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INFLUENCE OF WOOD PRE-WEATHERING ON SELECTED SURFACE PROPERTIES OF THE SYSTEM WOOD – COATING FILM

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ABSTRACT

Treatment of wood surfaces with various finish coating materials is recommended for long term protection of wood products exposed outdoor. Due to natural weathering, the colour and the surface roughness of uncoated wood is changed. However, in practice it can happen that wood in constructions has been weathered prior to application of a finish. In this work, selected properties of pine wood surface such as colour, surface roughness and stability of coating film were investigated. The surfaces of previous naturally weathered sapwood and heartwood of pine (*Pinus sylvestris*, L.) were tested. Two coating materials useable for wooden constructions in exterior conditions were used: dark brown polyurethane-based system and light brown oil-based surface treatment. Experiments showed that the dark brown polyurethane-based system made all the wood surface uniform in colour. It homogenized the surface colour as well as the differences in roughness which occurred as a result of pre-weathering. The light brown oil-based surface treatment did not sufficiently outweigh the colour changes and nor the surface roughness which arose as a result of pre-weathering of wood. The results of pull-off test for adhesion showed that the polyurethane coating film had the weakest point in the pre-weathered layer of wood substrate and also at the wood/coating interface. The oil-based surface treatment had the weakest place inside the coating film or in the coating penetration layer in the wood substrate. Pre-weathering did not significantly affect the pull-off strength of the system wood-coating film.

Key words: pine, heartwood, sapwood, weathering, coating, colour, roughness, adhesion.

INTRODUCTION

Weathering is wood surface degradation initiated primarily by solar radiation, but other factors can also be important (EVANS 2012). Wood can be allowed to weather naturally to achieve a grey patina. The service life of wood used in constructions and the maintenance of its natural appearance can be improved by well-designed construction systems, by using durable wood species and composite materials, and also by applying suitable preservatives and anti-weathering coatings (PÁNEK – REINPRECHT 2014). The research and development of effective and safe wood surface coatings with minimal use of harmful chemicals has become very important (MIKLEČIĆ *et al.* 2017).

Simultaneously with the primary change in colour of the untreated wood surface, also the surface roughness is changing due to the external fibres release; and the wood surface can slowly erode. Numerous studies have demonstrated that the properties mentioned above are significantly changed due to natural weathering (KERBER *et. al.* 2016; OBERHOFNEROVÁ – PÁNEK 2016; SANDAK *et al.* 2015; EVANS 2012; REINPRECHT *et. al.* 2011, MAMOŇOVÁ – REINPRECHT 2008; EVANTS *et al.* 1996).

Wood construction and decorative materials such as cladding, decking, furniture, parquetry and joinery are mainly finished with coating materials. To ensure the long term durability, wood is usually coated with various decorative and protective finishes such as opaque paints and semi-transparent stains as well as penetrating finishes or film-forming clear varnishes (GEORGE *et al.* 2005). Nowadays, polyurethane, oil, alkyd, acrylic and water-based coating materials belong to the most common surface treatments. Effects of the components of polyurethane coating on the adhesion of the coating films on wood were studied by DELPECH – COUTINHO (2000) and JAIC – ZIVANOVIC (1997). The influence of early/latewood, wood moisture content as well as machining process and surface pre-treatment has been researched in several works (COOL – HERNÁNDEZ 2016; UGULINO – HERNÁNDEZ 2016; TOLVAJ *et al.* 2014; PODGORSKI *et al.* 2010; DE MEIJER – MILITZ 1998).

In common coating processes, it is necessary to prepare the wood surface effectively and properly. Generally, weather-aged wood is grinded or sanded to remove degraded surface layers. The prepared surface should be coated. However, in special cases, wood is exposed to weather only for a few days and its surface was not grinded or sanded before coating. The effect of pre-weathering of wood (weathering of wood prior to finishing) on subsequent finishing with coating materials has been analysed in some studies (JIROUŠ-RAJKOVIČ *et al.* 2007; WILLIAMS *et al.* 2002; WILLIAMS – FEIST 2001; EVANTS *et al.* 1996; KLEIVE 1986; UNDERHAUG *et al.* 1983). The pre-weathering before finishing can cause chemical and physical changes on the wood surface that can influence its wettability and adhesion properties.

In this study, pine wood (*Pinus sylvestris*, L.) – sapwood and heartwood – samples were exposed to natural weathering for 30 and 90 days. The aim was to determine whether there is a significant change in colour and roughness at wood surfaces exposed outdoors under winter conditions. Further, the overlap of colour changes and the stability (adhesion) of polyurethane-based system and oil-based surface treatment was studied if applied to pre-weathered surfaces.

MATERIAL AND METHODS

Weathering of wood

Sapwood and heartwood samples of Scots pine (*Pinus sylvestris* L.) were prepared (Tab. 1). The average moisture content of air-conditioned samples was 14 ± 2%. All surfaces of testing samples were grinded with a sandpaper (gradually with grain size number 60, 80 and 120) using the belt grinder machine. The side surfaces of the samples were treated with silicone.

The samples were exposed natural weathering, fixed on metal stands at 45° slope oriented to the South, outside the Technical University in Zvolen, Slovakia, at ca. 300 m above sea level. Weathering lasted 30 and 90 days from December 2015 to March 2016. Non-weathered samples were packed in aluminium foil and stored indoor.

Tab. 1 Wood weathering set-up

Species	Dimensions [mm]	Duration [day]	Number
Pine – sapwood Pine – heartwood	150 × 74 × 16 (L × R × T)	30 90	5

Surface treatment and its application

Two different exterior surface treatments were used in this study:

1. Polyurethane-based system (Pullex Top Lasur) with coating materials:
   - Basic impregnating solvent coating material (Pullex Impragnier – Grund) – impregnating material for wood protection to the exterior with biocides content – provides protection against smearing, wood-burning fungi and insects. The samples were painted with one layer.
   - Top polyurethane coating material (Pullex Top Lasur) – thin film dark brown stain paint that provides long-term protection against weathering. The samples were painted with two layers.
2. Oil-based surface treatment with one coating material (Pullex Bodenol) – slight brown pigmented oil that protects the deciduous and coniferous wood in exterior against moisture and spotting. The samples were painted with two layers.

Both surface treatments were applied as recommended by producers in the technical documents. The surface of weathered samples (150 × 74 mm) was not sanded before coating. All samples were painted with two layers of a top coat. The average thickness of the coating films was 60 μm.

Colour analysis

Colours of the wood surfaces were analysed according to the CIE $L^*a^*b^*$ colour system using the Colour Reader CR-10 (Konica Minolta, Japan). This device works based on a D65 light source by simulating the daylight; its sensor head is 8 mm in a diameter.

In the native state, after weathering and after coating, the colour coordinates L^* (darkness: black (0) – white (100), a^* (– green, + red), and b^* (– blue, + yellow) of each sample were measured in five places. Measurements were performed on all samples conditioned in room at the temperature of 20 ± 2 °C and a relative air humidity of 60 ± 5 % for 24 hours.

Values of L^*, a^* and b^* were used for calculation of the total colour change ΔE^* according to the Eq. 1:

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

where: $\Delta L^* = L^*_2 - L^*_1$, $\Delta a^* = a^*_2 - a^*_1$, $\Delta b^* = b^*_2 - b^*_1$ (index 2 – value after weathering or coating, index 1 – value before weathering or coating).

Surface roughness

Before and after weathering and applying a coating material, the specimens were conditioned in a room with a temperature of 20 ± 2 ºC and a relative air humidity of 60 ± 5 % for 24 hours. Subsequently, the surface roughness was measured in the parallel and perpendicular directions to the wood grain. The arithmetic mean deviation of the profile R_a [μm] was measured using the contact profilometer POCKET SURF (tip radius of 0.005 mm) on the length of 0.8 mm in ten points.

Pull-off test for adhesion

Adhesion of coating films to weathered and non-weathered surfaces was evaluated by pull-off test according to the standard STN EN ISO 4624 Paints and varnishes. Pull-off test for adhesion. The testing machine PosiTest AT-M (Qualitest, Canada) was used. Small 20 mm diameter dollies were glued to the coating film using two-component epoxy resin (Pattex Repair Epoxy). After 24 h of curing at 20 °C and a relative air humidity of 60 %, perimeters of glued dollies were carefully incised to prevent propagation of failures out the tested area. Pulling was applied at a rate of 1 mm/min up to separation of the dolly from the surface. The disruption was also evaluated visually using a table magnifying glass.

Classification of failure location (wood – coating film – glue joint – metal dolly) from the pull-off strength test is shown in Fig. 1.

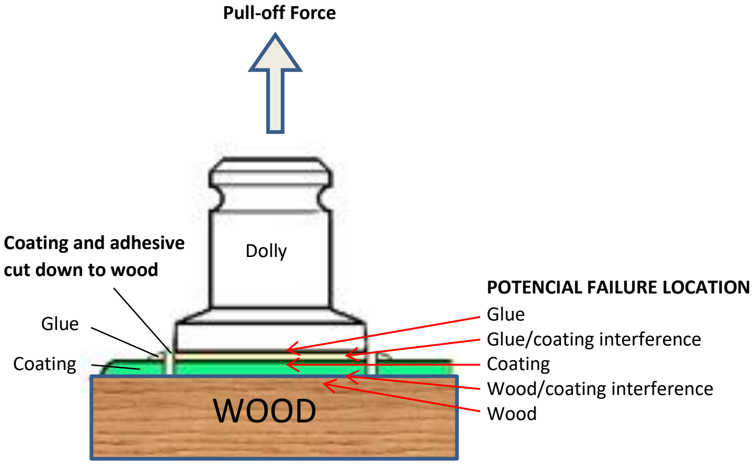


Fig. 1 Classification of failure location for the Pull-off strength test.

Statistical Analyses

The data were evaluated using the software STATISTICA 12 (StatSoft CR, Czech Republic). Analysis of variance test (with α significance value of 0.05) was used to compare differences in the mean. The data are presented as the mean value and the standard deviation (SD).

RESULTS AND DISCUSSION

Colour changes

The average values of colour parameters (the CIE $L^*a^*b^*$) of non-weathered, weathered and painted pine samples are summarised in Tab. 2.

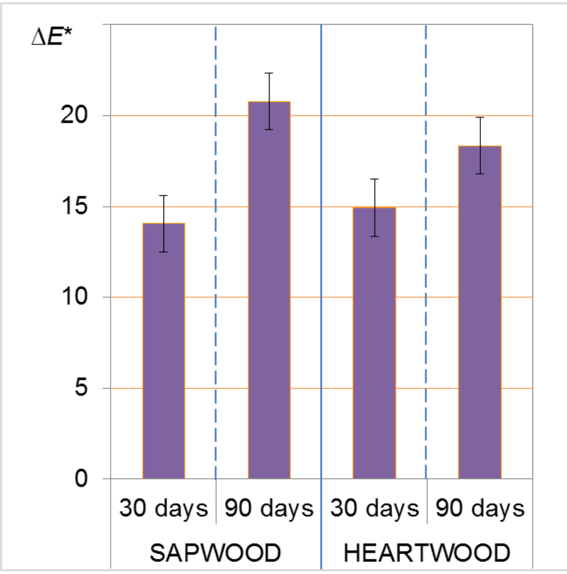
It was found that the largest changes in total colour ΔE^* occurred after the first 30 days of exposure (Fig. 2a). The colour change on the wood surface was visible with the naked eye. The L^* was the most sensitive parameter for wood surface colour change. During the weathering, the wood surface became darker – the L^* coordinate value was reduced (Fig. 2b). The darkening ranged from *ca.* 17% up to *ca.* 25%. Findings in this work agree with those reported by RUTHER – JELLE (2013) and OBERHOFNEROVÁ – PÁNEK (2016). The average a^* value of sapwood was reduced, but it remained positive (red colour). In the case of heartwood, the value of a^* was slightly increased (after 30 days) and subsequently it was significantly decreased (after 90 days), but it remained positive (red colour). The average value of the coordinate b^* on both sapwood and heartwood also increased slightly after 30 days of weathering. After 90 days of aging, it was again reduced at both sapwood and heartwood (it remained positive – red colour). Thus, the wood surfaces had a tendency to grey.

The colour of wood is a very important aesthetical property, and the chemical components of the wood structure have a fundamental influence on the colour (CSANÁDY *et al*. 2015). Changing colour of wood exposed to weather conditions is considered as the first indicator of photochemical reactions in wood components (KERBER *et al.* 2016). These reactions occur relatively quickly and they are mainly caused by the influence of sunlight. Our results have confirmed that the largest colour changes occur during the first 30 days of exposure. Only slight differences in changes of values at the coordinates a^* and *b** between the sapwood and the heartwood were observed. This can be caused by different chemical components of the sap and heart zones of the wood. Subsequent changes in the colour of weathered wood (for 90 days) from light-grey to dark-grey shades are explained by AYADI *et al.* (2003) as a result of impregnation or adsorption of dust and grime from the air and concurrent leaching of oxidized lignin by rain water.

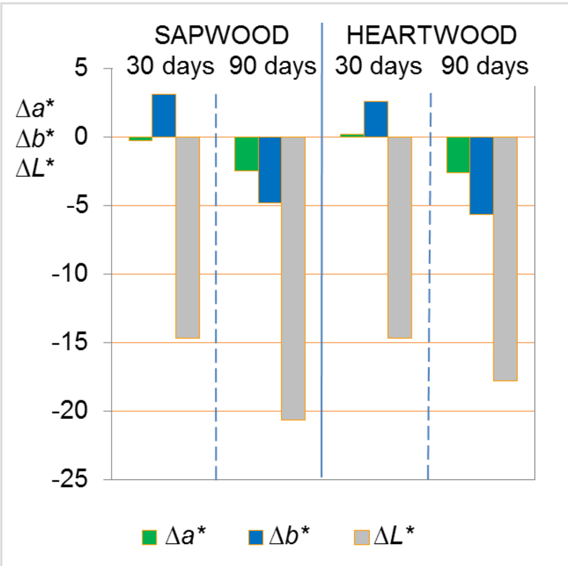
Tab. 2 CIE L*a*b* of non-weathered, weathered and painted pine samples.

	Non-weathered				Weathered for 30 days				Weathered for 90 days			
	n	*L**	*a**	*b**	n	*L**	*a**	*b**	n	*L**	*a**	*b**
Unpainted												
Sapwood	90	81.58	4.86	20.52	20	67.50	4.41	24.96	20	61.21	2.29	17.01
		(1.67)	(1.11)	(4.85)		(3.41)	(1.22)	(7.94)		(2.15)	(0.92)	(2.69)
Heartwood	90	77.90	7.30	23.18	20	63.23	7.72	25. 66	20	60.84	4.40	17.19
		(1.66)	(1.23)	(1.56)		(4.00)	(1.76)	(2.14)		(2.72)	(2.25)	(2.69)
Painted with polyurethane-based system (Pullex Top Lasur)												
Sapwood	10	25.28	2.21	1.44	10	25.49	2.30	1.48	10	25.48	2.23	1.24
		(0.15)	(0.33)	(0.18)		(0.28)	(0.28)	(0.13)		(0.29)	(0.29)	(0.09)
Heartwood	10	25.35	2.28	1.24	10	25.49	2.35	1.36	10	25.64	2.69	1.39
		(0.11)	(0.27)	(0.13)		(0.12)	(0.81)	(0.16)		(0.14)	(0.94)	(0.18)
Painted with oil-based surface treatment (Pullex Bodenol)												
Sapwood	10	48.14	17.81	36.49	10	44.88	17.21	26.34	10	41.93	11.95	20.60
		(3.92)	(1.69)	(2.50)		(1.92)	(0.58)	(2.68)		(1.73)	(1.45)	(2.08)
Heartwood	10	54.46	20.09	34.14	10	46.20	17.85	27.94	10	40.89	15.68	20.39
		(2.66)	(0.27)	(3.19)		(1.51)	(6.01)	(1.91)		(1.93)	(5.34)	(2.89)

Note: in parentheses there is value of standard deviation (SD)



a)



b)

Fig. 2 Total colour change Δ*E (a) and changes in colour space coordinates Δ*L**, Δ*a** and Δ*b** (b) after 30 and 90 days of natural weathering.**

The average values of colour parameters in CIE L*a*b* system (Tab. 2) after painting of pre-weathered surfaces indicated that only polyurethane-based system (Pullex Top Lasur) smoothed the colour changes completely (Fig. 3). On the other hand, the brown oil-based surface treatment (Pullex Bodenol) did not mask the colour changes of the pre-weathered surfaces (Fig. 3). The colour variations created on the wood surfaces during aging significantly affected the final colour of oil-based surface treatment (Tab. 2).

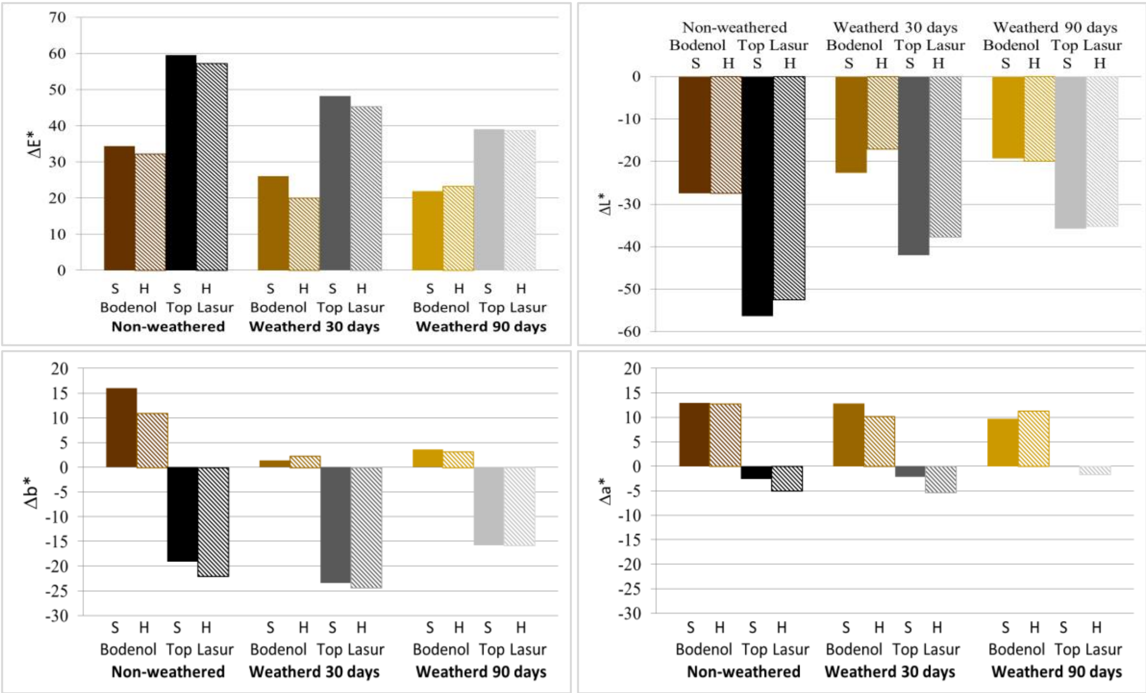


Fig. 3 Total colour change Δ*E and changes in colour space coordinates Δ*L**, Δ*a** and Δ*b** after painting of non-weathered and for 30 and 90 days weathered wood.**

Note: S – Sapwood, H – Heartwood

The surface roughness

The values of surface roughness after weathering and also after coatings are shown in Tab. 3.

As expected, the higher surface roughness was measured on weathered surfaces than on non-weathered surfaces in both perpendicular and parallel directions to grain. After weathering, the surface roughness in the transverse direction on sapwood was higher than on heartwood. The increases in surface roughness could possibly be related to the changes of components in the cell wall due to weathering.

After application of the polyurethane based system on the pre-weathered wood surface, the roughness significantly decreased in the longitudinal and especially in the transverse direction on both sapwood and heartwood surfaces. Surface roughness on pre-weathered wood was comparable with the roughness of non-weathered surface. This surface coating (polyurethane based system) is able to even the roughness caused by weathering as well as differences in roughness between sapwood and heartwood.

After application of the oil-based surface treatment, the values of roughness in the perpendicular and parallel directions (to the wood grain) on the pre-weathered surfaces were similar to the values of surface roughness before coating.

Tab. 3 Surface roughness of non-weathered, weathered and painted pine samples in the perpendicular – $R_{a\perp}$ and parallel – $R_{a||}$ to wood grain.

	Non-weathered			Weathered for 30 days			Weathered for 90 days		
	n	$R_{a\perp}$	$R_{a\|\|}$	n	$R_{a\perp}$	$R_{a\|\|}$	n	$R_{a\perp}$	$R_{a\|\|}$
Unpainted									
sapwood	140	4.05	1.98	50	4.83	2.19	50	4.42	2.01
		(0.81)	(0.81)		(0.82)	(0.88)		(0.77)	(0.66)
heartwood	140	3.94	1.98	50	4.80	2.34	50	4.23	1.72
		(0.91)	(0.80)		(0.92)	(0.67)		(0.65)	(0.43)
Painted with polyurethane-based system (Pullex Top Lasur)									
sapwood	20	0.77	0.62	20	1.34	0.91	20	1.14	0.78
		(0.47)	(0.30)		(0.65)	(0.53		(0.39)	(0.23)
heartwood	20	0.94	0.77	20	0.89	0.92	20	1.15	0.86
		(0.29)	(0.31)		(0.36)	(0.54		(0.31)	(0.26)
Painted with oil-based surface treatment (Pullex Bodenol)									
sapwood	20	3.16	1.49	20	4.91	1.90	20	4.24	2.24
		(0.82)	(0.56)		(0.71)	(0.68)		(0.90)	(0.60)
heartwood	20	3.29	1.72	20	4.37	1.77	20	3.53	2.15
		(0.79)	(0.57)		(0.97)	(0.70)		(0.76)	(0.48)

Note: in parenthesis there is value of standard deviation (SD)

Pull-off strength

Statistical evaluation of the effect of individual factors, such as: sapwood/heartwood, type of coating film (polyurethane/oil based system), duration of outdoor exposure (30/90 days or without aging) and their interactions on the pull-off strength are shown in Tab. 4.

Tab. 4 Analysis of variance of results of pull-off strength.

Factors	Sum of squares	Degrees of freedom	Mean square	F-values	Probability α = 0.05
Total	824.3627	1	824.3627	1989.204	0.0000
Parts of Wood (PW)	3.1832	1	3.1832	7.681	0.0079
Duration of Exposure (DE)	1.9113	2	0.9557	2.306	0.1106
Type of Coating film (TPF)	2.7221	1	2.7221	6.569	0.0136
PW * DE	0.4558	2	0.2279	0.550	0.5806
PW * TPF	0.1058	1	0.1058	0.255	0.6156
DE * TPF	1.1194	2	0.5597	1.351	0.2688
PW * DE * TPF	2.4712	2	1.2356	2.981	0.0602
Error	19.8921	48	0.4144		

Results of analysis of variance of the pull-off strength showed a statistically significant effect of the type of wood – sapwood /heartwood (p=0.0079: moderate impact) and a statistically low impact of the type of coating film – polyurethane/oil based system (p=0.0136: low impact) on the strength.

However, the pull-off strength of the coating film applied on the surface of pre-weathered wood was comparable with the wood surface without aging. The average value of pull-off strength of the polyurethane based system (Pullex Top Lasur) on the surface of heartwood pre-weathered for 30 days was higher compared to sapwood. However, these values were not statistically different from the values of non-weathered wood. A slight increase in pull-off strength on the heartwood after short-term pre-weathering may perhaps be due to greater wettability of the surface and consequently greater adhesion of the coating film to the surface. In the case of the oil-based system (Pullex Bodenol), after 90 days of pre-weathering of sapwood, the pull-off strength of the coating film showed about double variance in comparison with 30 days pre-weathering (Fig. 4). During the early stages of pre-weathering, hydrophobic lignin was decomposed by UV irradiation and leached from the wood surface by rain water, together with celluloses and hemicelluloses (REINPRECHT 2008), which could increase the wettability of wood (OBERHOFNEROVÁ – PÁNEK 2016). Afterward, wetting of the wood surface was decreased with increasing time of exposure to the exterior (GINDL *et al*. 2004; JIROUŠ-RAJKOVIČ *et al.* 2007). During weathering, the structure of the surface layer was changed. After the surface was coated with a coating, the impregnated pre-weathered layer remained still weakened.

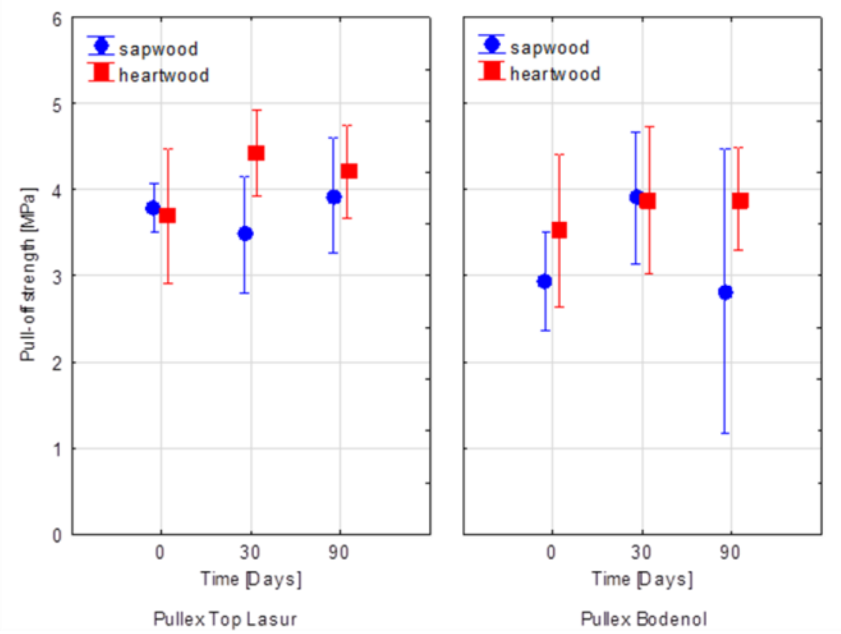


Fig. 4 The impact of duration of exposure on the pull-off strength (parts of wood and the type of coating film).

Examination of the surfaces of specimens and the pull-off test dollies needs to identify the location of failure. LIPTÁKOVÁ – KÚDELA (2002) specified that during the test, various types of failure in the system wood – coating film (the weakest point of the system) can occur: failure in the wood substrate, in the coating penetration layer of wood substrate, at wood/coating interface, or inside of the coating film.

The failures of the system polyurethane coating film – wood occurred in the pre-weathered layer of wood substrate and at the wood/coating interface. The failures located in the surface layer of wood substrate were detected both for non-weathered and pre-weathered samples. The measured values of the pull-off strength (Fig. 4) can be considered as the strength of the surface layers of wood. The failure in pre-weathered wood occurred more frequently in heartwood than in sapwood.

The samples pre-weathered for 30 and 90 days and subsequently coated with the oil-based surface treatment, exhibited failures predominantly inside the coating film and occasionally in the coating penetration layer of wood substrate. The test dollies pulled-off from the specimens showed the slight-brown colouring signalising the presence of the coating. It was visible with the naked eyes. The slight-brown colouring was visible on the wood surface as well. For this reason, the tensile strength measured in the system oil coating film – wood (Fig. 4) can be considered as a cohesive strength of the coating film.

The failure occurring in the wood – coating system differed depending on the type of coating. SLABEJOVÁ (2012) recognised that a coating film formed as a surface treatment system had greater cohesion than adhesion if compared to a simple coating. This statement was also confirmed by our results. The weakest place in the system wood – coating film of oil-based surface treatment was the coating film.

Other studies confirmed the significant effect of various types of coatings on adhesion to various pre-weathered wood species, *e.g.* fir (JAIC – ZIVANOVIC 1997), redcedar (WILLIAMS *et al.* 2002), ipê (DELPECH – COUTINHO 2000) and thermally modified wood (MIKLEČIĆ *et al*. 2017). In other studies (WILLIAMS – FEIST 1994, JIROUŠ-RAJKOVIČ *et al.* 2007), for pine wood, significant differences in paint adhesion on the pre-weathering wood surfaces were not found.

CONCLUSION

Due to short term natural weathering for 30 and 90 days in outdoors in winter time, Scot pine wood was changed:

- the colour of sapwood and heartwood surfaces become darker and greyish;
- the surface roughness of sapwood and heartwood increased. The value of R_a was higher in the perpendicular direction compared to the parallel direction to grain.

The effect of weathering of wood on subsequent finishing with selected commercial coating materials: dark brown polyurethane-based system (Pullex Top Lasur) and light brown oil-based surface treatment (Pullex Bodenol) was:

- only polyurethane-based system was able to mask the colour changes on the pre-weathered wood surfaces;
- only polyurethane-based system was able to homogenize the differences in surface roughness which arose as a result of pre-weathering; the roughness R_a (in parallel and perpendicular directions to the grain) was comparable to the roughness of coated non-weathered wood surfaces;
- the system wood – polyurethane coating film showed the lowest pull-off strength in the pre-weathered layer of wood substrate or at the wood/coating interface;
- the oil-based surface treatment did not sufficiently mask the colour changes induced by pre-weathering;
- the oil-based surface treatment did not change the surface roughness which arose as a result of pre-weathering. The values R_a (in parallel and perpendicular directions to the grain) were comparable to the values before finishing;
- the system wood – oil-based coating film showed the lowest pull-off strength inside of the coating film or in the coating penetration layer of wood substrate;
- greater variability in pull-off strength on the system wood – oil-based coating film (on the sapwood surfaces pre-weathered for 90 days) occurred probably due to greater surface degradation and subsequently reduced cohesive strength of wood surface layer;
- pre-weathering did not significantly affect the pull-off strength of the system wood – coating film.

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