Performance of Bark Beetle Damaged Norway Spruce Wood Against Water and Fungal Decay

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Norway spruce is one of the most important wood species in Central Europe. Unfortunately, bark beetles have prominently attacked spruce trees. Bark beetles colonize wood in symbiosis with ophiostomatoid fungi, which is visible in prominent blue staining. This reduces the commercial value of the infested wood. The relevant properties of blue stained wood were therefore determined: bending and compression strength, sorption properties, DVS analysis, water uptake, and durability against wood decay fungi. This information was applied in the Meyer-Veltrup model for assessment of material resistance. Scanning electron microscopy analysis confirmed severe infestation of blue stained wood, which was also evident from the color of the specimens. The mechanical properties were almost unaffected, as were the sorption properties. However, the durability and water exclusion efficacy of blue stained wood were considerably decreased, which indicates that decay can be expected to appear faster on blue stained wood than on control-untreated wood specimens.

Keywords: Bark beetle; Blue stain; Durability; Norway spruce; Sap stain; Water performance; Wood decay fungi

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INTRODUCTION

Norway spruce (*Picea abies*) is one of the most important wood species in Central Europe. The growing of spruce wood has been promoted even in regions in which this tree species is not naturally present. Spruce in these locations is fairly susceptible to various abiotic and biotic factors (Repe *et al.* 2013). The health of the forest thus decreases and the percentage of sanitary felling increases. Damage caused by insects, mostly bark beetles (Coleoptera, Scolytinae), is the most important reason for sanitary felling of Norway spruce in Central Europe, followed by pathogenic fungi and windthrow (Repe *et al.* 2013). The most devastating effects of bark beetles on spruce trees in Central Europe are associated with *Ips typographus*, *Pityogenes chalcographus*, *Ips amitinus*, and *Polygraphus poligraphus* (Kirisits 2001; Repe *et al*. 2015). *Ips typographus* is predominately aggressive towards Norway spruce. This beetle develops on weakened or freshly harvested trees. The damage caused by bark beetles has even increased due to global warming in the last decade (Repe *et al.* 2013).

Bark beetles are well-known vectors of ophiostomatoid fungi. These fungi are introduced into a new host tree during bark-beetle attacks and the construction of their egg galleries (Harrington 2005; Jankowiak *et al.* 2009). Bark beetles carry the fungal spores on specialized structures called mycangium, or freely on their bodies. The spores can also be eaten and passed through the digestive tract (Paine *et al.* 1997). Wood colonization by ophiostomatoid fungi can lead to blue to grey discoloration of the sapwood, which is

frequently referred to as blue stain or sap stain (Humar *et al.* 2008; Ratnasingam *et al.* 2016). Discoloration is a result of the micro-organismal pigment, melanin (Zink and Fengel 1989; Hernandez *et al.* 2016). Blue stain is a blue, grey, or black striped discoloration on wood. Fungi causing blue stain consume nutrients in the parenchyma cells of sapwood. However, in certain cases, enzymes associated with degradation have been determined; for instance, mannanase, pectinase, and amylase have been detected (Schirp *et al.* 2003). Although blue stain fungi belong to the same group of fungi as soft rot fungi (Troya *et al.* 1990), it is generally assumed that blue stain fungi do not cause any minor cell wall attack, so strength properties are hardly affected (Schmid 2006; Humar *et al.* 2008). It is presumed that fungal hyphae grow on the internal face of cell walls, without any enzymatical alteration on the surface (Liese 1964). However, some hyphae of blue stain fungi have also been seen within parenchyma cell walls (Liese 1964), or even between cell walls in the middle lamella region, which can affect the mechanical properties. Furthermore, blue stain fungi produce intra- and extracellular enzymes, some of which can degrade polysaccharides and pectins. Enzymes that degrade lignin are also present (Troya *et al.* 1990; Sharpe and Dickinson 1992).

Ophiostomatoid fungi, as well as other blue stain and sap stain fungi, affect wood permeability. These fungi are thus frequently used for bio-incising, a biotechnological method designed to enhance the permeability of refractory wood species by incubation with wood-inhabiting fungi or bacteria (Lehringer *et al.* 2010; Thaler *et al.* 2012). The most frequently used organism for a variety of biotechnological processes in the wood processing industry is called Cartapip 97. It is an albino strain of *Ophiostoma piliferum* (Mai *et al.* 2004). An increase in wood permeability is presumably induced by the selective degradation of pit membranes in bordered and half-bordered pits, entailing only negligible changes in the tracheid cell wall. The influence of micro-organisms on the permeability of wood has been known for some decades (Mai *et al.* 2004).

The main aim of this study was to elucidate how decreased moisture performance influences the service life of blue stained wood in aboveground applications. Water performance can be described as an ability of the wood to restrain water uptake during rainfall events and to release the water as fast as possible in order to keep moisture content below threshold required for fungal decay.

The material resistance of wood in an aboveground application is a function of inherent durability (as a consequence of the presence of biocides and/or biologically active extractives) and water performance (Meyer-Veltrup *et al.* 2017). The inherent durability of spruce is low, so good water performance efficacy considerably influences the material resistance of wood outdoors. Because the water performance of blue stained wood is presumably considerably reduced, it is of great commercial importance in forecasting the service life of blue stained wood. Material resistance is a key piece of data for the majority of the service life prediction models. However, information on material resistance is not sufficient to estimate service life, as service life in addition to material resistance depends on micro and macro climate, as well as conditions of use.

EXPERIMENTAL

In the frame of the present study, basic properties of blue stained and control wood were determined. These properties included mechanical properties (bending and compression strength), color, sorption properties, water uptake, and durability against

wood decay fungi. Some of these data were applied in a material resistance model (Meyer-Veltrup *et al.* 2017). This approach enables comprehensive assessment of quality of blue stained wood.

Materials

The research was performed on Norway spruce (*Picea abies*) wood. The wood originated from central Slovenia and had grown between 500 and 700 m above sea level. The diameter of the trees was between 35 and 45 cm. There were two types of wood used; control samples were made of undamaged spruce, without visible signs of decay or blue staining. The second set of specimens was made of wood from spruce trees that had been felled due to attack by European spruce bark beetle (*Ips typographus*) and were severely infested with Ophiostomatoid fungi, which causes blue staining. This material in the present study is therefore identified as blue stained wood. The density of the samples and ring width of the two sets of specimens were comparable.

Color of Wood

The color of the specimens was determined from scanned specimens and expressed in the CIE $L^*a^*b^*$ system (Humar *et al.* 2008). The L^*-axis represents the lightness, while, a^* and b^* are the chromaticity coordinates. In the CIE $L^*a^*b^*$ coordinates, $+a^*$ stands for red, $-a^*$ for green, $+b^*$ for yellow, $-b^*$ for blue, and L^* varies from 100 (white) to zero (black). Any color can thus be characterized (Brock *et al.* 2000).

Mechanical Properties

Static three-point bending tests were performed according to the EN 310 standard (CEN 1993) on a Zwick-Roell Z005 universal testing machine (Zwick-Roell, Ulm, Germany) to obtain the modulus of elasticity (MoE - bending) and bending strength (F_m – bending strength). In total, 20 test specimens (10 replicates for each specimen type) with dimensions 100 mm × 20 mm × 5 mm were prepared and conditioned in a standard climate (relative humidity = 65 ± 5%; temperature = 20 ± 2 °C) until a constant mass of the specimens was achieved. The specimens were tested for MoE and F_m immediately after incubation in the standard climate.

Compressive strength (F_m - compression) was determined according to the ASTM D1037-12 (2012) standard on a Zwick-Roell Z100 universal testing machine (Zwick-Roell, Ulm, Germany). In total, 20 test specimens (10 for each specimen type) with dimensions 50 mm × 20 mm × 20 mm were prepared and incubated in a standard climate until a constant mass of the specimens was achieved. The specimens were tested for compressive strength immediately after incubation in the standard climate. After the test, the compressive strength (F_m) was calculated.

Specimens used for mechanical properties were also used for determination of density. Density was determined after conditioning in a standard climate (RH = 65 ± 5 %; T = 20 ± 2 °C). In order to calculate density, all three dimensions of specimens were measured, and their mass was then determined. Density was determined on all 40 specimens.

SEM Analysis

Scanning electron microscopy (SEM) was performed to confirm the presence of fungal hyphae in the wood. Specimens were prepared, ensuring that they were oriented in all three anatomical planes, cutting the surface of each anatomical plane with a sliding

microtome, which has been shown to be the most appropriate surface preparation procedure for SEM imaging. SEM micrographs were then taken in low voltage (10 kV) and low vacuum (50 Pa) conditions with a large field (LFD) detector in an FEI Quanta 250 SEM microscope (Hillsboro, Oregon, United States) at a working distance of 10 mm.

Durability Test Against Wood-Destroying Basidiomycetes

The decay test was performed according to a modified CEN/TS 15083-1 (CEN 2005). Conditioned specimens (samples were conditioned in laboratory conditions prior exposure for 3 to 4 weeks) were steam-sterilized in an autoclave before exposure to wood decay fungi; 350 mL experimental glass jars with aluminum covers and cotton wool with 50 mL of potato dextrose agar (DIFCO) were prepared and inoculated with white rot fungi *Trametes versicolor* (L.) Lloyd (ZIM L057) and two brown rot fungi (*Gloeophyllum trabeum* (Pers.) Murrill (ZIM L018) and *Fibroporia vaillantii* (DC.) Parmasto (ZIM L037). The fungal isolates originated from the fungal collection of the Biotechnical Faculty, University of Ljubljana (and Ljubljana, Slovenia) are available to research institutions on demand (Raspor *et al.* 1995). Information regarding the origin of the fungal isolates and details about identification are available in the appropriate catalogue. One week after inoculation, two specimens per jar were positioned on a plastic HDPE mesh, which was used to avoid direct contact between the samples and the medium. The assembled test glasses were then incubated at 25 °C and 80% relative humidity (RH). After incubation, specimens were cleansed of adhering fungal mycelium, weighed to the nearest 0.0001 g, oven-dried at 103 ± 2 °C, and weighed again to the nearest 0.0001 g to determine mass loss through wood-destroying basidiomycetes. Fifteen blue stained and 15 control spruce wood specimens were used in this test.

Short-term Capillary Water Uptake Test

Measurements were carried out at room temperature of 20 °C at a relative humidity (RH) of 50 ± 5 %, on a Tensiometer K100MK2 device (Krüss, Hamburg, Germany), according to a modified EN 1609 (CEN 1997) standard, after conditioning at 20 °C and 65 % RH until constant mass. The axial surfaces of the specimens (1.5 × 2.5 × 5.0 cm3) were positioned to be in contact with the test liquid (distilled water), and their masses were subsequently measured continuously every 2 s for 200 s. Other parameters used were: velocity before contact 6 mm/min, sensitivity of contact 0.005 g, and depth of immersion 1 mm. Depending 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 cm. Ten blue stained and 10 controls spruce wood samples were used for this analysis.

Long-Term Water Uptake Test with Drying Process above Freshly Activated Silica Gel

Long-term water uptake was based on the ENV 1250-2 (CEN 1994) leaching procedure. Before the test, specimens (1.5 × 2.5 × 5.0 cm^3) were oven-dried at 103 ± 2 °C until constant mass and weighed to determine the oven-dry mass. The 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 mass of the specimens was determined after 1 h and 24 h, and the moisture content of the samples was calculated. In addition to wetting, outdoor performance is also influenced by drying. Wood that dries out quicker, in general, performs better. After 24 h of immersion, wet specimens were positioned above freshly activated silica gel for 24 h in a closed container, and the moisture

content of the samples was calculated according to the Meyer-Veltrup procedure (2017). Ten blue stained and 10 controls spruce wood samples were used for this analysis.

Water Vapor Uptake in a Water-Saturated Atmosphere

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 (15 mm × 25 mm × 50 mm) were oven-dried at 103 ± 2 °C to a constant mass and weighed to determine oven-dry mass. The specimens were stacked in a glass climate chamber with a ventilator above distilled water. Specimens were positioned on plastic mesh above the water using thin spacers (Meyer-Veltrup *et al.* 2017). 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. Ten blue stained and 10 controls spruce wood samples were used for this analysis.

Dynamic Vapor Sorption Analysis

Samples for dynamic vapor sorption (DVS) analysis were milled on a Retsch SM 2000 cutting mill (Retsch GmbH, Haan, Germany) with a Conidur® perforation sieve with 1.0 mm perforations. Prior to the experiment, the wood chips were conditioned for 24 h at 20 ± 0.2 °C and 1 ± 1% RH. Analysis of the wood samples was performed using a DVS apparatus (DVS Intrinsic, Surface Measurement Systems Ltd., London, UK). A small amount (approximately 100 mg) of pre-conditioned wood chips was placed on the sample holder, which was suspended in a microbalance within a sealed thermostatically controlled chamber, in which a constant flow of dry compressed air was passed over the sample at a flow rate of 200 cm^3/s and a temperature of 20 ± 0.2 °C. The schedule for DVS was set to steps of 0%, 10%, 20%, 30%, 40%, 50%, 60%, 70%, 80%, 90%, and 95% RH for both sorption and desorption steps. Two full isotherm runs were performed in order to fully capture the sorption behavior of the material. The DVS maintained a given RH until the weight change of the sample was less than 0.002%/min for at least 10 m. The running time, target RH, actual RH, and sample weight were recorded every 60 s throughout the isotherm run. Sorption and desorption isotherms were produced for each material by plotting equilibrium moisture content (EMC) change against relative humidity (RH).

Statistical Analysis

Statistical analysis was performed with Microsoft Excel with add on for statistical analysis Analyse-it for Microsoft Excel 4.90 (Analyse-it Software, Ltd., Leeds, United Kingdom). The difference between blue stained and control samples was statistically verified by Student's t-test.

Factor Approach to Quantifying the Resistance Dose

A model approach was applied according to Meyer-Veltrup *et al.* (2017) and Isaksson *et al*. (2014) in order to predict the field performance of the examined wood species. The model describes climatic exposure, on the one hand, and the resistance of the material on the other. The acceptance of the chosen design and material is expressed as follows,

$$\text{Exposure} \leq \text{Resistance} \quad (1)$$

The exposure can be expressed as an exposure dose (D_{Ed}) determined by daily

averages of temperature and MC. The material property is expressed as the resistance dose (D_{Rd}). The dose is expressed in days [d] with optimum moisture and temperature conditions for fungal decay (Isaksson *et al.* 2013).

$$D_{Ed} \leq D_{Rd} \quad (2)$$

where D_{Ed} is the exposure dose [d] and D_{Rd} is the resistance dose [d].

The exposure dose D_{Ed} depends on the annual dose at a specific geographical location and several factors describing the effect of driving rain, local climate, sheltering, distance from the ground, and detailed design. Isaksson *et al.* (2014) give a detailed description of the development of the corresponding exposure model. The present study focused on the counterpart of the exposure dose, which is the resistance, expressed as resistance dose D_{Rd}. This is considered to be the product of the critical dose D_{crit} and two factors taking into account the wetting capacity of wood (k_{wa}) and its inherent durability (k_{inh}). The approach is given by the following Eq. 3 according to Isaksson *et al.* (2014),

$$D_{Rd} = D_{crit} \times k_{wa} \times k_{inh} \quad (3)$$

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

Based on the results of the various moisture tests presented in this paper, the wetting capacity factor k_{wa} was evaluated. The methodology for the calculation of k_{wa} followed the Meyer-Veltrup procedure (2017), except that the size of the specimens differed. The original model prescribes samples ($0.5 \times 1.0 \times 20.0$ cm^3) that are of a different shape from that used in the present study ($1.5 \times 2.5 \times 5.0$ cm^3). Since the methodology is based on relative values, sample size has a minor influence on the outcome. Results from durability tests were used to evaluate the inherent resistance factor k_{inh}, and both factors were used to determine the resistance dose D_{Rd} of the four wood materials examined in this study (stone pine sapwood and heartwood, Scots pine, and Norway spruce). Only basidiomycetes were applied to determine k_{inh} in the research. Terrestrial microcosm tests and in-ground durability tests were not performed, as prescribed by the original Meyer-Veltrup approach (2017).

RESULTS AND DISCUSSION

The visual appearance of blue stained wood clearly indicated the presence of blue staining. Blue stained wood was darker. The L^* value of blue stained wood was 76.4, which is considerably lower than the L^* value determined for the control wood (86.9) (Table 1). In addition, blue stained wood was less reddish and more greenish, as indicated by the a^* value and less yellowish and more blueish, which can be seen from the b^* value (Table 1). SEM analysis was performed to confirm the influence of the fungal infestation on the discoloration. As shown in Fig. 1A, the wood was severely colonized. Hyphae were present in the tracheid and in the parenchyma cells. Based on the morphology, the hyphae did not belong to a fungal species belonging to Basidiomycota, as there were no clamp connections observed on the hyphae. There were no hyphae visible in the SEM images of control specimens (Fig. 1B).

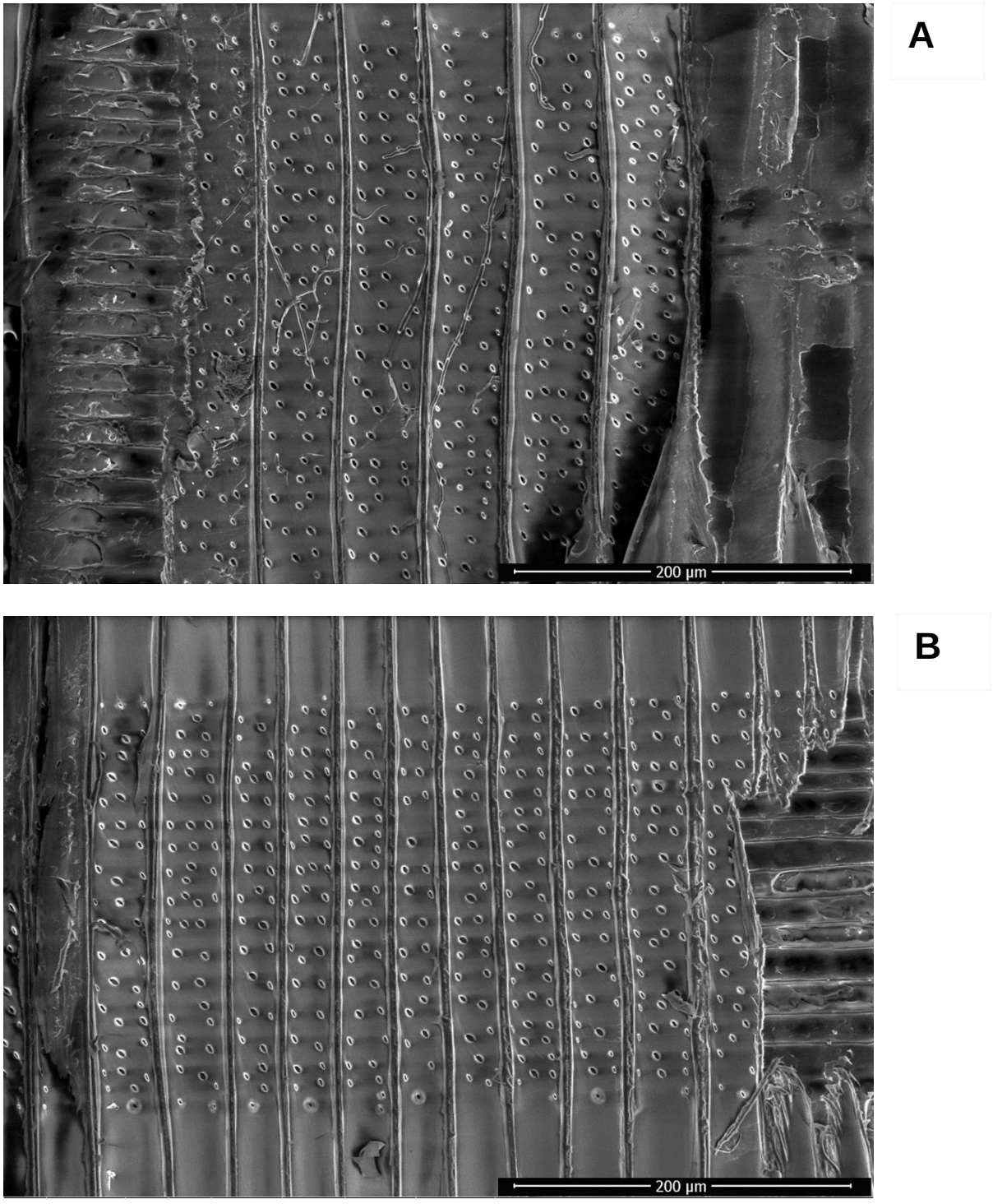

Fig. 1. SEM micrograph of blue stained (from beetle damaged trees) Norway spruce. Hyphae are visible in the cross field (A) and SEM micrograph of control Norway spruce (B).

Table 1. Basic Properties of Blue Stained (from beetle damaged trees) and Control Norway Spruce Wood*

		Blue Stained		Control	
		Avg.	Std. dev.	Avg.	Std. dev.
Color	*L** (lightness)	76.4	1.6	86.9	0.3
	*a** (red-green coordinate)	4.4	0.3	5.6	0.2
	*b** (yellow-blue coordinate)	8.1	0.3	11.6	0.3
Density (kg/m^3)		462.0	6.0	471.6	7.2
Bending Strength	MoE (N/mm^2)	9055	328	10790	277
	F_m bending (N/mm^2)	69.0	2.1	74.8	1.9
Compression Strength	F_m compression (N/mm^2)	36.5	1.1	35.3	1.9
	Wood Decay Fungi				
Mass Loss (%)	*G. trabeum*	41.6	2.9	36.8	2.9
	F. vaillantii	20.1	3.9	9.7	3.4
	T. versicolor	8.8	2.4	7.5	2.6
	Time of Contact				
Contact Angle (°)	1 s	58.6	10.3	72.9	7.4
	10 s	38.7	13.0	56.8	12.0
	30 s	19.4	18.3	48.2	11.4
	60 s	7.9	14.9	39.5	10.1
	Time of immersion				
Short Term Water Uptake (g/cm^2)	50 s	0.184	0.026	0.146	0.011
	100 s	0.221	0.030	0.167	0.010
	200 s	0.290	0.047	0.185	0.011
	Time of Immersion				
Liquid Water Uptake (%)	1 h	95.3	26.2	25.4	2.4
	24 h	107.5	20.8	55.2	4.6
	Time of Conditioning				
Water Vapor Uptake (%)	24 h	18.5	0.3	17.8	0.3
	4 w	27.5	0.3	27.5	0.4
Factors that Determine the Service Life of Wood*	k_{inh}	0.860		1	
	k_{wa}	0.815		1	
	D_{Rd} (d)	228		325	
	$D_{rd\ rel}$	0.701		1	

* Grey shaded cells indicate a significant difference ($p > 0.05$) between blue stained and control spruce wood. Factors are the mean value of individual factors calculated according to the methodology described in detail by Meyer-Veltrup *et al.* 2017. The k_{inh} factor accounts for the inherent protective properties of the material against wood decay fungi. The k_{wa} factor describes the wetting ability. This factor is a median value derived from short-term water uptake, 24 h immersion and water vapour uptake and desorption test.

In order to enable as relevant a comparison as possible, wood with comparable densities was analysed. Table 1 shows that there was no significant difference between the

densities of blue stained (462.0 kg/m^3) and control spruce (471.6 kg/m^3) (Table 1). The densities of both control and blue stained wood were in line with the data of the literature (Wagenführ 1996) and enable a comparison of the results with other reference sources. Comparable density is predominantly important for the assessment of mechanical properties, which largely depend on the density. The modulus of elasticity of blue stained wood (9055 N/mm^2) was significantly lower than that of control spruce (10790 N/mm^2). We were unable fully to elucidate the reasons for this difference. It is suspected that it might be associated with the fact that the chemical composition of blue stained wood changes slightly (Troya *et al*. 1990), though this difference may be within the natural variation of the mechanical properties of the wood (Zobel and Buijtenen 1989). However, the compression and bending strengths of the two investigated materials were comparable (Table 1). This is in line with previous observations (Humar *et al*. 2008). However, these data clearly indicate that key mechanical properties of blue stained wood are comparable to control wood (Lanvermann *et al*. 2014; Bučar and Merhar 2015), and can be applied for comparable applications, from a mechanical point of view.

Another parameter that influences wood applications is durability against wood decay fungi. Wood decay fungi are an important reason for the failure of wooden constructions in Europe (Dietsch and Winter 2018). The durability of the blue stained wood was therefore considered. As shown in Table 1, brown rot fungi *G. trabeum* and *F. vaillantii* caused a significantly higher mass loss of the blue stained wood than with the control specimens. However, this difference was not significant with specimens exposed to *T. versicolor*, which belongs to the group of white rot fungi that are not primary degraders of conifer wood in nature (Schmidt 2006). There are several reasons for the greater susceptibility of the blue stained wood. Some authors have suggested that the key contribution of blue stain fungi is increased permeability and the opening of new voids for fungal penetration into the wood (Dix and Webster 1995). It should be noted that fungal infestation of wood is a complex process, including interactions among fungi, wood, and environmental conditions (Deacon 1997). However, there have been some previous reports that the influence of blue stain fungi on degradation may even be negative, due to the possible antagonistic effects between blue stain fungi and degrading fungi (Graf 2001). Blue staining itself did not influence the durability classification of the wood. Because the mass loss of the control and blue stained wood was higher than 35%, standard CEN/TS 15083-1 (2005) classifies the wood as non-durable (Durability class 5). This is the wood class with the lowest durability. Beech wood, poplar, and pine sapwood are also classified as non-durable.

In addition to inherent durability, which is the result of the presence of toxic secondary metabolites and/or biocides in wood, water performance has been identified as another important factor influencing the service life of wood in outdoor applications (Meyer-Veltrup *et al*. 2017). Wood with better water exclusion efficacy lasts longer than comparable wood with lower water exclusion efficacy, regardless of comparable durability. Various water performance tests were therefore performed on blue stained and control spruce wood. The contact angle of water was significantly lower on blue stained wood than on control ones (Table 1). Specifically, the contact angle after 10 s of contact between water and blue stained wood was 38.7°, while a markedly higher contact angle was determined on control spruce (56.8°). The contact angle influences not only the performance of wood but it also influences the adhesion and quality of surface coatings (Petrič and Oven 2015). A similar effect of water on blue stained wood was also determined with other tests. Blue stained wood took up more water during short-term tests with a

tensiometer and with the long-term immersion test. After 1 h of immersion, the moisture content of blue stained wood reached 95.3%, while the moisture content of control wood remained almost four times lower (25.4%). This is clear evidence of the increased permeability of blue stained wood. The reasons for the increased permeability are predominantly associated with the fungal colonization of the wood, the degradation of the pits, and the opening of new voids (Thaler *et al.* 2012; Panek *et al.* 2013).

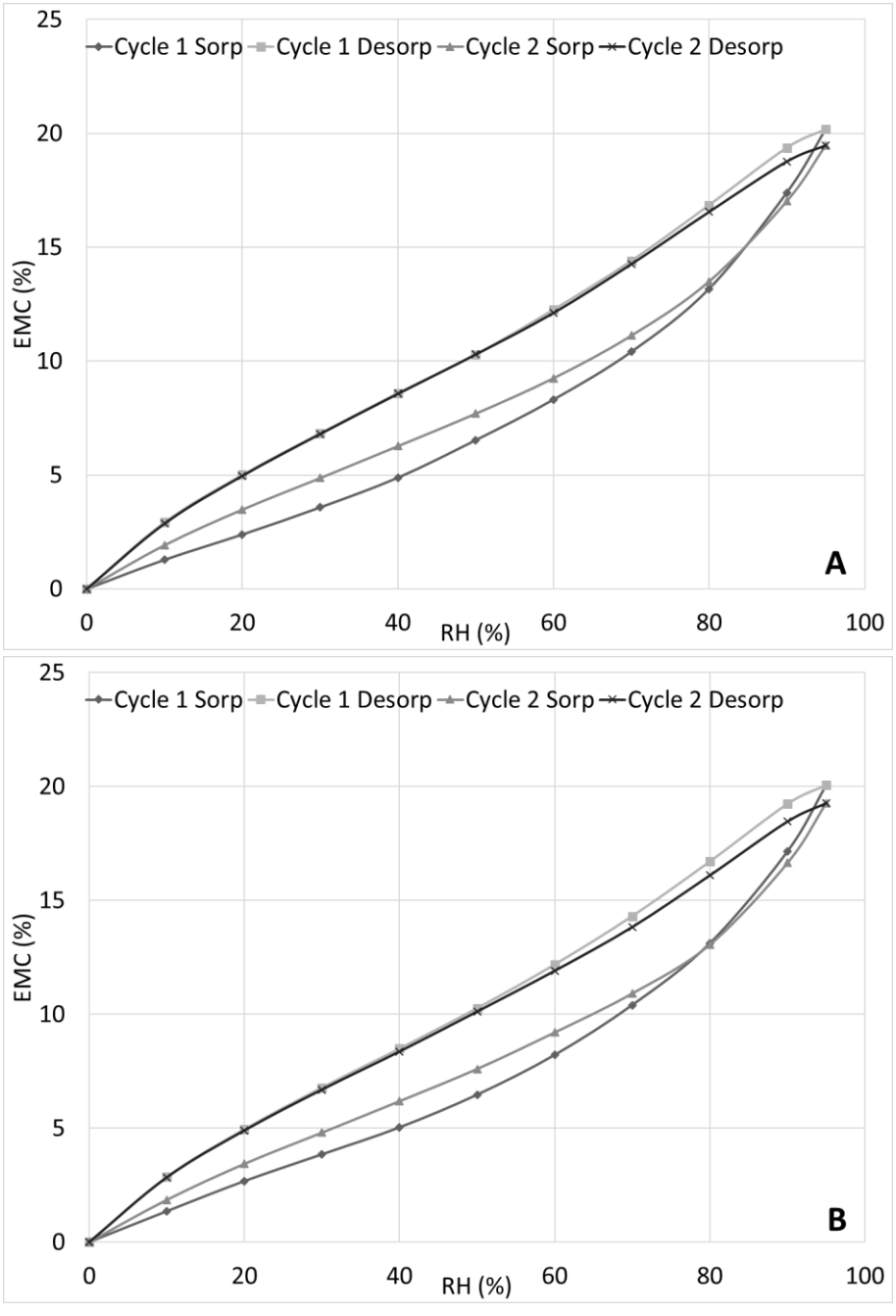

Fig. 2. Relationship between relative humidity and wood moisture content, as determined with DVS. A - control spruce, B - blue stained spruce wood. Two absorption and desorption cycles are displayed in every plot.

However, wood in outdoor applications is in contact not only with liquid but also with water vapors. In contrast to previous results, blue staining does not have any significant influence on the sorption properties of wood. This is evident from the MC of wood conditioned in a chamber with 98% to 100% relative humidity (Table 1) and DVS curves (Fig. 2). The MC of wood exposed to a humid atmosphere (RH = 98% to 100%) was 27.5% with both blue stained and control wood. The same influence of blue staining can be seen from the DVS curves; the first and second absorption/desorption cycles for blue stained wood and control spruce wood were comparable. This is clear evidence that blue stain fungi do not influence the sorption properties of wood.

In the last step, the authors tried to apply the Meyer-Veltrup (2017) model on blue stained wood. On the basis of the fungal durability and water performance tests, factors k_{wa} and k_{inh} were calculated for blue stained wood using Norway spruce as the reference material. Based on Eq. 3 and the procedure described by Meyer-Veltrup *et al.* (2017), the material resistance dose D_{Rd} was calculated assuming a wood-species independent critical dose D_{crit} of 325 days of optimum conditions for fungal decay. As can be seen from Table 1, blue stained wood exhibited poorer inherent durability (k_{inh} = 0.860) and water performance (k_{wa} = 0.815) than reference Norway spruce. This result showed that blue stained wood withstands only 228 days of optimal conditions prior to the development of the first signs of fungal decay. The service life of the same structure is thus presumed to be approximately 30% shorter if fabricated from blue stained wood and not of reference Norway spruce. However, the actual service life depends on climatic and microclimatic conditions at the relevant location. If blue stained wood is to be used in harsh conditions, it must be impregnated with wood preservatives, hydrophobic agents or modifying chemicals. However, due to good permeability, the impregnation of blue stained wood is easier than with the reference material (Thaler *et al*. 2012).

CONCLUSIONS

1. Bark beetle damaged Norway spruce was severely colonized by blue-stain fungi, as indicated from SEM micrographs and color of blue stained wood.
2. The results of this research indicate that the mechanical properties of blue stained wood are almost unaffected. Bending and compression strength properties of blue stained wood are comparable to the properties of reference spruce wood.
3. Sorption properties of blue stained wood are comparable to those of control spruce wood.
4. Performance of blue stained wood against wood decay fungi and water is considerably reduced. Reduced inherent durability and water performance results in a considerably reduced material resistance and consequent service life, as indicated from the Mayer-Veltrup model.

ACKNOWLEDGMENTS

The authors acknowledge the support of the Slovenian Research Agency within the framework of project L4-5517, L4-7547, program P4-0015 and the infrastructural center (IC LES PST 0481-09). Part of the research was also supported by project Tigr4smart. The

technical support of Simon Slabe is also acknowledged.

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Article submitted: January 19, 2018; Peer review completed: March 17, 2018; Revised version received and accepted: March 18, 2018; Published: March 21, 2018.
DOI: 10.15376/biores.13.2.3473-3486