Effect of the Number of UV-Protective Coats on the Color Stability and Surface Defects of Painted Black Locust and Norway Spruce Woods Subjected to Natural Weathering

Miloš Pánek,[a] and Ladislav Reinprecht [b]

This paper utilized 12 coating systems, based on an acrylate and a hydrophobic polymer, with the addition of light pigments, nano-sized polyvalent metal (AsS-chelate complex) for ultraviolet protection, and iodopropynyl butylcarbamate fungicide. This study deals with the impact of the number of coats on the color stability and the surface defects of painted black locust (*Robinia pseudoacacia* L.) and Norway spruce (*Picea abies* Karst L.) woods after up to three years of natural weathering, at a slope of 45°. The best coating system was created from three coats, which consisted of two pigmented acrylates (PerlColor) and one transparent hydrophobic water-repellent (AquaStop). The total color change, Δ*E**, of the weathered surfaces was approximately two times lower when the application involved a pigmented coating system compared with a transparent one. The color stability of the surfaces and their resistance to defects was better when the coating system was applied to black locust wood compared with spruce wood. Smoother surfaces of wood before painting resulted in a higher resistance against cracking and other defects caused by natural weathering; however, the effect of the initial wood roughness on the color stability of painted woods during natural weathering was usually negligible.

Keywords: Coatings; Wood; Weathering; UV-protections; Color stability; Surface defects

Contact information: a: Czech University of Life Sciences Prague, Faculty of Forestry and Wood Sciences, Kamýcká 129, 165 21 Prague 6 – Suchdol, Czech Republic; b: Technical University in Zvolen, Faculty of Wood Sciences and Technology, Masarykova 24, 960 53 Zvolen, Slovak Republic;
** Corresponding author: panekmilos@fld.czu.cz*

INTRODUCTION

Wood for exterior use is degradable by biotic and abiotic agents (Hon and Feist 1986; Van Acker *et al.* 2003; Alfredsen *et al.* 2007). These agents may result in a reduction of wood's mechanical and physical properties, as well as micro-cracks, discoloration, and other aesthetical defects in the wood's surface (Feist 1982, 1990; Evans 2008). Suitable types of pigments (Reinprecht and Pánek 2013) or UV-absorbing additives in transparent coating systems can stabilize the color of painted solid wood and are known to decrease or slow down the degradation on its surface (De Meier 2001; Gobakken and Lebow 2010; Syvrikaya *et al.* 2011; Forsthuber *et al.* 2013; Pánek and Reinprecht 2014). Currently, discovering and testing the best coating system for individual applications is of interest in the field (Oltean *et al*. 2010; Grüll *et al.* 2011, 2014; Sandak *et al.* 2013). Additionally, the health and ecological aspects of a color coating system with a low emission of volatile organic compounds (VOC) is important (De Meier 2001; Tesařová *et al.* 2010).

The degradation of the coating system on wood's surface differs depending on the climate conditions (Creemers *et al.* 2002; Valverde and Moya 2014), wood species, and other factors. Therefore, it is necessary to test selected coatings on various woods in different regions. A summary of such results can provide general information about the stability, aesthetics, preservation effects, and component additives that improve the specific properties of the coating. The weathering index rate (W_{ind} from 0 to 1000) predicted on the base of chemometric models of mid infrared spectra can be useful method for evaluation of climate effects at modelling the weathering kinetics of wood or coatings (Sandak *et al.* 2015).

Previous work has shown that the stability and durability of coatings on painted wood can be improved by increasing their total thickness, *e.g.*, by using a primer layer, a top-coat layer, and a final, water-repellent layer, or using more layers of the same coating (Masaryková *et al.* 2010). The stability of the coatings on a treated wood surface can be improved by the addition of hydrophobic agents, UV-additives, or other specific compounds (De Meier 2001; Ghosch *et al*. 2009; Grüll *et al.* 2011; Samyn *et al.* 2014). From an aesthetic and functional durability point of view, the effect of different wood species (Ozgenc *et al.* 2012; De Windt *et al.* 2014) and the effect of the initial surface roughness of the wood before application of coatings (Ozdemir and Hiziroglu 2009; Scrinzi *et al.* 2011; Reinprecht and Pánek 2015) have been previously documented. These effects depend on other specific conditions of the coating system, *i.e.*, the type and number of coating layers, pigments and UV-additives, and climatic conditions. The aforementioned conditions have been continuously studied to investigate and validate current systems.

Spruce is traditionally and the most often used wood species for houses, bridges, and other exterior constructions in the Central Europe. However, its lower natural durability (class 4 for decaying fungi according to the standard EN 350-2 (1997)) and poor permeability to liquid preservatives (Usta 2005; Pánek and Reinprecht 2008) make it unsuitable for application in severe environmental conditions. Black locust wood also has poor permeability; however, in addition it is significantly more durable against biological agents and has a pleasant color and surface appearance. Currently black locust is commonly chosen for exterior construction projects in the Central Europe. It is often used as a substitute for tropical wood species for decking or garden furniture. In this view, it is necessary to test different modern coating systems applied on surfaces of Norway spruce and black locust wood and compare obtained results from various climatic regions.

The aim of this work was to investigate the effect of the number of coats on the color change and other aesthetic defects on the surface of Norway spruce and black locust woods painted with a UV-protected coating system. The coating system contained nano-sized polyvalent metal (AsS-chelate) complex or also pigments, both as UV-protection. The wood was subjected to outdoor weathering lasting 36 months. In contrast to the study of Reinprecht and Pánek (2015), the coating systems used in this work did not contain a transparent primer layer; so wood was immediately treated with differently pigmented top-coat layers. The following kinds of layering were used: (1) one top-coat layer, (2) two top-coat layers, (3) one top-coat layer and one final water-repellent layer, or (4) two top-coat layers and one final water-repellent layer. The effects of the initial wood roughness on the surface quality of painted woods after weathering were also analyzed.

EXPERIMENTAL

Wood

Wood samples with dimensions of 375 × 78 × 20 mm (axial × radial × tangential) were prepared from black locust (*Robinia pseudoacacia* L.) and Norway spruce (*Picea abies* Karst L.) naturally dried boards, in accordance with the standard EN 927-3 (2006). The top surface of each sample had two different areas of roughness, with lengths of 187.5 mm. The surface area ground with 60-grit sandpaper was referred to as rough (R), and the surface area ground also with 120-grit sandpaper was referred to as smooth (S). Both transverse sections (78 x 20 mm) of the sample were treated with silicone for water-resistance and its other non-exposed sides with transparent UV-protective coating.

Coating Systems and their Application

Wood samples were painted with one of 12 coating systems (Table 1). They did not contain a primer layer usually recommended by producers, because the aim of this study was to search stability of coatings without this anchoring paint. The samples were immediately painted with one or two layers of a top-coat (*PerlColor*) in three pigmentations (T = transparent, P = pine, and L = larch). Then, one-half of the samples were treated with a single water-repellent (*AquaStop*) layer. All of these coatings were manufactured by the Böhme AG Farben & Lacke Co. (Switzerland).

Table 1. Color Components L^*, a^*, and b^* of "Rough" (R) Reference and Painted Norway Spruce and Black Locust Samples before Natural Weathering

Coating system		Norway spruce			Black locust		
		*L**	*a**	*b**	*L**	*a**	*b**
	Reference	84.2 (1.2)	4.2 (0.3)	19.2 (0.5)	68.5 (0.9)	5.4 (0.4)	22.3 (0.8)
1.	*PerlColor*-T (1x)	82.4 (1.2)	3.5 (0.7)	28.0 (0.6)	65.2 (2.2)	9.3 (1.0)	38.2 (1.1)
2.	*PerlColor*-P (1x)	61.7 (0.5)	18.8 (0.3)	42.2 (0.4)	53.7 (0.3)	16.7 (0.2)	36.4 (0.5)
3.	*PerlColor*-L (1x)	59.0 (1.4)	18.5 (0.6)	38.9 (0.5)	37.7 (1.8)	10.2 (0.9)	38.5 (1.7)
4.	*PerlColor*-T (2x)	82.0 (0.4)	3.6 (0.2)	32.1 (0.6)	63.9 (5.8)	9.3 (1.0)	38.3 (1.1)
5.	*PerlColor*-P (2x)	49.9 (0.4)	22.3 (0.2)	35.3 (0.5)	47.5 (0.8)	20.1 (0.5)	31.6 (0.5)
6.	*PerlColor*-L (2x)	47.5 (2.0)	21.6 (0.3)	32.1 (2.2)	42.7 (0.7)	19.6 (0.3)	25.8 (1.0)
7.	*PerlColor*-T (1x) + AS	78.7 (1.4)	4.9 (0.6)	32.7 (1.7)	60.0 (1.0)	10.1 (0.7)	41.1 (0.9)
8.	*PerlColor*-P (1x) + AS	56.0 (0.9)	21.1 (0.3)	42.8 (0.7)	45.0 (1.1)	19.8 (0.4)	31.6 (1.4)
9.	*PerlColor*-L (1x) + AS	56.6 (3.3)	17.8 (0.9)	39.1 (0.6)	46.8 (0.8)	18.5 (0.4)	33.0 (0.7)
10.	*PerlColor*-T (2x) + AS	78.0 (1.6)	6.0 (0.9)	34.2 (0.8)	62.1 (0.9)	11.2 (1.3)	42.6 (1.5)
11.	*PerlColor*-P (2x) + AS	49.4 (0.3)	23.5 (0.2)	35.7 (0.1)	38.7 (1.1)	19.0 (0.4)	22.7 (1.5)
12.	*PerlColor*-L (2x) + AS	46.0 (0.2)	22.0 (0.1)	31.6 (0.4)	37.7 (1.8)	19.2 (1.3)	20.2 (2.7)

AS: *AquaStop*; pigments in the top-coat *PerlColor* layer: T = transparent, P = pine, L = larch; number of layers: (1x) = one layer; (2x) = two layers of *PerlColor*. The values represent a mean ± (SD) of 18 measurements. Wood samples with initially smooth surfaces (grinded with 120-grit sandpaper) exhibited very similar initial color components as in table present rough samples grinded with 60-grit sandpaper

PerlColor is a top-coat containing acrylate resin modified with oils, a nano-sized polyvalent metal AsS-(arsinoaryltio)-chelate complex for UV protection, hydrophobic additives, iodopropynyl butylcarbamate fungicide, and pigments on the base of iron oxides. *AquaStop* is a transparent, water-repellent, and sunblock coating containing the nano-sized metal AsS-chelate. Individual layers of both coatings were deposited with a manual low-pressure air spraying technique at 120 ± 10 g.m^{-2}. Before the other layers of coatings were applied, the previously painted samples were sanded with 240-grit sandpaper. Between consecutive coatings, the samples were dried for 24 h at 20 °C and 65% relative humidity.

Natural Weathering

Natural outdoor weathering of the wood samples took place under metal stands at a slope of 45°, oriented to the South, 300 m above sea level, according to the standard EN 927-3 (2006). The exposure field is situated in a valley of the industrial town, Zvolen, with many foggy days, smog, and high temperature differences between summer (35 °C) and winter (-25 °C). The mean climatic conditions of the testing area are listed as follows: mean temperature of 9.4 °C; relative humidity of 83%; 700 mm/year of precipitation; and 1100 kWh/m^2 of irradiation. Three replicates for each type of coating system for each wood species were exposed to weathering for 0, 6, 12, 24, and 36 months.

Color and Surface Defect Measurements

The color parameters of the individual wood samples before and after weathering (6, 12, 24, and 36 months) were measured with a CR-10 Tristimulus colorimeter using CIE Standard Illuminant D_{65} and CIE 10° Standard Observer (Konica Minolta Inc., Japan). For each type of coating system (12 total), the wood species (Norway spruce and black locust), surface roughness (rough or smooth), the color parameters were recorded from six sites, using three replicates, for a total of 18 measurements. The evaluation of color change was done using the L*a*b* color system, based on the L^*, a^*, and b^* components (CIE 1986): where L^* is the lightness from 100 (white) to 0 (black), a^* is the chromaticity coordinate (+ red; – green), and b^* is the other chromaticity coordinate (+ yellow; – blue). The total color difference of the samples, between weathered and initial state, ΔE^*, was calculated using Eq. 1:

$$\Delta E^* = \sqrt{(\Delta L^*)^2 + (\Delta a^*)^2 + (\Delta b^*)^2} \quad (1)$$

The surface quality of the painted samples during weathering (after 12, 24, and 36 months) was analyzed visually using a magnifier at 10X magnification. The aesthetic defects in the surface of the painted samples were measured according to methodology by Van Acker *et al.* (1992) (De Windt *et al.* 2014; Table 4).

Statistical Analyses

The data were analyzed using the software program, STATISTICA 12 (StatSoft CR, Czech Republic). Duncan's tests were used to compare differences in the means, and the data was tabulated using Microsoft® Excel 2013 (Redmond, WA, USA). The data are represented as the mean value and the associated standard deviation (SD).

RESULTS AND DISCUSSION

Color Stability of Painted Woods after Weathering

The color stability of painted black locust and Norway spruce was increased to a statistically significant degree because of the presence of light pine and light larch pigments in the *PerlColor* top-coat layer (Tables 2 and 3). On average, the effect of natural weathering on the total color difference, ΔE^*, of wood surfaces painted with the pigmented coating systems was approximately two times lower than those painted with transparent coats. However, it should be noted that the effect of the pigment in the top-coat was significantly influenced by the number of coats, (the effect was evidently higher for two *versus* one coat), wood species (for black locust was higher than for Norway spruce), as well as by the positive supporting effect of the final water-repellent, *AquaStop* (Table 2). The influence of the initial roughness of the wood surface before painting (rough R compared with smooth S) on the color stability of painted wood during natural weathering was not statistically significantly in most cases, regardless of the wood species, pigmentation of coatings, and the number of coats (Table 2, see Duncan's tests).

A positive effect of the light pine and light larch pigments was confirmed by Duncan's tests (Table 3, see effect No. 1), showing that the effect of pigments was more apparent after 36 months of weathering compared to 6 months of weathering. This result agrees with the previous results by Evans and Chowdhury (2010) and Grüll *et al.* (2011). An affirmative effect of pigments on the color stability of painted wood samples after 36 months of weathering was not demonstrated when only one-layer of *PerlColor* was applied; a complete degradation of transparent and also pigmented coating systems occurred when the system included *PerlColor*-T(1x), *PerlColor*-P(1x), and *PerlColor*-L(1x) (Tables 2 and 3).

An improved long-term color stability was demonstrated for both transparent and pigmented top-coats if they were applied in two layers, *i.e.*, *PerlColor*(2x). The best color stability was determined for coating systems in which two layers of pigmented *PerlColor* were combined with the final water-repellent, *AquaStop* (AS), *i.e.*, systems with *PerlColor*-P(2x) + AS and *PerlColor*-L(2x) + AS (Tables 2 and 3). A positive effect of more layers of pigmented coatings on the color stability of painted wood was manifested mainly in the final phase of outdoor weathering, after 36 months (Table 2), and it was also confirmed by the Duncan's test (Table 3, see effect No. 2).

The color stabilization effect of the final *AquaStop* layer was different for black locust compared with Norway spruce samples (Tables 2 and 3). This water-repellent layer had a statistically significant effect in stabilizing the colors of black locust wood that was previously painted with the pigmented, *PerlColor* coatings. However, a positive color stabilization effect of *AquaStop* on the Norway spruce samples was evident during the application of both the transparent and pigmented *PerlColor* coatings. These results were confirmed by Duncan's tests (Table 3, see effect No. 3).

The painted surfaces of wood treated with *AquaStop* were more resistant to defects from weathering. This water-repellent layer apparently increased the stability of the coating systems against surface defects (Table 4). Generally, this hydrophobic layer extended the durability of painted wood during weathering. This result agrees with Ghosch *et al.* (2009) and Samyn *et al.* (2014), as hydrophobic layers reduce a synergistic degradation effect of UV-radiation and water (Owen *et al.* 1993; Sudiyani *et al.* 1999).

Table 2. The Total Color Differences Δ*E** of Painted and Reference Black Locust and Norway Spruce Samples During Natural Weathering from 6 to 36 Months

Coating system / roughness	**Wood**	**Black locust**				**Norway spruce**			
		Outdoor weathering (months)				**Outdoor weathering (months)**			
		6	**12**	**24**	**36**	**6**	**12**	**24**	**36**
PerlColor - T (1x)	S	14.3 (3.2)	27.1 (4.1)	35.4 (2.2)	37.7 (2.1)	19,2 (3.2)	29,8 (3.2)	43,3 (2.2)	45,2 (2.1)
	R	19.3 (5.5)a	29.8 (5.2)c	35.8 (3.6)d	37.3 (4.2)d	25.5 (3.3)a	38.8 (2.2)a	43.8 (2.2)d	45.1 (1.8)d
PerlColor - P (1x)	S	9.6 (2.0)	16.2 (2.7)	28.7 (2.5)	33.7 (1.7)	14.9 (2.6)	22.8 (2.3)	32.0 (2.0)	37.7 (2.3)
	R	13.4 (4.2)b	18.3 (2.8)d	27.8 (2.7)d	33.5 (1.4)d	19.3 (2.2)b	27.8 (2.6)a	33.1 (2.4)d	37.1 (2.5)d
PerlColor - L (1x)	S	11.8 (2.4)	17.1 (2.5)	29.6 (4.5)	34.6 (2.6)	16.6 (5.9)	25.2 (1.4)	34.4 (2.3)	42.2 (2.0)
	R	11.1 (3.0)d	16.6 (3.1)d	29.9 (5.5)d	35.0 (3.1)d	24.2 (7.2)a	29.3 (1.9)b	35.7 (1.3)d	41.8 (1.7)d
PerlColor -T (2x)	S	11.8 (1.7)	13.7 (2.9)	24.3 (7.4)	34.7 (3.9)	13.3 (1.2)	21.6 (3.1)	32.9 (6.1)	41.9 (2.3)
	R	11.3 (3.0)d	12.9 (3.2)d	25.2 (7.9)d	36.6 (3.9)d	18.0 (3.5)a	31.1 (3.0)a	41.6 (2.8)a	45.1 (2.1)c
PerlColor - P (2x)	S	4.5 (1.9)	5.9 (2.1)	11.0 (3.0)	16.8 (2.7)	7.6 (2.0)	13.3 (4.1)	17.9 (4.8)	25.0 (5.9)
	R	5.0 (1.8)d	8.1 (3.2)d	14.8 (3.9)b	18.8 (3.1)d	9.5 (4.0)d	15.9 (4.3)d	21.3 (2.2)c	24.3 (1.1)d
PerlColor - L (2x)	S	7.4 (2.5)	8.4 (2.6)	10.3 (1.8)	15.4 (3.3)	7.3 (1.5)	13.5 (4.4)	19.8 (4.7)	25.0 (2.6)
	R	5.1 (1.9)d	6.0 (2.1)d	10.8 (3.9)d	16.8 (3.6)d	8.6 (2.1)d	17.6 (4.8)b	22.4 (3.4)d	24.0 (1.8)d
PerlColor - T (1x) + AS	S	13.8 (1.5)	18.3 (2.7)	30.1 (5.6)	38.0 (2.4)	12.1 (2.6)	16.9 (2.5)	22.8 (4.8)	38.7 (3.5)
	R	14.2 (2.8)d	17.9 (3.0)d	29.6 (6.8)d	37.6 (3.3)d	12.1 (2.2)d	20.5 (4.9)c	33.9 (8.9)a	40.6 (5.9)d
PerlColor - P (1x) + AS	S	5.8 (1.2)	7.3 (1.2)	10.0 (4.2)	22.1 (6.9)	7.4 (1.3)	11.8 (1.8)	19.5 (5.5)	31.2 (8.1)
	R	5.9 (0.7)d	7.2 (0.9)d	10.2 (2.7)d	20.4 (6.9)d	10.1 (2.3)d	16.1 (2.2)b	24.5 (4.5)a	30.7 (7.2)d
PerlColor - L (1x) + AS	S	5.7 (1.9)	7.7 (2.4)	6.8 (2.0)	10.0 (5.7)	11.7 (2.2)	16.4 (2.4)	17.6 (2.7)	27.1 (6.6)
	R	5.8 (1.4)d	7.8 (1.6)d	9.7 (4.0)c	16.7 (6.6)a	11.6 (1.9)d	17.6 (2.4)d	25.1 (4.5)a	30.9 (3.1)b
PerlColor - T (2x) + AS	S	16.7 (1.9)	18.6 (2.4)	24.4 (4.4)	38.0 (3.5)	12.9 (1.6)	17.4 (1.7)	18.9 (2.4)	31.1 (6.8)
	R	16.0 (2.1)d	17.9 (2.3)d	22.0 (4.2)d	34.3 (4.3)b	13.9 (1.2)d	19.0 (1.3)d	26.9 (6.3)a	39.2 (5.7)a
PerlColor - P (2x) + AS	S	4.6 (2.7)	6.4 (3.4)	5.4 (3.0)	4.6 (3.4)	7.5 (1.6)	11.1 (1.2)	12.1 (1.8)	17.0 (4.0)
	R	5.8 (3.5)d	7.6 (3.5)d	7.7 (4.4)d	6.9 (5.1)d	6.6 (1.9)d	10.9 (1.8)d	14.8 (2.4)d	21.3 (2.8)b
PerlColor - L (2x) + AS	S	3.5 (1.1)	5.0 (1.6)	4.3 (1.3)	2.2 (1.2)	8.7 (1.9)	12.7 (1.8)	13.4 (2.0)	14.1 (3.4)
	R	3.2 (1.5)d	4.6 (1.8)d	4.2 (1.9)d	3.1 (2.1)d	8.4 (1.3)d	13.1 (1.5)d	16.4 (2.6)c	22.0 (4.8)a
Reference	S	14.1 (5.3)	20.3 (1.6)	19.6 (2.3)	22.7 (2.3)	18,6 (1.6)	31,6 (3.2)	41,1 (1.6)	44,1 (2.3)
	R	12.8 (1.2)d	22.3 (1.4)d	26.7 (2.3)a	29.1 (5.0)a	20.0 (1.5)d	34.1 (3.2)d	40.7 (1.6)d	42.6 (1.4)d

S: smooth; R: rough; AS: *AquaStop*. Values represent a mean of 18 measurements with the associated standard deviation in parentheses. Duncan's tests (effect of initial roughness of wood) were evaluated at the (a) 99.9% significance level, (b) 99% significance level, and (c) 95% significance level; when no significant difference was detected at the $P < 0.05$ significance level, values were assigned (d)

Table 3. Duncan's Test of the Total Color Differences ΔE^{*} of the Norway Spruce (*Picea abies*) and Black Locust *(Robinia pseudoacacia)*

a) 6th Month

Coating system	Transparent								Pine-pigmented								Larch-pigmented							
	Norway spruce				Black locust				Norway spruce				Black locust				Norway spruce				Black locust			
Effect No.	**1**	**2**	**3**	**4**	**1**	**2**	**3**	**4**	**1**	**2**	**3**	**4**	**1**	**2**	**3**	**4**	**1**	**2**	**3**	**4**	**1**	**2**	**3**	**4**
PerlColor (1x)	-	-	-	-	-	-	-	a	b	-	-	-	a	-	-	a	d	-	-	-	d	-	-	a
PerlColor (2x)	-	a	-	-	-	d	-	d	a	a	-	-	a	a	-	c	a	a	-	-	b	b	-	d
PerlColor (1x) + AS	-	-	a	-	-	-	d	d	a	-	a	-	a	-	b	d	d	-	d	-	a	-	a	a
PerlColor (2x) + AS	-	d	d	-	-	c	a	b	a	d	d	-	a	d	d	c	b	c	d	-	a	d	b	a
Reference	-	-	-	-	-	-	-	a	-	-	-	-	-	-	-	a	-	-	-	-	-	-	-	a

b) 36th Month

Coating system	Transparent								Pine-pigmented								Larch-pigmented							
	Norway spruce				Black locust				Norway spruce				Black locust				Norway spruce				Black locust			
Effect No.	**1**	**2**	**3**	**4**	**1**	**2**	**3**	**4**	**1**	**2**	**3**	**4**	**1**	**2**	**3**	**4**	**1**	**2**	**3**	**4**	**1**	**2**	**3**	**4**
PerlColor (1x)	-	-	-	-	-	-	-	a	a	-	-	-	b	-	-	b	c	-	-	-	c	-	-	a
PerlColor (2x)	-	a	-	-	-	c	-	a	a	a	-	-	a	a	-	a	a	a	-	-	a	a	-	a
PerlColor (1x) + AS	-	-	a	-	-	-	d	d	a	-	a	-	a	-	a	a	a	-	a	-	a	-	a	a
PerlColor (2x) + AS	-	a	a	-	-	d	c	a	a	a	a	-	a	a	a	a	a	a	a	-	a	a	a	a
Reference	-	-	-	-	-	-	-	a	-	-	-	-	-	-	-	a	-	-	-	-	-	-	-	a

a): smooth samples/ 6th month of weathering; b): smooth samples/ 36th month of weathering. Evaluated Effects: (No. 1) Presence of Pigment in Paints, *i.e.,* Pigmented *versus* Transparent; (No. 2) Number of PerlColor Layers, *i.e.*, 2-layers *versus* 1-layer; (No. 3) Using of Final AquaStop, *i.e.*, Use *versus* Non Use; and (No. 4) Wood Species, *i.e.,* Black Locust *versus* Norway Spruce. Values represent a mean of 18 measurements with the associated standard deviation in parentheses. Duncan´s tests for effects No. 1 to No. 4: (a) 99.9% significance level, (b) 99% significance level, (c) 95% significance level; when no significant difference was detected at the $P < 0.05$ significance level, values were assigned (d)

Out of the two wood species, the black locust was a better substrate for maintaining the original color of painted samples during natural weathering; *e.g.*, after 36 months, the total color difference (ΔE^{*}) ranged from 2.2 to 38.0 and 14.1 to 45.2 for painted black locust and Norway spruce samples, respectively (Table 2). Results were confirmed using Duncan's test (Table 3, see effect No. 4).

The influence of the duration of outdoor weathering on the color stability of painted woods was also shown in this work. Results from the Duncan's tests showed a higher statistical influence of all coating system effects, No. 1 through No. 4, for the 36th month compared with the 6th month of weathering (Table 3).

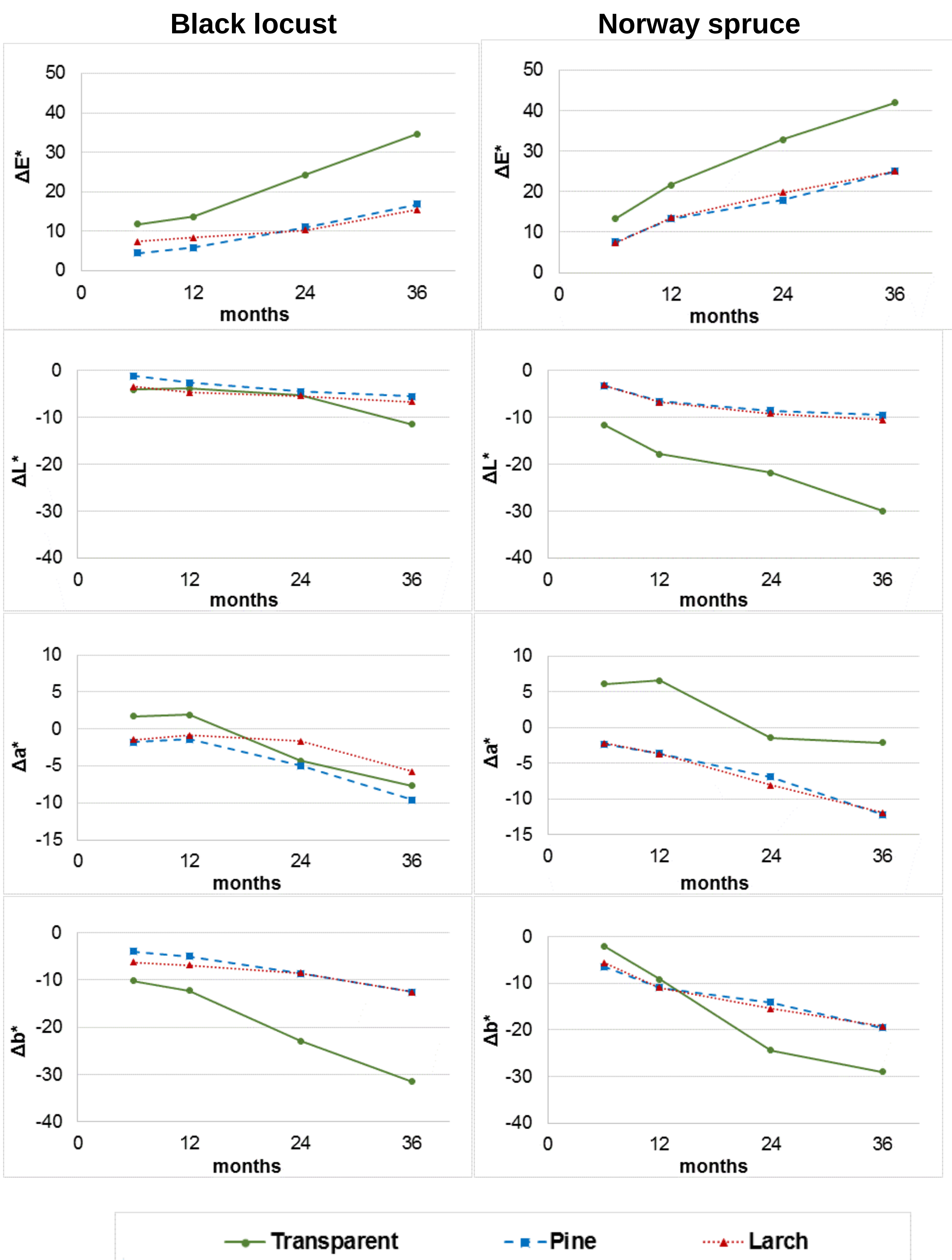

Fig. 1. Changes in the color parameters, Δ*L**, Δ*a**, Δ*b**, and Δ*E** for smooth wood samples treated with two layers of *PerlColor*(2x) during outdoor weathering from 6 to 36 months.
Note: The other types of coating systems (see Table 2) painted on the smooth or rough wood surfaces obtained similar color changes in ΔL, Δa*, Δb*, and their total color difference, ΔE*, is presented in Table 2*

In summary, wooden structures, exposed to exterior weathering, required painting with a coating systems that had enough thickness, because during outdoor exposure the coatings are gradually degraded (Masaryková *et al.* 2010; Grüll *et al*. 2014). Clearly, the positive influence of more layers of coating on the color stability, *i.e*., two layers of *PerlColor* or two layers of *PerlColor* combined with one final layer of *AquaStop*, was found to be beneficial in this work. The coating thickness was more important for the color stability at the end of age testing (after 36 months), independent of wood species (Table 3, see effects No. 2 and No. 3).

The color stability results of painted wood are shown according to changes in the individual color components, ΔL^*, Δa^*, and Δb^*, and their influence on the total color difference of painted and weathered woods. Changes in ΔL^*, Δa^*, and Δb^*, together with ΔE^* for painted black locust and Norway spruce samples, are shown for one selected type of coating system, *i.e*., the *PerlColor*(2x) (Fig. 1).

Surfaces of both wood species, painted with the other eleven types of coating systems, exhibited similar trends in color change during weathering. In all cases, the influence of ΔL^* and Δb^* on the total color difference $\Delta E^*$of wood painted with the transparent coatings was observed. Because of a slight UV-inhibition effect of transparent coatings for the lignin degradation in wood surfaces (Hon and Chang 1984; Teacà *et al.* 2013), and the penetration of dust particles into surface layers of damaged coatings (Evans 2008), there in this experiment was a darkening (decrease of L^* after ageing), bluing (decrease of b^*), and transition from reddening to greening (firstly increase and then decrease of a^*) occurrence to the wood (Fig. 1). When using transparent coatings, the darkening was manifested more significantly for the Norway spruce, which in a native state is lighter than the black locust; while changes of the chromaticity coordinates (a^*; b^*) were quite similar for both painted wood species (Fig. 1).

Surface Defects in Painted Woods during Weathering

Similar to the color stabilization effects, more layers of coating resulted in the best suppression of surface defects in painted wood during natural weathering (Table 4). A positive influence of the coating thickness was very important, especially after 12 months when compared with 2 to 3 years (Table 4).

A visual assessment of the defects created on painted surfaces showed a higher resistance when the coating systems were applied to black locust wood, especially for the pigmented coatings. The best coating systems were *PerlColor*-P(2x) and *PerlColor*-L(2x), in combination with the final, water-repellent layer, *AquaStop* (Table 4). A possible explanation that there was a more significant worsening of adhesion from the coatings on Norway spruce wood, which has a different anatomical and chemical structure than black locust wood. Another explanation is in the kinetics of water sorption, because spruce wood has a faster sorption and desorption of water, and therefore also a worse dimensional stability in comparison to black locust wood in wet conditions as was shown by Van Acker *et al.* (2014). However, these explanations are only hypotheses because tests of adhesion before and during weathering were not conducted in this experiment. Generally, a longer weathering duration caused more intensive destruction of the coatings (Table 4).

For both of the wood species, a positive effect of a finer grinding method (smooth initial surface), to measure of visual defects formed during outdoor exposure, was confirmed. Unlike results of color fastness evaluations usually carried out independently on different initial wood roughness, this result confirmed the effect of superior surface quality of wood for a longer period of coating quality, in accordance with Scrinzi *et al.* (2011) and Slabejová *et al.* (2014).

Table 4. Visual Rating of Defects on Painted Smooth or Rough Black Locust and Norway Spruce Woods after Natural Weathering

Coating system	**Outdoor weathering (months)**					
	12		**24**		**36**	
	Black locust wood					
	Smooth	Rough	Smooth	Rough	Smooth	Rough
PerlColor-T (1x)	10	10	10	10	10	10
PerlColor-P 1x)	6	6	10	10	10	10
PerlColor-L (1x)	6	7	9	9	10	10
PerlColor-T (2x)	6	6	7	10	10	10
PerlColor-P (2x)	3	4	6	8	8	9
PerlColor-L(2x)	2	4	5	7	8	9
PerlColor-T (1x) + *AquaStop*	6	6	8	9	10	10
PerlColor-P (1x) + *AquaStop*	2	4	6	8	10	10
PerlColor-L (1x) + *AquaStop*	2	4	4	6	8	9
PerlColor-T (2x) + *AquaStop*	4	5	6	6	10	10
PerlColor-P (2x) + *AquaStop*	2	2	3	3	4	5
PerlColor-L (2x) + *AquaStop*	2	2	3	3	4	5

Coating system	**Outdoor weathering (months)**					
	12		**24**		**36**	
	Norway spruce wood					
	Smooth	Rough	Smooth	Rough	Smooth	Rough
PerlColor-T (1x)	10	10	10	10	10	10
PerlColor-P (1x)	5	7	7	8	10	10
PerlColor-L (1x)	5	7	8	9	10	10
PerlColor-T (2x)	7	10	10	10	10	10
PerlColor-P (2x)	4	6	8	9	9	9
PerlColor-L (2x)	4	7	7	9	8	9
PerlColor-T (1x) + *AquaStop*	4	5	9	10	10	10
PerlColor-P (1x) + *AquaStop*	2	4	8	9	10	10
PerlColor-L (1x) + *AquaStop*	2	5	6	8	8	9
PerlColor-T (2x) + *AquaStop*	4	6	7	8	10	10
PerlColor-P (2x) + *AquaStop*	2	3	4	6	8	9
PerlColor-L (2x) + *Aqua Stop*	2	3	4	7	7	9

Values represent a mean of 6 replicates. The evaluation was based on the level of degradation: *i.e*., 0=none; 2=small aesthetical changes; 4=mild (easy to retreat); 6=moderate (maintainable); 8=striking (maintenance is difficult); 10=advanced (maintenance coat cannot restore the defects). De Windt *et al*. (2014)

Generally, the pigmented coating systems were, to a statistically significant degree, more resistant against surface defects than transparent ones, regardless of the wood species. This result, together with a better color stability of wood painted with pigmented coatings, meant that the use of light pigments in coatings is ideal for their application in harsh outdoor conditions that require the longest possible lifespan (Tables 2 and 4).

CONCLUSIONS

1. Smaller color changes and less important surface defects in painted wood surfaces were observed when using more layers of coating. This also included coating systems containing light pine or light larch pigments.
2. Color stability and resistance to surface defects was higher when the coating systems were applied on the black locust wood compared with Norway spruce wood.
3. The color stability of the coatings was not usually influenced by a different initial roughness of the wood; however, on rougher woods the creation of more important surface defects on paintings was visually observed during weathering.
4. A positive effect of the final water-repellent, *AquaStop*, layer in the coating systems improved the color stability and durability of painted woods, primarily in combination with pigmented top-coats.
5. A sufficient time for exterior testing of coating systems is necessary, for example 1 or 3 years. Six months of outdoor ageing was generally not enough time for an accurate comparison of different wood factors, *e.g.*, wood species and wood roughness, and different coating factors, *e.g.*, pigment in coatings, number of coats, and the use of water-repellent layer, on the color stability and long-term quality of coatings on painted woods.

ACKNOWLEDGMENTS

This work was supported by the Slovak Research and Development Agency under the contract No. APVV-0200-12, and by the Grant Agency of the Faculty of Forestry and Wood Sciences in Prague, Projects No. A07/15 and A31/16. The authors would also like to thank Ms. S. Bagócsiová for her technical assistance.

REFERENCES CITED

Alfredsen, G., Flæte, P. O., and Evans, F. G. (2007). "Comparison of four methods for natural durability classification," in: *Workshop COST Action E37*, Braşov, Romania, pg. 23.

CIE (1986). *Colorimetry*, 2nd Ed., Commission Internationale de l'Eclairage, Vienna, Austria, pg. 74.

Creemers, J., De Meijer, M., Zimmermann, T., and Sell, J. (2002). "Influence of climatic factors on the weathering of coat wood," *Holz als Roh-und Werkstoff* 60(6), 411-420. DOI: 10.1007/s00107-002-0338-5

De Meier, M. (2001). "Review on the durability of exterior wood coatings with reduced VOC-content," *Progress in Organic Coatings* 43(4), 217-225. DOI: 10.1016/S0300-9440(01)00170-9

De Windt, I., Van den Bulcke, J., Wuijtens, I., Coppens, H., and Van Acker, J. (2014).

"Outdoor weathering performance parameters of exterior wood coating systems on tropical hardwood substrates," *European Journal of Wood and Wood Products* 72(2), 261-272. DOI: 10.1007/s00107-014-0779-7

EN 350-2 (1997). "Durability of wood and wood-based products - Natural durability of solid wood. Part 2: Guide to natural durability and treatability of selected wood species of importance in Europe," European Committee for Standardization (CEN), Brussels, Belgium.

EN 927-3 (2006). "Paints and varnishes - Coating materials and coating system for exterior wood - Part 3: Natural weathering test," European Committee for Standardization (CEN), Brussels, Belgium.

Evans, P. D. (2008). "Weathering and photoprotection of wood," *ACS Symposium Series* 982, 69-117.

Evans, P. D., and Chowdhury, M. J. (2010). "Photostabilization of wood with higher molecular weight UV absorbers," in: *41st Annual Meeting of the International Research Group on Wood Protection*, Biarritz, France, IRG/WP 10-30524.

Feist, W. C. (1982). "Weathering of wood in structural uses," in: *Structural Use of Wood in Adverse Environments*, Meyer, R. W., and Kellong, R. M. (eds.),Van Nostrand Reinhold, New York, pp. 156-178.

Feist, W. C. (1990). *Outdoor Wood Weathering and Protection*, Advances in Chemistry Series 225, Washington DC, USA, pp. 263-298.

Forsthuber, B., Schaller, C., and Grüll, G. (2013). "Evaluation of the photostabilizing efficiency of clear coatings comprising organic UV absorbers and mineral UV screeners on wood surfaces," *Wood Science and Technology* 47(2), 281-297. DOI: 10.1007/s00226-012-0487-6

Ghosch, S. C., Militz, H., and Mai, C. (2009). "Natural weathering of Scots pine (*Pinus sylvestris* L.) boards modified with functionalised commercial silicone emulsions," *BioResources* 4(2), 659-673. DOI: 10.15376/biores.4.2.659-673

Gobakken, L. R., and Lebow, P. K. (2010). "Modelling mould growth on coated modified and unmodified wood substrates exposed outdoors," *Wood Science and Technology* 44(2), 315-333. DOI: 10.1007/s00226-009-0283-0

Grüll, G., Truskaller, M., Podgorski, L., Bollmus, S., and Tscherne, F. (2011). "Maintenance procedures and definition of limit states for exterior wood coatings," *European Journal of Wood and Wood Products* 69(3), 443-450. DOI: 10.1007/s00107-010-0469-z

Grüll, G., Tscherne, F., Spitaler, I., and Forsthuber, B. (2014). "Comparison of wood coating durability in natural weathering and artificial weathering using florescent UV-lamps and water," *European Journal of Wood and Wood Prod*ucts 72(3), 367-376. DOI: 10.1007/s00107-014-0791-y

Hon, D. N.-S., and Chang, S.-T. (1984). "Surface degradation of wood by ultraviolet light," *Journal of Polymer Science Part A: Polymer Chemistry* 22(9), 2227-2241. DOI: 10.1002/pol.1984.170220923

Hon, D. N.-S., and Feist, W. C. (1986). "Weathering characteristics of hardwood surfaces," *Wood Science & Technology* 20(2), 169-183. DOI: 10.1007/BF00351028

ISO 7724 (1984). "Paints and varnishes-colorimetry. Part 1: Principles," International Organization for Standardization, Geneva, Switzerland.

Masaryková, M., Pánek, M., and Reinprecht, L. (2010). "Micro-structural analysis of coatings with nanoscale particles after ageing in Xenotest," in: *Wood Structure and*

Properties, Lagaňa, R., and Kúdela, J. (eds.), Arbora Publishers, Zvolen, Slovakia, pp. 209-216.

Oltean, L., Teischinger, A., and Hansmann, C. (2010). "Visual classification of the wood surface discolouration due to artificial exposure to UV light irradiation of several European wood species - a pilot study," *Wood Research* 55(3), 37-48.

Owen, J. A., Owen, N. L., and Feist, W. C. (1993). "Scanning electron microscope and infrared studies of weathering in Southern pine," *Journal of Molecular Structure* 300, 105-114. DOI: 10.1016/0022-2860(93)87010-7

Ozdemir, T., and Hiziroglu, S. (2009). "Influence of surface roughness and species on bond strength between the wood and the finish," *Forest Products Journal* 59(6), 90-94.

Ozgenc, O., Hiziroglu, S., and Yildiz, U. C. (2012). "Weathering properties of wood species treated with different coating applications," *BioResources* 7(4), 4875-4888. DOI: 10.15376/biores.7.4.4875-4888

Pánek, M., and Reinprecht, L. (2008). "Bio-treatment of spruce wood for improving its permeability and soaking. Part 1 - Direct treatment with the bacterium *Bacillus subtilis*," *Wood Research* 53(2), 1-12.

Pánek, M., and Reinprecht, L. (2014). "Colour stability and surface defects of naturally aged wood treated with transparent paints for exterior constructions," *Wood Research* 59(3), 421-430.

Reinprecht, L., and Pánek, M. (2013). "Vplyv pigmentov v náteroch na prirodzené a urýchlené starnutie povrchov smrekového dreva [Effect of pigments in paints on the natural and accelerated ageing of spruce wood surfaces]," *Acta Facultatis Xylologiae Zvolen* 55(1), 71-84.

Reinprecht, L., and Pánek, M. (2015). "Effects of wood roughness, light pigments, and water repellent on the color stability of painted spruce subjected to natural and accelerated weathering," *BioResources* 10(4), 7203-7219. DOI: 10.15376/biores.10.4.7203-7219

Samyn, P., Stassens, D., Paredes, A., and Becker, G. (2014). "Performance of organic nanoparticle coatings for hydrophobization of hardwood surfaces," *Journal of Coating Technology and Research* 11(3), 461-471. DOI: 10.1007/s11998-014-9576-9

Sandak, J., Sandak, A., Pauliny, D., Riggio, M., Bonfa, S., and Meglioli, S. (2013). "A multi sensor approach for prediction of weathering effects on exposed timber structures," *Advanced Materials Research* 778, 794-801. DOI: 10.4028/www.scientific.net/AMR.778.794

Sandak, A., Sandak, J., Burud, I., Csiha, C., and Noel, M. (2015). "Degradation kinetics of the short term weathered thin wood samples," in: *Advances in Modification and Functional Bio-based Surfaces COST Action FP1006*, Thessaloniki, Greece, pp. 84-86.

Scrinzi, E., Rossi, S., Deflorian, F., and Zanella, C. (2011). "Evaluation of aesthetic durability of waterborne polyurethane coatings applied on wood for interior applications," *Progress in Organic Coatings* 72(1-2), 81-87. DOI: 10.1016/j.porgcoat.2011.03.013

Slabejová, G., Fekiač, J., and Pánek, M. (2014). "Vplyv vybraných faktorov na zmenu farby transparentných povrchových úprav bukového dreva, [Influence of selected

factors on colour change of the transparent finishes at beech wood],” *Acta Facultatis Xylologiae Zvolen* 56(1), 23-30.
Sudiyani, Y., Tsujiyama, S., Imamura, Y., Takahashi, M., Minato, K., and Kajita, H. (1999). “Chemical characteristics of surfaces of hardwood and softwood deteriorated by weathering,” *Journal of Wood Science* 45(4), 348-353. DOI: 10.1007/BF00833502
Syvrikaya, H., Hafizoglu, H., Yasav, A., and Aydemir, D. (2011). “Natural weathering of oak (*Quercus petrae*) and chestnut (*Castanea sativa*) coated with various finishes,” *Color Research and Application* 36(1), 72-78. DOI: 10.1002/col.20581
Teacà, C. A., Rosu, D., Bodîrlàu, R., and Rosu, L. (2013). “Structural changes in wood under artificial UV light irradiation by FTIR spectroscopy and color measurements - A brief review,” *BioResources* 8(1), 1478-1507. DOI: 10.15376/biores.8.1.1478-1507
Tesařová, D., Chladil, J., Čech, P., and Tobiášová, K. (2010). Ekologické Povrchové Úpravy [Ecology Finishes], Monography MZLU, Brno, Czech Republic.
Usta, I. (2005). “A review of the configuration of bordered pits to stimulate the fluid flow,” in: *36th Annual Meeting of the International Research Group on Wood Protection*, Bangalore, India, IRG/WP 05-40315.
Valverde, J. C., and Moya, R. (2014). “Correlation and modeling between color variation and quality of the surface between accelerated and natural tropical weathering in *Acacia mangium*, *Cedrela odorata* and *Tectona grandis* wood with two coating,” *Color Research and Applications* 39(5), 519-529. DOI: 10.1002/col.21826
Van Acker, J., De Windt, I., Li, W., and Van den Bulcke, J. (2014). “Critical parameters on moisture dynamics in relation to time of wetness as factor in service life prediction,” in: *45th Annual Meeting of the International Research Group on Wood Protection*, St George, USA, IRG/WP 14–20555.
Van Acker, J., Stevens, M., and Nys, M. (1992). “Xenon simulation of natural weathering of external joinery preserving - Finishing systems,” *Proceedings from the 23rd Annual Meeting of the International Research Group on Wood Preservation*, IRG/WP 92–2412, pg. 13.
Van Acker, J., Stevens, M., Carey, J., Siera-Alvarez, R., Militz, H., Le Bayon, I., Kleist, G., and Peek, R. D. (2003). “Biological durability of wood in relation to end-use. Part 1. Towards a European standard for laboratory testing of the biological durability of wood,” *Holz als Roh-und Werkstoff* 61(1), 35-45. DOI: 10.1007/s00107-002-0351-8

Article submitted: February 3, 2016; Peer review completed: March 4, 2016; Revised version received: March 23, 2016; Accepted: April 1, 2016; Published: April 12, 2016.
DOI: 10.15376/biores.11.2.4663-4676