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EFFECT OF UV RADIATION ON CHANGE IN COLOR OF STEAMED BEECH WOOD

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ABSTRACT

The wood of the beech (*Fagus Sylvatica L.*) was steamed with a saturated steam-air mixture at a temperature of t = 95°C, or saturated steam at t = 115°C and t = 135°C to obtain a pale pink, red-brown and rich brown-red color. Subsequently, samples of unsteamed and steamed beech wood were irradiated with a UV lamp in a Xenotest Q-SUN Xe-3-HS after drying in order to test the color stability of steamed beech wood. The color change of the wood surface was evaluated by means of measured values on the coordinates of the color space CIE $L^*a^*b^*$. The results show that the surface of unsteamed beech wood as well as steamed beech wood with a steam-air mixture at a temperature of t = 95°C and saturated steam with a temperature of t = 125°C darkened and turned brown to a brown-yellow color due to UV radiation. The deep brown-red color of the surface of beech wood steamed with saturated steam with a temperature of t = 135°C brightened to a brown-yellow color similar to the color of unsteamed beech wood. The analysis of the changes in the color space CIE L^* a^* b^* shows that the greater the darkening and browning of the beech wood by steaming, the smaller the changes in the values of ΔL^*, Δa^* Δb^* of the steamed beech wood caused by UV radiation. The positive effect of steaming on UV resistance is evidenced by the decrease in the overall color difference ΔE^*. While the value of the total color difference of unsteamed beech wood caused by UV radiation is ΔE^* = 15.3, for beech wood steamed with a saturated steam-air mixture at t = 95°C it decreased to ΔE^* = 9.5, which is a decrease of 37.9%, for steamed beech wood steamed with saturated steam with temperature t = 115°C is ΔE^* = 6.2 which is a decrease of 59.4% and for steamed beech wood steamed with saturated steam with temperature t = 135°C is ΔE^* = 4.5 which is a decrease of 70.5%.

KEYWORDS: Wood, *Fagus sylvatica* L., UV radiation, color difference, saturated water steam.

INTRODUCTION

The color of wood is a basic physical-optical property, which belongs to the group of macroscopic features on the basis of which the wood of individual woody plants differs visually. The color of the wood is formed by chromophores, i.e. functional groups of the type: -C = O, -CH = CH-CH = CH-, -CH = CH-, aromatic nuclei found in the chemical components of wood (lignin and extractive substances such as dyes, tannins, resins and others), which they absorb some components of the electromagnetic radiation of daylight and thus create the color of the wood surface perceived by human vision.

The color of wood changes in thermal processes such as: wood drying, wood steaming, thermo-wood production technologies. The wood darkens and, depending on the wood, acquires color shades of pink, red, brown to dark brown-gray (Deliiski 1991, Molnár and Tolvaj 2004, Cividini et al. 2007, González et al. 2009, Todaro et al. 2012, Bekhta and Niemz 2013, Dzurenda 2014, Milić et al. 2015, Barcík et al. 2015, Baranski et al. 2017, Dzurenda 2022).

Beech sapwood is heated in the process of steaming with saturated humid air or saturated water steam and changes its physical, mechanical and chemical properties. The action of heat initiates chemical reactions in wet wood, such as: extraction of water-soluble substances, degradation of polysaccharides, cleavage of free radicals and phenolic hydroxyl groups in lignin, resulting in the formation of new chromophoric groups causing a change in the color of the wood. These facts are used for full-volume modification of wood color into non-traditional color shades of beech wood of individual trees. Depending on the length of steaming time and the temperature of the steaming medium, it acquires a pale pink to red-brown color shade (Deliiski 1991, Tolvaj et al. 2009, Dzurenda 2014, Milić et al. 2015, Geffert et al. 2017, Dzurenda and Dudiak 2021, Dzurenda 2022).

The color of the wood also changes due to the long-term effects of sunlight on its surface. The surface of the wood darkens and mostly yellows and browns. This fact is also referred to in the professional literature as natural aging (Hon 2001, Reinprecht 2008, Baar and Gryc 2011).

Solar radiation falling on the wood surface is partly absorbed and partly reflected from the surface. The absorbed spectrum of infrared electromagnetic radiation is converted into heat and the photon flux of ultraviolet and part of visible radiation of wavelengths λ = 200 - 400 nm is the source of initiation of photolytic and photooxidation reactions with lignin, polysaccharides and accessory substances of wood. Of the chemical components of wood, lignin is the most subject to photodegradation, which captures 80 – 85% of UV radiation, carbohydrates absorb 5 – 20% and 2% of the accessory substance (Kuo and Hu 1991, Gandelová et al. 2009). These reactions cleave the lignin macromolecule with the simultaneous formation of phenolic hydroperoxides, free radicals, carbonyl and carboxyl groups and to a lesser extent depolymerize polysaccharides to polysaccharides with a lower degree of polymerization to form carbonyl, carboxyl groups and gaseous products (CO, CO_2, H_2). Although photodegradation of natural wood is a widely studied phenomenon of (Hon 2001, Müller et al. 2003, Pandey 2005, Persze and Tolvaj 2012, Baar and Gryc 2011, Denes and Lang 2013, Zivkovic et al. 2013, Geffertová et al. 2018) the issue of photodegradation and color stability of steamed wood has so far received less attention (Banadics et al. 2019, Dzurenda et al. 2020, 2022, Varga et al. 2021).

The aim of the work is to investigate the color fastness of the pale pink-brown color of beech wood obtained by the process of steaming with a saturated steam-air mixture with a temperature of $t = 95°C$, or red-brown and rich brown-red color of steamed beech wood with saturated steam at temperatures $t = 125°C$ and $t = 135°C$ through a simulated aging process - UV radiation in Xenotest Q-SUN Xe-3-HS. The color fastness of the wood is evaluated through changes in the coordinates L^*, a^*, b^* of the CIE color space $L^*a^*b^*$ and the total color difference ΔE^*.

MATERIAL AND METHODS

Material

Wet wood beech blanks made of sapwood, or mature wood without the presence of a false heartwood with dimensions 40 × 100 × 800 mm and moisture content $w_p = 63.8 \pm 3.5\%$ was steamed with a saturated steam-air mixture at a temperature of $t = 95°C$, or saturated with steam at $t = 115°C$ and $t = 135°C$ for $\tau = 9$ h in order to obtain a pale pink-brown, red-brown and deep brown-red color in a pressure autoclave: APDZ 240 (Himmasch AD, Haskovo, Bulgaria) installed in the company Sundermann s.r.o. Banská Štiavnica (Slovakia).

Methods

The beech wood steaming mode is shown in Fig. 1. The temperatures of the saturated steam-air mixture and saturated water steam in individual steaming modes are given in Tab. 1. The temperature values t_{max} and t_{min} are the temperatures for controlling the supply of saturated steam to the pressure autoclave for carrying out the technological process. The temperature t_4 is a parameter of the saturated water steam pressure in the autoclave to which the pressure in the autoclave must be reduced before the pressure device can be opened safely before the autoclave is opened.

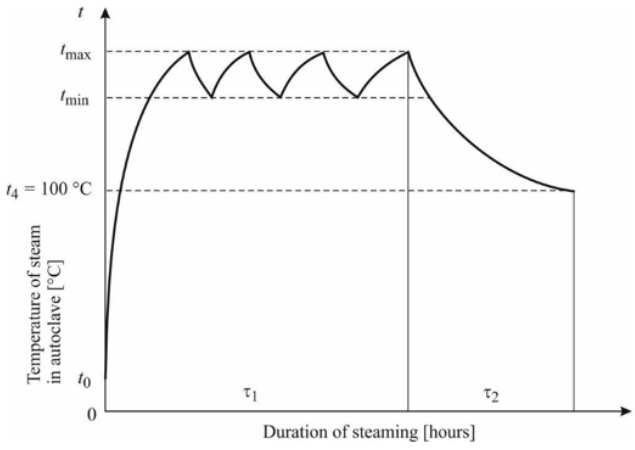

Fig. 1: Mode of color modification of beech wood with steamed with a saturated steam-air mixture or saturated water steam.

Tab. 1: Mode of color modification of beech wood with steamed with a saturated steam-air mixture or saturated water steam.

Mode	Temperature in autoclave (°C)			Time of operation (h)		
	t_{min}	t_{max}	t_4	τ_1 - phase I	τ_2 - phase II	Total time
t_I = 95 ± 2.5°C	92.5	97.5	-	8.0	1.0	9.0
t_{II} = 115 ± 2.5°C	112.5	117.5	100	7.5	1.5	9.0
t_{III} = 135 ± 2.5°C	132.5	137.5	100	7.5	1.5	9.0

The steamed and unsteamed beech wood blanks were subsequently dried to a moisture content of w = 10 ± 0.5%. Samples measuring 100 × 50 × 15 mm (L × R × T) were made to test the color fastness of the wood. Color measurement was performed on a radial surface machined by planing. The color coordinates of beech wood samples in the color space CIE *L*a*b*,* before irradiation are given in Tab. 2.

*Tab. 2: Values coordinate color space CIE L*a*b* of unsteamed and steamed beech wood.*

Labeling of samples	Wood color	Color coordinates in the space CIE *L*a*b**		
		L*	a*	b*
Unsteamed beech wood	light white-gray-yellow	74.6 ± 2.1	7.8 ± 1.5	19.0 ± 1.9
Steamed at t = 95 ± 2.5°C	pale pink-brown	69.1 ± 1.8	11.3 ± 1.1	20.6 ± 1.3
Steamed at t = 115 ± 2.5°C	red-brown	63.2 ± 1.6	11.5 ± 1.2	23.2 ± 1.1
Steamed at t = 135 ± 2.5°C	deep brown-red	53.5 ± 1.4	12.4 ± 0.8	25.3 ± 1.2

In the Q-SUN Xe-3-HS xenon test chamber (Q-Lab Corporation, USA), beech wood samples were irradiated for τ = 298 h. During the exposure, the color of the irradiated surface was measured regularly at τ = 24 h intervals. The mode for simulating outdoor conditions was used, i.e. when the wood is exposed to radiation outdoors but is protected from rain (Tab. 3). The samples placed in the Xenotest chamber were regularly and systematically relocated according to the recommended scheme to ensure their same irradiation intensity and temperature (Kúdela and Kubovský 2016).

Tab. 3: Aging parameters set according to ASTM G 155.

Step	Mode	Radiation intensity ($W \cdot m^{-2}$)	Black panel temperature (°C)	Air temperature (°C)	Relative humidity (%)	Time (min)
1	Radiation	0.35	63	48	30	102
2	No radiation	–	–	38	–	18

According to ASTM G 155, the radiation intensity was set to 0.35 $W \cdot m^{-2}$ at a radiation wavelength λ = 340 nm. This is the average annual radiation intensity in the temperate zone. The temperature, checked on the black panel, signals the maximum surface temperature. The color was measured on each body in ten places, which means that 30 measurements were always made for one set of bodies.

The color of the irradiated unsteamed and steamed beech wood surface samples, in the color space CIE *L*a*b**, was measured with a Color reader CR-10 colorimeter (Konica Minolta, Japan). A D65 light source was used and the diameter of the optical scanning aperture was 8 mm.

The total color difference ΔE^* of the color change of the surface of beech wood samples due to UV radiation is determined according to the following equation ISO 11 664-4:

$$\Delta E^* = \sqrt{(L^*_{298} - L^*_0)^2 + (a^*_{298} - a^*_0)^2 + (b^*_{298} - b^*_0)^2} \quad (1)$$

where: L^*_0, a^*_0, b^*_0 values at the surface color coordinates of the dried milled unsteamed and steamed beech wood prior to exposure. L^*_{298}, a_{298}, b^*_{298} values on the surface color coordinates of the dried milled unsteamed and steamed beech wood during UV exposure.

The measured values on the brightness coordinate L^* and the chromaticity coordinates a^*, b^*, as well as the calculated values of the total color differences ΔE^* during the observed exposure periods were statistically and graphically evaluated using Excel and Statistica 12 programs (V12.0 SP2, USA).

RESULTS AND DISCUSSION

The color of unsteamed and steamed beech wood before and after UV irradiation in the Q-SUN Xe-3-HS test chamber is shown in Fig. 2. According to the visual evaluation of the color of beech wood before and after UV radiation, it can be stated that while the light white-gray-yellow color of unsteamed beech wood, the pale pink-brown color of beech wood steamed steam-air mixture with temperature t = 95°C and red-brown the color of steamed beech wood saturated with water steam darkened due to photodegradation reactions induced by UV radiation and acquires a brown-yellow color shade, so the deep brown-red color of steamed beech wood with saturated water steam with temperature t = 135°C lightened to a paler brown shade.

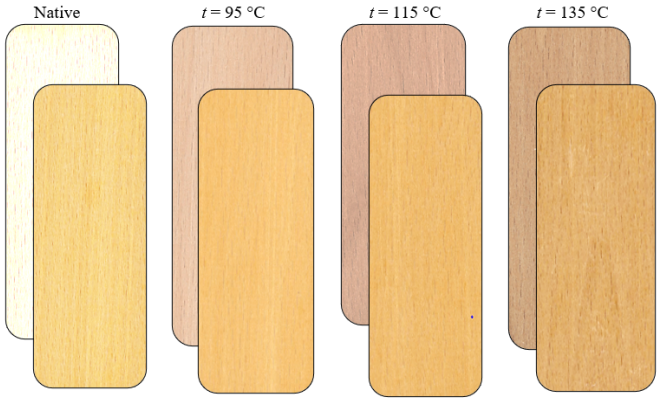

Fig. 2: View of beech wood before and after UV irradiation: native; steamed at t = 95°C; steamed at t = 115°C and steamed at t = 135°C.

The course of color changes of unsteamed and steamed beech wood in the color space CIE $L^*a^*b^*$ under the influence of UV radiation in Xenotest Q-SUN Xe-3-HS for 298 h at the individual coordinates L^*, a^*, b^* show Figs. 3 to 5.

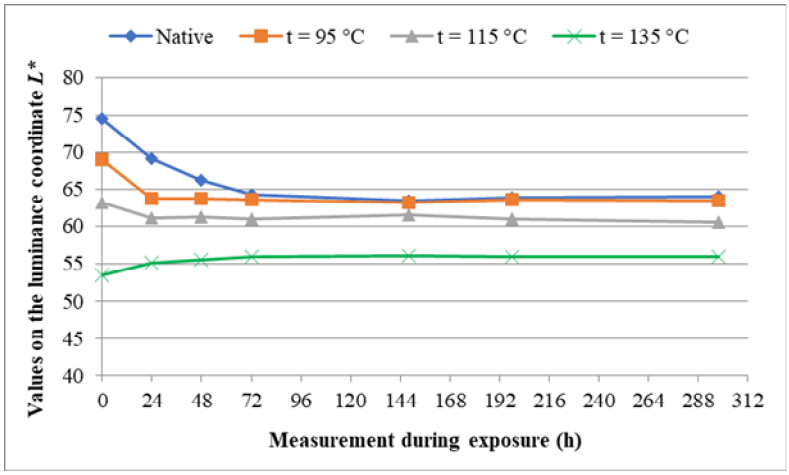

Fig. 3: The course of changes of values on the brightness coordinate L in the process of UV irradiation of samples of unsteamed and steamed beech wood.*

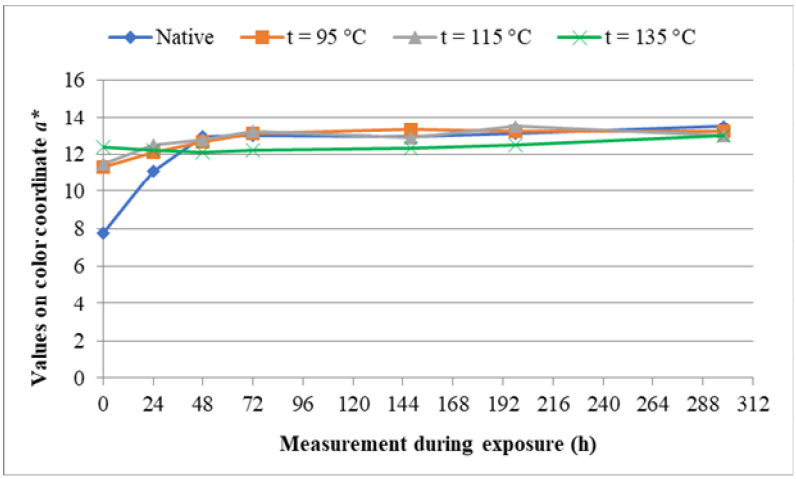

Fig. 4: The course of changes of values on the coordinate of red color a in the process of UV irradiation of samples of unsteamed and steamed beech wood.*

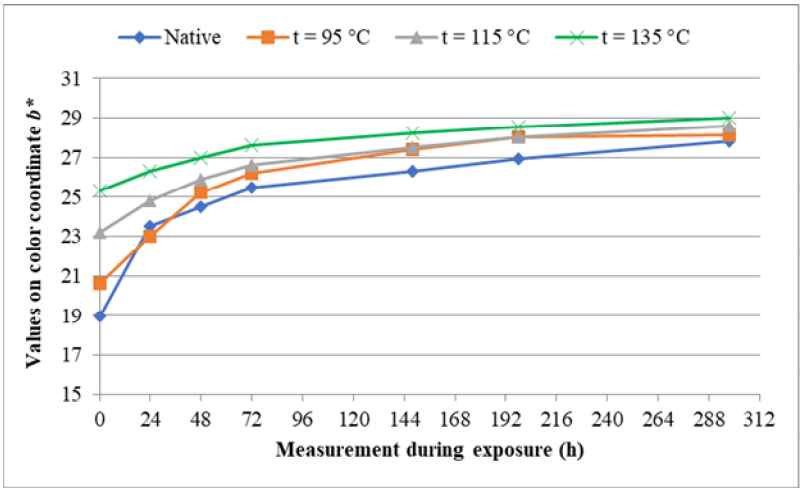

Fig. 5: The course of changes of values on the coordinate of yellow color b in the process of UV irradiation of samples of unsteamed and steamed beech wood.*

Based on experimentally determined values of color changes on the coordinate of brightness *L**, chromatic coordinates of red color *a** and yellow color *b** of beech wood samples induced by photodegradation reactions of individual beech wood components with UV radiation in Xenotest Q-SUN Xe-3-HS it can be stated that significant changes in the color of the wood occur in the first 72 hours of UV radiation. The degree of darkening and browning of unsteamed and steamed beech wood induced by UV radiation during 298 h of irradiation in the color space CIE *L*a*b** is declared by the displacements on the individual boards listed in Tab. 4.

Tab. 4: Sizes of changes in ΔL, Δa *, Δb* values in the CIE L* a*b* color space of unsteamed and steamed beech wood before and after UV irradiation in the Q-SUN Xe-3-HS test chamber.*

Beech wood	Color coordinates of samples in the CIE *L*a*b** sample area before and after UV irradiation in the Q-SUN Xe-3-H test chamber								
	L_0^*	L_{298}^*	ΔL^*	a_0^*	a_{298}^*	Δa^*	b_0^*	b_{289}^*	Δb^*
Unsteamed beech wood	74.6	64.0	-10.6	7.8	13.5	+ 5.7	19.0	27.8	+ 8.8
Steamed at t = 95 ± 2.5°C	69.1	63.5	- 5.6	11.3	13.2	+ 1.9	20.6	28.1	+ 7.5
Steamed at t = 115 ± 2.5°C	63.2	60.5	- 2.7	11.5	13.0	+ 1.5	23.2	28.6	+ 5.4
Steamed at t = 135 ± 2.5°C	53.5	56.0	+ 2.5	12.4	13.0	+ 0.6	25.3	29.0	+ 3.7

Unsteamed beech wood darkened due to photochemical reactions induced by UV radiation and recorded a decrease in the brightness coordinate value of ΔL* = -10.4 and browned by an increase in points on the red chromaticity coordinate value of Δa* = +5.7 and in the yellow color coordinate value of Δb* = +8.8. The above findings on the darkening of native - thermally untreated beech wood are in accordance with the opinions of experts dealing with changes in the properties of native wood of individual trees due to solar radiation, or UV radiation (Hon 2001, Müller et al. 2003, Pandey 2005, Chang et al. 2010, Baar and Gryc 2011, Kúdela and Kubovský 2016, Geffertová et al. 2018, Dzurenda et al. 2020).

Steamed beech wood shows smaller changes in the coordinates of brightness L*, red color a* and yellow b* compared to unsteamed beech wood. Numerically, this is documented by changes in the individual coordinates of the color space CIE L*a*b*. While the darkness of steamed beech wood with a steam-air mixture with temperature t = 95°C due to UV radiation increased, the values decreased from L_0* = 69.1 to L_{298}* = 63.5 i.e. ΔL* = -5.6 and the darkness of beech wood treated with saturated water steam at t = 115°C was reduced by UV radiation by decreasing the values by ΔL* = -2.7, so the brightness of steamed beech with steam with temperature t = 135°C increased from L_0* = 53.5 to L_{298}* = 58.1 i.e. the value of ΔL* = +2.5.

On the chromatic coordinates of the color space CIE L*a*b*, the color changes of beech wood steamed with a steam-air mixture with a temperature of t = 95°C increased on the coordinate red color a* by the difference Δa* = + 1.9 and on the yellow coordinate b* difference Δb* = +7.5. The red-brown color of steamed beech wood formed by steaming with saturated steam with a temperature of t = 115°C due to UV radiation increased on the coordinate red color by value of Δa* = +1.5 and on the coordinate yellow color by value of Δb* = +5.4. Changes in the values of beech wood steamed with saturated steam with a temperature of t = 135°C due to UV radiation increased in the red coordinate by value of Δa* = +0.6 and in the yellow coordinate by value of Δb* = +3.7.

A comparison of the values of changes ΔL^*, Δa^*, Δb^* at the color space CIE coordinates $L^*a^*b^*$ induced by UV radiation of steamed and unsteamed beech wood shows that the values at the luminance coordinate L*, red a* and yellow b* color at the color space CIE $L^*a^*b^*$ are lower for steamed wood and decrease with increasing darkness of the color obtained by the steaming process.

Based on the above findings, it can be stated that steamed beech wood, due to chemical changes and partial decomposition of functional groups of chromophores, is more resistant to photochemical reactions with UV radiation causing a change in the color of the wood surface. The fact that steamed wood, unlike unsteamed wood, is more resistant to UV radiation is also pointed out in the works of the authors (Dzurenda et al. 2020, 2022, Varga et al. 2021).

In the work: Influence of UV radiation on color stability of natural and thermally treated maple wood with saturated water steam, developed by Dzurenda et al. 2020 the lightening of the surface color of steamed maple wood after its irradiation in Xenotest 450 with a xenon lamp emitting UV radiation with a wavelength of 340 nm, intensity 42 ± 2 $W \cdot m^{-2}$ for 7 days is reported. The lightening of the red-brown color of steamed maple wood is declared by the increase of the values on the lightness coordinate from $L_1^* = 65.3$ to the value of $L_2^* = 70.7$, i.e. to $\Delta L^* = +5.4$, the increase of the value on the chromatic coordinate of the yellow color from $b_1^* = 19.4$ to the value $b_2^* = 28.9$, i.e. to $\Delta b^* = +9.3$, with a slight change in the red coordinate value from $a_1^* = 10.8$ to $a_2^* = 10.3$, i.e. to $\Delta a^* = -0.5$. The effect of UV radiation on steamed agate wood is discussed in Varga et al. 2021 states that while the surface of steamed agate wood darkened slightly at a steaming temperature t = 100°C, the surface of agate wood brightened at a steaming temperature t = 120°C.

The changes in the values at the individual coordinates of the color space CIE L*a*b* induced on the surface of unsteamed and steamed beech wood by UV radiation in Xenotest Q-SUN Xe-3-HS are reflected in the quantification of the color change of the beech wood surface expressed by the total color difference ΔE*. The influence of UV radiation on the magnitude of color changes of the analyzed beech wood samples in the form of the total color difference ΔE* is shown in Fig. 6.

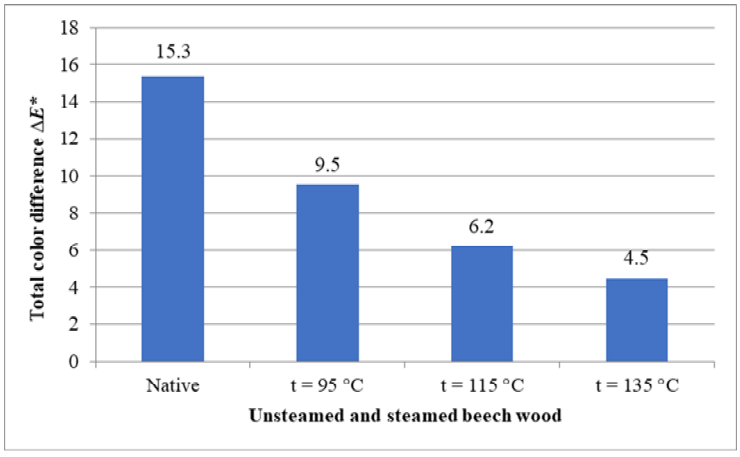

Fig. 6: Influence of UV radiation on the size of the total color difference ΔE of unsteamed and steamed beech wood.*

The lower values of the total color difference ΔE^* of steamed beech wood indicate the benefit of steaming on its resistance to UV radiation causing color change in the process of natural aging. While the color change of unsteamed beech wood caused by UV radiation reaches the value $\Delta E^* = 15.3$, for steamed beech wood steamed with temperature $t = 95°C$ it is $\Delta E^* = 9.5$, which is a decrease of 37.9% compared to the total color difference of unsteamed beech wood, for steamed beech wood steamed with saturated steam with temperature $t = 115°C$ is $\Delta E^* = 6.2$ which is a decrease of 59.4% and for steamed beech wood steamed with saturated steam with temperature $t = 135°C$ is $\Delta E^* = 4.5$ which is a decrease of 70.5%.

CONCLUSIONS

The paper presents the results of surface color changes of unsteamed and steamed beech wood due to UV radiation in Xenotest Q-SUN Xe-3-HS during 298 h irradiation: *(1)* The surface color of unsteamed beech changes color under the influence of UV radiation more than the surface of steamed beech wood. *(2)* The measured changes in the values at the coordinates of the color space CIE $L^*a^*b^*$ caused by UV radiation in unsteamed beech wood are: $\Delta L^* = -10.6$; $\Delta a^* = +5.7$; $\Delta b^* = +8.8$. *(3)* Changes in the values of the coordinates color space CIE $L^*a^*b^*$ induced by UV radiation in steamed beech wood at $t = 95°C$ are: $\Delta L^* = -5.6$; $\Delta a^* = +1.9$; $\Delta b^* = +7.5$, at steam temperature $t = 115°C$: $\Delta L^* = -2.7$; $\Delta a^* = +1.5$; $\Delta b^* = +5.4$ and at the steaming temperature $t = 135°C$ are: $\Delta L^* = +2.5$; $\Delta a^* = +0.6$; $\Delta b^* = +3.7$. *(4)* The rate of color change of beech wood induced by UV radiation, expressed in terms of the total color difference ΔE^*, shows that while the value of the total color difference of unsteamed beech wood is $\Delta E^* = 15.3$, beech wood steamed at a steaming temperature t = 95°C is $\Delta E^* = 9.5$, for steamed beech wood steamed with saturated steam t = 115°C is $\Delta E^* = 6.2$ and for steamed beech wood steamed with saturated steam t = 135°C is $\Delta E^* = 4.5$, which is a decrease of 70.5% over unsteamed beech wood. *(5)* The decrease in changes the values of ΔL^*, Δa^*, Δb^* and the total color difference ΔE^* caused by UV radiation indicate a positive effect of steaming beech wood. The functional groups of the chromophores break down in the wood during steaming. Steamed beech wood is more resistant to photochemical reactions by UV radiation causing color changes in the process of natural aging.

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