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Changes in moisture performance of wood after weathering

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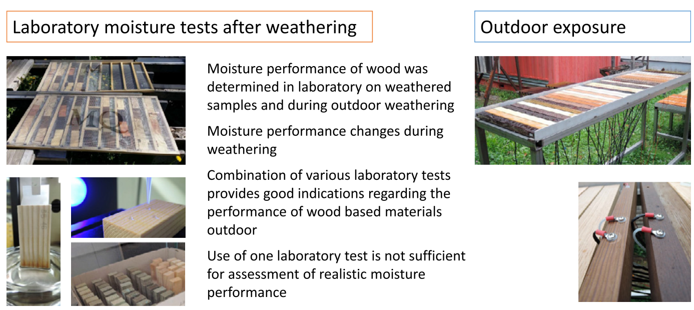
H I G H L I G H T S

- The importance of wood in outdoor applications is increasing.
- Durability of wood is predominantly influenced by inherent durability and wetting ability.
- There is no standard procedure for assessment of wetting ability.
- Wetting ability changes during weathering.

G R A P H I C A L   A B S T R A C T



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After the durability of wood against wood decay fungi, its water performance is the next most important factor that influences the performance of wood in outdoor, above-ground applications. It is therefore of major importance to optimize methods that are able to predict the moisture behaviour of wood in outdoor applications. In order to elucidate these questions, samples were prepared from European oak (*Quercus robur*/*Q. petraea*), sweet chestnut (*Castanea sativa*), European larch (*Larix decidua*), Scots pine heartwood and sapwood (*Pinus sylvestris*), Norway spruce (*Picea abies*) and beech (*Fagus sylvatica*). The moisture performance of the samples was altered by thermal modification, wax, oil and biocide treatment. Two types of specimens were prepared; smaller specimens ($1.5 \times 2.5 \times 5.0$ cm) were exposed to natural weathering for three periods (9, 18 and 27 months) and subsequently analyzed in the laboratory with various methods (contact angle, short- and long-term water uptake and water vapor uptake). In parallel, bigger specimens ($2.5 \times 5.0 \times 50$ cm) were exposed outdoors in a monolayer exposure and equipped with moisture monitoring sensors for 18 months. Water performance of wood could change as a result of weathering, being the most evident at thermally modified wood, where the decrease of the moisture performance was the most evident. The results of the study clearly showed that the water performance of the majority of the materials decreased with natural weathering. These results indicate that in order to elucidate the moisture performance of wood fully, a variety of laboratory tests needs to be applied, relating to both liquid water performance and water vapour interactions with wood.

1. Introduction

Wood is one of the most important building materials worldwide. In recent years, the use of wood in above-ground applications, particularly in Use Class 2 (outside, not in ground contact, covered) and Use Class 3 (outside, not in ground contact, not covered) applications [10] has increased considerably [23,26]. Modern trends stimulate the use of wood even in applications for which wood has not been traditionally used (bathrooms and multi-story buildings). In the past, predominantly durable species from the tropics and preservative-treated wood have been used for outdoor applications [5]. Due to increased environmental awareness,

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suppliers and end users are looking for alternatives. The development of a new generation of wood-based materials has enabled the use of less durable wood in applications with higher relative humidity [13,35].

In order to increase the use of wood further, we need to develop models for service life prediction and integrate them into building information modelling (BIM) software. Reliable information regarding service life, maintenance intervals, visual appearance etc. is nowadays a must. If these data are not provided, it could result in reduced selection of wood by architects and investors. One of the important factors that contributes to overall performance is durability. In the past, the durability of wood was mainly related to its inherent durability [34,7], which reflects the presence of biologically active secondary metabolites (extractives) [33,30] and/or biocides [19]. However, recent reports indicate that the service life of wood above ground is strongly influenced (in addition to its durability against fungi) by its water exclusion efficacy [31]. Both parameters contribute to the overall performance of wood in above-ground applications [22], so both of them require scientific attention. This is also one of the reasons for the improved performance of modified wood [29].

The moisture performance of wood is a complex phenomenon and is a function of sorption properties, capillary water uptake in various directions, the contact angle of water on the surface, water release during drying etc. [24,6]. The interactions between water and wood must hence be investigated with a variety of methods [14]. Another question is how the moisture performance changes with aging and/or weathering.

Moisture performance is usually determined on freshly cut/modified/impregnated wood [22]. It is well known that moisture performance can change during the wood's service life. For example, there have been numerous reports about the excellent moisture performance of freshly thermally modified wood [13], but which deteriorates after exposure in Use Class 3.2 conditions, resulting in increased water uptake [16,32,36]. Deteriorated moisture performance has mostly been ascribed to micro-cracks and to bacterial degradation of pit membranes and blue staining [28]. The primary objective of this study was thus to monitor the moisture performance of various wood species (and treatments) before and after weathering, and to compare the moisture performance of weathered smaller specimens with long term moisture measurements.

2. Material and methods

2.1. Material

The wood species chosen for this study are important in central Europe: oak heartwood (*Quercus* sp.), sweet chestnut heartwood (*Castanea sativa*), European larch heartwood (*Larix decidua*), Scots pine heartwood and sapwood (*Pinus sylvestris*), Norway spruce (*Picea abies*) and beech (*Fagus sylvatica*) wood (Table 1). Scots pine and beech were chosen as reference for wood with poor performance in Europe. Norway spruce was included because spruce is the most important wood species for construction applications in Europe and serves as the reference in some novel models for service life prediction [22]. The performance of spruce wood is much better than that of Scots pine sapwood, presumably due to its better water exclusion efficacy, being ascribed to: aspirated bordered pits and the anatomy of the ray parenchyma. Larch wood, on the other hand, is one of the first choices of architects for decking applications in Central Europe. English oak was included as one of the commercially important durable species, and sweet chestnut served as control. Sweet chestnut has a similar anatomical structure to oak (ring porous wood) but better durability. Specimens were defect-free, without visible signs of decay or blue staining, as prescribed in European standard EN 113 [8]. We prepared two different types of specimens; smaller specimens (1.5 cm × 2.5 cm × 5.0 cm) were used for assessment of moisture performance in the laboratory, while bigger (2.5 cm × 5.0 cm × 50.0 cm) samples were used for monitoring wood moisture content. Some of the materials were subsequently treated with various solutions or thermally modified. The materials used are classified into various durability classes according to EN 350 standard [11]; sweet chestnut is classified as a durable species (2nd durability class (DC)), oak heartwood is classified as durable to slightly durable (2nd–4th DC), European larch and Scots pine are moderately durable species (3–4rd DC). Norway spruce is classified as slightly durable (4–5th DC), beech and Scots pine sapwood are classified as not durable species (5th DC) (Table 1).

2.2. Impregnation and modification of wood

Some selected wood species (Table 1) were treated with commercial treatments frequently used for wood in outdoor applications. Seventeen different materials were prepared for this experiment. In total, 646 specimens were prepared, including 2 parallel specimens for each material exposed outdoor for MC measurements (2.5 × 5.0 × 50 cm^3), and smaller specimens used for lab trials (9 specimens per exposure (3 exposures + non-exposed samples); 36 specimens per single material). Details about wood materials used for the different treatments are provided in Table 1.

Thermal modification was performed according to the commercial Silvapro® process [27]. This process is characterized by a vacuum in the first step, as the main mode of removing oxygen from the chamber. Modification of wood was performed for 3 h at 230 °C on Norway spruce and at 215 °C on beech wood. These modification temperatures are frequently used in industrial processes for the relevant wood species. The entire process took 24 h. The process was controlled through temperature sensors mounted inside the small specimens. After modification, the specimens were conditioned for four weeks under laboratory conditions (T = 23 °C; RH = 65%). In order to upgrade the wood properties (durability, hydrophobicity), wood samples were treated with various solutions, including (1) a 10% natural wax suspension mixed with distilled water [21]; (2) tung oil [17]; and (3) a commercial copper-ethanolamine formulation (CuEA) (Silvanolin, Silvaprodukt) that contains five ingredients: copper(II) hydroxide, ethanolamine, quaternary ammonium compound, octanoic acid and boric acid [18] (Table 1). The concentration of active ingredients and consequent retention conformed to Use Class 3 requirements (aboveground and uncovered [10]). Wax emulsion and tung oil were chosen to improve the hydrophobic properties of wood, while copper treatment was selected to improve the fungicidal properties of non-durable wood [4].

Impregnation with all treatment solutions was performed according to the full cell process, i.e., 30 min vacuum (80 mbar), 120 min pressure (9 bar), 15 min vacuum (80 mbar) and 20 min soaking. Uptakes of the treatment solutions were determined gravimetrically. Specimens were conditioned for four weeks after impregnation.

2.2.1. Outdoor exposure

Specimens were exposed to outdoor weathering in the field test site of the Department of Wood Science and Technology, Biotechnical Faculty, Ljubljana, Slovenia (N 46°02′55.4″, E 14°28′44.6″, 300 m above sea level). The first set of material (Out A) was exposed from January 2014 to October 2014. The second set of material (Out B) was weathered for 18 months, from January 2014 until August 2015, while the third set (Out C) of specimens was isolated after 27 months of exposure (May 2016). Larger parallel specimens were exposed somewhat later (October 2015) and analysed after 18 months.

2.3. Contact angle measurements

The sessile drop method was used to determine the contact angles of distilled water on the surfaces of specimens, using a Theta optical tensiometer from Biolin Scientific Oy (Espoo, Finland). After calibration, the goniometer microscope was focused and adjusted on the image of a drop. The contact angles were measured in Young-Laplace contact angle analysis mode in OneAttension software version 2.4 (r4931) (Biolin Scientific). The shapes of drops were observed in an optical goniometer and recorded by a digital camera installed in the axial extension of the lens [15]. Droplets of 4 μL were applied at three different places 10 mm apart from each other on the radial surface of five parallel specimens. In total, 30 contact angles were determined per material/aging procedure. The image recording was set for 62 s (15 FPS), and the time when the contact angles started to be calculated (0 s) was after detachment of the dispenser tip from the drop, which happened approximately 2 s after the first contact of the drop with the substrate. The measurements were taken at a constant temperature of 23 °C.

2.4. Short-term capillary water uptake test

The measurements were carried out at room temperature (23 °C) at a relative humidity (RH) of 50% ± 5% on a Tensiometer K100MK2 device (Krüss, Germany), according to modified [9] standard (1997), after conditioning at 20 °C and 65% RH until constant mass. The axial surfaces of the specimens were positioned to be in contact with water, and their masses were subsequently measured continuously every 2 s for 200 s after 1 mm immersion in water. Based on the final weight of the immersed sample and the square surface of the axial surface of specimens, the uptake of water was calculated in grams per square centimetre.

2.5. Long-term water uptake test

Long-term water uptake was based on the EN 1250-2 standard leaching procedure [12]. Before the test, specimens were oven dried at 103 ± 2 °C until constant

Table 1
Materials and treatments used in respective experiments.

Wood species	Scientific Name	Treatment					Abbrev.	Durability class (EN 350, (2015)
		Wood	Thermal modif.	Cu-EA	Wax	Tung Oil		
Oak	*Quercus*	x					*Q*	2–4
Sweet chestnut	*Castanea sativa*	x					*Cs*	2
European larch	*Larix decidua*	x					*Ld*	3–4
		x				x	*LdOl*	
Scots pine	*Pinus sylvestris*	x					*PsH*	3–4
Norway spruce	*Picea abies*	x					*Pa*	4–5
		x	x				*PaTm*	
		x		x			*PaCu*	
		x	x	x			*PaTmCu*	
		x			x		*PaWa*	
		x				x	*PaOl*	
		x	x		x		*PaTmWa*	
		x	x			x	*PaTmOl*	
Beech	*Fagus sylvatica*	x					*Fs*	5
		x	x				*FsTm*	
		x	x		x		*FsTmWa*	
Scots pine (sapwood)	*Pinus sylvestris*	x					*PsS*	5

mass and weighed to determine the oven-dry mass. Dry wood blocks were placed in a glass jar and positioned with weights to prevent them from floating; 100 g of distilled water was then added per specimen. The water was replaced six times on five subsequent days, as prescribed by the standard. The mass of the specimens was determined after 1, 3, 7, 16, 24, 48, and 95 h, and the moisture content (MC) of the samples was calculated. Because there was a large amount of data, the results are only reported as average moisture content after 1 and 24 h of soaking in distilled water. These values were the most descriptive.

2.6. Water vapour uptake

In addition to liquid water uptake, wood also absorbs water from the air. An experiment was performed to determine the performance of wood in a climate with high relative humidity. Specimens were oven-dried at 103 ± 2 °C to a constant mass and weighed to determine the oven-dry mass. The specimens were stacked in a glass climate chamber with 98% humidity. Specimens were positioned on plastic mesh above water using thin spacers [2]. After 24 h of exposure, they were weighed again and their moisture content was calculated. Specimens were then left in the same chamber for an additional 3 weeks until a constant mass was achieved.

2.7. Wood moisture monitoring

Moisture content (MC) of wood was monitored on larger specimens (2.5 cm × 5.0 cm × 50 cm) exposed above ground in a mono layer exposure. MC was determined with resistance measurements. Insulated electrodes (stainless steel screws) were applied in the centre of specimens and linked to a moisture monitoring device, which enables wood MC measurements between 6% and 60% (Gigamodule, Scanntronik). Moisture content was recorded twice a day, at midnight and noon, similar as reported [3,25].

2.8. Data analysis

Results were analyzed with MS Excel. Data are presented as absolute values, index and rank. Due to the limited space, standard deviations are not provided. The idea of the index value was to easily illustrate changes of respective parameter during weathering. Values obtained at control samples are always considered as one. If the respective parameter increases, index decreases and vice-versa. As there is no standard criteria available for moisture performance, we have decide to rank the samples from the best one (rank 1), to the worst one (17).

3. Results and discussion

The prime objective of this study were not to describe the properties of the tested materials but to determine the water performance before and after weathering. The tests are described in order. The majority of the tests elucidated the interaction between liquid water and wood. Results are presented as ranks and in absolute values. However, ranks were not always sufficient to describe the weather performance, as there might be rather small differences between the materials, so absolute values should be always kept in mind.

3.1. Contact angle

The first test was the contact angle test. The contact angles between water and wood after one second are reported in Table 2. High contact angles indicate better hydrophobicity and, in general, better moisture performance. As can be seen from Table 2, the highest contact angle was determined on spruce wood treated with wax emulsion (PaWa; 115.1°). A fairly high contact angle was determined on wax treated thermally modified beech (FsTmWa; 113.5°) and spruce (Pa; 108.8°). However, the lowest contact angles were measured on copper preservative treated materials (PaCu; 87.9° and PaTmCu; 72.6°). The copper-based preservative used contains quaternary ammonium compounds, which act as surfactants and consequently influence the contact angle [18]. However, the first 9 months of weathering was sufficient to notice the first differences. The chemical differences of the wood surface have already been described in detail [35]. On average, contact angles decreased by 20% after weathering. However, the change of the contact angles was not uniform. For example, the contact angle on wax treated wood did not decrease but increased and remained stable during the next periods of weathering. One of the components of wax emulsion is an emulsifier, which has a negative influence on hydrophobicity but was leached from the wood during the weathering procedure, which had a positive effect on the contact angle. On the other hand, the contact angle of water on other materials sooner or later started to decrease. The most pronounced deterioration was determined on copper preservative treated spruce wood (PaCu), with which the contact angle decreased from 87.9° to 8.5°. A fairly notable decrease was also determined on oak wood (Q), Scots pine heartwood (PsH) and thermally modified spruce wood (PaTm). Another important indicator with high practical value is the rank of the material within a specific aging period. Among the tested materials, the highest rank was determined for wax treated spruce (PaWa), thermally modified beech (FsTmWa) and thermally modified spruce wood (PaTmWa).

3.2. Short-term capillary water uptake

Short-term water uptake is an indication of water penetration in an axial direction. Although the axial plane represents a fairly

Table 2
Contact angle between water and wood surface after 1 s for various aged and non-aged wood based materials. In addition, the index represents changes in the short-term water uptake with aging. The rank of the materials after each period of aging is also expressed. A darker cell background indicates a lower rank.

Wood species	Aging period											
	C	Out A	Out B	Out C	C	Out A	Out B	Out C	C	Out A	Out B	Out C
	Contact angle (°)				Index				Rank			
Cs	89.8	82.4	90.1	56.5	1.0	1.1	1.0	1.6	13	8	8	8
Fs	75.6	81.6	68.1	35.9	1.0	0.9	1.1	2.1	16	9	10	13
FsTm	90.4	76.3	65.2	67.2	1.0	1.2	1.4	1.3	12	10	12	5
FsTmWa	113.5	126.1	126.1	130.3	1.0	0.9	0.9	0.9	2	2	1	2
Ld	93.3	62.9	59.6	55.9	1.0	1.5	1.6	1.7	11	17	13	10
LdOl	108.5	106.9	96.6	55.5	1.0	1.0	1.1	2.0	4	5	6	11
Pa	108.8	69.5	56.2	67.9	1.0	1.6	1.9	1.6	3	12	15	4
PaCu	87.9	66.5	68.0	8.5	1.0	1.3	1.3	10.3	14	15	11	17
PaOl	105.9	108.2	91.7	56.4	1.0	1.0	1.2	1.9	6	4	7	9
PaTm	103.1	69.8	72.2	32.8	1.0	1.5	1.4	3.1	8	11	9	14
PaTmCu	72.6	67.2	56.0	26.0	1.0	1.1	1.3	2.8	17	14	16	15
PaTmOl	97.8	106.0	101.6	57.8	1.0	0.9	1.0	1.7	9	6	4	7
PaTmWa	105.1	126.3	125.0	110.5	1.0	0.8	0.8	1.0	7	1	2	3
PaWa	115.1	123.3	118.2	130.5	1.0	0.9	1.0	0.9	1	3	3	1
PsH	108.3	68.6	57.1	37.2	1.0	1.6	1.9	2.9	5	13	14	12
PsS	93.6	65.6	53.5	59.8	1.0	1.4	1.7	1.6	10	16	17	6
Q	84.4	83.4	97.5	14.4	1.0	1.0	0.9	5.9	15	7	5	16

Out A: 9 months of weathering; Out B: 18 months of weathering; Out C: 27 months of weathering.

small proportion of wood in outdoor applications, it is one of the most important pathways for water penetration into wood, and one of the weakest points in terms of fungal infection. The susceptibility of wood to uptake water in an axial direction increases with weathering. The highest relative increase appears on materials that take up the smallest amount of water before weathering, since even the smallest increase results in an extreme change of the index. For example, oil treated spruce had a water uptake of 0.001 g/cm^2; after 27 months of weathering the water uptake increased to 0.122 g/cm^2, which can be expressed as a 12200% increase, but this uptake qualifies oil treated spruce as one of the 6 best performing materials after 27 months of weathering, considering short-term water uptake only. If only the ranks of the tested materials are considered, then the best performing material after 27 months of weathering was wax treated thermally modified beech (FsTmWa). FsTmWa was thus found to be the best performing material, regardless of the weathering period. All wax treated materials performed similarly well. On the other hand, the opposite relationship was noted with thermally modified spruce (PaTm). PaTm performed best before weathering, absorbing only 0.001 g/cm^2 water. After 27 months of weathering, short term water uptake into weathered material increased to 0.562 g/cm^2, which makes thermally modified spruce one of the worst performing materials after weathering. A similar effect was also evident with thermally modified beech (FsTm) (Table 3). This clearly confirms previous observations of the negative effect of weathering

Table 3
Short term water uptake determined by tensiometer with various aged and non-aged wood based materials. In addition, the index represents the changes in short-term water uptake with aging. The rank of the materials after each period of aging is also expressed. A darker cell background indicates a lower rank.

Wood species	Aging period											
	C	Out A	Out B	Out C	C	Out A	Out B	Out C	C	Out A	Out B	Out C
	Short term water uptake (g/cm^2)				Index				Rank			
Cs	0.099	0.159	0.166	0.214	1.0	1.6	1.7	2.2	10	9	8	9
Fs	0.195	0.348	0.453	0.474	1.0	1.8	2.3	2.4	16	13	14	14
FsTm	0.047	0.358	0.344	0.438	1.0	7.6	7.3	9.3	9	14	11	13
FsTmWa	0.001	0.001	0.001	0.018	1.0	1.0	1.2	21.0	1	1	3	1
Ld	0.046	0.156	0.188	0.207	1.0	3.4	4.1	4.5	8	8	9	7
LdOl	0.001	0.001	0.064	0.122	1.0	1.0	76.0	145.6	1	1	6	6
Pa	0.117	0.295	0.425	0.381	1.0	2.5	3.6	3.2	13	11	13	11
PaCu	0.146	0.377	0.461	0.332	1.0	2.6	3.2	2.3	15	15	16	10
PaOl	0.001	0.032	0.013	0.099	1.0	38.2	16.0	118.3	1	6	5	4
PaTm	0.001	0.394	0.456	0.562	1.0	470.4	545.5	671.3	1	17	15	15
PaTmCu	0.133	0.339	0.417	0.421	1.0	2.6	3.1	3.2	14	12	12	12
PaTmOl	0.005	0.001	0.001	0.103	1.0	0.2	0.2	19.4	7	1	1	5
PaTmWa	0.001	0.001	0.001	0.039	1.0	1.0	1.0	47.0	1	1	1	2
PaWa	0.001	0.001	0.002	0.055	1.0	1.0	2.7	65.8	1	1	4	3
PsH	0.099	0.251	0.317	0.714	1.0	2.5	3.2	7.2	11	10	10	16
PsS	0.213	0.380	0.483	0.859	1.0	1.8	2.3	4.0	17	16	17	17
Q	0.111	0.140	0.073	0.211	1.0	1.3	0.7	1.9	12	7	7	8

Out A: 9 months of weathering; Out B: 18 months of weathering; Out C: 27 months of weathering on the moisture performance of thermally modified wood [16,32]. The other poor performing material was Scots pine sapwood (PsS). However, the low moisture performance of Scots pine sapwood is already well known [22].

There was a correlation between contact angle measurements and short-term water uptake data; higher contact angles resulted in lower water uptakes. The correlation coefficient for control specimens was −0.66, for specimens exposed for 9 months (Out A) it was −0.86, for specimens exposed for 18 months (Out B) it was −0.87, while this coefficient started to decrease, to −0.49, with further aging (Out C).

3.3. Long-term water uptake tests

Water uptakes determined after 1 h of immersion are reported in Table 4. This parameter was very similar to short-term water uptake, since both tests are based on the same principle, i.e., capillary water uptake. Similarly as already reported, the moisture performance of oil (PaOl, PaTmOl) and wax (PaWa, PaTmWa, FsTmWa) treated materials improved after weathering, while the performance of other materials deteriorated. The highest loss of performance was noted on thermally modified spruce (PaTm) and beech (FsTm). For example, the MC of non-weathered control specimens (PaTm) after one hour of immersion was 12.9%, while after 27 months of weathering the MC reached 78.2% (Table 4). This is also reflected in the rank of each material. The rank of thermally modified spruce decreased from 8th to 17th. A similar but less pronounced decrease can also be noted with thermally modified beech.

A comparison of methods for assessment of water performance is shown in Table 5. The correlation between short-term uptake and water uptake after 1 h is better than between contact angle and water uptake. This result is understandable, since contact angle reflects the surface characteristics only, while short-term uptake and MC after immersion reflect the permeability of the specimens. It should be noted that the axial planes of the specimens were not sealed, so axial planes make a considerable contribution to the water uptake of specimens. As can be seen from Table 5, the correlation between short-term uptake and MC after immersion ranged between 0.97 (Out B) and 0.84 (Out C). There are only two outliers: Scots pine heartwood (PsH) and sapwood (PsS).

MCs after 24 h of immersion were considerably higher than after 1 h of immersion. For example, the MC of spruce wood (Pa) after 1 h of immersion was 37.1%, and increased up to 64.2% after an additional 23 h (Table 6). Similarly as already reported, the MC of specimens increased with prior weathering. However, the influence of weathering on water uptake after 24 h was less pronounced than determined by other methods. Weathering is more of a surface phenomenon, so it has a higher influence in the short-term water uptake tests. In the long-term water uptake tests, the central parts of specimens were also soaked, so the overall effect of weathering on water uptake after 24 h was less evident. This increase was most pronounced on thermally modified spruce (PaTm) and beech (FsTm). The water performance of wax treated

Table 4
Water uptake after 1 h of immersion with various aged and non-aged wood based materials. In addition, the index represents the changes in short-term water uptake with aging. The rank of the materials after each period of aging is also expressed. A darker cell background indicates a lower rank.

Wood species	Aging period											
	C	Out A	Out B	Out C	C	Out A	Out B	Out C	C	Out A	Out B	Out C
	Water uptake (%)				Index				Rank			
Cs	19.5	20.1	25.2	28.2	1.0	1.0	1.3	1.4	11	9	9	9
Fs	23.8	40.7	54.7	51.0	1.0	1.7	2.3	2.1	12	13	12	12
FsTm	11.4	31.2	52.0	53.0	1.0	2.8	4.6	4.7	6	11	11	13
FsTmWa	9.5	6.3	7.5	8.3	1.0	0.7	0.8	0.9	4	3	5	4
Ld	12.8	12.7	18.5	23.8	1.0	1.0	1.4	1.9	7	7	7	8
LdOl	10.6	7.0	6.4	10.3	1.0	0.7	0.6	1.0	5	4	3	6
Pa	37.1	42.3	64.5	37.8	1.0	1.1	1.7	1.0	16	14	13	11
PaCu	33.0	44.8	66.1	55.5	1.0	1.4	2.0	1.7	15	15	14	14
PaOl	7.8	8.0	8.2	6.5	1.0	1.0	1.1	0.8	2	5	6	2
PaTm	12.9	65.5	66.7	78.2	1.0	5.1	5.2	6.1	8	16	15	17
PaTmCu	29.8	34.3	69.3	67.3	1.0	1.2	2.3	2.3	14	12	16	15
PaTmOl	4.3	2.9	2.2	1.8	1.0	0.7	0.5	0.4	1	1	1	1
PaTmWa	8.3	6.2	5.6	7.6	1.0	0.7	0.7	0.9	3	2	2	3
PaWa	13.9	8.6	7.2	9.4	1.0	0.6	0.5	0.7	9	6	4	5
PsH	29.2	27.7	33.4	34.1	1.0	0.9	1.1	1.2	13	10	10	10
PsS	43.3	66.4	85.3	77.2	1.0	1.5	2.0	1.8	17	17	17	16
Q	16.9	15.9	19.0	22.6	1.0	0.9	1.1	1.3	10	8	8	7

Out A: 9 months of weathering; Out B: 18 months of weathering; Out C: 27 months of weathering

Table 5
Correlation between water uptake after 1 h of immersion and contact angle measurements and short-term water uptake in relation to various weathered and non-weathered wood based materials.

	Weathering	Contact angle				Short-term water uptake			
		Control	Out A	Out B	Out C	Control	Out A	Out B	Out C
Water uptake after 1 h	Control	−0.31				0.87			
	Out A		−0.73				0.92		
	Out B			−0.80				0.97	
	Out C				−0.52				0.84

specimens (PaWa, PaTmWa, FsTmWa) did not deteriorate; it even improved. Weathered wax treated specimens took up less water than control, non-weathered ones. The reasons for this phenomenon have already been explained.

As expected, there was an excellent correlation determined between water uptake after 1 h and 24 h of immersion. This correlation was evident with control (0.89) and weathered specimens. The highest correlation was determined with specimens weath-

Table 6
Water uptake after 24 h of immersion with various aged and non-aged wood based materials. In addition, the index represents the changes in the short-term water uptake with aging. The rank of the materials after each period of aging is also expressed. A darker cell background indicates a lower rank.

Wood species	Aging period											
	C	Out A	Out B	Out C	C	Out A	Out B	Out C	C	Out A	Out B	Out C
	Water uptake (%)				Index				Rank			
Cs	43.6	42.6	52.0	60.7	1.0	1.0	1.2	1.4	10	9	9	10
Fs	49.3	63.7	77.7	76.7	1.0	1.3	1.6	1.6	11	14	12	13
FsTm	29.4	49.9	63.7	67.8	1.0	1.7	2.2	2.3	8	11	11	12
FsTmWa	20.0	13.1	13.6	14.5	1.0	0.7	0.7	0.7	4	2	3	3
Ld	25.0	22.2	30.5	37.8	1.0	0.9	1.2	1.5	7	7	7	7
LdOl	20.4	16.6	19.9	22.2	1.0	0.8	1.0	1.1	5	4	5	6
Pa	64.2	63.6	90.9	65.8	1.0	1.0	1.4	1.0	16	13	15	11
PaCu	66.4	67.9	89.7	76.8	1.0	1.0	1.4	1.2	17	15	14	14
PaOl	15.9	21.0	20.2	17.2	1.0	1.3	1.3	1.1	3	6	6	4
PaTm	51.5	91.3	86.3	90.1	1.0	1.8	1.7	1.8	13	17	13	16
PaTmCu	55.3	59.1	94.2	87.3	1.0	1.1	1.7	1.6	15	12	16	15
PaTmOl	6.9	5.6	4.8	3.9	1.0	0.8	0.7	0.6	1	1	1	1
PaTmWa	15.8	13.3	11.9	14.4	1.0	0.8	0.8	0.9	2	3	2	2
PaWa	24.7	18.3	18.8	18.4	1.0	0.7	0.8	0.7	6	5	4	5
PsH	50.4	46.5	54.5	55.4	1.0	0.9	1.1	1.1	12	10	10	9
PsS	54.9	75.5	101.0	93.0	1.0	1.4	1.8	1.7	14	16	17	17
Q	34.7	34.0	42.8	47.4	1.0	1.0	1.2	1.4	9	8	8	8

Out A: 9 months of weathering; Out B: 18 months of weathering; Out C: 27 months of weathering

Table 7
Correlation between water uptake after 24 h of immersion and some other water performance tests performed on various weathered and non-weathered wood based materials.

	Weathering	Contact angle				Short-term water uptake				MC after 1 h			
		Con.	Out A	Out B	Out C	Con.	Out A	Out B	Out C	Con.	Out A	Out B	Out C
Water uptake after 24 h	Con.	−0.39				0.77				0.89			
	Out A		−0.77				0.95				0.97		
	Out B			−0.81				0.96				0.98	
	Out C				−0.60				0.83				0.97

Table 8
Moisture content after 24 h of conditioning at 98%-100% of various aged and non-aged wood based materials. In addition, the index represents the changes in the short-term water uptake with aging. The rank of the materials after each period of aging is also expressed. A darker cell background indicates a lower rank.

Wood species	Aging period											
	C	Out A	Out B	Out C	C	Out A	Out B	Out C	C	Out A	Out B	Out C
	Moisture content (%)				Index				Rank			
Cs	5.4	6.8	5.7	11.0	1.0	1.3	1.1	2.0	11	13	11	15
Fs	5.0	6.4	5.7	10.3	1.0	1.3	1.1	2.0	10	11	12	12
FsTm	4.0	5.3	5.0	9.6	1.0	1.3	1.3	2.4	8	8	9	10
FsTmWa	6.4	3.6	4.1	6.0	1.0	0.6	0.6	0.9	16	6	6	5
Ld	3.7	4.5	4.3	9.0	1.0	1.2	1.2	2.4	6	7	7	8
LdOl	1.2	1.5	2.8	5.9	1.0	1.2	2.3	4.8	3	2	4	4
Pa	6.3	8.8	7.1	10.7	1.0	1.4	1.1	1.7	15	17	17	14
PaCu	7.1	6.7	6.6	12.9	1.0	0.9	0.9	1.8	17	12	16	17
PaOl	1.1	2.7	1.8	3.0	1.0	2.5	1.6	2.8	2	4	2	2
PaTm	5.8	7.0	5.5	9.8	1.0	1.2	1.0	1.7	12	14	10	11
PaTmCu	4.9	5.9	5.9	8.7	1.0	1.2	1.2	1.8	9	9	14	7
PaTmOl	0.9	0.7	0.7	1.0	1.0	0.8	0.8	1.2	1	1	1	1
PaTmWa	2.0	2.1	2.2	5.5	1.0	1.1	1.1	2.8	4	3	3	3
PaWa	2.0	3.0	2.9	6.2	1.0	1.4	1.4	3.0	5	5	5	6
PsH	6.0	7.0	5.8	10.6	1.0	1.2	1.0	1.8	14	15	13	13
PsS	5.8	7.8	6.2	12.1	1.0	1.3	1.1	2.1	13	16	15	16
Q	4.0	6.0	4.6	9.1	1.0	1.5	1.2	2.3	7	10	8	9

Out A: 9 months of weathering; Out B: 18 months of weathering; Out C: 27 months of weathering ered for 18 months (Out B; 0.98) (Table 7). There was also a fairly good correlation determined between other methods Table 8.

3.4. Water vapour uptake

Moisture content and, consequently, the moisture performance of wood during outdoor exposure is determined by the uptake of liquid water and water vapour. The water vapour uptake into wood was therefore also determined. The lowest MC of control specimens was determined on oil-treated and thermally modified wood specimens. It appears that the film of oil acts as a barrier, which prevented the diffusion of water vapour into the wood specimens. The reduced sorption properties of thermally modified wood are well known and have been reported in previous studies [32]. Surprisingly, the sorption properties of weathered wood changed, as reported for capillary water uptake tests; weathered wood absorbed more water vapour than non-weathered. Despite that, wax-treated (PaWa, PaTmWa, FsTmWa) and oil-treated woods (LdOl, PaOl, PaTmOl) always performed best and were ranked among the 6 best performing materials in the group of weathered materials. The highest MC after 24 h of conditioning at 98% RH was determined with copper-treated spruce, presumably because of the hygroscopic nature of copper and boron compounds [20] in the preservative used.

The correlation between water vapour uptake and other water performance measures is shown in Table 9. It is rather surprising that water vapour uptake correlated with the majority of the

Table 9
Correlation between MC after 24 h of conditioning at 98% RH and other water performance tests performed on various weathered and non-weathered wood based materials.

	Weathering	MC after 24 h of conditioning at 98% RH			
		Control	Out A	Out B	Out C
Contact angle	Control	−0.23			
	Out A		−0.80		
	Out B			−0.72	
	Out C				−0.44
Short term water uptake	Control	0.61			
	Out A		0.84		
	Out B			0.85	
	Out C				0.70
MC after 1 h immersion	Control	0.70			
	Out A		0.81		
	Out B			0.83	
	Out C				0.75
MC after 24 h immersion	Control	0.82			
	Out A		0.86		
	Out B			0.89	
	Out C				0.85

Table 11
Correlation between MC after three weeks of conditioning at 98% RH and other water performance tests performed on various weathered and non-weathered wood based materials.

	Weathering	MC after 3 weeks of conditioning at 98% RH			
		Control	Out A	Out B	Out C
Contact angle	Control	−0.22			
	Out A		−0.60		
	Out B			−0.48	
	Out C				−0.22
Short term water uptake	Control	0.70			
	Out A		0.53		
	Out B			0.50	
	Out C				0.40
MC after 1 h immersion	Control	0.75			
	Out A		0.52		
	Out B			0.47	
	Out C				0.35
MC after 24 h immersion	Control	0.71			
	Out A		0.55		
	Out B			0.56	
	Out C				0.48
MC after 24 h of conditioning at 98% RH	Control	0.59			
	Out A		0.75		
	Out B			0.71	
	Out C				0.77

Table 10
Moisture content after 3 weeks of conditioning at 98%-100% of various aged and non-aged wood based materials. In addition, the index represents the changes of the short-term water uptake with aging. The rank of the materials after each period of aging is also expressed. A darker cell background indicates a lower rank.

Wood species	Aging period											
	C	Out A	Out B	Out C	C	Out A	Out B	Out C	C	Out A	Out B	Out C
	Moisture content (%)				Index				Rank			
Cs	16.2	16.8	15.3	21.1	1.0	1.0	0.9	1.3	9	10	9	8
Fs	17.9	19.3	16.8	23.6	1.0	1.1	0.9	1.3	14	15	14	16
FsTm	11.6	12.6	12.7	17.4	1.0	1.1	1.1	1.5	4	4	4	6
FsTmWa	11.5	11.0	11.0	17.3	1.0	1.0	1.0	1.5	3	3	3	5
Ld	17.0	18.4	16.2	22.8	1.0	1.1	1.0	1.3	12	14	11	12
LdOl	14.2	14.3	15.1	21.2	1.0	1.0	1.1	1.5	8	8	8	9
Pa	18.6	19.8	18.5	23.0	1.0	1.1	1.0	1.2	15	16	17	14
PaCu	19.3	18.1	17.5	23.6	1.0	0.9	0.9	1.2	17	13	15	15
PaOl	8.9	13.2	12.7	17.2	1.0	1.5	1.4	1.9	2	5	5	4
PaTm	12.0	14.1	13.0	17.1	1.0	1.2	1.1	1.4	6	7	6	3
PaTmCu	13.1	13.6	13.3	18.0	1.0	1.0	1.0	1.4	7	6	7	7
PaTmOl	5.9	5.2	4.3	6.1	1.0	0.9	0.7	1.0	1	1	1	1
PaTmWa	11.7	11.0	10.7	15.8	1.0	0.9	0.9	1.4	5	2	2	2
PaWa	16.5	16.0	16.5	21.9	1.0	1.0	1.0	1.3	10	9	13	10
PsH	17.0	17.9	15.9	22.8	1.0	1.1	0.9	1.3	11	11	10	13
PsS	18.7	19.8	17.9	24.3	1.0	1.1	1.0	1.3	16	17	16	17
Q	17.0	17.9	16.4	22.5	1.0	1.1	1.0	1.3	13	12	12	11

Out A: 9 months of weathering; Out B: 18 months of weathering; Out C: 27 months of weathering.

methods for assessment of water performance. This indicates that similar factors influence liquid water and the water and water vapour interactions with wood.

3.5. Wood moisture monitoring outdoors

The same specimens that were used for assessment of MC after 24 h of conditioning (RH24h), were used for a test lasting 3 weeks (Table 10). Similarly as reported for the RH24h test, the lowest MC was determined on thermally modified wood treated with oil (PaTmOl) (5.9%). Oil was also effective on spruce wood (PaOl). Thermally modified wood absorbs less water and acts synergistically with the oil treatment. As well as oil, wax caused lower MC values after 3 weeks of conditioning, too. The highest MC of non-weathered wood was determined on Scots pine (PsS; 18.7%). In contrast to the majority of other tests, the influence of weathering on the sorption properties was fairly uniform. The MC of the weathered specimens was higher by 20% up to 90%. Differences between other water performance tests were more pronounced. One possible explanation for this is that weathering is a surface phenomenon. On the other hand, all parts of the wood, surface and interior, contribute to the sorption properties. Since the interior represents the major part, the influence of weathering is less pronounced.

As can be seen from Table 11, the moisture content of wood that was conditioned above water for three weeks, does not correlate with other moisture performance tests relating to specimens that were exposed to a water saturated climate for 24 h. As expected, the best correlation was for the two water vapour tests.

However, the most important question was how the moisture content of wood determined in the laboratory correlated with outdoor data, as reported in Table 12. Since we were unable to obtain moisture measurement data for non-weathered specimens outdoors, data from the first three months were taken as a starting point. An analysis was performed for the first year of exposure, the period between 12 and 18 months of exposure, and the total period of exposure. Even if the samples exposed for longer periods were exposed to all seasons, the weather in the exposure periods were not fully comparable. It should be considered, that at least samples exposed for longer period, were exposed to all seasons, and the whole spectra of weather events in temperate climate.

Similarly as in the laboratory tests, wax treated thermally modified wood performed best during all periods of outdoor exposure. In contrast to all the lab tests, the third best performing material was oak (Q). The excellent moisture performance of oak exposed outdoors has already been reported [1]. Although oak and sweet chestnut have similar anatomical structures, the water performance of oak in outdoor tests was much better than that of sweet chestnut. The average MC of oak samples was 13.8%, while sweet chestnut reached 18.6% (Table 12). The highest total MC was determined on Scots pine wood (PsS; 38.1%). The average MC of

Table 13
Correlation between MC determined through continuous moisture monitoring outdoors and different water performance laboratory tests determined on various weathered and non-weathered wood based materials.

	Weathering	MC during outdoor exposure		
		1–3 m	1–12 m	12–18 m
Contact angle	Control	−0.28		
	Out A		−0.48	
	Out B		−0.56	−0.63
	Out C			−0.36
Short term water uptake	Control	0.68		
	Out A		0.51	
	Out B		0.57	0.72
	Out C			0.79
MC after 1 h immersion	Control	0.65		
	Out A		0.68	
	Out B		0.64	0.73
	Out C			0.75
MC after 24 h immersion	Control	0.46		
	Out A		0.57	
	Out B		0.60	0.69
	Out C			0.71
MC after 24 h of conditioning at 98% RH	Control	0.21		
	Out A		0.42	
	Out B		0.37	0.47
	Out C			0.52
MC after 24 h of conditioning at 98% RH	Control	0.43		
	Out A		0.48	
	Out B		0.44	0.40
	Out C			0.35

Table 12
Moisture content after 3 weeks of conditioning at 98%-100% of various aged and non-aged wood based materials. In addition, the index represents the changes of the short-term water uptake with aging. The rank of the materials after each period of aging is also expressed. A darker cell background indicates a lower rank.

Wood species	Aging period											
	1-3m	1-12m	12-18m	total	1-3m	1-12m	12-18m	total	1-3m	1-12m	12-18m	total
	Moisture content (%)				Index				Rank			
Cs	18.0	16.9	22.0	18.6	1.0	0.9	1.2	1.0	8	8	12	9
Fs	30.7	24.1	30.6	26.2	1.0	0.8	1.0	0.9	16	16	16	16
FsTm	15.5	15.0	22.2	17.4	1.0	1.0	1.4	1.1	5	4	13	5
FsTmWa	10.1	9.4	11.5	10.1	1.0	0.9	1.1	1.0	1	1	1	1
Ld	17.1	16.4	19.6	17.5	1.0	1.0	1.1	1.0	7	7	6	6
LdOl	22.1	18.8	20.4	19.4	1.0	0.9	0.9	0.9	14	14	8	12
Pa	20.0	18.0	20.1	18.7	1.0	0.9	1.0	0.9	11	11	7	11
PaCu	22.1	21.1	23.5	21.9	1.0	1.0	1.1	1.0	15	15	14	15
PaOl	20.8	17.9	18.9	18.2	1.0	0.9	0.9	0.9	13	10	4	8
PaTm	19.0	18.5	27.8	21.6	1.0	1.0	1.5	1.1	10	13	15	14
PaTmCu	20.8	18.5	21.9	19.6	1.0	0.9	1.0	0.9	12	12	11	13
PaTmOl	15.4	16.2	19.3	17.2	1.0	1.1	1.3	1.1	4	6	5	4
PaTmWa	12.0	12.0	13.6	12.5	1.0	1.0	1.1	1.0	2	2	2	2
PaWa	18.9	17.7	20.7	18.7	1.0	0.9	1.1	1.0	9	9	9	10
PsH	16.7	16.2	21.3	17.9	1.0	1.0	1.3	1.1	6	5	10	7
PsS	47.2	37.2	39.8	38.1	1.0	0.8	0.8	0.8	17	17	17	17
Q	13.1	13.3	14.8	13.8	1.0	1.0	1.1	1.1	3	3	3	3

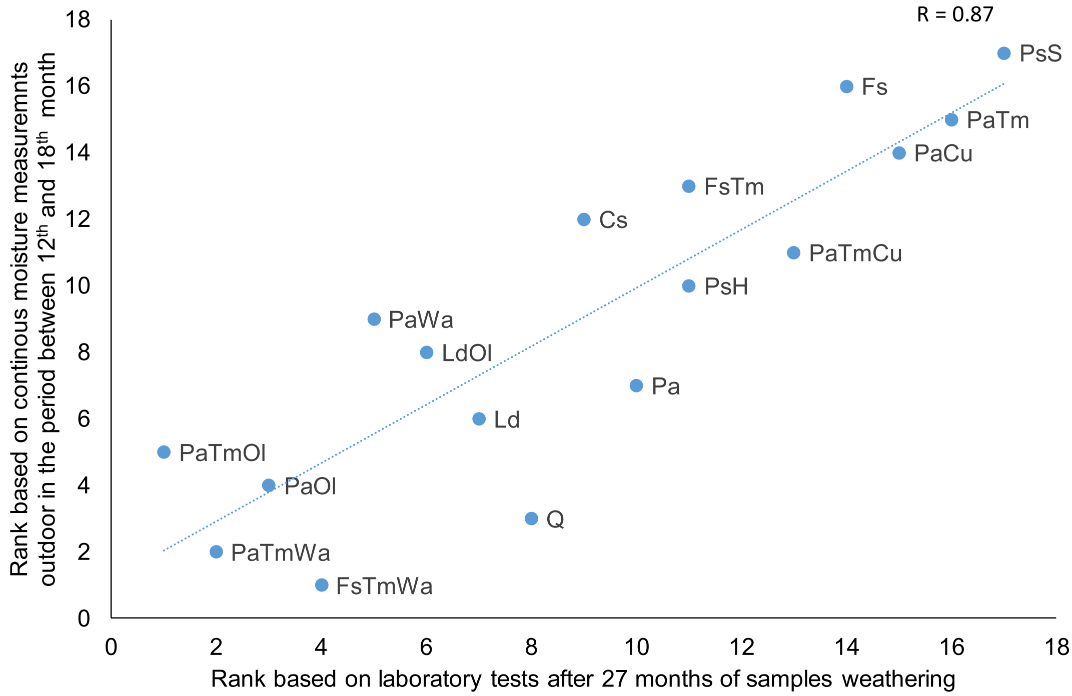

Fig. 1. Correlation between average ratings of the various weathered wood based materials determined in the laboratory (laboratory rating) and ratings of the same materials determined based on continuous moisture measurements during the 12th and 18th months of weathering. The legend for abbreviations of the materials is the same as for Table 1.

wood at the end of the test was about 50% higher than the MC of wood samples in the first three months. The highest increase was determined on thermally modified spruce wood samples (PaTm – 46%) and thermally modified beech (FsTm – 48%). This can also be seen in the ranking of the wood samples. The rank of thermally modified spruce at the beginning was 10 and it decreased to 15. In contrast, wax treated thermally modified beech (FsTmWa) was always ranked first.

In the next step, we were interested in how the different methods for assessment of water performance in the laboratory correlates with outdoor measurements. It can clearly be seen that the capillary methods (short-term water uptake and immersion) correlate much better with MC determined outdoors than contact angle measurements and methods based on water vapour (Table 13). This is evident for both non-weathered control specimens and weathered ones.

In order to combine the various laboratory water performance methods, we calculated the average of the ranks of the samples and compared them with the ranks determined in outdoor tests. We tried combinations of various factors, and the best result was achieved if short-term water uptake, MC after 1 h and 24 h of immersion, and MC after 24 h of conditioning at 100%RH were considered as the output from the laboratory measurements. As shown in Fig. 1, the correlation between the rating based on the laboratory tests and the rating based on the outdoor moisture monitoring is fairly good (R = 0.87). This result clearly indicates that various tests need to be performed to assess outdoor moisture performance. These tests need to consider short- and long-term water penetration, as well as water vapour tests.

4. Conclusions

In order to elucidate the moisture performance of wood fully, a variety of laboratory tests need to be applied. These tests should consider capillary water and water vapour interactions with wood.

Weathering has a considerable influence on the water performance of wood. The water performance of most materials deteriorates with weathering. This was proven with laboratory tests, as well as with outdoor moisture content measurements.

The highest deterioration of water performance was determined on thermally modified wood. This was confirmed in the lab and in the field trials.

In order to predict the behaviour of wood in outdoor exposure using laboratory tests, the tests need to be performed on control and on previously weathered specimens.

Conflict of interest

None.

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