ACTA FACULTATIS XYLOLOGIAE ZVOLEN, 65(1): 23−34, 2023
Zvolen, Technická univerzita vo Zvolene
DOI: 10.17423/afx.2023.65.1.02

THE EFFECT OF OUTDOOR WEATHERING OF THERMALLY MODIFIED SPRUCE AND PINE WOODS ON THEIR SURFACE PROPERTIES

Zuzana Vidholdová – Miloš Pánek – Ladislav Reinprecht

ABSTRACT

Products from thermally modified wood used outdoors should be stable against sun, rain, wind, and biological agents. The effect of 1- to 24-month outdoor weathering of the Norway spruce (*Picea abies*) and Scots pine (*Pinus sylvestris*) thermally modified woods "Thermo-D produced in Oy Lunawood Ltd Finland" (TWs) on their selected surface properties – colour, gloss, roughness, and mould resistance is analysed in the paper. With prolonged weathering, the surfaces of both Thermo-D wood samples lost their original yellow-red shadow. They continuously turned greyer – in the CIE $L^*a^*b^*$ colour system, they obtained greener and bluer colours, together with the logarithmic increase in the total colour difference ΔE^*_{ab}. Surfaces of both Thermo-D wood samples within the first four months of outdoor weathering turned much lighter with a higher gloss. However, they got darker and matter due to adsorbing soot and dirt. Similar changes, i.e., as in the lightness and gloss, occurred in the roughness of weathered Thermo-D woods, which firstly decreased and subsequently increased with further prolongation of weathering. Moulds *Aspergillus niger* and *Penicillium brevicompactum,* in all cases, intensively attacked spruce and pine wood – natural wood, Thermo-D wood, weathered natural wood, weathered Thermo-D wood.

Keywords: spruce, pine, thermowood, weathering, colour, gloss, roughness, mould resistance.

INTRODUCTION

Weathering is one of the most common degradation processes observed outdoors above ground, directly effecting surfaces of wood or other materials. Weathering of wood generally includes a cascade of events that follow photochemical degradation and water leaching of wood components and lead to changes in its surfaces – discoloration, increased roughness, and checking (Meyer and Kellogg,1982; Evans *et al.*, 2008; Kúdela and Ihracký, 2014; Pánek and Reinprecht, 2014; Niklewski *et al.*, 2022). Solar radiation, it means ultra-violet (UV) rays and, to a lesser extent, also visible light rays, cause photochemical damage, especially in lignin and some extractives are more susceptible (Hon and Chang, 1984; Feist, 1990; Pandey, 2005). Photo-damages of the cell wall constituents of wood and following water-leaching of the decomposed products often result in exposing other wood constituents that, in turn, become subject to new degradation from solar radiation. Weathering is an important issue for all wood products exposed outdoors as it affects their appearance, service life, and wood-coating performance (Jirouš-Rajković and Miklečić, 2021). Weathering of wood is not to be confused with wood decay caused by brown-rot, white-rot, or soft-rot fungi acting in the presence of excess moisture and a certain proportion of air for an extended period, when the wood can be biodeteriorated rapidly, mainly due to enzymatic reactions in its all volume. Practice and experiments showed that products from softwood and hardwood species primarily treated at high temperatures above 180 °C (TWs – thermowoods) better resist to decaying fungi as products from the same natural wood species (Ahola *et al*., 2002; Reinprecht and Vidholdová, 2008; Reinprecht and Repák, 2022). On the contrary, the weathering resistance of thermowood is not always higher compared to natural wood.

The popularity of thermally modified claddings for new buildings is increasing fast. The material is seen as native, organic, and aesthetic, and it is also marketed as long-lasting and maintenance-free option. Compared to natural – unmodified wood, thermally modified wood has altered characteristics. Its chemical composition is changed by degrading mainly the hemicelluloses and extractives in the wood cells. The level of change in the wood cell walls depends on the wood species, the type of heat treatment – in air, oils, etc., the time and temperature at treatment, at which the temperature and the absence of oxygen play an important role (Hill, 2006). As a result of changes in the chemical and anatomical structure of wood it has changed acidity, wettability, surface free energy, and mechanical and physical properties (Reinprecht, 2016; Sandberg *et al*., 2021).

The colour and gloss stability of the thermally modified wood is important for the interior and mainly for outdoor exposures connected with its intensive weathering. For example, Ayadi *et al*., (2003) found that thermally modified ash, beech, maritime pine, and heartwood of poplar showed much less discoloration in comparison to unmodified wood species after UV-exposure. It was speculated that the more stable colour was partly caused by increased phenol content and higher stability of the condensed lignin. Baysal *et al*., (2014) reached a similar conclusion for thermally modified Scots pine and noted that a longer thermal modification time resulted in a more colour-stable surface. Nuopponen *et al*., (2004) reported that the lignin content of thermally modified Scots pine wood samples was higher than the lignin content of unmodified samples after 7 years of natural weathering. Also, weathering products of lignin were easily leached out with water from the unmodified wood, whereas in the heat-treated wood they were largely unleachable. Deka *et al*. (2008) found that colour changes of heat-treated spruce wood were lower than untreated spruce wood after long-term artificial UV light exposure. It could be due to an increase in lignin stability by its condensation at the time of the heat treatment process at 210 °C. Tomak *et al.*, (2018) have also reported a less negative effect of natural outdoor weathering over four years on the colour stability of thermally modified ash, iroko, Scots pine and spruce wood species. On the contrary, some of studies showed that thermal modification of wood decreases its resistance to weathering. Jämsä *et al*., (2000) stated extensive greying, increased surface roughness and cracking after a five-year weathering trial of thermally modified pine and spruce boards. Yildiz *et al*., (2011) reported that thermal modification of alder delayed/decreased the rate of colour change caused by weathering factors but did not completely prevent it. Srinivas and Pandey (2012) also stated that the thermal modification of rubberwood was ineffective in restricting colour changes and suggested that the condensed structures formed in thermal modification were more susceptible to UV-induced degradation. Ahola *et al*., (2002) reported that thermal treatment had no influence on mould and blue stain growth on coated thermally modified spruce and pine wood during outdoor weathering. However, the moisture content of thermally modified wood was lower compared to unmodified wood.

The aim of this experiment was to determine effects of the natural outdoor weathering of spruce and pine thermowood on their selected surface properties – stability of colour and gloss, change of roughness, and mould resistance.

MATERIALS AND METHODS

Wood

Samples from the thermally modified Norway spruce wood (*Picea abies* L. Karst.) (signed – spruce TW) and the thermally modified Scots pine wood (*Pinus sylvestris* L.) (signed – pine TW), marked with the class Thermo–D – as the selected representatives of softwood with different contents of extractives, were used in the experiment. Four test samples with a dimension of 378 × 78 × 20 mm^3 were prepared from each type of solid tongue-and-groove boards (Oy Lunawood Ltd., Iisalmi, Finland) recommended for outdoor use – i.e., from spruce TW and pine TW, as well. The surfaces of test samples were before weathering sanded with the sandpaper grit of 80.

Natural outdoor weathering of wood

Exposure of all test samples in the exterior was carried out according to the standard EN 927–3 (2006) in frames facing south at an angle of 45° and placed approximately 1 m above the ground for 1, 2, 3, 4, 6, 12, and 24 months from November 11, 2015, to November 11, 2017, at Suchdol, Prague (50° 07′49,68″N; 14° 22′13,87″ E, elevation above sea level 285 m). The climatic conditions at the exposure site were as follows: average daily temperature: 10.17 °C (daily extremes 36 °C, −15.70 °C), average daily precipitation 1.52 mm, and average daily incident solar energy 10 899 kJ.m^{-2}. The weathered samples were stabilized at 20±2 °C and 65% relative humidity in the laboratory before the measurements. Tab. 1 shows an overview of the climatic conditions during 24 months of weathering.

Tab. 1 Overview of the air climatic conditions in the exposure site during outoor weathering.

Average climatic parameter	Months of exposure							
	0-1	1-2	2-3	3-4	4-6	6-12	12-24	0-24
Temperature (°C)	5.86	3.50	2.60	3.01	8.49	15.70	9.81	10.17
Humidity (%)	78.38	82.69	77.12	76.92	65.02	69.24	71.39	71.57
Total precipitation (mm)	45.20	15.20	20.70	47.40	45.10	389.20	550.30	1 112.40
Global solar rad. (kJ.m^{-2})	2 838	2 081	3 381	5 443	13 523	14 592	11 073	10 899

Note: Based on data from the meteostation at the Czech University of Life Sciences http://meteostanice.agrobiologie.cz/)

Colour evaluation

The colour characteristics of the wood surfaces were measured using a spectrophotometer CM-600d (Konica Minolta, Japan). The equipment was configured to a D65 light source and observation angle of 10°. Parameters L*, a* and b* were measured at 8 points (Fig. 1) on each test sample over the tangential surface at the beginning of the experiment and after 1, 2, 3, 4, 6, 12, and 24 months of weathering. The colorimetric parameters of each wood sample were analysed according to the CIE L*a*b* system (ISO 7724-3: 1984).

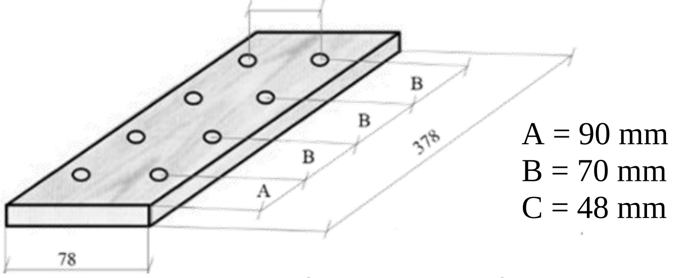


Fig. 1 Measurement points on samples for the analysis of the colour, gloss, and roughness.

A positive value of L^*, a^*, or b^* means a lighter, redder, or yellower colour, respectively. From the relative colour changes ΔL^*, Δa^*, and Δb^*, namely differences between chromaticity coordinates of the weathered thermally modified wood sample and the thermally modified wood sample, the total colour difference ΔE^*_{ab} was calculated for each point in the tested sample by the equation (1):

$$\Delta E^*_{ab} = \sqrt{\Delta L^{*2} + \Delta a^{*2} + \Delta b^{*2}} \tag{1}$$

Gloss evaluation

The gloss of the wood surfaces was measured with an MG268-F2 glossmeter (KSJ, Quanzhou, China) at an angle of 60° according to EN ISO 2813 (2015). Gloss was measured at 8 points (Fig. 1) on each sample over the tangential surface at the beginning of the experiment and after 1, 2, 3, 4, 12, and 24 months of weathering.

Surface roughness evaluation

The surface roughness of wood samples was determined as its average value Ra (μm) according to EN ISO 4287:1998/AC and EN ISO 4288 (1997) using the profilometer Form Talysurf Series Intra 2 (Taylor-Hobson, UK). The measurement parameters were set in accordance with the standard – a base length was 15 mm. Parameters Ra were measured at 8 points (Fig. 1) traversing lengths oriented perpendicularly to the length of the samples over the tangential surface at the beginning of the experiment and after 1, 2, 3, 4, and 24 months of weathering.

Mould resistance evaluation

For the mould growth activity (MGA) test, there from the nonweathered and 24-month weathered natural spruce and pine wood samples, and also from the nonweathered and 24-month weathered TW spruce and TW pine samples, all with a dimension of 378 × 78 × 20 mm^3, were prepared specimens with a dimension of 50 ×10 × 5 mm^3. Specimens were exposed to moulds in accordance with the standard ČSN 49 0604 (1980). The natural and thermally modified Norway spruce and Scots pine specimens included the top surface: (I.) without weathering "Reference", (II.) with two-year /24-month/ weathering "Original surface", and (III.) with two-year /24-month/ weathering and following brushing "Brushed surface". The specimens sterilized with UV-light were placed into Petri dishes with a diameter of 120 mm on a 3 to 4 mm-thick layer of 4.9 wt.% Czapek–Dox agar medium (HiMedia Ltd., Mumbai, India) and inoculated with a spore suspension of the microscopic fungus *Aspergillus niger* Tiegh. (strain BAM 122; Bundesanstalt für Materialforschung und -prüfung, Berlin), and the microscopic fungus *Penicillium brevicompactum*, respectively. Both spore suspensions were prepared in sterile redistilled water in 10^6 to 10^7 spores/ml concentrations. The incubation of the inoculated test specimens lasted 28 days at a temperature of 28 °C ± 2 °C and a RH of 90% to 95%. The mould resistance of the specimens was determined by the MGA values (from 0 to 4) using these criteria: 0 = no mould growth on the top surface; 1 ≤10%; 2 >10% but ≤25%; 3 >25% but ≤50%; 4 >50%.

Statistical analyses

Statistical analyses were performed with MS Excel 2016, using mean value - average (Avg.), standard deviation (SD), and points graphs. The effect of increased exposure time of weathering (Time → t) from 1 to 24 months on selected surface parameters of wood was analysed using correlations "y = f(t)" and their coefficients of determination "r^2". The statistical software STATISTICA 12 was used to evaluate Duncan's tests to measure differences between average parameters of colour (L^*, a^*, b^*, ΔE^*_{ab}), gloss (GU), and roughness (Ra) of spruce and pine TWs.

RESULTS AND DISCUSSION

Colour and gloss of weathered thermowood

The most well-known effect of exposing unprotected wood to outdoor weathering, including periods of sun and rain, is a change in colour of its surface. Tab. 2 and Fig. 2 show the average values of chromaticity coordinates L^*, a^*, and b^* for spruce and pine TWs at the beginning and after 1, 2, 3, 4, 6, 12, and 24 months of natural outdoor weathering. With prolonged weathering, the surfaces of both TWs lost their original yellow-red shades and continuously obtained more grey shades defined in the CIE $L^*a^*b^*$ colour system with the observation of greener and bluer colours (Fig. 1a and b). During the first months of weathering (in the wintertime – from November 2015 to March 2016), the wood surfaces become lighter – after 4th month of exposure, lighter maxima L^* were observed, i.e., 61.97 for spruce TW and 58.70 for pine TW, at which only then they got darker due adsorbed soot and dirt.

Tab. 2 The colour parameters (y = L^*, a^*, b^*) of the Norway spruce and Scots pine TWs after their outdoor weathering from 0 to 24 months.

Wood Species	Time (Months)	L^* (-) Avg.	SD	a^* (-) Avg.	SD	b^* (-) Avg.	SD
Norway spruce - Thermo-D	0	49.94	0.92	10.75	0.16	25.07	0.18
	1	57.43	1.11	8.73	0.09	23.39	0.41
	2	59.44	1.15	8.20	0.15	20.90	0.71
	3	61.20	0.95	7.33	0.21	18.50	0.81
	4	61.97	1.86	6.74	0.27	16.94	0.77
	6	58.24	3.58	2.84	0.97	8.21	1.20
	12	44.33	3.71	1.42	0.25	3.22	0.94
	24	39.55	1.86	1.04	0.06	1.72	0.16
Correlation "y=f(t)" Determination coefficient "r^2"		–		$a^* = 8.718 \cdot e^{-0.104 \cdot t}$ $r^2 = 0.914$		$b^* = 24.472 \cdot e^{-0.122 \cdot t}$ $r^2 = 0.949$	
Scots pine - Thermo-D	0	50.13	1.37	10.75	0.42	25.32	1.28
	1	57.87	1.45	8.65	0.13	25.17	1.22
	2	57.83	2.54	7.85	0.23	22.25	1.16
	3	58.20	1.47	6.62	0.48	19.01	0.25
	4	58.70	1.12	5.60	0.32	16.18	0.43
	6	54.01	0.98	1.97	0.19	5.53	0.53
	12	45.99	1.38	1.20	0.08	2.42	0.21
	24	35.41	1.63	1.01	0.07	1.54	0.14
Correlation "y=f(t)" Determination coefficient "r^2"		–		$a^* = 7.848 \cdot e^{-0.104 \cdot t}$ $r^2 = 0.886$		$b^* = 23.003 \cdot e^{-0.130 \cdot t}$ $r^2 = 0.920$	

Note: Individual mean value – average (Avg.) and standard deviation (SD) were determined from 32 values (8 values per sample).

Changes in the chromaticity coordinates a^* and b^* show the performance of outdoor weathered wood surfaces and can be correlated with the wood greying. Experiments showed a trend that both TWs became after weathering less red (a^* lower and closer to zero – see Fig. 2a and Tab. 2) and less yellow (b^* lower and closer to zero – see Fig. 2b and Tab. 2). The yellow colour changed 2.4 times faster than the red colour (Fig. 2c). Both chromaticity coordinates a^* and b^* showed a systematic trend to decreasing values with prolongation of exposure time (Tab. 2), and their exponential decrease was described by the following equations: for spruce TW: $a^* = 8.718 \cdot e^{-0.104 \cdot t}$ with $r^2 = 0.914$; $b^* = 24.472 \cdot e^{-0.122 \cdot t}$ with $r^2 = 0.949$, and for pine TW: $a^* = 7.848 \cdot e^{-0.104 \cdot t}$ with $r^2 = 0.886$; $b^* = 23.003 \cdot e^{-0.130 \cdot t}$ with $r^2 = 0.920$.

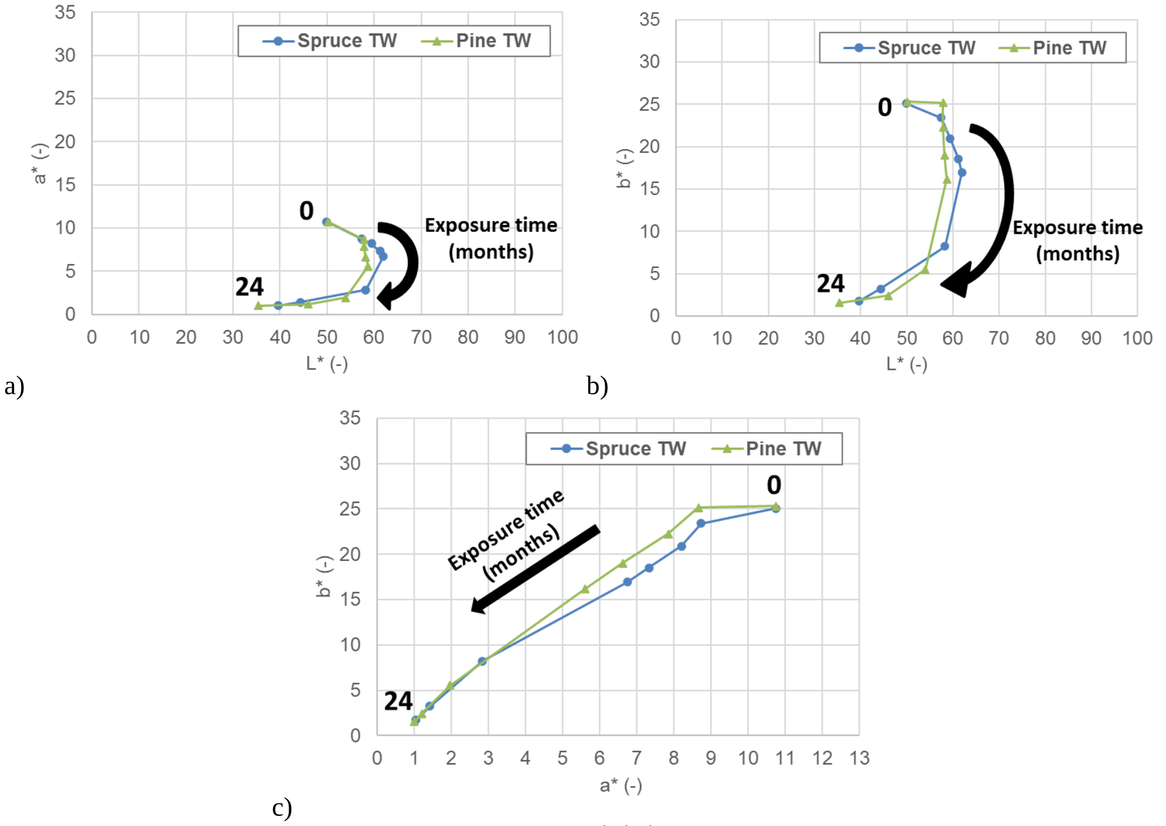
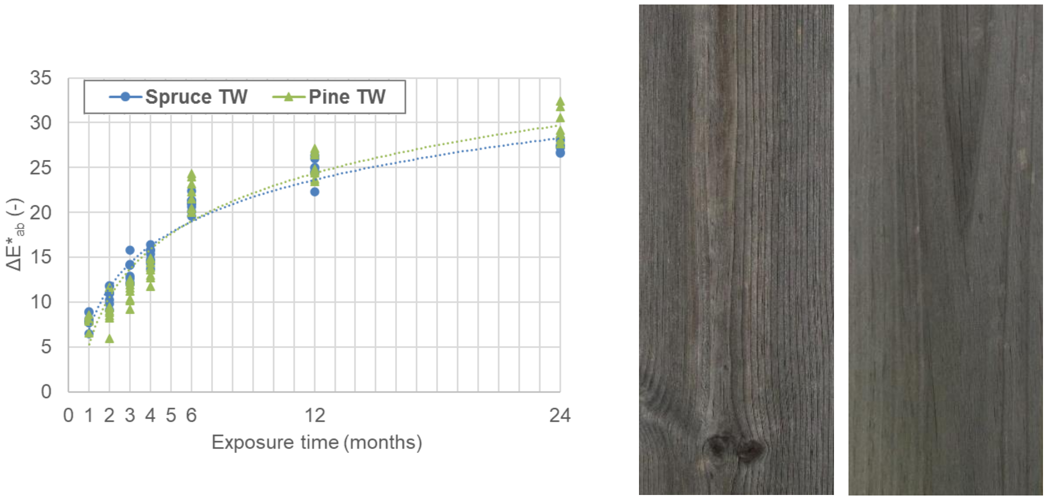


Fig. 2 Correlations between coordinates of the CIE $L^*a^*b^*$ colour system for weathered Norway spruce and Scots pine thermally modified woods (TWs).
a) The chromaticity coordinate a^* and the lightness (L^*); b) The chromaticity coordinate b^* and the lightness (L^*); c) The chromaticity coordinate b^* and the chromaticity coordinate a^*

A similar tendency of lightening and darkening for pine and spruce TWs, treated at 212 °C for 90 min, was at natural outdoor weathering from October 2011 to October 2015 reported in the study of Tomak *et al.* (2018). They also found that the dark colour of thermally modified samples lightened during the first six months of weathering. Based on the FTIR analyse, the considerable decrease in lignin, mainly in the aromatic ring of syringyl and guaiacyl lignin and asymmetric bending in CH_3 in the first weathering exposure period were found. Also, Kucuktuvek *et al.* (2017) investigated colour changes of Scots pine thermally modified at 210, 220, and 230 °C/1, 2 or 3h, after weathering from May 2016 to October 2016. They found that after weathering all the pine TWs becomes lighter. However, the un-heated pine wood become darker. Ugovšek *et al.* (2019) evaluated the weathering performance of wooden windows and façade elements made from thermally modified and unmodified Norway spruce wood – performed field tests in Žiri (Slovenia), Ljubljana (Slovenia), Hannover (Germany), Skellefteå (Sweden), and Madrid (Spain) from October 2015 until September 2016. They noticed that the colour changes depended on specific locations and weather conditions, where the amount of precipitation played an important role.

Similar colour changes were demonstrated in the case of spruce and pine TWs. The total colour difference (ΔE^*_{ab}) showed a systematic trend to increase values with a longer duration of exposure time (Fig. 3). Logarithmic increases of ΔE^*_{ab} were described by these equations: for spruce TW: $\Delta E^*_{ab} = 7.027 + 6.687 \cdot \ln(t)$ with $r^2 = 0.953$, and for pine TW: $\Delta E^*_{ab} = 5.266 + 7.690 \cdot \ln(t)$ with $r^2 = 0.904$.



Spruce TW: $\Delta E^*_{ab} = 7.027 + 6.687 \cdot \ln(t)$; $r^2 = 0.953$

Pine TW: $\Delta E^*_{ab} = 5.266 + 7.690 \cdot \ln(t)$; $r^2 = 0.904$

a) b) Spruce TW Pine TW

Fig. 3 a) Logarithmic correlations between the total colour difference ΔE^*_{ab} of spruce and pine TWs and the time (t) of their weathering
b) Final grey colour and roughness structure of TWs after 24-months of their weathering.

After 24-months, at the end of weathering, the silver-grey surface was visible on both TW surfaces. However, according to Duncan's test for the total colour difference ΔE^*_{ab}, significant contrast was occurred between the weathered spruce TW and pine TW (p-value was 0.004 – see Tab. 3). Kržišnik *et al.* (2018) found that at weathering the unmodified Norway spruce wood underwent a greater colour change than the thermally modified wood. In outdoors, water rain leaches photo-degradation products from wood surfaces, and a grey surface composed of partially degraded cellulose, some portion of hemicelluloses, and only low lignin content is left (Feist, 1990; Tomak *et al.*, 2018; Kropat *et al.*, 2020). In contrast, the blue-stain fungi acting in exterior darken the wood (Zink and Fengel, 1989; Kržišnik *et al.*, 2018).

Tab. 3. Duncan's multiple range tests for comparison the changes of colour (L^*, a^*, b^*, ΔE^*_{ab}), gloss (GU), and roughness (Ra) between the naturally weathered Norway spruce and Scots pine TWs.

Exposure time (Months)	L^* (–)	a^* (–)	b^* (–)	ΔE^*_{ab} (–)	GU (–)	Ra (μm)
0	0.883 ^{d}	0.975 ^{d}	0.595 ^{d}	–	0.255 ^{d}	0.489 ^{d}
1	0.739 ^{d}	0.651 ^{d}	0.265 ^{d}	0.854 ^{d}	0.024 ^{c}	0.595 ^{d}
2	0.065 ^{d}	0.038 ^{d}	0,003 ^{b}	0.005 ^{b}	0.000 ^{a}	0.002 ^{b}
3	0.034 ^{c}	0.000 ^{a}	0.526 ^{d}	0.000 ^{a}	0.000 ^{a}	0.000 ^{a}
4	0.042 ^{c}	0.001 ^{b}	0.093 ^{d}	0.003 ^{b}	0.000 ^{a}	–
6	0.022 ^{c}	0.081 ^{d}	0.091 ^{d}	0.076 ^{d}	–	–
12	0.184 ^{d}	0.196 ^{d}	0.076 ^{d}	0.123 ^{d}	0.037 ^{d}	–
24	0.001 ^{b}	0.847 ^{d}	0.683 ^{d}	0.004 ^{b}	0.808 ^{d}	0.000 ^{a}

Note $^{a\text{-}d}$ = indexes of statistical significance (p-value): a—very significant difference at the 99.9% level; b—significant difference at the 99% level; c—less significant difference at the 95% level; and d—insignificant difference at the <95% level.

Along with colour, gloss is another important aesthetic property of wood, particularly in terms of user's preferences. The average surface gloss of the Norway spruce and Scots pine TWs at their natural outdoor weathering is shown in Fig. 4. Initially, before weathering, the TW surfaces had a gloss value of less than 10, which means that the surfaces were matte. The surfaces during the first 4 months of weathering acquired a higher gloss, meaning that the surfaces were semi-matte (GU values were between 10 and 35), but then became matte again and even more matte due to adsorbed soot and impurities. According to Duncan's test for the gloss, there after 24 months of weathering, an insignificant difference occurred between the spruce and pine TW (p-value was 0.808 – see Tab. 3). Kucuktuvek *et al.* (2017) also noted that a surface gloss of the Scots pine modified by high temperatures was increased after natural half-year weathering from May 2016 to October 2016.

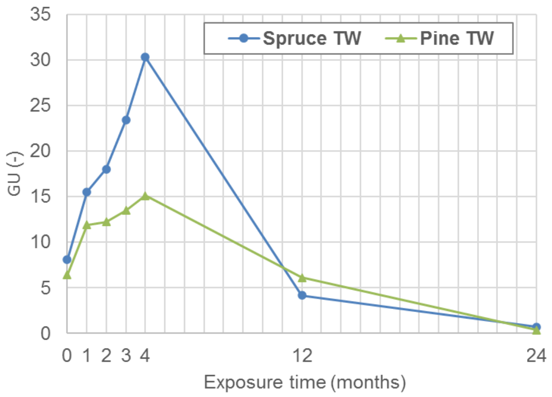


Fig. 4 The gloss (GU) of the Norway spruce and Scots pine TWs during natural weathering.

Roughness of weathered thermowood

Surface roughness of spruce and pine TWs at the beginning and after 1, 2, 3, 4, 6, 12, and 24 months of natural weathering is shown in Fig. 4. During the first four months, the trend of the change in roughness was for both wood species evidently different. However, at the end of weathering period, both surfaces became rougher. After 24 months, a higher roughness was found – about 121% for spruce TW, and about 40% for pine TW (Fig. 5). According to Duncan's test for the roughness after 24 months of weathering, significant difference occurred between the weathered spruce and pine TWs (p-value was 0.000 – see Tab. 3). The increase in surface roughness may be related to the photo-degradation of wood lignin and hemicelluloses, the water-leaching of depolymerized polar substances from wood surfaces by rain, fog or dew, and the spatial release of cellulose fibrils (Nuopponen *et al.*, 2004; Reinprecht 2016; Tomak *et al.*, 2018).

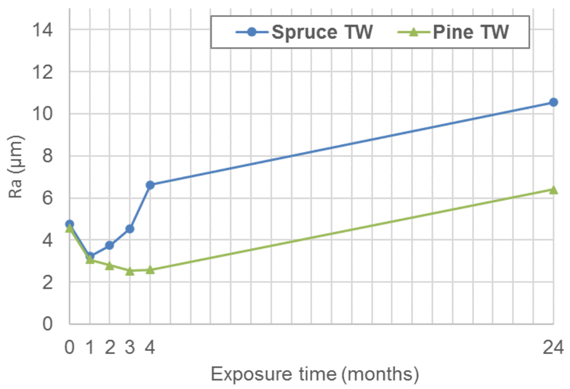


Fig. 5 Roughness (Ra) of the Norway spruce and Scots pine TWs during natural weathering.

Mould resistance of weathered thermowood

Mould growth on wood surfaces is a very important factor which can negatively affect the visual appearance and health parameters of wood products exposed in outdoors (Kržišnik *et al.*, 2018). In our experiment the moulds *Aspergillus niger* and *Penicillium brevicompactum* always intensively attacked spruce and pine woods – natural wood, Thermo-D wood, weathered natural wood, weathered Thermo-D wood (Tab. 4, Fig. 6).

Tab. 4 The mould growth activity (MGA) of two microscopic fungi evaluated after 28 days on the top surfaces of the Norway spruce and Scots pine thermowood "TWs" as well as natural wood – types I., II., and III.

Wood species	Mould growth activity (MGA) (0-4)			
	A. niger		*P. brevicompactum*	
	Thermowood - TW	Natural wood	Thermowood - TW	Natural wood
Norway spruce				
I. – Without weathering "Reference"	4	4	4	4
II. – 24-month weathered "Original surface"	4	4	4	4
III. – 24-month weathered "Brushed surface"	4	4	4	4
Scots pine				
I. – Without weathering "Reference"	4	4	4	4
II. – 24-month weathered "Original surface"	3 – 4	4	4	4
III. – 24-month weathered "Brushed surface"	4	4	4	4

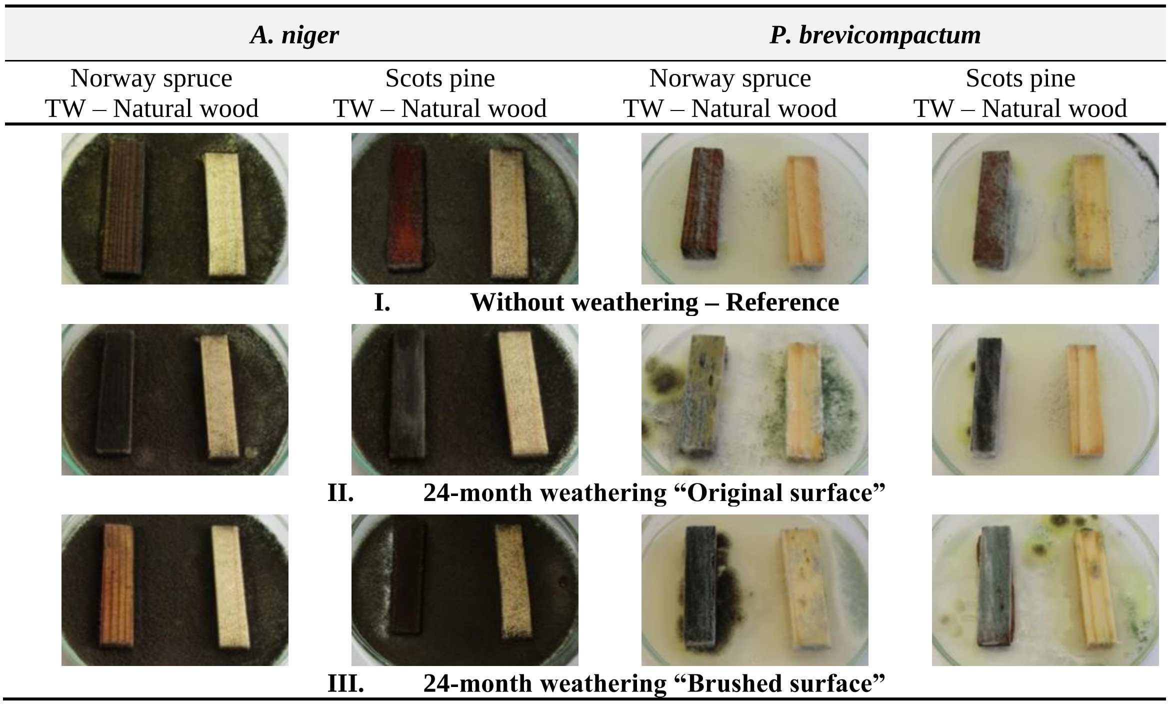


Fig. 6. The mould growth activity (MGA) of two microscopic fungi evaluated after 4 days on the top surfaces of the Norway spruce and Scots pine TWs and natural wood.

Note: In each Petri dish is one TW specimen (in left) and one natural wood specimen (in right).

Generally, the thermal modification processes usually did not have an influence on develop the moulds and blue stain fungi on wood surfaces during wood exposure to laboratory and field trials (Ahola *et al.*, 2002; Reinprecht and Vidholdová, 2008; Kržišnik *et al.*, 2018). According to study of Ugovšek *et al.* (2019), the mould growth on wooden surfaces in the field test also may depend on the specific location and weather conditions – so if the precipitation was higher, the mould growth on wooden surfaces was also higher.

CONCLUSION

Based on the analysis of the 1- to 24-month natural outdoor weathering effect of the thermally modified Norway spruce (*Picea abies*) and Scots pine (*Pinus sylvestris*) wood "Thermo-D" – TWs, the following conclusions can be drawn:

- with prolonging of weathering, the surfaces of both thermally modified woods – spruce and pine TWs – lost their original yellow-red shadows, continuously obtained more grey shadow defined in the CIE $L^*a^*b^*$ colour system by bluing and greening, and the total colour difference ΔE^*_{ab} increased logarithmically with a weathering time;
- during the first 4-months of weathering, the surfaces of both TWs turned lighter with a higher gloss, and only then they got darker and matter due to adsorbed soot and dirt;
- during the first 4-months of weathering, the surfaces of both TWs obtained a lower roughness and only then they got rougher due to the leaching of polar by sun rays depolymerized phenolic and saccharide substances from wood surfaces by following action of rain, fog or dew;
- during the first 4-months of weathering, the surface of the Norway spruce TW was more susceptible to the temporary change in the lightness, gloss, and roughness than the surface of the Scots pine TW;
- at the end of weathering, the colour evidently changed for the surfaces of both TWs and they obtained silver-grey shadows;
- at the end of weathering, the roughness of TWs surfaces increased for both wood species; however, the Norway spruce TW had a significantly higher roughness than the Scots pine TW.
- The moulds *Aspergillus niger* and *Penicillium brevicompactum* in laboratory conditions always intensively attacked the Norway spruce and Scots pine wood – natural wood, Thermo-D wood, weathered natural wood, weathered Thermo-D wood.

REFERENCES

Ahola, P., Jämsä, S., Viitanen, H., Viitaniemi, P., 2002. Mould and blue stain on heat treated wood. Proceedings of Cost Action 18 Meeting, Portugal, 4 April 2002.

Ayadi, N., Lejeune, F., Charrier, B., Merlin, A., 2003. Color stability of heat-treated wood during artificial weathering. Holz als Roh - und Werkstoff 61, 221–226. https://doi.org/10.1007/s00107-003-0389-2

Baysal, E., Degirmentepe, S., Şimşek, H., 2014. Some surface properties of thermally modified Scots pine after artificial weathering. Maderas. Ciencia y tecnología 16, 355–364. https://doi.org/10.4067/S0718-221X2014005000028

ČSN 49 0604: 1980. Ochrana dřeva. Metody stanovení biocidních vlastností ochranných prostředků na dřevo. Úřad pro normalizaci a měření: Praha, Česká republika,1980.

Deka, M., Humar, M., Rep, G., Kričej, B. Šentjurc, M., Petrič, M., 2008. Effects of UV light irradiation on colour stability of thermally modified. copper ethanolamine treated and non-modified wood: EPR and DRIFT spectroscopic studies. Wood Science and Technology 42(1), 5–20. https://doi.org/10.1007/s00226-007-0147-4

Evans, P.D., Urban, K., Chowdhury, M.J.A., 2008. Surface checking of wood is increased by photodegradation caused by ultraviolet and visible light. Wood Science and Technology 42(3), 251–265. https://doi.org/10.1007/s00226-007-0175-0

EN 927–3: 2006 Paints and varnishes - Coating materials and coating systems for exterior wood - Part 3: Natural weathering test. European Committee for Standardization: Brussels, Belgium, 2006.
EN ISO 2813:2015. Paints and Varnishes, Determination of Gloss Value at 20°, 60° and 85°; European Committee for Standardization: Brussels, Belgium, 2015.
EN ISO 4287:1998/AC. Geometrical product specifications (GPS). Surface texture. Profile method. Terms, definitions and surface texture parameters. European Committee for Standardization: Brussels, Belgium, 1998.
EN ISO 4288:1997. Geometrical product specifications (GPS) - Surface texture: Profile method - Rules and procedures for the assessment of surface texture. European Committee for Standardization: Brussels, Belgium, 1997.
Feist, W.C., 1990. Outdoor wood weathering and protection. In: Rowell, R.M., Barbour, J.R. (eds) Archaeological wood—properties. chemistry. and preservation. Adv Chem Ser 225. Am Chem Soc. Washington. DC. USA.
Hill, C.A.S., 2006. Wood modification: Chemical, thermal and other processes. John Wiley & Sons. Chichester. UK.
Hon, D.N.S., Chang, S.T., 1984. Surface degradation of wood by ultraviolet light. Journal of Polymer Science: Polymer Chemistry Edition 22(9), 2227–2241. https://doi.org/10.1002/pol.1984.170220923
ISO 7724-3: 1984. Paints and Varnishes—Colorimetry—Part 3: Calculation of Colour Differences; International Organization for Standardization: Geneva, Switzerland, 1984.
Jämsä, S., Ahola, P., Viitaniemi, P., 2000. Long-term natural weathering of coated Thermowood. Pigment & Resin Technology 29, 68–74. https://doi.org/10.1108/03699420010317807
Jirouš-Rajković, V., Miklečić, J., 2021. Enhancing weathering resistance of wood - A review. Polymers 13, 1980. https://doi.org/10.3390/polym13121980
Kropat, M., Hubbe, M.A. and Laleicke, F., 2020. Natural, accelerated, and simulated weathering of wood: A review. BioResources 15(4), 9998.
Kržišnik, D., Lesar, B., Thaler, N., Humar, M., 2018. Influence of natural and artificial weathering on the colour change of different wood and wood-based materials. Forests 9, 488. https://doi.org/10.3390/f9080488
Kucuktuvek, M., Baysal, E., Turkoglu, T., Peker, H., Gunduz, A., Toker, H., 2017. Surface characteristics of Scots pine wood heated at high temperatures after weathering, Wood Research 62(6), 905–918.
Kúdela, J., Ihracký, P., 2014. Influence of diverse conditions during accelerated ageing of beech wood on its surface roughness. Acta Facultatis Xylologiae Zvolen res Publica Slovaca 56(2), 37.
Meyer, R.W. Kellogg, R.M., 1982. Structural uses of wood in adverse environments. Van Nostrand Reinhold Company. New York. USA.
Niklewski, J., van Niekerk. P.B., Marais. B.N., 2022. The effect of weathering on the surface moisture conditions of Norway spruce under outdoor exposure. Wood Material Science & Engineering, 1–11. https://doi.org/10.1080/17480272.2022.2144444
Nuopponen, M., Wikberg, H., Vuorinen, T., Maunu, S.L., Jämsä, S., Viitaniemi, P., 2004. Heat-treated softwood exposed to weathering. Journal of Applied Polymer Science 91, 2128–2134. https://doi.org/10.1002/app.13351
Pandey, K.K. 2005. Study of the effect of photo-irradiation on the surface chemistry of wood. Polymer Degradation and Stability 90(1), 9–20. https://doi.org/10.1016/j.polymdegradstab.2005.02.009
Pánek, M., 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., Vidholdová, Z., 2008.Termodrevo – príprava, vlastnosti, aplikácie (Thermowood – preparation, properties, applications). Technická univerzita vo Zvolene, Slovak republic.
Reinprecht, L., 2016. Wood deterioration. protection and maintenance. Chichester: John Wiley & Sons. Ltd., UK.
Reinprecht, L., Repák, M., 2022. Beech wood thermally modified in the melt of polyethylene glycol. BioResources 17(01), 652-672. https://doi.org/ 10.15376/biores.17.1.652-672

Sandberg, D., Kutnar, A., Karlsson, O., Jones, D., 2021. Wood modification technologies – Principles, sustainability, and the need for innovation. CRC Press, Taylor and Francis Group, LLC, Oxon, UK.
Srinivas, K., Pandey, K.K., 2012. Photodegradation of thermally modified wood. Journal of Photochemistry and Photobiology B: Biology 117, 140–145. https://doi.org/10.1016/j.jphotobiol.2012.09.013
Tomak, E.D., Ustaomer, D., Ermeydan, M.A., Yildiz, S., 2018. An investigation of surface properties of thermally modified wood during natural weathering for 48 months. Measurement, 127, 187–197. https://doi.org/10.1016/j.measurement.2018.05.102
Ugovšek, A., Šubic, B., Starman, J., Rep, G., Humar, M., Lesar, B., Thaler, N., Brischke, C., Meyer-Veltrup, L., Jones, D., Häggström, U., 2019. Short-term performance of wooden windows and facade elements made of thermally modified and non-modified Norway spruce in different natural environments. Wood Material Science & Engineering 14(1), 42–47. https://doi.org/10.1080/17480272.2018.1494627
Yildiz, S., Yildiz, U. C., Tomak, E. D., 2011. The effects of natural weathering on the properties of heat-treated alder wood. BioResources 6(3), 2504–2521.
Zink, P., Fengel, D., 1989. Studies on the colouring matter of blue-stain fungi part 2. Electron microscopic observations of the hyphae walls. Holzforschung 43 (6), 371–374. https://doi.org/10.1515/hfsg.1989.43.6.371

ACKNOWLEDGMENTS

This work was supported by the Scientific Grant Agency of the Ministry of Education SR – VEGA Grant, No. 1/0656/23. Infrastructural support was obtained from EVA4.0 project financed by OP RDE, No. CZ.02.1.01/0.0/0.0/16_019/0000803.

AUTHORS' ADDRESSES

Zuzana Vidholdová (zuzana.vidholdova@tuzvo.sk)
Ladislav Reinprecht (reinprecht@tuzvo.sk)
Technical University in Zvolen
Faculty of Wood Sciences and Technology
Department of Wood Technology
T. G. Masaryka 24
960 01 Zvolen
Slovakia

Miloš Pánek†
Czech University of Life Sciences Prague
Faculty of Forestry and Wood Sciences
Kamýcká 129
16521 Prague 6-Suchdol
Czech Republic