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COULD COLOUR PREDICT HARDNESS OF HOT-PRESSED SELF-LAMINATED BEECH BOARDS?

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Abstract

Laminated self-bonded densified boards were obtained by pressing five veneers of beech (Fagus sylvatica L.*) parallel-grain-oriented, without adhesive and without surface activation. The boards were pressed according to an experimental design based on fifteen different combinations of pressing parameters: temperature (200, 225, and 250°C), pressure (4, 5, and 6MPa), and time (240, 300, and 360s). The image of the 40 board edges (radial sections) was analysed with ImageJ software in the red-green-blue (RGB) colour space. Brinell hardness tests were also performed. The results show an almost linear relation between the brightness values (defined as the arithmetic mean of the RGB channels) and the Brinell hardness. It is suggested that brightness is a predictor of strength for self-bonded laminated boards.*

Key words: *digital image processing; densification; RGB system; self-bonding; veneer.*

INTRODUCTION

A new bonding technique to obtain laminated boards from veneers without the use of adhesives or activation techniques has been studied by us in recent years (Cristescu 2006, 2008). Self-bonding is achieved solely through the effect of heat and pressure. A previous study by Cristescu et al. (2015) showed that all physical and mechanical properties increase with increasing pressing parameter levels. The pressing parameter range was 200-250°C for temperature, 4-6MPa for pressure and 240-360s for time. The area of the boards was 135x135mm^2, and the thickness varied between 5 and 8.5mm. The importance of the inter-laminar bonding quality for the overall strength was shown to be very high (Cristescu et al. 2015). It was found that if the bonding was non-resistant or resistant to soaking for 48h in water, the rupture in the three-point bending was caused respectively by tension in the bottom layer or by shear forces.

It was also noticed that the colour of the board surface depends on the pressing parameter levels. Using the same pressing technique and laboratory equipment as Cristescu (2008), Jiang (2012) searched for a correlation between the surface darkening, the shear strength and the hardness of boards. The study was based on veneers of beech (*Fagus sylvatica* L.) from different sources, with different thicknesses (2.0-2.7mm) and different densities (550-680kg/m^3). Jiang used a colorimeter to obtain lightness, chroma and hue values for boards of different colour. Four regions were measured on each side of the samples to investigate whether the colour is evenly distributed on the surface. Jiang´s conclusions were that the surface colour was evenly distributed for most samples and that it was mainly affected by the temperature, and that the time and pressure had a much less significant effect. Jiang found no correlation between surface colour and strength. Bekhta et al. (2014) studied thermo-mechanical densification of veneers, and concluded that both temperature and pressure of densification affected to a great extent the colour of the veneers, but the effect of temperature was more evident than that of pressure. Based on preliminary observations by Cristescu (2008) it was decided to measure the darkening of the sample edges, and investigate the correlation to mechanical properties of the boards. The pressure and pressing time have a significant effect on the degree of compression (Cristescu et al. 2015) so it was expected to find this effect in the edge colour as well.

The literature shows controversial opinions with regard to colour as a strength predictor for thermal-treated wood. The results depend on the size of the samples, their surface roughness (planed or not), the initial moisture content, and the duration and the temperature of the thermal treatment. Studies on wood colour were in general carried out using spectrophotometry in CIELab colour system (Esteves and Pereira 2008). Bekhta and Niemz (2003) showed that a colour parameter, especially the total colour difference, can be used as a predictor of wood strength. Todorovic et al. (2012) found that for beech the colour could be used to predict mass loss, density loss and brittleness. Tuong and Manh (2010) found a relationship in thermal-treated acacia wood between lightness and mass loss. Repellin (2006) shows that for Retification process (Navi and Sandberg 2012), the relation between colour and mass loss was not linear neither for beech or pine. Based on literature, Repellin's explanation for the nonlinearity was that, while the change in colour comes from the modification of extractives, lignin and hemicelluloses, the mass loss is mainly caused by thermal degradation of hemicelluloses.

Johansson and Morén (2006) studied the thermal treatment of birch boards of various lengths with cross-sectional dimensions of 50×100mm for 3h at 200°C according to the Thermowood process (Navi and Sandberg 2012). They found that the colour distribution through the thermally-treated boards was not homogeneous and that colour was not therefore suitable as a predictor of strength.

On the other hand, Sundqvist et al. (2006) studied the thermal treatment in steam of small samples (110x31x4mm) under laboratory conditions. The results showed a correlation between colour and strength, especially for heating times of less than two hours. Kubojima et al. (1998) obtained similar results with an increase in strength during the first two hours of thermal treatment. Sundqvist (2004) speculated that an initial increase in strength and hardness can be due to condensation in the lignin and hemicelluloses, as molecules degrade and can form new chemical bonds. It was suggested that a similar phenomenon occurs within self-laminated board in both the veneers and bond-lines of self-bonded beech boards (Cristescu and Karlsson 2013). That study showed how changes in colour were connected to the chemical changes during hot-pressing of beech.

The fixed aperture size (50 or 13mm in diameter) of colorimeter and spectrophotometer available was not suitable to measure colour for the thickness between 5 and 8.5mm of the self-bonded boards. The alternative of using digital image analysis seemed reasonable as it is a modern and versatile method to evaluate differences in colour. A digitized colour image is an array of pixels and each pixel contains numerical components that define a colour. The RGB colour model is an additive colour model in which red, green, and blue light are added together in various ways to reproduce a broad array of colours. The name of the model comes from the initials of the three additive primary colours, red, green, and blue. RGB is a device-dependent colour model, i.e. different devices detect or reproduce a given RGB value differently, since the colour elements and their response to the individual R, G, and B levels vary from between devices. Thus an RGB value does not define the same colour across devices without some kind of colour management. Recently, Forsthuber et al. (2014) used a calibrated photo-scanner to study several wood species. When comparing the colorimetric values calculated from images of calibrated photo-scanner to the ones given by a spectrophotometer, a strong correlation between the colour changes (relative values) obtained by the two methods was found. The correlation between absolute values was however weak, explained by different light sources of the two devices.

OBJECTIVE

The objective was to investigate the relation between colour and Brinell hardness in self-bonded boards from beech.

MATERIAL AND METHODS

Defect-free rotary-cut 2.2mm thick veneers of beech (*Fagus sylvatica* L.) from Romania were used for the study. Prior to cutting, the logs were plasticized by heating with steam at 80°C, then rotary-cut at 40-50°C, followed by drying at 140-170°C to reach a moisture content (MC) of 7-10%.

The veneers were conditioned to an equilibrium moisture content of 9% before sample preparation. The oven-dry density of the veneers ranged from 580 to 605kg/m^3.

Five-ply boards with parallel-oriented-veneers were pressed in a laboratory press (Fjellman®, No. 2032, Mariestad, Sweden) at different temperatures, pressures and times according to an experimental design discussed in Cristescu et al. 2015. The design combines the pressing levels presented in Fig. 1. The surface area of the boards was 140x140mm^2, and the final thickness varied between 5.5 and 8.5mm depending on pressing conditions.

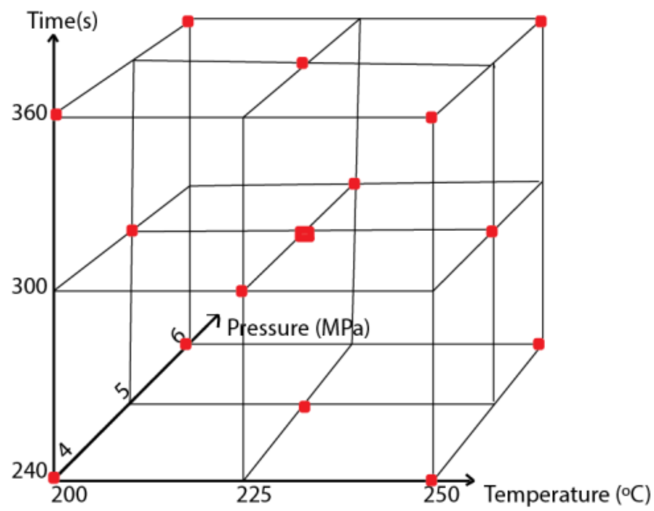

Fig. 1.
Selected parameter combinations used when manufacturing the boards. Each dot in the figure represents one test group

Colour measurement

Digital imaging was used to analyse and compare the colour of the board edges. A photograph of one radial edge from each board (one image of all edges at the same time) was taken with a Sony Exmor IMX145 camera. All board edges in one and the same image enabled a unique reference for the entire set of samples. No calibration of the camera was carried out since relative and not absolute values were intended for this comparison study (Wyszecki and Stiles 1982). The light was indirect midday sunlight.

As a feasibility study, Image acquisition was performed with different digital cameras (a Canon IXIS 70, a Canon 500D, and a Sony Exmor IMX145), using basic automatic photography settings. It was noticed that regardless of the type of camera used, the RGB values obtained were almost similar if the position of the samples and the source of light were the same. This confirms the influence of illumination on colorimetric results (Wyszecki and Stiles 1982).

After the image was acquired, the ImageJ software was used for image processing. ImageJ has been successfully used as an analytical tool for more than 25 years in medical (Abràmoff et al. 2004), biology (Schneider et al. 2012) and wood research (Hagman 1996). At a rectangular shaped area of approximately 20.000 pixels, covering 30-60% of each board edge was selected for the colour analysis. The colour at the selected area was split into red, green and blue image components (channels), and the brightness, defined as the arithmetic mean of the RGB was calculated (Ferreira and Rasband 2012).

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a)
b)
c)

Fig. 2.
Photograph of the board edges (LR section) of three samples: a) 200°C, 5MPa, 300s, b) 225°C, 5MPa, 300s, and c) 250°C, 5MPa, 300s

Brinell Hardness Test

A Brinell test according to EN 1534 (CEN 2010) was used for hardness measurements. The Brinell test was run on an Instron 5500 test machine. All the samples were conditioned at 20°C and 65% relative humidity (RH) for 24h before testing. A steel ball 10mm in diameter was pressed against the sample for 15s until the compression force reached 1000N. The force was then held constant for 25s. After withdrawing the ball, the samples were allowed to recover for at least three minutes. The indentation diameter was measured and the Brinell hardness was calculated according to:

$$HB = \frac{2F}{g\pi D\left[D - \sqrt{(D^2 - d^2)}\right]} \qquad (1)$$

where:
HB - Brinell hardness (kg/mm^2)
F - maximum applied force (N)
g - acceleration of gravity (m/s^2)
π - 3.14
D - diameter of the indentation ball (mm)
d - average diameter of the residual indentations (two independent measurements)

RESULTS AND DISCUSSION

The results are presented in Table 1, together with the pressing conditions for the test groups. It is well known that there is good correlation between densification and hardness of compressed wood (Stamm 1964, Fang et al. 2012, Ulker et al. 2012, Rautkari et al. 2013), and this is also confirmed in this study. The samples in group no. 15 were damaged during pressing because of internal gas pressure and could not be used further.

Table 1

Pressing parameters for the test groups, brightness, density and Brinell hardness (HB). Standard deviation in brackets

Group No.	Temp. (°C)	Press. (MPa)	Time (s)	No. of samples	Brightness		Density (kg/m^3)		HB (Kg/mm^2)	
1	200	4	240	2	154	(2.1)	615	(19)	3.5	(0.0)
2	200	4	360	2	150	(3.5)	650	(6)	3.9	(0.0)
3	200	5	300	2	144	(0.8)	670	(20)	4.3	(0.0)
4	200	6	240	2	141	(1.2)	680	(29)	4.7	(0.1)
5	200	6	360	2	137	(7.6)	690	(22)	5.4	(0.2)
6	225	4	300	2	134	(8.3)	700	(12)	4.6	(0.9)
7	225	5	240	2	141	(1.1)	710	(16)	5.3	(0.3)
8	225	5	300	12	127	(3.2)	744	(39)	6.4	(2.7)
9	225	5	360	2	123	(1.2)	750	(28)	7.2	(0.3)
10	225	6	300	2	115	(8.1)	765	(27)	8.9	(0.3)
11	250	4	240	2	81	(0.7)	828	(28)	7.8	(0.0)
12	250	4	360	2	83	(4.7)	866	(17)	10.9	(0.0)
13	250	5	300	2	81	(7.9)	901	(19)	10.8	(0.7)
14	250	6	240	2	77	(2.5)	973	(20)	9.8	(1.6)
15	250	6	360	2	73	(1.2)	-		-	

The brightness measurements were a very rapid tool in the comparison study of the self-laminated boards. As seen in Table 1, the brightness incorporates information from the entire densified wooden structure and does not require homogeneity. A colour difference within the sample does not seem to be an obstacle to evaluating board edges in the RGB colour space.

With the help of digital image analysis, comparisons could be done not only between samples but also within the sample. In high resolution images it was possible to distinguish between different type of compressed cells and newly formed structures of the board. According to Sehlstedt-Persson (2003), at high temperatures much of the colour change in solid wood emanates from colour changes in constituents of the sap and extractives. As seen in Fig. 2, the differences in nuance on a board edge are caused by the rays containing non-structural carbohydrates, mostly sugars in the case of beech (Barbaroux and Bréda 2002). The differences in nuance also occur in the bond-line zones. The thickness and the colour of a bond-line are important indicators for the quality of self-bonding. Future studies could compare colorimetric values of rays, bond-lines to other areas of a board edge, and the information could be further used for modelling of the thermo-mechanical process or to evaluate the chemical reactions that occur during the bonding process.

The Brinell hardness test indicated clear difference between boards pressed under different conditions. Fig. 3 shows three examples of indentations from the Brinell test. Boards pressed under low temperature conditions had indentation with a diameter of up to 5 mm (Fig. 3a), and boards pressed under more severe conditions had the smallest indentations, around 3 mm in diameter (Fig. 3c).

a. ***b.*** ***c.***

Fig. 3.

Photographs of indentations after Brinell tests at different pressing conditions: a) 200°C, 5MPa, 300s, b) 225°C, 5MPa, 300s, and c) 250°C, 5MPa, 300s

The relation between brightness and hardness is presented in Fig. 4. The linearity confirms the hypothesis that brightness can be considered a predictor of hardness in the case of hot-pressed self-laminated beech boards. Digital imaging measurements are rapid and easy to perform and can contribute to a correct assessment of a board mechanical properties within a group.

This study is limited to a set of small size boards made from veneers cut from one and the same veneer sheet. For a more general approach an additional study should include a more diversified material selection into the digital imaging analysis. The relation between brightness and other mechanical properties should also be evaluated. Another interesting subject to study would be the relation between colour and the pressing parameters used to obtain self-bonded boards, and not only from beech but from other species as well.

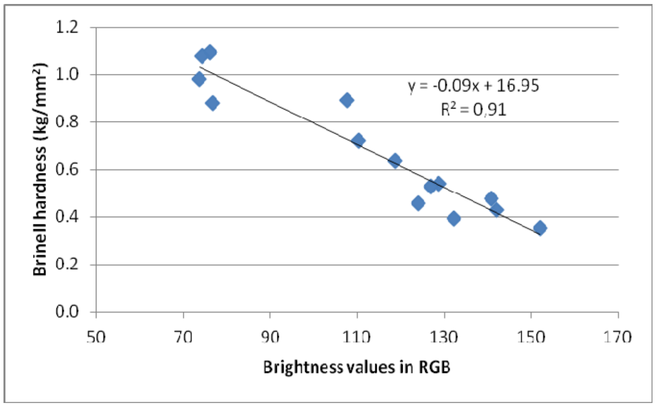

Fig. 4.
Relation between Brinell hardness and brightness

CONCLUSIONS

The relation between Brinell hardness and brightness of laminated self-bonded densified beech boards has been studied. A strong correlation was found between the hardness and the brightness of the board edges (radial sections). It is suggested that the colour could be considered as predictor of strength in general for self-bonded laminated beech boards. For the purpose of comparing the colour between several boards in a set of samples pressed from the same raw material, image acquisition with a common digital camera and the analysis with ImageJ software proved to be a fast and reliable method.

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