Color Changes of Compression and Opposite Spruce Wood (*Picea abies* L. Karst.) Affected by Different Drying Conditions

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The color changes of compression and opposite spruce (*Picea abies* L. Karst) wood were evaluated as a function of different drying conditions. Compression wood samples and their corresponding opposite wood samples from the opposite part of the log were compared after three different drying modes. The color of the samples before and after the drying was characterized using the color coordinates L^*, a^*, b^*, C^*_{ab}, C, h^*, S_{ab}, and the color difference (ΔE^*) in the standard color space according to the International Commission on Illumination (CIELAB). The drying temperature was the most remarkable factor for discoloration of the samples. The lightness (L^*) of the samples decreased with increased temperature. However, darkening was more pronounced in the opposite wood samples. The overall color difference (ΔE^*) was found to be higher in the opposite wood. The compression wood was more statured in color with a deeper hue angle due to the drying process.

Keywords: Color change; Compression wood; Opposite wood; Artificial drying; Spruce

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INTRODUCTION

Compression wood (CW), a type of reaction wood, is produced by gymnosperms to orientate stems and branches in response to displacement and the requirements for light. It is formed on the lower side of branches and of the stem or trunk of a leaning tree. The accompanying changes in the physical and chemical properties of the wood result in its different mechanical and physical properties compared to normal wood, including differences in color, fiber properties, workability, distortion, and strength. These differences have important consequences for wood-based industries in the processing and serviceability of products containing reaction wood (Gardiner *et al*. 2014).

Heterogeneity in the wood anatomical structure can remarkably affect its color. Compression wood appears dark because it absorbs more light (due to a high lignin content) and scatters less light (due to the thick tracheid walls) (Nečesaný 1956). The color of wood is the main optical characteristic of some wood species. It characterizes the appearance of wood and its importance is increased in the production of furniture, musical instruments, artistic objects, sport equipment, *etc*. The surface appearance of wood is often evaluated by examining its texture, roughness, and color (Vidholdová and Reinprecht 2019). The color of wood is also influenced by chemical components of wood such as cellulose, hemicelluloses, and lignin (Požgaj *et al.* 1993). It is well known that the color changes as the temperature rises. The darkening of wood is caused by the thermal degradation of hemicelluloses and lignin.

This darkening can be initiated at temperatures as low as 65 °C, depending on moisture content, heating medium, pH, species, and exposure period (White and Dietenberger 2001). In general, softwoods become slightly darker, while hardwoods become considerably darker. The artificial (high temperature) drying of spruce wood results in a more or less pronounced surface yellowing of sapwood. The yellowing of sapwood is a consequence of the enrichment of sugars and nitrogenous compounds towards the timber surface during the initial capillary phase of drying (Terziev *et al*. 1993; Terziev 1995). Sundqvist (2002) exposed Norway spruce (*Picea abies*), Scots pine (*Pinus sylvestris*), and white birch (*Betula pubescens*) to temperatures of 65 °C, 80 °C, and 95 °C for 1, 3, and 6 days. Each of these species showed pronounced darkening when the temperature exceeded 80 °C. Repola *et al.* (2003) also examined *P. abies* and *P. sylvestris* samples exposed to temperatures of 50 °C, 70 °C, 90 °C, and 110 °C and reported that the discoloration of sapwood remarkably increased at temperatures above 70 °C. At temperatures of 90 °C and 110 °C the lightness (L^*) was remarkably decreased. They also pointed out that a^* and b^* values increased with increasing drying temperature, but it had less of an effect on wood appearance than changes of L^*. The color of wood is also greatly influenced by production and technological processes (Repola *et al.* 2003).

The aim of this paper is to analyze the color change of compression and opposite spruce wood due to artificial drying, under three different temperatures (60 °C, 80 °C, and 90 °C/120 °C) and to evaluate the properties of CW compared to opposite wood (OW) before and after the drying process.

EXPERIMENTAL

Materials

Spruce logs (3 pieces) (*Picea abies* L. Karst) that possessed some compression wood content (Fig. 1) were selected from the forests of the Technical University in Zvolen (Slovakia).

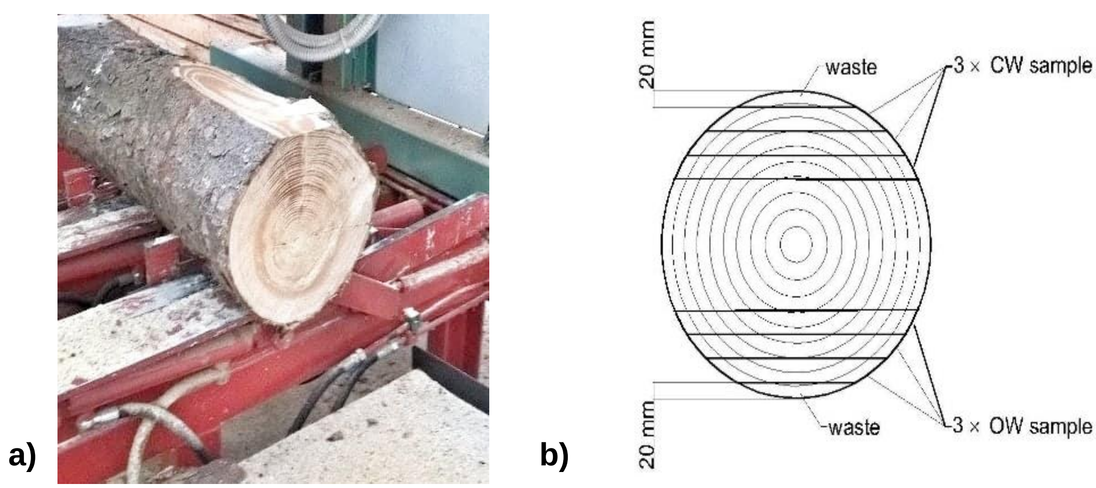

Fig. 1. Spruce log with darker areas of compression wood (CW) and opposite wood (OW) (a) and sawing pattern (b)

The diameter of the logs was approximately 38 cm on the narrow end, and their length was 1 m. The thickness of compression wood zone on both ends of the logs was not smaller than 11 cm.

Methods

Cutting

A total of six boards were cut out from the sapwood zone of the log according to the sawing pattern in Fig. 1b. Subsequently, two drying samples were cut out from each board (6 compression and 6 opposite wood samples in total). The dimensions of the drying samples were 100 × 300 × 30 mm (w × l × t).

Drying

The process of drying was conducted in a laboratory kiln Memmert HCP 108 (Memmert GmbH + Co. KG, Schwabach, Germany) at the Department of Wood Technology, at the Technical University in Zvolen, Slovakia.

Three drying modes were used with maximal temperatures 60 °C (No. 1), 80 °C (No. 2), and 90 °C/120 °C (No. 3), as shown in Table 1. The same psychrometric difference (Δt) of 2 °C was maintained in the stage above the fiber saturation point (FSP) for all drying modes. The psychrometric difference was increased to 12 °C after reaching the FSP boundary of all samples (approximately 30% of moisture content) when drying modes No. 1 and No. 2 were used.

During drying mode No. 3, when the moisture content of all samples decreased below the FSP, the drying temperature was increased to 120 °C without regulation of relative humidity of the surrounding air.

Table 1. Drying Modes

Drying Mode	Above FSP			Below FSP		
	t (°C)	Δ*t* (°C)	φ (%)	*t* (°C)	Δ*t* (°C)	φ (%)
No. 1	60	2	91	60	12	52
No. 2	80	2	93	80	12	59
No. 3	90	2	94	120	-	-

The following properties were measured on the all samples: Initial (w_i) and final (w_f) moisture contents of wood using the gravimetric method according to STN EN 490 103 (1993). The density (ρ_0) of wood at 0% moisture content was measured according to STN EN 490 108 (1993).

The temperature was continuously measured (every minute) during the whole drying process. The temperature of CW and OW samples in the drying process (under the surface and in the middle of sample) was measured using a Comet MS6R device (COMET, Rožnov pod Radhoštem, Czech Republic) and type T (Cu-CuNi) thermocouples (Fig. 2).

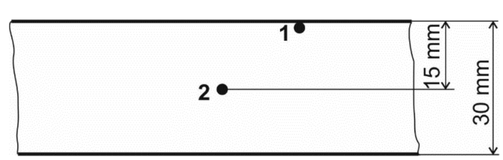

Fig. 2. Position of thermocouples in the drying sample

Optical characteristics

The colorimetric parameters of the samples were measured on the surface before and after drying and milling process (2 mm under the surface after drying), using the CIELAB system (Fig. 3). The coordinates $L*$ (lightness or black-white relation, $a*$ (coordinate red-green), and $b*$ (coordinate yellow-blue) were used to determine overall color change.

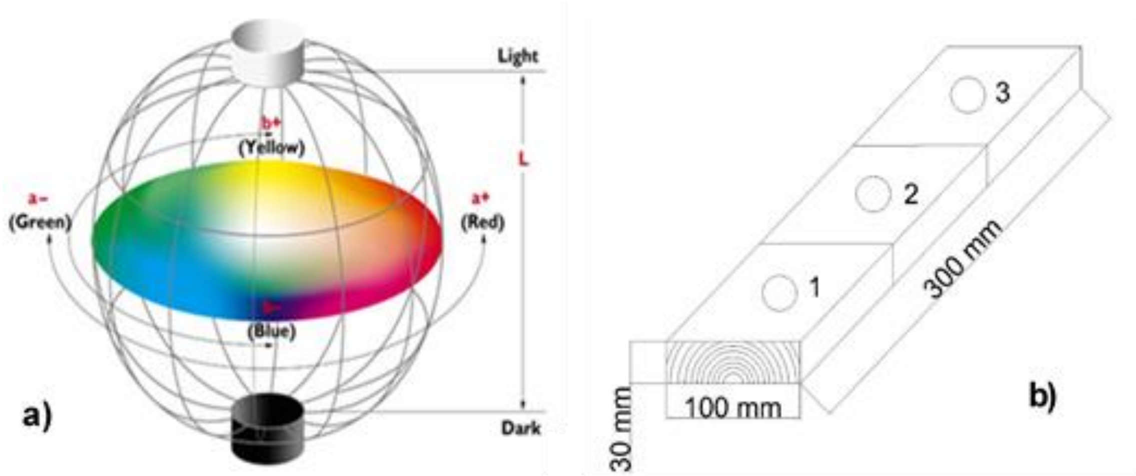

Fig. 3. Graphical representation of the CIELAB color space (a) and measured points on sample (b) (Griffith 2011)

The color measurements of all samples were performed with a colorimeter CR-10 Color Reader (Konica Minolta Sensing, Inc., Sakura, Japan). All measurements were recorded at three points (Fig. 3). All of the color parameters were calculated according to the following section.

The color difference, ΔE^*, was calculated according to Eq. 1,

$$\Delta E^* = \sqrt{(L_2^* - L_1^*)^2 + (a_2^* - a_1^*)^2 + (b_2^* - b_1^*)^2} \quad (1)$$

where L_1^*, a_1^*, and b_1^* are the values of the color spectra before the drying process and L_2^*, a_2^*, and b_2^* are the values of color spectra after the drying process or milling (*2 mm under the surface*) process.

The overall color change $\Delta E*$ (Table 2) was classified under the rules of distribution of color changes according to Cividini *et al.* (2007). All color characteristics were analyzed using Statistica 7.0 software (TIBCO Software, v.7.0, Palo Alto, CA, USA).

Table 2. Evaluation Criteria of Overall Color Change $\Delta E*$

Range of ΔE^*	Rate of Color Difference
$\Delta E* < 0.2$	No visible difference
$2 > \Delta E* > 0.2$	Small difference
$3 > \Delta E* > 2$	Color difference visible with high quality screen
$6 > \Delta E* > 3$	Color difference visible with medium quality screen
$12 > \Delta E* > 6$	High color difference
$\Delta E* > 12$	Different colors

From the measured data of the colorimetric system L^*, a^*, b^* and also ΔE^*, it was possible to analyze the following additional properties:

Chroma – The chromatic character or chroma can be described as the colorfulness of an area judged as a proportion of the brightness of a similarly illuminated area that appears white or highly transmitting (Schanda 2007):

$$C_{ab}^* = (a^{*2} + b^{*2})^{\frac{1}{2}} \quad (2)$$

Hue angle – The hue angle is an attribute of a visual sensation according to which an area appears to be similar to one of the perceived colors red, yellow, green or blue, or to a combination of two of them. The hue angle ranges from 0° to 360° in the Redness–Greenness (a), and the Yellowness– Blueness (b*) plane is based on the concept of equal perceived difference (Schanda 2007):

$$h^* = \mathrm{Arctan}\left(\frac{a^*}{b^*}\right) \quad (°) \quad (3)$$

Saturation – The saturation can be described as the colorfulness, of an area judged in proportion to its brightness (Schanda 2007):

$$S_{\mathrm{ab}} = \frac{C_{\mathrm{ab}}^*}{\sqrt{C_{\mathrm{ab}}^{*2} + L^{*2}}} \cdot 100 \quad (\%) \quad (4)$$

RESULTS AND DISCUSSION

Table 3 shows the density of the samples in the oven-dry state, initial, and final moisture contents, as well as the drying times of the tested samples. The average density of CW measured at 0% moisture content (MC) was 562.3 kg·m^{-3} while the density of OW was 480.1 kg·m^{-3}. It had a 17% higher value. Klement and Huráková (2015) also reported of higher density of spruce compression wood (527 kg·m^{-3} *vs.* 441 kg·m^{-3}). The reason for a higher density value of compression wood is the thicker cell walls containing more lignin (Warensjö 2003; Diaz-Vaz *et al*. 2009). The density of compression wood is also affected by the ratio of compression wood and position in the trunk.

The time necessary for reaching the final moisture content was different for compression and opposite wood, and it was dependent on the temperature of the drying air as well. A higher temperature resulted in a shorter drying time.

The drying time for CW was longer compared to opposite wood. However, when the high-temperature drying mode was used, the difference between compression and opposite wood was minimal. The present observations are consistent with Straže and Gorišek (2006), which shows that compression wood, comparing to normal secondary xylem of spruce, has slightly lower gas permeability in the transverse direction. The research also confirmed slower drying characteristics of compression wood in all samples.

The courses of temperature (under the surface and in the middle of the samples) are shown in Fig. 4. Only the temperatures of the CW samples are shown because the courses were similar for the opposite wood samples. It was clear that the temperature had a remarkable effect on the drying time. Differences between the temperature under the surface and in the middle of the samples were minimal; however, a slightly higher temperature was measured under the surface. Drying modes No. 1 and No. 2 showed high variability in drying times between the compared groups of samples. Drying mode No. 3 had negligible differences in drying times between the samples.

Table 3. Density, Moisture Content, and Drying Time of Samples

Drying Mode	Samples	Density at 0% MC ρ_0 (kg·m^{-3})	Average Density at 0% MC ρ_0 (kg·m^{-3})	Initial Moisture Content w_i (%)	Final Moisture Content w_f (%)	Drying Time τ (h)
No. 1	CW_1	571.1	570.3	83.20	10.50	241.0
	CW_2	569.4		84.06	10.63	
	OW_1	472.6	479.0	83.21	10.21	189.0
	OW_2	485.4		82.48	10.13	
No. 2	CW_1	563.2	562.5	86.76	10.70	201.0
	CW_2	561.8		86.25	10.45	
	OW_1	483.6	481.9	85.25	9.98	168.0
	OW_2	480.1		87.90	10.51	
No. 3	CW_1	565.2	554.2	89.78	9.60	150.5
	CW_2	543.1		88.89	9.71	
	OW_1	497.2	479.3	87.59	9.59	149.0
	OW_2	461.4		86.76	9.38	

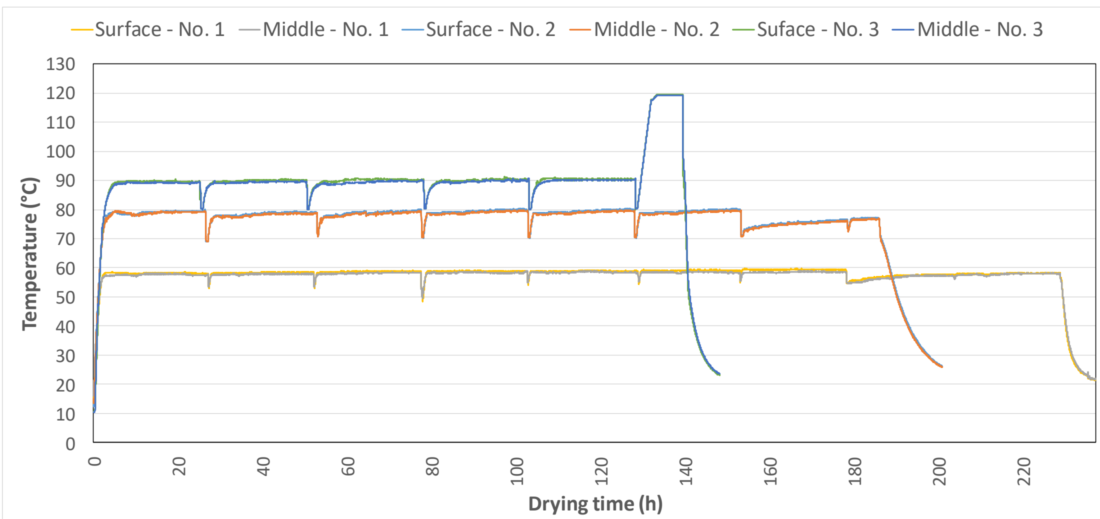

Fig. 4. Curves of temperature of compression wood samples and temperature of surrounding air. The periodic downward spikes in the curve correspond to brief opening of the oven door.

When the high-temperature drying mode was used (90 °C/120 °C), the temperature of the sample increased to 120 °C after reaching the FSP boundary. The difference between the temperature under the surface and in the middle of the sample was minimal. The differences in color coordinates were remarkable before the drying process. Compression wood samples showed higher values of parameters *a** and *b**. The lightness of compression wood (parameter *L**) was lower than opposite wood (on average 14.8%). This was caused by a higher lignin content and thicker cell walls of compression wood.

Klement and Huráková (2015) also showed that the darker color of CW can also be caused by the position in the trunk (sapwood/heartwood). Because the differences in initial moisture content were minimal and the samples were cut out from the sapwood zone of the trunk, the authors could exclude these findings. Based on the research of Tarmian *et al.* (2011), it is well known that compression wood has higher lignin content than normal wood. Thus, the high lignin content of compression wood is probably responsible for its dark color. All drying modes were also analyzed by the color coordinates *L**, *a**, and *b**. Analyses showed lower values for the *L** coordinate in CW for drying mode No. 1. According to the author of the spruce reaction wood, it is known to have more latewood (Nečesaný 1956), and therefore the *L** coordinate is lower. Color changes in drying mode No. 2 showed similar values as drying mode No 1. Changes that were measured in both drying modes before drying were not changed after milling. The *a** color coordinate of CW increased only during drying mode No. 2 and decreased during drying mode No. 1.

Based on the works of Nečesaný (1956) and Gardiner (2004), CW appears darker because it absorbs more light and has a different chemical composition as well. Findings of Gardiner (2004) provide that CW had a higher content of lignin.

Drying mode No. 3 resulted in changes between the CW and OW that were more pronounced before the drying process. The values of the color coordinates were almost equal after the drying and milling process.

Table 4. Values of *L**, *a**, and *b** Coordinates and Selected Statistical Characteristics

Samples	Coordinates	Before Drying			After Drying			After Milling		
		Mean	Standard Deviation	Standard Error	Mean	Standard Deviation	Sample Variance	Mean	Standard Deviation	Standard Error
Drying Mode No. 1										
CW	*L**	**72.9**	0.208	0.071	**72.7**	0.697	0.486	**74.8**	0.702	0.000
	*a**	**5.3**	0.902	1.098	**7.3**	0.785	0.616	**7.5**	0.876	0.202
	*b**	**23.8**	1.013	1.671	**26.4**	0.727	0.529	**24.1**	0.157	0.071
OW	*L**	**83.4**	0.708	0.298	**80.9**	0.942	0.888	**82.3**	0.320	0.354
	*a**	**3.4**	0.928	1.059	**6.3**	0.324	0.105	**3.8**	0.100	0.053
	*b**	**20.8**	1.052	0.926	**22.8**	0.509	0.259	**19.5**	0.471	0.017
Drying Mode No. 2										
CW	*L**	**75.4**	0.644	0.779	**69.5**	0.800	0.640	**71.7**	0.849	1.202
	*a**	**5.6**	1.019	1.019	**7.5**	0.662	0.438	**7.2**	0.571	1.071
	*b**	**21.7**	0.657	0.657	**26.8**	0.820	0.672	**23.8**	0.932	0.066
OW	*L**	**78.9**	0.541	0.541	**72.7**	0.519	0.269	**81.0**	0.943	0.474
	*a**	**3.5**	0.879	0.879	**6.8**	0.947	0.897	**3.3**	0.792	0.075
	*b**	**19.3**	0.850	1.013	**26.7**	0.818	0.669	**19.4**	0.436	0.288
Drying Mode No. 3										
CW	*L**	**78.6**	0.694	0.518	**61.7**	0.956	0.915	**65.7**	0.914	1.104
	*a**	**4.6**	0.774	0.697	**10.1**	0.871	0.758	**8.3**	0.493	0.339
	*b**	**23.9**	0.632	0.140	**29.1**	0.662	0.439	**24.2**	0.657	0.455
OW	*L**	**80.4**	0.524	1.143	**63.7**	0.545	0.297	**69.4**	0.590	0.495
	*a**	**3.2**	0.803	0.962	**8.6**	0.875	0.766	**7.3**	0.150	0.000
	*b**	**19.8**	0.460	0.029	**28.4**	0.729	0.531	**23.4**	0.645	0.418

Repola *et al.* (2003) also reported an increase in the value of a^* and b^* parameters with a temperature increase for spruce and pine wood (50, 70, 90, and 110 °C). A higher value of OW lightness (L^*) compared to CW was measured after 2 mm milling (for all three drying modes). The higher values of a^* and b^* parameters were measured for the CW samples. The average values and basic statistical color characteristics of the parameters L^*, a^*, and b^*, before and after drying and after milling (2 mm) are shown in Table 4.

The values of color difference, saturation, and color saturation are shown in Table 5. The color difference values were evaluated according to Table 2 in the various stages of the drying process. From a practical point of view, the most important is the comparison of color differences before drying and after milling.

The color differences ΔE^* were small for OW and for CW in both drying modes No. 1 and No. 2. The CW had a color difference before drying after milling from 2.9 up to 4.3, which was a little higher than OW (visible with high quality screen).

The OW had a color difference from 1.7 up to 2.2 (small difference). The high-temperature drying mode (No. 3) had the biggest influence and resulted in a different color for OW and high color difference for CW according to Table 5. It was clear that with increased temperature the color difference increased. This change was more noticeable for OW because CW is naturally darker.

Table 5. Values of the Color Difference, Color Saturation, and Saturation

Samples	Process	Color Difference ΔE^* (-)	Color Saturation C^*_{ab}	Saturation S_{ab} (%)
Drying Mode No. 1				
CW	Before and after drying	3.2	24.4	31.7
	After drying and after milling	3.1	27.3	35.2
	Before drying and after milling	2.9	25.2	32.0
OW	Before and after drying	4.3	21.0	24.4
	After drying and after milling	4.2	23.5	27.9
	Before drying and after milling	1.7	19.9	23.5
Drying Mode No. 2				
CW	Before and after drying	8.0	22.4	28.5
	After drying and after milling	3.9	27.8	37.1
	Before drying and after milling	4.3	24.8	32.6
OW	Before and after drying	10.2	19.6	24.1
	After drying and after milling	11.6	27.5	35.4
	Before drying and after milling	2.2	19.7	23.6
Drying Mode No. 3				
CW	Before and after drying	18.5	24.3	29.6
	After drying and after milling	6.6	30.8	44.7
	Before drying and after milling	13.4	25.5	36.3
OW	Before and after drying	19.5	20.0	24.2
	After drying and after milling	7.6	29.6	42.2
	Before drying and after milling	12.3	24.5	33.3

The authors' observations were in accordance with the research of Sanquist (2002) that showed more darkening with the use of temperature above 80 °C. Saturation of both CW and OW increased with increased temperature. Bekhta and Niemz (2003) also reported increased saturation for high-temperature drying of spruce wood (t = 20, 100, 150, and 200

°C and relative humidity = 95%). The value of saturation reached its peak at 150 °C and it was followed by a decrease at the temperature of 200 °C. In this study, the CW samples reached higher values of color saturation compared to OW samples under the conditions of all three drying modes. The values of C^*_{ab} before and after the drying process ranged from 22.4 to 24.4 for CW and from 19.6 to 21.0 for OW. Saturation (S_{ab}) ranged from 28.5 to 48.7% for CW and from 23.5 to 42.2% for OW.

A graphical representation of the hue angle for CW and OW is shown in Figs. 6, 7, and 8.

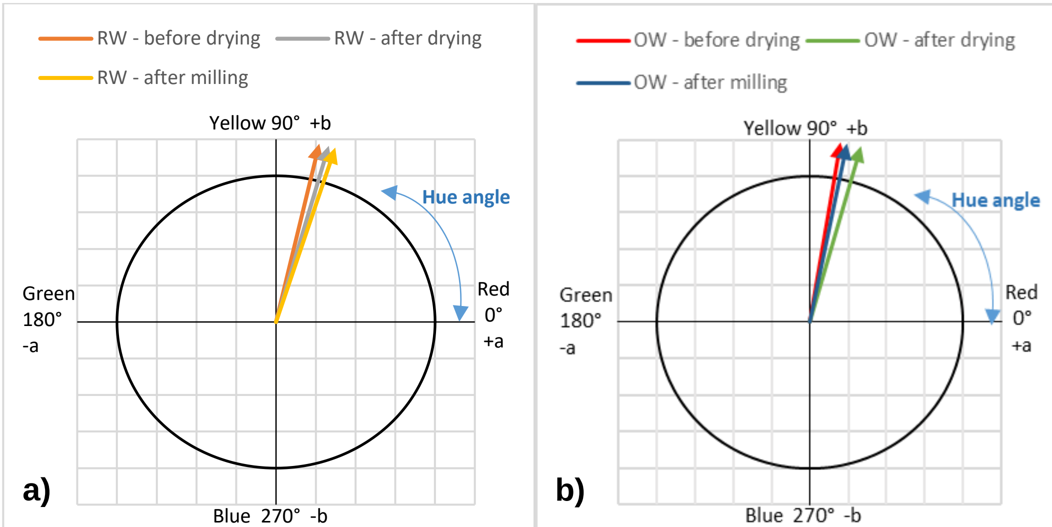

Fig. 6. Hue angle change of compression wood (a), opposite wood (b) drying mode No. 1 (60 °C)

The hue angle of OW before the drying process was always smaller compared to CW. The CW became redder and its hue angle decreased. The hue angle of OW increased and it became yellower. However, it decreased towards the red color under the conditions of drying mode No. 2 (80 °C). Shelstedt - Persson (2003) reported a clear influence of drying time and temperature on the change of spruce and pine wood hue angle (h^*). Shelstedt - Persson reported that sapwood became redder.

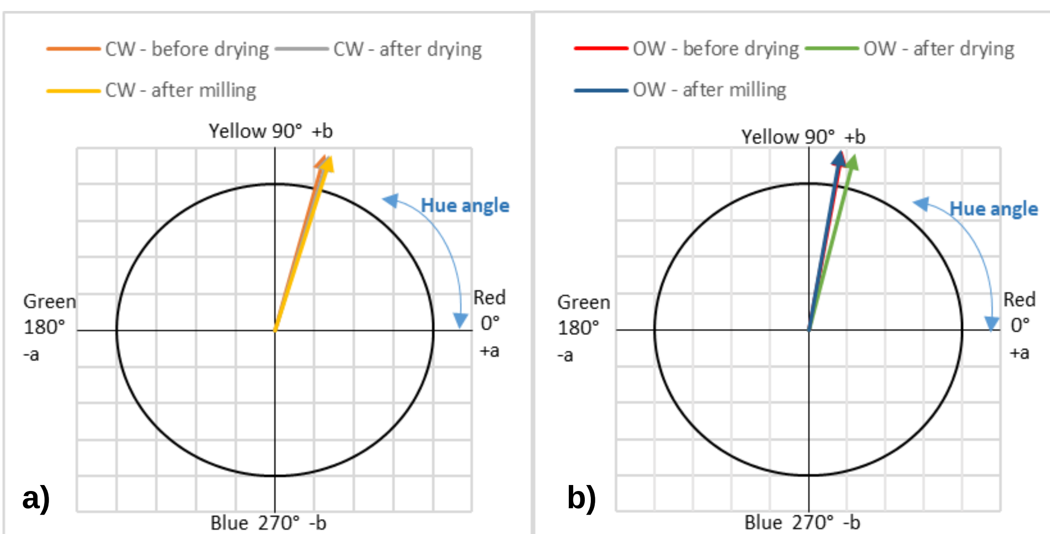

Fig. 7. Hue angle change of compression wood (a) and opposite wood (b) for drying mode No. 2 (80 °C)

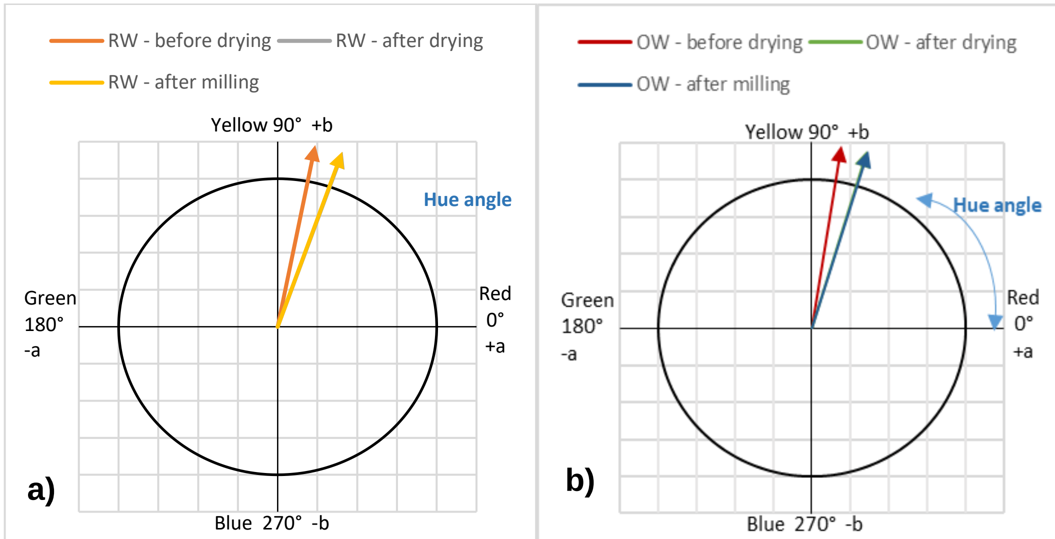

Fig. 8. Hue angle change of compression wood (a) and opposite wood (b) for drying mode No. 3 (90 °C/120 °C)

The authors present findings that the color in compression wood was darker and redder than the opposite wood both before and after drying. It was found that the compression wood became more statured in color with a deeper hue angle due to the drying process.

CONCLUSIONS

The authors' measurements have shown the following findings:

1. The oven-dry density of CW was 14.5% higher compared to OW. The average density of CW samples was 562 kg·m^{-3} and the average density of OW samples was 480 kg·m^{-3}. The differences between initial moisture content of CW and OW were minimal.
2. The CW reached the required final moisture content of 10% noticeably later than OW, but under the conditions of drying mode No. 3 (90/120 °C), the required final moisture content was reached at approximately same time.
3. The temperature of surrounding air had a noticeable effect on the drying time. The differences between the temperature under the surface and in the middle of the samples were negligible.
4. The value of parameters L^*, a^*, and b^* changed with increased temperature. The changes were more noticeable on OW samples. The value of parameter a^* changed to the greatest extent. However, the changes in L^* and b^* parameters were also noticeable.
5. The OW became redder as a result of increased temperature and its hue angle decreased. The CW became redder only at 80 °C and it became yellower at 60 °C and 120 °C. Due to increased temperature, the color difference of OW changed more.

6. The color difference of OW compared to CW was slightly bigger at 60 °C and 80 °C. However, the biggest difference was seen at high-temperature drying (90/120 °C). The color of OW rapidly changed. The color difference of CW was even lower at this temperature than at 80 °C. The compression wood was more statured in color with a deeper hue angle due to the drying process.

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