as the lowest limit, whereas Viitanen (1997) stated that wood moisture content around fibre saturation point (25 – 30%) is required for onset of decay. To allow regular moisture measurements, a continuous moisture measurement (CMM) set up has been installed based on recording of the voltage outputs of calibrated load cells while simultaneously weather data are also monitored. Recorded voltage data are converted to moisture content by using the calibration curve of the load cell and the oven dry weight of the specimens. This CMM was first used by Van den Bulcke et al. (2013, 2009) to check the outstanding performance of plywood in exterior applications often based on non-durable wood species and often without the need to additionally incorporate biocides. The objective is to link specific laboratory immersion tests with outdoor CMM data (Continuous Moisture Measurements - ToW concept). Since both wetting and drying parameters are important a test method was developed using first water permeability (absorption using contact with water during 144h) followed by water vapour permeability (desorption in a second step for 144h). As such lab testing reflects the risk of water accumulation and relates to the ToW measured outdoors. In search for correlation with the time of wetness recorded with the CMM equipment different wood species as well as modified and hydrophobated solid wood have been assessed, however most promising results were obtained for plywood (De Windt et al. 2017).

METHODS AND MATERIALS

Standard lab and field testing and non-destructive monitoring

Standard laboratory based decay tests exist to determine the durability of a wood based material, as well as different field tests. The assessment of such tests is often either expressed in terms of mass loss, and / or in terms of the subjective rating of the condition of the specimen. Given that more objective measures are needed, other techniques, preferentially non-destructive ones, are becoming part of the tools available to assess the condition of a specimen through time. A couple of them will be highlighted briefly here, however many other techniques are not presented here. The data generated by these methods enables to objectively quantify the state of a certain material in function of recorded variables and can be used as input for the statistical framework which will be described further on.

Continuous Moisture Measurement (CMM)

The CMM test set-up consists of a series of single load cells fixed on a table (Van den Bulcke et al. 2009, 2011). On top of the load cells aluminium T-shaped holders are fastened, which are bent at an angle of 45° and on which samples are mounted. The set-up is facing south-southwest to capture maximum rain and solar radiation. This system records the load cell responses with a logging interval of 5 min. Calibration of the load cells enables to accurately calculate mass changes through time. Adjacent to the CMM set-up a fully equipped weather station is installed consisting of a solar radiation sensor, a tipping bucket rain gauge, a relative humidity probe, a thermometer, an anemometer and a wind vane. As such weather data is collected as well. This set-up enables continuous monitoring of the moisture behavior (ToW) of specimens in outdoor exposure and represents a reliable outdoor (semi field) testing. In combination with local electrical resistance based moisture measurements, this proves to be a very useful method (Li et al. 2013, 2016b).

X-ray Computed Tomography (X-ray CT) scanning

X-ray computed tomography (CT) has proven to be an invaluable technique in various research fields and many types of commercial scanners are available tailored to different needs. The use of X-ray CT in wood research has also increased considerably the last decade, given the significant increase of related publications. X-ray CT as a tool for qualitative and quantitative assessment has become a common tool in wood research with specific focus on micro CT scanning. It allows to visualize the internal structure of an object in a non-destructive way and is as such invaluable for continuous monitoring. It also allows to track, in 3D, moisture absorption and desorption in wood and wood based products (Van den Bulcke et al. 2011, Li et al. 2016a).

Vibration analysis (Resonalyzer)

Flexural vibration has been used to non-destructively measure the mechanical strength of wood based materials (Haines et al. 1996). A so-called 'Resonalyser' technique was further developed to determine the elastic properties of orthotropic plates from resonance frequencies (Lauwagie et al. 2003) of free hanging specimen. These methods are thus feasible to non-destructively visualize and quantify the mechanical strength of wood, but also of wood products such as plywood and MDF (Li et al. 2016).

Near-InfraRed Imaging (NIR)

Investigating wood and wood-based materials using infrared spectroscopy has since long been explored (Schimleck et al. 2002, Kelley et al. 2004, Thumm et al. 2010, Tsuchikawa and Schwanninger 2014). Only point-by-point data could be gathered in the past, yet recently, image-based systems have been developed that are already used frequently in food and pharmaceutical industries for rapid screening (Koehler et al. 2002). Such hyperspectral cameras are able to collect spatial and spectral information simultaneously, resulting in a volume with a spectral profile for each pixel of the image. Obviously, 2D NIR scanning is thus a valuable complementary technique to X-ray CT imaging (Defoirdt et al. 2017).

Statistical and reliability analysis

Mass loss data from decay tests, rating data from field test, and more advanced data generated from abovementioned techniques need to be processed properly. Most importantly, the variability which is present, has to be dealt with statistically. Variability is important on an intra- and inter-product level. Naturally one tries to minimize intra-product variability to maximize inter-product comparability. It is obvious that by implementation of a set of specimens as similar as possible, both the variability of the test itself as well as the material variability is accounted for. A large dataset is said to be a representative selection of a population. Naturally the size of such a set is limited by logistic feasibility, thus one is forced to balance the number of specimens (and sample size) that can be tested with the variability expected and the required certainty. Fitting of probability density functions (pdf) and the implementation of confidence limits as part of reliability analysis should be part of the toolbox to study performance of wood and wood-based products. It has been shown that 2- and 3-parameter Weibull distributions are good candidates. An example is shown in Fig. 3 of mass loss data of different wood species (De Windt et al. 2013) subjected to the lab fungal test CEN/TS 15083-1 (2005).

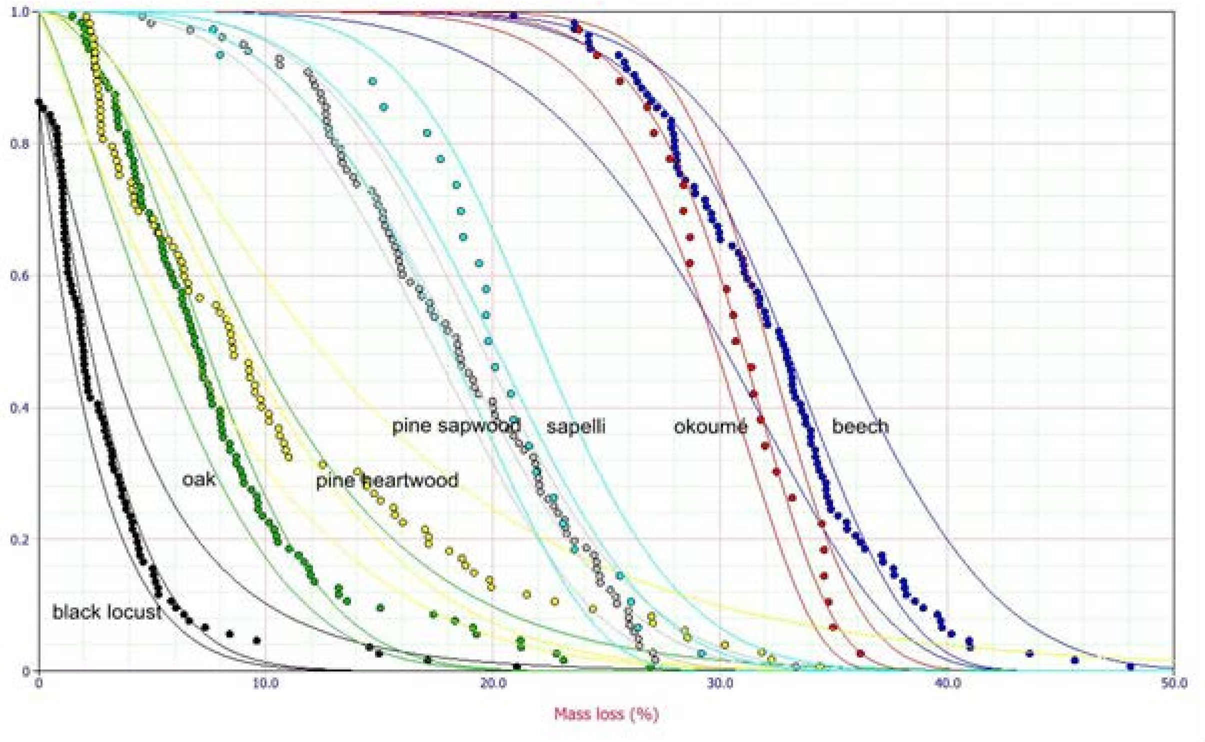

Fig. 3.
Cumulative distribution functions (cdf) for the different wood species with the 95% confidence intervals.

For field testing, at least two extra variability factors have to be considered: probably inhomogeneous conditions on a single field test and the differences between different field sites. Moreover, the factor time and related time-to-failure are crucial in this kind of tests. Even more than in laboratory testing it is obvious that the amount of specimens tested is crucial to get an overall assessment of the different types of variability. This has the implication that even more specimens are necessary to be able to assess performance with a sufficient level of certainty, i.e. increasing confidence of our test results. Therefore, reliability calculations further complicate, since different sites represent an exposure to different stress levels. In such a case it is possible to fit an acceleration model (e.g. an Arrhenius function) to the different distribution functions, i.e. in addition to time-to-failure and the related probability, a factor stress is added to represent the dose-response function we are looking for. As such the complete representation of the probability of time-to-failure for different stress levels will be a three-dimensional function, not only tackling sample variability, but also variability between fields and changes through time.

Benchmarking

Service life predictions methods like the one identified in ISO 15686-8 (2008) use reference service life as a basis for comparison. This approach can be very useful when discussing different parameters related to the fit for purpose objective. Reference products or commodities can be used for benchmarking. Especially when longtime service life appraisal exists for specific wood products it is useful to compare their performance directly with the innovative products under evaluation. Hence it is recommended to include in all types of lab and field testing not only reference products that are deemed to fail or perform higher than expected, but especially the commonly known and accepted products. Clearly the end user would accept and implement innovative products easier if one can prove they are similar or better than the products generally accepted as adequately performing, meaning fit for purpose.

Materials

Softwood as well as hardwood, untreated as well as modified and hydrophobated solid wood were tested. An overview of all materials under test was given in Table 1.

Table 1

Overview of the test material

Code	Wood species	Key botanical species	Modification - Treatment
Softwoods			
RAD PINE	radiata pine	*Pinus radiata* D.Don	-
PINE-SAP	Scots pine (sapwood)	*Pinus sylvestris* L.	-
PINE-HW	Scots pine (heartwood)	*Pinus sylvestris* L.	-
SPRUCE	Norway spruce	*Picea abies* (L.) H.Karst.	-
LARCH	European larch	*Larix decidua* Mill.	-
SIB LARCH 2	Dahurian larch	*Larix gmelinii* (Rupr.) Kuzen.	-
W RED CEDAR	western red cedar	*Thuja plicata* Donn ex D.Don	-
TM-RAD PINE	radiata pine	*Pinus radiata* D.Don	Thermal
TM-RAD PINE 2	radiata pine	*Pinus radiata* D.Don	Thermal
FU-RAD PINE	radiata pine	*Pinus radiata* D.Don	Furfurylation
AC-RAD PINE	radiata pine	*Pinus radiata* D.Don	Acetylation
TM-PINE	Scots pine	*Pinus sylvestris* L.	Thermal
TM-SPRUCE	Norway spruce	*Picea abies* (L.) H.Karst.	Thermal
TM-SPRUCE 3	Norway spruce	*Picea abies* (L.) H.Karst.	Thermal
TM-SPRUCE 4	Norway spruce	*Picea abies* (L.) H.Karst.	Thermal
HF-PINE-SAP A	Scots pine (sapwood)	*Pinus sylvestris* L.	Non-ionic emulsion (silane, silicone resin and siloxane)
HF-PINE-SAP B	Scots pine (sapwood)	*Pinus sylvestris* L.	Cationic emulsion (siloxane)
HF-PINE-SAP C	Scots pine (sapwood)	*Pinus sylvestris* L.	Siliconate
Hardwood			
Code	**Wood species**	**Key botanical species**	**Modification**
POPLAR	poplar	*Populus × canadensis* Moench cv 'Ghoy'	-
BEECH	European beech	*Fagus sylvatica* L.	-
SAPELLI	sapelli	*Entandrophragma cylindricum* Sprague	-
OAK	European oak	*Quercus robur* L. & *Quercus petraea* (Matt.) Liebl.	-
TEAK	teak	*Tectona grandis* L.f.	-
TM-POPLAR	poplar	*Populus × canadensis* Moench	Thermal
TM-BEECH 2	European beech	*Fagus sylvatica* L.	Thermal
TM-OBECHE	obeche	*Triplochiton scleroxylon* K.Schum.	Thermal
TM-LIMBA	limba	*Terminalia superba* Engl. & Diels	Thermal
TM-ASH	European ash	*Fraxinus excelsior* L.	Thermal
TM-CELTIS	celtis d'Afrique	*Celtis adolfi-friderici* Engl. & *Celtis tessmannii* Rendle	Thermal

Hydrophobation was performed by vacuum impregnation of Scots pine sapwood specimens using water based treating solutions containing 10% active ingredient provided by Dow Corning. The test specimens had cross sections of 50 by 25mm² and a growth ring angle close to 45°, similar to the stakes as provided for e.g. EN 252 (2014) in ground field testing. The sampling procedure for the results presented in this paper focussed on having matched samples for all tests. At least three replicates of each wood species or treatment were tested.

Laboratory testing of moisture dynamics

Regarding Time of Wetness both surface and end-grain phenomena have an impact on water uptake. Therefore, the earlier developed floating test method by Rapp et al. (2000) to reveal how fast water enters through a wood surface and how easy it dries afterwards was refined and complemented by a submersion test. Both methods are briefly outlined in Table 2.

Table 2

Brief overview of floating and submersion tests to assess moisture dynamics

Parameter	Floating test	Submersion test
specimen cross section	50 by 25 mm²	
specimen length	50 mm	150 mm
edge sealing	yes	no
water penetration	one surface	whole specimens
absorption phase	1, 4, 8, 24, 48, 72, and 144 h	
desorption phase	1, 4, 8, 24, 48, 72, and 144 h	
preferred unit	g/m²	kg/m³

To compare the mass changes of the test materials during water uptake a curve was fitted to the data. The absorption curves fitted for both the floating test and the submersion test are based on the formula equation (1):

$$f(x) = a * x^b \quad (1)$$

When parameter b is close to 0.5, parameter a approximates the absorption coefficient. This is based on the linear relation between water uptake and the square root of time (2002). Deviating b-values indicate special absorption phenomena e.g. capillary water uptake.

Water vapour release show curves based on formula (2):

$$f(x) = a + be^{\frac{-x}{c}} \quad (2)$$

In this equation parameter a approximates the remaining water after drying. Parameter b reflects the amount of water evaporated during 144h desorption. Consequently, the sum of parameter a and parameter b equals the increase in g/m² during 144h absorption. Parameter c is a measure for the desorption rate. A low c-value indicates that the specimen will dry quickly, a high c-value reflects slow drying of the test specimen. In general, high measures for parameters a, b and c indicate an increased risk of moisture accumulation.

Field testing of moisture dynamics

The continuous moisture measurement (CMM) set up aims at monitoring water absorption and desorption behaviour of specimens while subjected to outdoor exposure. The test consists of a frame upon which two parallel series of single load cells are fixed. The precision of the load cells is 1.0g. All specimens were inclined 45° facing south west direction. Weather data are recorded by means of a weather station consisting of a pyranometer, a pluviometer, a relative humidity probe, a thermometer, an anemometer and a windvane adjacent the test set up. All data were registered by a delta-T logging unit every 5min. More details concerning CMM can be found in Van Acker and De Smet (2007) and in Van den Bulcke et al. (2009). The continuous moisture measurement (CMM) set up included the same set of material as detailed in Table 1. Specimens were identical to the ones used for the submersion test and cross sections were sealed (Fig. 4). After installation specific rain events were selected to analyse major differences. All data were converted to hourly data by averaging and missing data were omitted from the analysis.

Fig. 4.
Continuous Moisture Measurement.

RESULTS AND DISCUSSION

Laboratory testing of moisture dynamics

Although different absorption and desorption mechanisms were expected resulting in short term (<1 hour) and long term (>6 days) results, the results presented here focus on the 144h absorption and 144h desorption. Van Acker and co-authors (2014) already ranked a broad range of indigenous and tropical wood species both for the floating and submersion test based on mean values of 144 h absorption and desorption. Values after 144 hours of floating were considered high when over 5000 g/m² and corresponding values for desorption should then be over 2000g/m². Furthermore, four groups were defined and within each group two subgroups were distinguished as detailed in Table 3.

Table 3

Classification of absorption and desorption for both floating [g/m²] and submersion (kg/m³) based on upper limit criteria.

Class	Floating test [g/m²]		Submersion test [kg/m³]	
	Absorption	Desorption	Absorption	Desorption
1	750	250	90	15
2	950	400	110	20
3	1150	500	130	25
4	1350	600	150	30
5	1750	750	170	40
6	2750	1000	210	55
7	5000	2000	250	70
8	∞	∞	∞	∞

Given the criteria in Table 3 and the parameters derived from curve fitting discrimination between species based on moisture dynamics is possible.

A classification of the test materials along their moisture dynamics is given in Table 4 (softwoods) and Table 5 (hardwoods).

Table 4

Moisture dynamics parameters of softwoods and modified softwoods using classes as defined in Table 3 for floating [g/m²] and submersion [kg/m³]

Softwoods	Floating - absorption				Floating - desorption					Submersion - absorption				Submersion - desorption				
	Class	[g/m²]	f(x)=a*x^b		Class	[g/m²]	f(x)=a+b*exp(-x/c)			Class	[kg/m³]	f(x)=a*x^b		Class	[kg/m³]	f(x)=a+b*exp(-x/c)		
		144h	a	b		144h	a	b	c		144h	a	b		144h	a	b	c
RAD PINE	8	6729	2152	0.22	8	2741	-	6721	174	6	209	79	0.19	6	44	-	210	93
PINE-SAP	7	4256	516	0.42	7	1423	1214	3051	49	7	235	49	0.31	6	45	31	205	47
PINE-HW	4	1259	71	0.58	4	559	592	648	14	5	170	19	0.44	5	32	30	137	37
SPRUCE	5	1503	98	0.55	5	743	786	678	17	5	165	20	0.42	5	36	32	131	38
LARCH	5	1673	112	0.54	5	650	648	935	50	6	185	11	0.57	6	41	-	187	102
SIB LARCH 2	5	1505	93	0.56	5	629	631	783	48	5	169	10	0.57	6	42	11	156	90
W RED CEDAR	4	1314	85	0.55	3	401	387	881	43	4	138	20	0.39	1	12	2	135	54
TM-RAD PINE	8	5715	816	0.41	8	3705	1896	3688	206	7	248	35	0.40	8	72	36	212	84
TM-RAD PINE 2	8	6938	1666	0.30	8	4144	-	6883	300	8	383	78	0.32	8	117	20	364	109
FU-RAD PINE	7	2918	680	0.29	7	1246	-	2844	177	8	258	61	0.29	8	90	-	259	149
AC-RAD PINE	7	3355	713	0.32	7	1923	800	2463	188	6	184	27	0.39	8	69	59	124	61
TM-PINE	1	245	13	0.58	1	99	111	130	4	1	51	2	0.64	1	10	11	40	17
TM-SPRUCE	1	612	30	0.61	1	219	220	390	8	3	111	7	0.55	2	19	20	88	30
TM-SPRUCE 3	1	319	17	0.58	1	112	129	181	3	2	102	11	0.45	2	19	19	81	39
TM-SPRUCE 4	1	600	29	0.61	1	243	265	319	9	1	89	7	0.51	2	17	17	70	36
HF-PINE-SAP A	8	8630	1319	0.39	6	1400	568	8087	63									
HF-PINE-SAP B	8	6793	811	0.43	4	608	364	6436	44									
HF-PINE-SAP C	8	10839	1815	0.38	1	130	-	10995	32									

ONLINE ISSN 2069-7430
ISSN-L 1841-4737
PRO LIGNO
www.proligno.ro
Vol. 13 N° 4 2017
pp. 8-26

Table 5

Moisture dynamics parameters of hardwoods and modified hardwoods using classes as defined in Table 3 for floating (g/m²) and submersion (kg/m³)

Hardwoods	**Floating - absorption**				**Floating - desorption**					**Submersion - absorption**				**Submersion - desorption**				
	Class	**g/m²**	**f(x)=a*x^b**		**Class**	**g/m²**	**f(x)=a+b*exp(-x/c)**			**Class**	**kg/m³**	**f(x)=a*x^b**		**Class**	**kg/m³**	**f(x)=a+b*exp(-x/c)**		
		144h	**a**	**b**		**144h**	**a**	**b**	**c**		**144h**	**a**	**b**		**144h**	**a**	**b**	**c**
POPLAR	6	2210	135	0.56	4	534	523	1677	29	8	264	21	0.51	6	55	30	232	63
BEECH	6	2588	143	0.58	7	1090	1112	1460	27	8	324	39	0.43	8	107	68	257	75
SAPELLI	4	1331	64	0.61	5	735	779	532	9	4	136	9	0.55	5	40	42	93	24
OAK	5	1459	105	0.53	5	687	707	730	19	5	167	15	0.48	5	40	38	127	37
TEAK	1	653	40	0.56	2	263	315	307	9	2	98	5	0.59	3	24	21	77	45
TM-POPLAR	1	557	16	0.72	1	110	135	382	10	3	111	27	0.24	1	14	12	99	36
TM-BEECH 2	3	992	51	0.59	2	348	374	568	21	5	160	14	0.50	5	37	32	128	44
TM-OBECHE	5	1392	50	0.67	2	294	104	1244	75	4	133	4	0.70	1	14	-	133	61
TM-LIMBA	2	768	31	0.64	2	291	305	440	13	5	155			5	31	25	129	50
TM-ASH	3	1099	71	0.55	2	303	328	695	35	4	134	13	0.47	4	27	27	106	39
TM-CELTIS	3	960	45	0.61	3	427	443	484	16	4	132	6	0.63	5	33	29	100	51

ONLINE ISSN 2069-7430
ISSN-L 1841-4737
PRO LIGNO
www.proligno.ro
Vol. 13 N° 4 2017
pp. 8-26

Focussing on softwoods first and on pine in particular one can observe the highest uptake combined with a moderate drying rate for Scots pine sapwood. Radiata pine even has a lower absorption amount (but higher rate, parameter a) combined with a faster drying (desorption parameter c). European and Siberian larch are actually rather similar in behaviour when submersion is considered (open end-grain, cross section uptake). Spruce and Scots pine heartwood show a similar rather low uptake as Siberian larch but are slower in drying after submersion. Western red cedar is not only the lowest in absorption it also dries rather fast. All these observations mainly have an impact when wood is exposed to end grain water trapping.

Moisture dynamics along tangential face simulating wetting of a surface during a rain event, revealed the very fast drying of radiate pine and modified radiate pine which is inevitably related to drying after a rain event on an exposed surface. This somewhat special characteristic of radiate pine was also noticed by the absorption b parameter being different from the general 0.5 value. Overall high water uptake is balanced by fast drying. This is not valid for all the modified radiata pine. Thermal treatment and to a lesser extent furfurylation and acetylation had a less beneficial effect on the moisture dynamics of radiate pine resulting in a less favourable classification. Regarding the good durability of modified radiate pine, the wetting ability and drying rate were not representative for its overall material resistance. The set of modified Scots pine and spruce all show a very low uptake (absorption), but also rather low drying rate (c- values) resulting in low ToW.Pine sapwood treated with the hydrophobation product A showed altered moisture dynamics in comparison to untreated Scots pine sapwood although less altered than treated with product B. For pine sapwood treated with product C an increased absorption was observed. The desorption values were in line with the absorption values indicating low risk for accumulating water leading to issues on ToW. The low c-value for product C however indicated fast drying.

In Table 5 the same parameters were provided for hardwoods. Even more than western red cedar as softwood, teak can be considered as an eminent wood species related to moisture dynamics with limited absorption and higher class for drying than for wetting. Comparing the data and parameters of the modified hardwoods with the TMT spruce and Scots pine (Table 4) only the thermally modified poplar (TM-POPLAR) was showing good moisture dynamics. The values for TM-POPLAR were similar to the ones determined for teak. Sapelli also shows similarity to teak, a species where the desorption class was higher than the absorption class, pointing at a low risk for moisture accumulation.Only the modified celtis allowed for a similar observation though only for the submersion test. Differentiation was higher when considering the submersion test. Quite some of the modified materials showed higher classification on desorption than on absorption, also radiate pine. Ease of drying after getting wet might be a more important parameter than just the ability of getting wet.

Continuous Moisture Measurement (CMM)

When assessing time of wetness related properties moisture content changes of individual specimens were recorded just before and after a rain event during outdoor exposure alongside the actual precipitation. A moderate rain is considered to be between 2.5 and 7.6mm/h. Details for softwoods are presented in Fig. 5 and 6 and for hardwoods in Fig. 7.

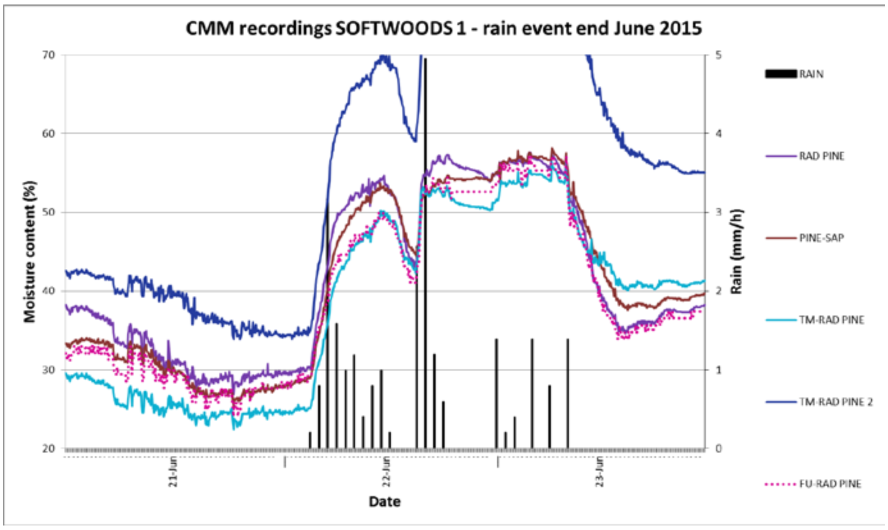

Fig. 5.
Field test moisture recordings (CMM) of softwoods with high absorption.

The wood species with a higher water absorption are presented in Fig. 5. These results confirmed the findings of laboratory testing: radiate pine, thermally modified and furfurylated radiata pine and Scots pine sapwood showed high moisture contents, even higher than 50% during a rain shower.

The remaining softwoods presented in Fig. 6 had distinctly lower moisture content levels. This group was divided in two subgroups. The first subgroup comprises western red cedar, larch species, Scots pine heartwood and spruce. These softwoods had moisture contents around 20% during dryer periods and moisture contents of maximum 40% during rain events. A second group consisted of wood species with a moisture content of ±10% during long dry periods and a moisture content up to 30% when it rained. TM Scots pine, acetylated radiate pine and TM spruce (with somewhat higher dynamics) belong to this group.

The hardwoods as shown in Fig.7 were in general overlapping with the above groupings identified for softwoods. Unmodified poplar showed a similar moisture content level as spruce unmodified. Both beech and sapelli had an equally low moisture content during the dry periods with clearly lower absorption during actual rain of sapelli. Oak showed a merely equally positive pattern as sapelli, though more distinct differences between the dry period and during the rain event. Thermally modified TM obeche was more impacted by wetting and drying than TM ash. TM poplar, TM limba, TM beech and TM celtis in this order were showing lower absorption. However, they all came to a similarly low moisture content after this rain event.

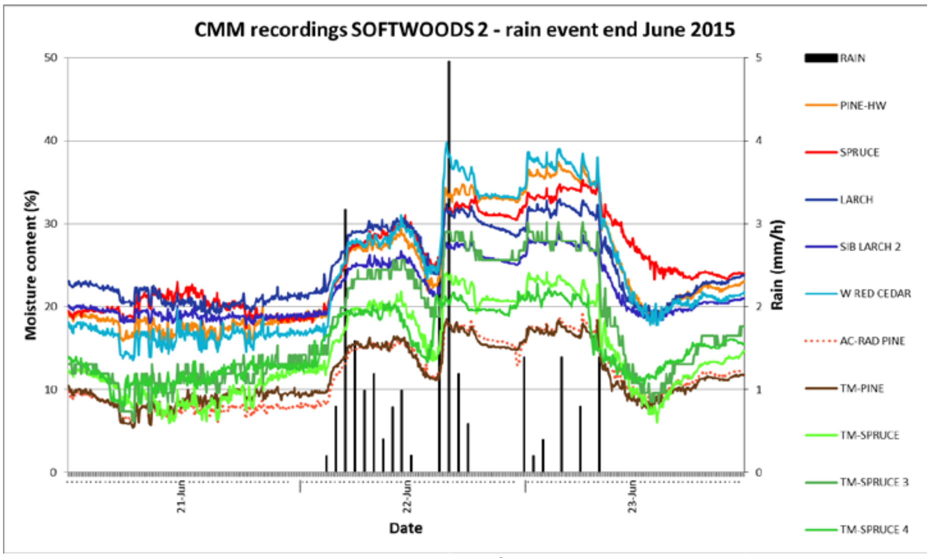

Fig. 6
Field test moisture recordings (CMM) of softwoods.

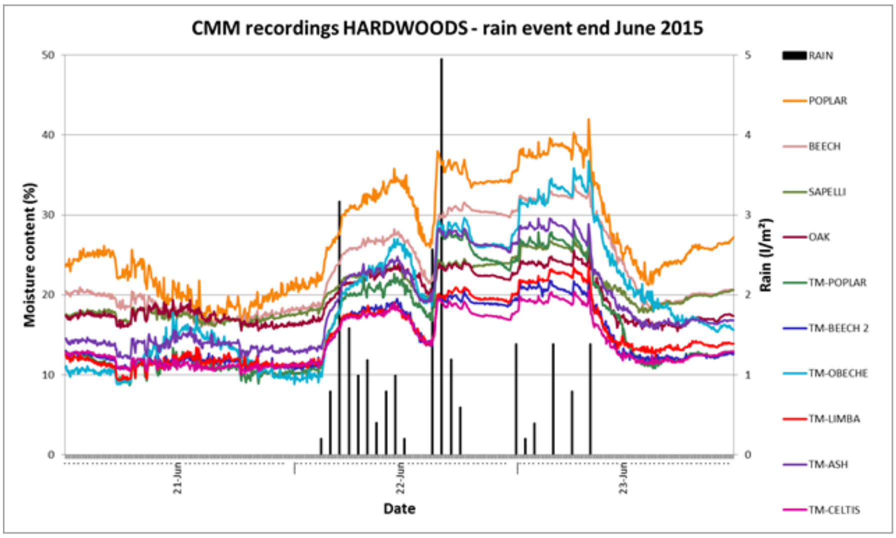

Fig. 7.
Field test moisture recordings (CMM) of hardwoods.

Considering hydrophobing agents all treated Scots pine sapwood treated showed lower moisture content than its reference (Fig. 8).

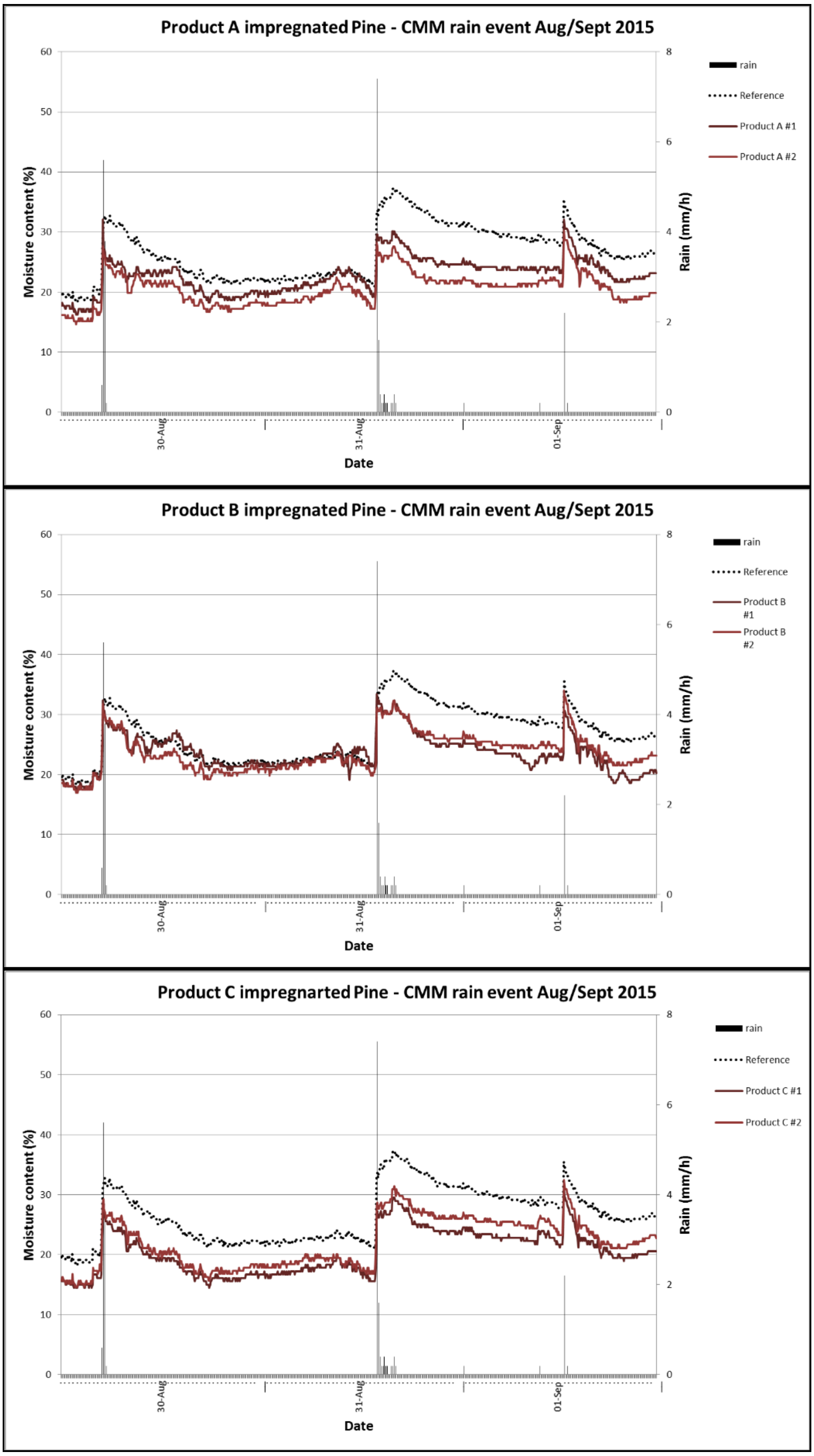

Fig. 8.
The continuous moisture measurement of Scots pine sapwood treated with hydrophobing products A, B and C.

The major differences between the performance of each product was found in the reactivity to rain and the subsequent drying phase. Product C followed the same trend as the reference though at lower moisture content. Product B treated wood did not differ from the reference for the rain shower on August 30th, but was not that sensitive to the longer rain event the next day. The product A induced lower absorption overall but also revealed slower drying. Comparing results from the floating test (Table 4) with the results obtained from CMM is difficult when interpreting small differences between the hydrophobation treatment. Clearly this interrelationship will also change when weathering is more involved.

In general, based on the absorption rate and amount of water uptake as well as the drying rate as derived from laboratory testing of moisture dynamics a good estimate of the risk for moisture accumulation could be made and hence the duration that a material has a beneficial moisture content for the development of rot (ToW) as observed in the CMM.

CONCLUSIONS

The concept of service life prediction (SLP) is of major importance for the utilisation of wood and wood products. Many products are compared to alternatives based on man-made materials. Besides the ability to predict performance it is also relevant to know what is actually expected from a specific commodity. The service life prediction framework presented in this paper including both material resistance as well as moisture dynamics, a toolbox for non-destructive monitoring, decay testing, reliability analysis, and benchmarking can help in selecting fit-for-purpose wood based products in the construction sector.

Material resistance against decay depends partially on the presence of active ingredients preventing or slowing down wood degradation, and partially on the moisture dynamics of the material. The moisture dynamics of indigenous and tropical wood next to modified and hydrophobated wood was studied by means of simple laboratory tests such as the floating test or submersion test. Although both test methods reveal overall similarity the floating test focusses on face water penetration valid for plank surfaces and most wood based panels whereas the submersion test mainly relates to water trapping in constructions. The parameters derived allowed for additional information on absorption and desorption rate, maximal absorption and residual moisture content after desorption.

A continuous moisture measurement during a rain event confirmed this methodology and allowed to discuss the moisture dynamics by means of time of wetness (ToW, time of being above a certain moisture content). Interesting species related differences reflecting practical experience were found. However, the importance of the moisture dynamics can be overruled by the intrinsic natural durability of wood or the enhanced durability by means of special treatments e.g. wood preservation or wood modification. This was clearly illustrated by the increased ToW of modified wood suggesting an increased risk of decay although modified wood is durable.

Linking service life and moisture dynamics is not straightforward, neither is durability testing sufficient to show full potential. Nonetheless, the ToW is a valuable measure in the performance assessment of wood and wood based products.

ACKNOWLEDGEMENT

Part of the analyses were performed within the framework of the European Project PerformWood (Performance standards for wood in construction – delivering customer service life needs – project number 319132) which is hereby gratefully acknowledged for the financial support. Also the support of the European Commission is gratefully acknowledged through the European Project SILEX ‘‘Improving sustainability of construction materials using innovative silicon based treatment’’, with project number LIFE11 ENV/BE/1046. Additionally, also the national project DO-IT HOUTBOUW: “Sustainable innovation in the field of technology and comfort of living for wood construction applications” provided funding through IWT (Flemish agency for Innovation by Science and Technology) – VIS Traject 110803 coordinated by Wood.be (former CTIB-TCHN, Belgian technical centre of wood transformation and furniture). The author also acknowledge the help of Piet Dekeyser, Stijn Willen and Rik De Rycke (†) for their technical assistance as well as several researchers of the UGent-Woodlab active on this topic: Jan Van den Bulcke, Imke De Windt, Nele Defoirdt, Wanzaho Li, Michiel Vanpachtenbeke and Liselotte De Ligne.

REFERENCES

Brischke C, Rapp AO (2010) Service life prediction of wooden components – Part 1: Determination of dose response functions for above ground decay, Proceedings International Research Group on Wood Protection, IRG/WP 10-20439, 14p.

Brischke C, Meyer L, Hesse C, Van Acker J, De Windt I, Conti E, Humar M, Viitanen H, Kutnik M, Malassenet L (2014) Moisture dynamics of wood and wood-based products – Results from an inter-laboratory test, Proceedings International Research Group on Wood Protection, IRG/WP 14-20539, 20p.

CEN/TS 15083-1 (2005) Durability of wood and wood-based products – Determination of the natural durability of solid wood against wood-destroying fungi, test methods – Part 1: Basidiomycetes. CEN (European committee for standardization), Brussels, 24p.

Defoirdt N, Gardin S, Van den Bulcke J, Van Acker J (2009) Moisture dynamics of WPC and the impact of fungal testing, International Biodeterioration and Biodegradation 64:65-72.

Defoirdt N, Sen A, Dhaene J, De Mil T, Pereira H, Van Acker J, Van den Bulcke J (2017) A generic platform for hyperspectral mapping of wood. Wood Science and Technology 51(4):887-907.

Defoirdt N, Van den Bulcke J, Bensadoun F, Ivens J, Verpoest I, Van Acker J (2017) Moisture behaviour and biological durability of high performance flax fibre reinforced composites. Proceedings International Research Group on Wood Protection, IRG/WP 17-40803.

De Windt I, Van den Bulcke J, Brischke C, Welzbacher CR, Gellerich A, Bollmus S, Humar M, Plaschkies K, Scheiding W, Alfredsen G, Van Acker J (2013) Statistical analysis of durability tests - Part 1: Principles of distribution fitting and application on laboratory tests. Proceedings International Research Group on Wood Protection, IRG/WP 13-20504, 12p.

De Windt I, Li W, Van den Bulcke J, Van Acker J (2017) Classification of uncoated plywood based on moisture dynamics. Construction & Building Materials, accepted for publication, 22p.

EN 252 (2014) Field test method for determining the relative protective effectiveness of a wood preservative in ground contact. European Committee for Standardization, Brussels, 28p.

EN 335 (2013) Durability of wood and wood- based products. Use classes: definitions, application to solid wood and wood based products. European Committee for Standardization, Brussels, 18p. & ISO 21887 (2007), Durability of wood and wood-based products - Use classes.

Haines DW, Leban JM, Herbe C (1996) Determination of Young's modulus for spruce, fir and isotropic materials by the resonance flexure method with comparisons to static flexure and other dynamic methods, Wood Science and Technology 30:253-263.

Hunt GW, Garatt GA (1938) Wood preservation. McGraw-Hill, NY. 457 pp.

ISO 15686-8 (2008) Buildings and constructed assets - Service-life planning - Part 8: Reference service life and service-life estimation. ISO (International organization for standardization), Geneva.

Jones D, Brischke C (2017) Performance of Bio-based Building Materials. ISBN: 978-0-08-100982-6, 650p.

Kelley SS, Rials TG, Snell R, Groom LH, Sluiter A (2004) Use of near infrared spectroscopy to measure the chemical and mechanical properties of solid wood, Wood Science and Technology 30:257-276.

Koehler IV FW, Lee E, Kidder LH, Lewis EN (2002) Near infrared spectroscopy: the practical chemical imaging solution, Spectroscopy Europe, 14:12-19.

Kutnik M (2013) Focus on European standardisation. Towards a revision of the EN350 natural durability standard: a different approach to the inherent resistance and performance of wood and wood-based materials, Proceedings International Research Group on Wood Protection, IRG/WP 13-10811, 9p.

Lauwagie T, Sol H, Roebben G, Heylen W, Shi YM, Van der Biest O (2003) Mixed numerical-experimental identification of elastic properties of orthotropic metal plates, Ndt & E Inter 36:487-495.

Li W, Van den Bulcke J, De Windt I, Van Loo D, Dierick M, Brabant L, Van Acker J (2013) Combining electrical resistance and 3-D X-ray computed tomography for moisture distribution measurements in wood products exposed in dynamic moisture conditions. Building and Environment 67:250-259.

Li W, Van den Bulcke J, De Schryver T, Van Acker J (2016a) Investigating water transport in MDF and OSB using a gantry-based X-ray CT scanning system. Wood science and technology, 50(6):1197-1211.

Li W, Van den Bulcke J, De Windt I, Dhaene J, Van Acker J (2016b) Moisture behavior and structural changes of plywood during outdoor exposure. European Journal of Wood and Wood Products 74(2): 211–221.

Mukhopadhyaya P, Kumaran K, Normandin N, Goudreau P (2002) Effect of Surface Temperature on Water Absorption Coefficient of Building Materials. Journal of Building Physics 26:179-195.

Rapp AO, Peek RD, Sailer M (2000) Modelling the moisture induced risk of decay for treated and untreated wood above ground. Holzforschung, 54(2):111-118.

Schimleck L, Evans R, Matheson AC (2002) Estimation of *Pinus radiata* D. Don clear wood properties by near-infrared spectroscopy. Journal of Wood Science 48: 132-137.

Thumm A, Riddell M, Nanayakkara B, Harrington J, Meder R (2010) Near infrared hyperspectral imaging applied to mapping chemical composition in wood samples, J. Near Infrared Spect 18: 507-515.

Tsuchikawa S, Schwanninger M (2002) A review of recent near-infrared research for wood and paper (Part 2), Appl Spectrosc Rev 48:560-587.

Rapp AO, Peek RD, Sailer M (2000) Modelling the moisture induced risk of decay for treated and untreated wood above ground, Holzforschung 54: 111-118.

Suttie E, Brischke C, Englund F, Heisel E, Jermer J, Lorenzo D, Polášek M, Thelandersson S, Van Acker J (2013) Performance standards for wood in construction – delivering customer service life requirements, Proceedings International Research Group on Wood Protection, IRG/WP 13-20537, 18p.

Van Acker J, De Smet J (2007) Service life prediction of plywood. Proceedings International Research Group on Wood Protection, Document IRG/WP 07-20367. 11p.

Van Acker J, De Windt I, Li W, Van den Bulcke J (2014). Critical parameters on moisture dynamics in relation to time of wetness as factor in service life prediction. Proceedings International Research Group on Wood Protection, Document IRG/WP 14-20555. 22p.

Van den Bulcke J, Van Acker J, De Smet J (2009) An experimental set-up for real-time continuous moisture measurement of plywood exposed to outdoor climate. Building and Environment 44(12): 2368-2377.

Van den Bulcke J, De Windt I, Defoirdt N, De Smet J, Van Acker J (2011) Moisture dynamics and fungal susceptibility of plywood. International Biodeterioration and Biodegradation 65(5):708-716

Van den Bulcke J, De Windt I, Brischke C, Welzbacher C R, Rapp A O, Van Acker J (2013) Statistical analysis of durability tests - Part 2: Principles of time-to-failure and application on field test data, Proceedings International Research Group on Wood Protection, IRG/WP 13-20512, 13p.

Viitanen H (1997) Modelling the time factor in the development of brown rot decay in pine and spruce sapwood - the effect of critical humidity and temperature conditions. Holzforschung 51(2):99-106.