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THE IMPACT OF ULTRAVIOLET RADIATION ON THE COLOUR AND WETTABILITY OF WOOD USED FOR FACADES

*The study examined the effect of UV radiation on the colour and wettability of cedar, gaboon, meranti and Scots pine wood. The tested species of exotic wood are mainly used in European countries for facades. For this kind of usage they act as a substitute for pine wood. In the study, the colour parameters were determined using the CIE L*a*b* colour space model. The tests showed that the most significant changes in the lightness of the wood occurred after 20 hours of UV radiation exposure. After that time, the L* value change was linear. The cedar wood turned the darkest and it also showed the greatest total change of colour ΔE. Comparable colour changes ΔE, and thus the greatest colour stability of all the tested wood species, were shown by the gaboon and meranti. In addition, it should be noted that all the tested wood species were characterized by a much smaller susceptibility to colour change under UV radiation than the pine sapwood and heartwood. The results also revealed that UV radiation significantly affects the contact angle, and therefore the surface free energy of the cedar and pine sapwood.*

Keywords: cedar, gaboon, meranti, Scots pine, ultraviolet radiation, colour, surface energy

Introduction

Wood used for facades is exposed to a number of biotic and abiotic factors. An important factor that predetermines whether wood can be used as an exterior wall material is colour stability and water permeability, and, in the case of impregnation, permeability to chemicals. In several European countries, Scots pine is the wood species commonly used for facades. However, more and more often exotic species of wood, such as cedar, gaboon or meranti, are used. Its main advantages are: the absence of knots, a uniformly coloured heartwood and its original texture.

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Colour is described as the phenomenon of the selective reflection and dissipation of light rays of a particular wavelength which reach the eye in the form of a spectrum determined for a given body. During the process of the natural ageing of wood, e.g. its use outdoors, the colour of wood changes. Colour changes are a good indication of the qualitative evaluation of wood surface resistance to the impact of environmental factors [Aydin and Colakoglu 2005; Tolvaj and Mitsui 2010]. The degree of colour change depends on many factors, including wood species [Pastore et al. 2004; Tolvaj et al. 2013], type of protective layer [Aydin and Colakoglu 2005; Deka et al. 2008], and conditions of use [Persze and Tolvaj 2012]. Colour change is also affected by the chemical composition of the wood [Hon and Glasser 1979; Yazaki et al. 1994; Gierlinger et al. 2004]. Temperature and UV radiation exposure time are the factors with the greatest effect on wood colour change [Sharratt et al. 2009, Huang et al. 2012a]. With an increase in temperature and the time of its impact, the colour of unprotected and protected wood surfaces at first darkens but, in time, it can also turn grey or fade [Feist 1983; Feist and Hon 1984].

Changes in wood surface properties can be reflected in changes in the free surface energy determined by the contact angle [Petrič and Oven 2015]. Wetting, which is regarded as a property of the wood surface, has a crucial impact on the processes of adhesion related to surface coating and the formation of protective layers [Cao and Kamdem 2007; Sandberg 1996]. Changes in wood moisture content have a direct impact on the changes in its structural properties and the physico-chemical properties of its surface. In the case of wood finished with varnish or paint, the contact angle determines the quality and the protective properties of the obtained layer. Wood with a low capacity of moisture absorption maintains its resistance much longer than wood species with a higher susceptibility to wetting. It should be noted that apart from the properties of the wetting substance, the parameters of the wood surface, i.e. the arrangement of annual growth rings, the ratio of late wood to early wood, wood type (sapwood, heartwood), type of anatomical section, also have an impact on surface wettability [Mantanis and Young 1997]. Gindl et al. [2006] studied the effects of ultraviolet light exposure on the wetting properties of wood. Nussbaum [1999] and Huang et al. [2012b] stated that the type of wood machining affects wood wetting. Moreover, the ratio of non-structural elements in wood is important [Nzokou and Kamdem 2004]. The variety in the methodology of wood wettability tests is worth noting. In the case of tests for wood wettability, it is important to determine the time after which the contact angle is calculated, and thus the surface free energy for the wood-reference liquid system. The wetting angle can be determined after a drop of the liquid separates itself from a needle, i.e. when $t = 0$ s [Kúdela 2014], several seconds after placing the drop of the reference liquid on the wood surface and before the total absorption of the drop into the wood structure [Santoni and Pizzo 2011].

The purpose of the tests was to determine the impact of ultraviolet radiation on the colour and wettability of exotic wood used for facades. It was particularly important to determine the direction of the changes in the wood colour components, i.e. L^*, a^* and b^*, depending on the UV radiation time. This factor is crucial in the process of predicting the character of wood colour difference and choosing the wood species for facades more efficiently, resulting in the higher aesthetic value of buildings with such facades.

Materials and methods

The following species of wood were used for the analysis: cedar *(Thuja plicata* Donn. ex D. Don*),* gaboon *(Aucoumea klaineana* Pierre*),* meranti *(Shorea* spp.*)* and Scots pine *(Pinus sylvestris* L.). The heartwood of the cedar was used for testing. The Scots pine (sapwood and heartwood) was used as a comparative material. The sample used for analysis had a tangential-radial section on the broad surface. Selection of this wood section for testing resulted from the fact that wooden elements used for facades have most often tangential-radial sections. Basic data concerning the tested wood species is presented in table 1. Planing was used to finish the surface of the wood samples. The wood moisture content was determined in accordance with ISO 13061-1:2014. The density of the wood was determined in accordance with ISO 13061-2:2014. The wood moisture ranged from 6.38% (±0.11%) to 6.73% (±0.25%) in all the tested wood species. The density of the cedar wood amounted to 361 kg/m^3 (±10 kg/m^3), the gaboon wood to 412 kg/m^3 (±12 kg/m^3), and the meranti wood to 539 kg/m^3 (±24 kg/m^3), while the density of the sapwood and the pine heartwood totalled 466 kg/m^3 (±17 kg/m^3) and 558 kg/m^3 (±9 kg/m^3), respectively.

Table 1. Selected information concerning analysed wood species

Latin name	English trade name of wood (and code) according to EN-13556:2003	Origin	Structure of wood
Aucoumea klaineana Pierre	gaboon (AUKL)	Africa	diffuse-porous hardwood
Pinus sylvestris L.	Scots pine (PNSY)	Europe	softwood
Shorea spp.	dark red meranti (SHDR)	Asia	diffuse-porous hardwood
Thuja plicata Donn. ex D. Don	western red cedar (THPL)	North America	softwood

The wood samples were subjected to ultraviolet radiation within a spectrum range of 340-360 nm. Four fluorescent lamps were used. Each of them had a capacity of 100W. The used source of radiation imitated solar radiation, in particular the UVA component. The UVA component causes the greatest changes in the appearance and structure of organic materials exposed to the external environment. This results from the fact that UVA constitutes 90-95% of the solar radiation reaching Earth [Miller et al. 1998]. The wood samples were exposed to UV radiation for 300 hours, with the colour parameters determined every 20 hours. The tests were carried out indoors, in normal climatic conditions (a temperature of 20 ±2°C and relative humidity of 65 ±5%). The colour parameters were determined using the CIE $L^*a^*b^*$ colour space model. A 3nh NH300 colorimeter was used. The lightness (L^*), the chromatic coordinate on the red-green axis (a^*) and the chromatic coordinate on the yellow-blue axis (b^*) were determined before and after radiation, as well as the ΔE colour difference, in accordance with ISO 7724-3:2003. In the case of the analysed parameters of wood colour, the trend lines were set and the parameters of the equation of curve (y) as well as the coefficient of determination r^2 were provided.

Table 2. Data for surface tension and components of the test liquids

Liquid	Properties				
	surface tension	dispersion	polar	acid	base
	[mN/m]	[mJ/m^2]	[mJ/m^2]	[mJ/m^2]	[mJ/m^2]
Water (H_2O)	72.80	21.90	51.00	25.5	25.50
Diiodomethane (CH_2I_2)	50.80	50.80	0.00	0.00	0.00

Re-distilled water was used as a reference liquid for the wettability calculations. The surface free energy of the tested wood species was determined in accordance with the Owens-Wendt method [Owens and Wendt 1969], on the basis of the sessile drop method, measuring the contact angles of the re-distilled water and diiodomethane (tab. 2). A Phoenix 300 goniometer manufactured by Surface Electro Optics was used to determine the wettability parameters. Given the number of variables influencing the wettability of wood [Petrič and Oven 2015], the time after which the wetting angle should be marked has not been determined unambiguously. Liptáková and Kúdela [1994] and Kúdela [2014] determined the angle after a drop of liquid separated itself from the needle and in the condition of balance. Huang et al. [2012a] diversified the time the wetting angle of jack pine wood (*Pinus banksiana*) depending on the type of reference liquid. Therefore, in this case it was assumed that the test of the values of the contact angles would be performed 3 seconds after placing the drop of the reference liquid on the samples' surface. The statistical study of the test results was carried out at a significance level of 0.050.

Results and discussion

Substantial colour differences were noted in the case of the exotic wood species and pine (sapwood – S and heartwood – H) exposed to UV radiation. The most significant change was a darkening of the wood, in particular of the cedar and pine heartwood. The numerical values confirmed the results of the organoleptic observations.

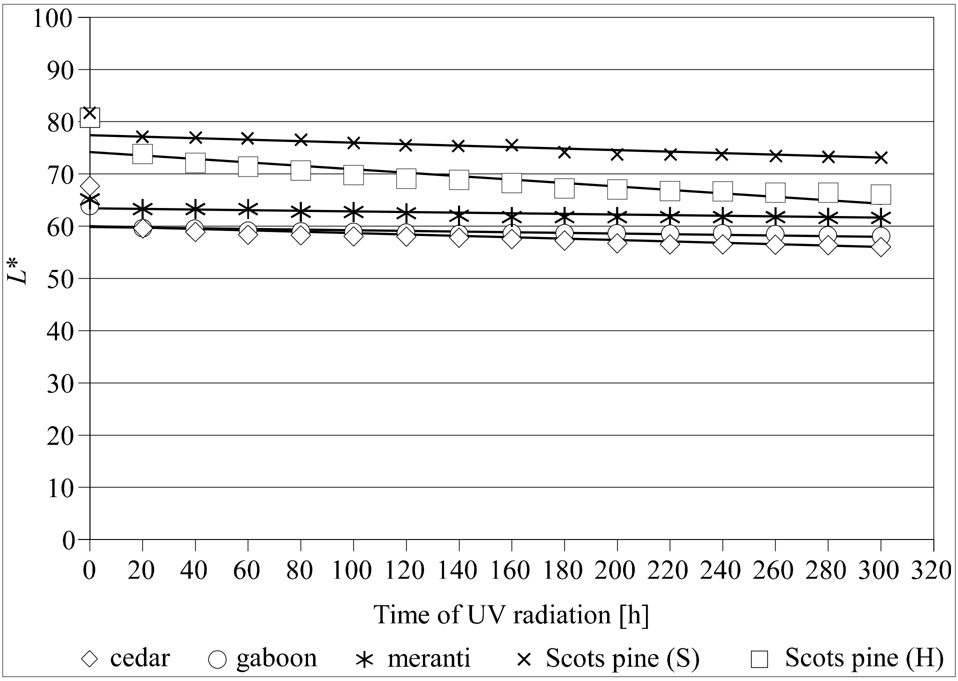

Fig. 1. Change of lightness (*L) of wood under UV radiation exposure**

The changes in wood lightness under the influence of UV radiation are presented in figure 1. The study showed that the most substantial changes in wood lightness occurred after 20 hours of UV radiation exposure. After that time, the *L** value change was linear. The research results obtained confirm the results of research conducted by other authors. Tolvaj and Mitsui [2010] showed that the greatest changes in the lightness of wood species such as black locust, beech, Japanese cedar and spruce occurred within the first 20 hours of sunlight irradiation time.

The lightness of the cedar, gaboon and meranti directly after planing were at a comparable level, i.e. 67.67 (±1.36), 63.90 (±1.50) and 65.14 (±2.65), respectively. The pine wood was characterized by a colour much lighter than the exotic wood tested. The *L** values for the pine sapwood and heartwood were 81.43 (±3.48) and 80.76 (±0.81), respectively. It was observed that the greatest difference in wood lightness was in the case of the cedar. After 20 and 300 hours of UV radiation exposure, a drop in the *L** value by 12% and 18%, respectively, was found. The smallest changes in lightness were noticed in the case of the meranti wood. After 20 and 300 hours of UV radiation exposure, the *L** value for the meranti wood amounted to 63.29 (±5.31) and 61.60 (±1.74) respectively, translating into a 3% and 5% decrease in the *L** value.

Changes in the other colour component values were also observed. The tests showed that the most significant changes in the *a** colour component for the gaboon, meranti and pine wood occurred after 20 hours of UV radiation exposure (fig. 2). After that time, the *a** value change was linear.

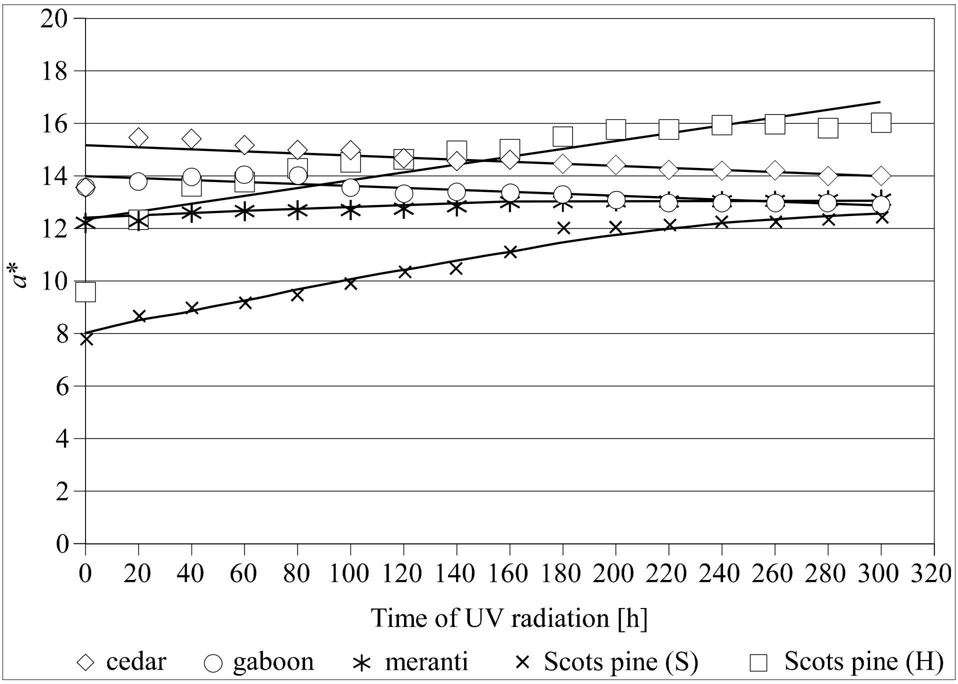

Fig. 2. Change in *a parameter of wood colour under UV radiation exposure**

Based on the analysis of the changes in the chromatic coordinate on the red-green colour axis, it was concluded that, after UV exposure, the meranti and pine wood (sapwood and heartwood) showed a tendency to become redder, while the cedar showed a tendency to become greener. The gaboon wood showed a colour change from red to green (Δ*a** after 20 and 300 hours of UV exposure was 0.18 (±0.02) and –0.15 (±0.02), respectively). The biggest changes in the *a** parameter were observed in the case of the pine wood. After 300 hours of UV exposure, the Δ*a** values for the pine sapwood and heartwood were 4.66 (±0.29) and 6.44 (±1.16), respectively. The changes in the redness of the meranti were not as noticeable as those of the pine wood. In the case of the meranti, the Δa^* value after 300 hours of UV exposure totalled 0.90 (±0.07).

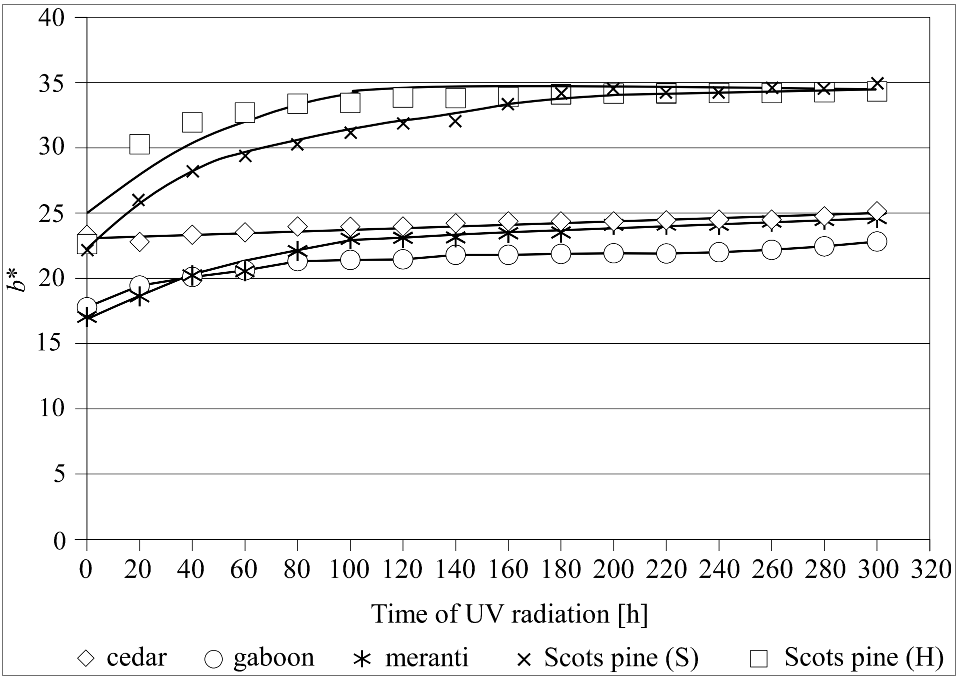

Fig. 3. Change in *b parameter of wood colour under UV radiation exposure**

Changes in the chromatic coordinate value on the yellow-blue colour axis (b^*) were analysed and the results are presented in figure 3. It was concluded that after UV radiation exposure, the colour of the gaboon, meranti and pine (sapwood and heartwood) changed to yellow. In turn, the cedar wood showed a colour change from blue to yellow. The biggest changes in the b^* parameter were observed for the pine wood. After 300 hours of UV exposure, the Δb^* values for the pine sapwood and heartwood were 12.71 (±0.79) and 11.71 (±1.11), respectively. In the case of the meranti and gaboon, the Δb^* values after 300 hours of UV radiation exposure amounted to 7.58 (±1.93) and 5.05 (±1.60), respectively.

Lignin is a natural polymer which constitutes a kind of binder in wood structure. Softwood contains more cellulose (up to 60%) and lignin (up to 30%), but less hemicelluloses (ca. 10%) than hardwood. In hardwood, the cellulose content amounts to 50%, lignin ca. 20% and hemicelluloses ca. 30% [Požgaj et al. 1993]. According to Persze and Tolvaj [2012], chromophoric groups in wood are mostly found in the lignin, extractives and their derivatives. Lignin derivatives are mainly responsible for the process of wood yellowing. Yellowing is the main wood colour change resulting from lignin photodegradation. Due to the fact that softwood contains more lignin, it is more susceptible to the yellow oriented colour change, confirmed in the tests conducted. Persze and Tolvaj [2012] state that low extractive contents may be the reason for the low thermal effect on specimens exposed to light irradiation. This results in wood colour changes in the red colour space. Those dependencies were also confirmed by tests carried out by Mitsui et al. [2001]. Colour parameter changes may result from the differences in extractive contents in particular wood species. Pandey [2005] tested colour changes in natural wood, without extractives. Wood samples without extractives were characterised by moderate colour changes over a longer irradiation time.

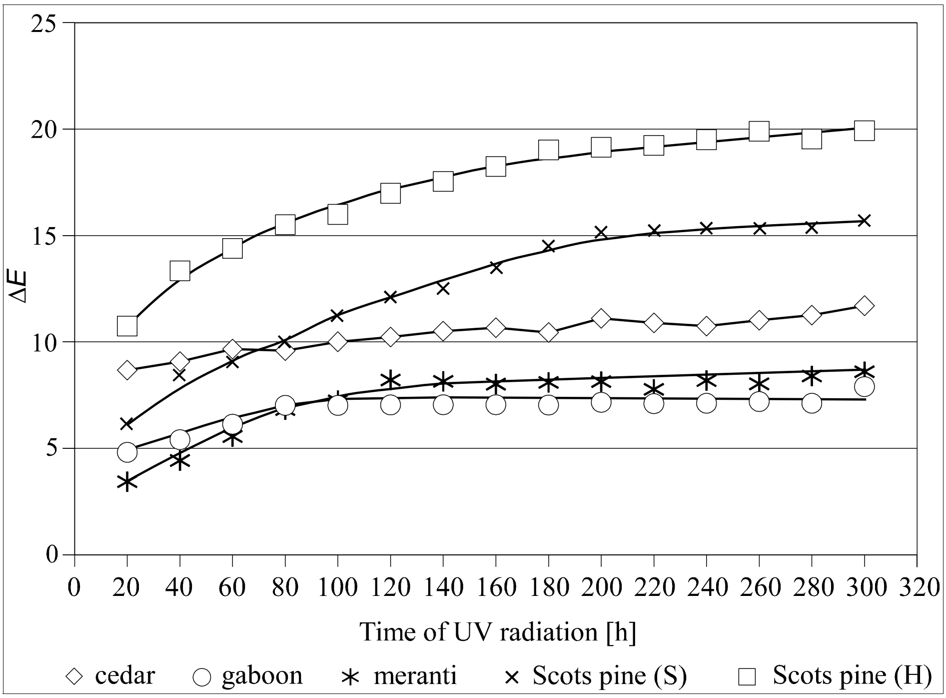

Fig. 4. Total colour difference (Δ*E*) of the tested wood species

The most important parameter to describe the stability of the colour of the tested wood species is the total colour difference ΔE, which is the resultant of the changes in individual parameters, i.e. colour components**.** On the basis of the calculated ΔE values, it can be concluded that the greatest total colour difference in the gaboon, meranti and pine woods occurred at the beginning of UV radiation exposure (fig. 4). The colour changes are particularly noticeable within the first 100 hours of exposure. These relations were not so strong in the case of the cedar wood, whose ΔE remained within a narrow spectrum. The most significant colour changes, and thus the lowest colour stability, were characteristic of the pine wood. The ΔE value of the pine heartwood after 100 and 300 hours of UV radiation exposure amounted to 15.99 (±1.64) and 19.92 (±1.58), respectively. The ΔE value for the pine sapwood after 100 and 300 hours of UV radiation exposure totalled 11.29 (±1.18) and 15.70 (±0.91), respectively. In general, it can be stated that the gaboon and meranti were characterized by similar ΔE values, which were half the ΔE value of the pine sapwood.

Changes in the particular colour components and the total colour difference in the tested wood species under UV radiation exposure in time (t) were described using curves. Table 3 presents the relations between $L^*(t)$, $a^*(t)$, $b^*(t)$ and $\Delta E(t)$ determined for $t \geq 20$ h. Based on the presented comparisons, it is possible to forecast the changes in the wood colour components and the total colour difference depending on the UV irradiation time. It should be noted that the values of the coefficient of determination r^2 were from 0.84 to 0.99. This indicates the significant correlation between the colour components of the tested wood and the UV irradiation time.

Table 3. Equations of curves describing the relations between L^*, a^*, b^*, ΔE and the time (t) of UV exposure (a – directional factor, b – absolute term) and r^2 – coefficient of determination)

Wood species	Parameters			
	a^*		b^*	
	$y = at + b$	r^2	$y = a\ln(t)+b$	r^2
cedar	$y = -0.0053t + 15.47$	0.96	$y = 0.69\ln(t) + 20.78$	0.98
gaboon	$y = -0.0043t + 14.06$	0.87	$y = 1.07\ln(t) + 16.31$	0.97
meranti	$y = 0.0024t + 12.47$	0.85	$y = 2.27\ln(t) + 11.90$	0.97
Scots pine (S)	$y = 0.0151t + 8.48$	0.93	$y = 3.45\ln(t) + 15.47$	0.98
Scots pine (H)	$y = 0.0113t + 13.12$	0.88	$y = 1.42\ln(t) + 26.68$	0.92
	L^*		ΔE	
	$y = at + b$	r^2	$y = a\ln(t) + b$	r^2
cedar	$y = -0.0115t + 59.33$	0.96	$y = 1.04\ln(t) + 5.33$	0.94
gaboon	$y = -0.0046t + 59.39$	0.88	$y = 0.91\ln(t) + 2.39$	0.84
meranti	$y = -0.0069t + 63.34$	0.85	$y = 1.89\ln(t) - 1.92$	0.89
Scots pine (S)	$y = -0.0159t + 77.54$	0.95	$y = 3.84\ln(t) - 5.99$	0.97
Scots pine (H)	$y = -0.0258t + 72.83$	0.92	$y = 3.51\ln(t) + 0.22$	0.99

Wood exposed to UV radiation should be characterized in terms of the surface properties determining further behaviour in an aggressive environment (water, impregnating agents) and, as a consequence, susceptibility to degradation. An analysis of the water contact angle makes it possible to determine the characteristics of the surface properties. Determining these characteristics makes it possible to predict interactions between the wood and the wetting materials. During analysis of the contact angles, the change in their values in time constitutes an important factor [Gindl et al. 2001; Wolkenhauer et al. 2009].

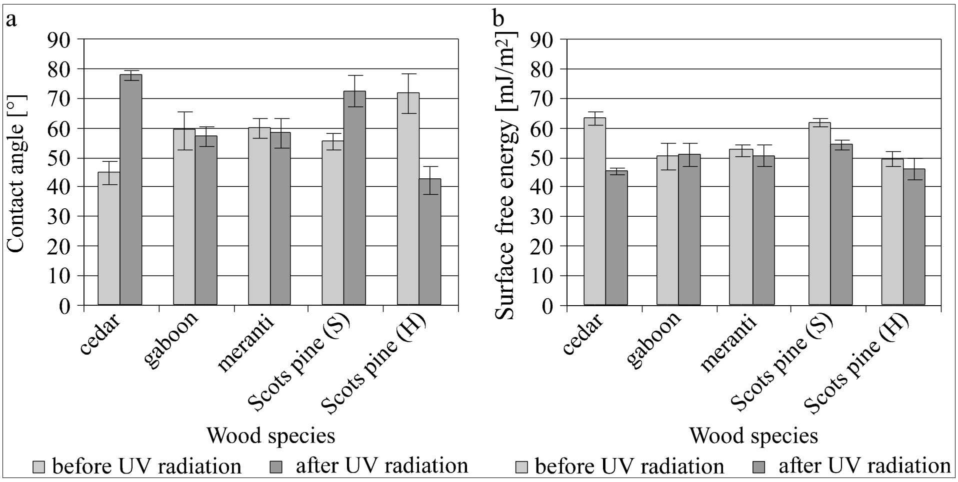

Fig. 5. Contact angle of water on wood (a) and surface free energy (b) of wood before and after 300 hours of UV radiation

The tests showed that the UV radiation had a significant impact on the contact angle of the cedar and pine sapwood (fig. 5a). Those dependencies determined the value of the surface free energy (fig. 5b). This was due to the fact that the tested softwood had a lower density than the hardwood. The decisive factor was the openness of the wood structure for water permeability. Water not only penetrated the crevices of the cell walls, but it also went through the cellular pits and cell bore holes. After 300 hours of UV irradiation, the contact angle of the cedar and pine sapwood was, respectively, 75% and 30% greater than the contact angle of the cedar and pine sapwood after planing. The surface free energy of the cedar and pine sapwood was, respectively, 28% and 12% lower than the surface free energy of the cedar and pine sapwood after planing. These changes may have resulted from the extractive changes in the wood under the influence of UV irradiation [Teacă et al. 2013]. As a result of wood aging, the wood fibers rise, which leads to an increase in wood surface area and its greater susceptibility to wetting. Those dependencies have been confirmed by tests conducted by Nzokou et al. [2011].

Conclusions

The tests conducted showed that ultraviolet radiation significantly contributed to the change in colour and wettability of the tested wood species. After irradiation, the cedar, gaboon and meranti wood were darker than the pine heartwood or sapwood. All the tested wood species showed the greatest decrease in lightness after 20 hours of UV irradiation. After that time, the L^* value change was linear. All the tested exotic wood species were characterised by less significant colour changes, as compared to the pine sapwood and heartwood. It was concluded that the greatest total colour changes in the case of the gaboon, meranti and pine wood occurred after 100 hours of irradiation. Such dependencies were not observed for the cedar wood. The significant influence of UV irradiation on the contact angle and the surface free energy of the cedar and pine sapwood was also observed.

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EN 13556:2003. Round and sawn timber – Nomenclature of timbers used in Europe
ISO 7724-3:2003. Paints and varnishes. Colorimetry. Part 3: Calculation of colour differences
ISO 13061-1:2014. Physical and mechanical properties of wood – Test methods for small clear wood specimens – Part 1: Determination of moisture content for physical and mechanical tests
ISO 13061-2:2014. Physical and mechanical properties of wood – Test methods for small clear wood specimens – Part 2: Determination of density for physical and mechanical tests

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