

Effect of Log Soaking and the Temperature of Peeling on the Properties of Rotary-Cut Birch (*Betula pendula* Roth) Veneer Bonded with Phenol-Formaldehyde Adhesive

Anti Rohumaa,^{a,*} Akio Yamamoto,^a Christopher G. Hunt,^b Charles R. Frihart,^b Mark Hughes,^a and Jaan Kers^c

Heating logs prior to peeling positively affects the surface properties of veneer as well as the wood-adhesive bond strength. However, the mechanism behind this increase in strength is not fully understood. The aim of the present study was to separate the influence of soaking temperature and peeling temperature on the physical surface properties and bonding quality. Rotary-cut birch (*Betula pendula* Roth) logs were soaked at 70 °C, and half of them were subsequently cooled to 20 °C prior to peeling. Surface roughness measurements, scanning electron microscopy (SEM), surface integrity testing, color measurements, and wood-adhesive bond testing were conducted with an automated bonding evaluation system. The results showed that logs soaked at 70 °C and peeled at 20 °C had roughness, color, integrity, bond strength, and wetting properties more similar to logs soaked and peeled at 70 °C than those soaked and peeled at 20 °C. In every test conducted, the effect of soaking temperature was greater than the effect of peeling temperature. High-temperature soaking not only caused softening of the material during the peeling process, but it also caused irreversible changes in the wood material, which affected the veneer surface characteristics and bond strength development.

Keywords: Veneer; Log soaking; ABES; Bonding strength; Roughness

Contact information: a: Department of Forest Products Technology, School of Chemical Technology, Aalto University, Vuorimiehentie 1, 02150 Espoo, Finland; b: US Forest Service, Forest Products Laboratory, One Gifford Pinchot Drive, Madison, WI 53726, USA; c: Department of Polymer Materials, Tallinn University of Technology, Ehitajate tee 5, Tallinn 19086 Estonia;

* Corresponding author: anti.rohumaa@aalto.fi

INTRODUCTION

Adhesive bonding of wood is a complicated phenomenon involving many factors, which affect the formation of the bond and its subsequent performance (Marra 1992). Among these factors, the wood processing parameters play a particularly important role. In the manufacture of plywood and laminated veneer lumber (LVL), logs are commonly heated prior to veneer peeling in order to soften the wood, obtain veneer with lower roughness, and reduce the severity of knife checks. As a consequence, knife wear and adhesive consumption can be reduced (Sellers 1985). One method of heating the logs is to soak them in water at an elevated temperature. The temperature of soaking depends on the wood species, the manufacturer, and the season of soaking. In Nordic countries, these temperatures commonly vary between 20 °C and 70 °C. However, in factories, the soaking

temperature is not controlled very well, so it is strongly influenced by the ambient outdoor temperature. This results in variable log core temperatures both prior to and during peeling.

Heating logs to a high temperature softens the wood (Marchal *et al.* 2009; Dupleix *et al.* 2013). Taking the wood polymers above their glass transition temperatures (T_g) (Salmen 1982) reduces the cutting forces and limits premature knife damage (Bailleres *et al.* 2015). This subsequently affects the surface properties of the veneer such as roughness (Aydin *et al.* 2006), wettability (Rohumaa *et al.* 2014), and integrity (Rohumaa *et al.* 2016). Elevated soaking temperatures also affect the color of wood (Mayer and Koch 2007; Yamamoto *et al.* 2015a). Additionally, in birch, the chemistry of the sap is affected, which influences veneer color (Yamamoto *et al.* 2015b; Yamamoto *et al.* 2015c). At higher temperatures, the formation of deep lathe checks is reduced (Meriluoto 1965; Dupleix *et al.* 2013), which is beneficial because shallower checks are less detrimental to veneer strength perpendicular to grain (Kontinen *et al.* 1992) as well as bond quality in plywood (Rohumaa *et al.* 2013). When heating the logs to 70 °C instead of 20 °C, bond strength increases by approximately 50% (Rohumaa *et al.* 2014) when it is measured between veneers where the lathe checks are not present (*i.e.*, on the ‘tight’ side of the veneer).

While soaking logs is known to affect several veneer and plywood properties, the mechanism behind the increase in bond strength is not fully understood. Part of what makes comprehension of this mechanism so difficult is the fact that it is not clear what effect soaking has on the wood and on the peeling process. On the one hand, soaking raises the temperature of the wood material for peeling, which is generally assumed to be the same as the soaking temperature. Often this assumption is correct, since cooling a log takes more than 12 h and peeling usually takes place more-or-less directly after soaking. Thus, it can be assumed that the temperature of peeling is the same as the temperature of soaking and peeling affects the quality of the veneer surface, as peeling may take place above the T_g . On the other hand, soaking for extended periods of time (8 to 48 h), as is usually the case, affects the material properties of wood, which can change the chemistry of the veneer (Yamamoto *et al.* 2015a). Clearly, it is difficult to separate whether contributions made to bonding arise from the softening of wood during peeling or from the changes in the surface of the veneer caused by prior soaking. This fact might have led to the misconception that softening of the material during peeling plays the main role in determining veneer quality and bond strength. However, it is still unclear which aspects contribute the most to the surface properties of veneer that affect bonding. No known systematic investigation has been carried out on the simultaneous effects of soaking and peeling temperature on the surface properties of veneer and bonding quality.

The aim of the present study was to separate the influence of soaking temperature and peeling temperature from each other and evaluate their effects on physical surface properties. This study also clarifies the changes in bond formation and performance caused by heating logs.

EXPERIMENTAL

Materials

Veneer material preparation

Birch (*Betula pendula* Roth) stems were felled in winter, sectioned into logs 1.2 m in nominal length, and immersed in a water tank heated to 70 °C. The core temperature of the logs was monitored using embedded thermocouples. The logs remained immersed until

the core had risen to 70 °C and remained there for at least 12 h. After soaking, half of the soaked logs were placed in a water tank at 20 °C and soaked until the core of the log reached 20 °C. Following soaking, the logs from both test groups were promptly rotary cut on an industrial scale lathe manufactured by the Raute Corporation (Model 3HV66; Raute Oyj, Lahti, Finland) into veneer with a nominal thickness of 0.8 mm. The veneer was visually inspected, and specimens approximately 900 × 400 mm² in size and free from obvious defects such as knots or sloping grain were cut from the veneer ribbon. The specimens were subsequently dried at 160 °C in a laboratory scale veneer dryer (Raute Oyj, Lahti, Finland) to an average final moisture content (MC) of 6%. After drying, the veneers were conditioned at 20 °C and 65% relative humidity (RH) to obtain MC approximately 12%, which is generally used in standard testing of wood material.

Following the previously described process, two groups of materials were prepared that hereinafter are referred to as ‘hot’ and ‘cold’. Hot material was prepared from logs soaked at 70 °C and peeled at 70 °C, while cold material was prepared from logs soaked at 70 °C, cooled to 20 °C, and then peeled. All subsequent measurements were carried out on the tight side (*i.e.*, the opposite side to the lathe checks side) of the veneer surfaces to eliminate any influence from variation in the number, depth, or form of lathe checks in the veneer sheets. The material processing used in the present study was identical to that reported by Rohumaa *et al.* (2014); this makes it possible to compare bond strength and wettability data obtained from the present study with data on veneer properties and bonding characteristics obtained from the researchers following log soaking at 20 °C and peeling at 20 °C (Rohumaa *et al.* 2014).

Methods

Surface roughness

A Mitutoyo Surftest 402 (Mitutoyo Europe GmbH, Neuss, Germany) was used to evaluate the roughness of the veneer surface across the wood grain. The cut-off length was 2.5 mm. The sampling length was 12.5 mm, and the detector tip radius was 5 μm (SFS-EN ISO 3274 1998). Roughness parameters R_a , R_{max} , and R_z were obtained. R_a represented the arithmetic mean deviation of the profile, and R_{max} was the maximum two-point height of profile. R_z was the height of the profile irregularities in ten points (SFS-EN ISO 4288 1998).

Contact angle

Contact angle (CA) measurements were performed using a CAM 200 Goniometer (KSV NIMA, Espoo, Finland) with de-ionized water. The water droplet volume was approximately 10 μL. CA was measured at intervals of 120 ms for the first second and every 5 s thereafter, up to 50 s. At least 30 CA determinations were made at different locations on the tight side of the veneer surface for each group.

Scanning electron microscopy

To perform scanning electron microscopy (SEM), veneer samples of 5 × 5 × 0.8 mm³ were mounted on aluminum stubs with silver double-sided sticky tape and gold-coated using a Denton Desk-1 sputter coater (Cherry Hill, NJ, USA). The samples were examined and photographed at 10 kV at a working distance of 12 mm with a LEO EVO40 SEM (Carl Zeiss SMT Inc., Thornwood, NY, USA) at magnifications ranging from 72× to 1000×.

Surface integrity: Evaluation of loosely attached particles on the veneer surface

Veneer surface integrity was tested using a Huygen internal bond tester (Model 1314, Huygen Corporation, Wauconda, IL, USA). The Huygen internal bond tester is commonly used for testing paper and paperboards; however, in the current study, the test veneer was affixed between a stainless steel sample base and an aluminum angle using double-sided tape (P-02, Nitto Denko Corporation, Osaka, Japan) by applying a constant pressure of 0.12 MPa for 5 s. After affixing the tape on the veneer surface, the same device was used to remove the tape from the veneer. A pendulum, held in a horizontal position by an electromagnet, was released and struck the vertical leg of the aluminum angle. The impact separated the tape from the veneer, pulling any loosely attached wood fragments with it. The quantity and size of the loose particles on the veneer surface were evaluated by fluorescence microscopy.

Before double-sided tape was attached to the veneer surface, the surface was pretreated with a 1% solution of Acridine Orange and air dried. After removing the tape from the veneer surface, fluorescence images of the particles adhering to the tape were obtained using a Leica DMLAM (Leica Microsystems GmbH, Wetzlar, Germany) light microscope modified by installing a TV zoom lens and removing the objective. A Leica DC300 color digital camera captured the images, which were processed with Leica Application Suite software. The specimens were illuminated with a blue LED (wavelength 470 nm), and the Leica L4 filter set was used. The area of evaluation was $6 \times 6 \text{ mm}^2$.

Color measurement

The color of the dry veneer surface was evaluated with a spectrophotometer (Spectrolino, Gretag-Macbeth AG, Regensdorf, Switzerland). Birch earlywood was chosen for color evaluation to minimize measurement deviation. The CIELab space system was used to express the color of the veneer surface using three parameters: L^* , a^* , and b^* . The parameter L^* represents lightness (0 = black, 100 = white), a^* is the color coordinate for greenness and redness (-60 = green, 60 = red), and b^* is the coordinate for blueness and yellowness (-60 = blue, 60 = yellow).

Bond formation

Matched specimens ($20 \times 117 \text{ mm}^2$) were cut from the conditioned veneer sheets. A liquid phenol-formaldehyde (PF) resin (Prefere 14J021, Dynea Chemicals Oy, Hamina, Finland) was applied to an area of $5 \times 20 \text{ mm}^2$ at one end of the veneer specimens with a resin spread rate of about 100 g m^{-2} . The adhesive was applied with a micropipette (HandyStep electronic, Brand GmbH + Co., KG, Wertheim, Germany). After adhesive application, the veneer-resin assembly was placed in an automatic bond evaluation system (ABES; Adhesive Evaluation Systems Inc., Corvallis, Oregon, USA), and hot pressing began after approximately 5 s. Shear strength was measured after pressing times ranging from 20 to 180 s. The platen temperature was $130 \text{ }^\circ\text{C}$, and the press pressure was 2.0 MPa. At least 7 bonded specimens were tested immediately after press opening for each substrate type and pressing time.

Analysis

An analysis of variance (ANOVA) was used to evaluate the significance of the differences between the means of the different treatments. Differences among means were compared and segregated by Tukey's test ($P < 0.05$).

RESULTS AND DISCUSSION

Previous studies have shown that the temperature at which a birch log is soaked affects the strength of the bond developed with a phenol-formaldehyde (PF) resin (Rohumaa *et al.* 2014); however, it has been still unclear as to the biggest contributing factor to the surface properties of veneer that subsequently affects bonding. Is it the elevated soaking temperature that alters the chemistry of the wood, or is it the temperature at which the wood is peeled that affects the physical properties of the veneer surface by softening the material? In the present study, all logs underwent soaking at 70 °C prior to peeling, irrespective of the peeling temperature (20 °C or 70 °C). Because soaking at an elevated temperature alters the chemical properties of the wood material (Yamamoto *et al.* 2015a), it might be expected that reactions that are initiated by a higher soaking temperature should occur in logs that are cooled before peeling as well as those that are peeled directly after soaking at 70 °C. Thus, it would be expected that similar chemical changes, brought about by soaking, would have occurred in all logs. However, due to the different peeling temperatures, the physical properties of the material and its topography would most likely be affected by the material softening that occurs at higher temperature.

Color measurements suggested similarities in the chemistry of the veneer surfaces produced from logs peeled both hot and cold. As can be seen in Table 1, the color of the veneer surfaces from both the hot and cold peeled logs was similar. The lightness (L^*) values were 74.6 and 74.1, respectively, and the color coordinate b^* , which represents yellowing, was also similar: 19.06 and 19.13 on the hot- and cold-peeled surfaces, respectively. The color measurements showed no statistical differences between hot- and cold-peeled veneer surfaces. It is important to note that the color of both the hot- and cold-peeled surfaces in this study was lighter and less yellow than veneers that were produced from material that was soaked and peeled at 20 °C ($L^* = 72.92$ and $b^* = 28.53$, unpublished data from the veneers obtained by Rohumaa *et al.* (2014)).

Table 1. Veneer Surface Properties and Bond Strength Values

Sample Codes		Hot-Soaked and Peeled at 70 °C	Cold-Soaked at 70 °C and Cooled to 20 °C	Soaked and Peeled at 20 °C (Rohumaa <i>et al.</i> 2014)
CIELab* color coordinates	L^*	74.63 (2.50) A	74.11 (1.63) A	72.92 (0.99) B
	a^*	3.97 (0.88) A	3.99 (0.97) A	3.56 (0.43) A
	b^*	19.06 (1.07) A	19.13 (0.99) A	28.53 (1.01) B
Average roughness values (μm)	R_{max}	71.70 (12.72) A	70.22 (11.95) A	62.32 (9.95) B
	R_z	60.83 (9.01) A	55.65 (9.33) A	48.25 (6.80) B
	R_a	9.64 (1.64) A	9.30 (1.79) A	7.44 (1.44) B
Contact angle (°) ¹		31.19 (10.88) A	54.52 (9.91) B	101.31 (4.17) C
Bond strength (MPa) ²		6.28 (0.37) A	5.43 (0.46) B	3.94 (0.36) C
A, B, and C indicate significantly different groups using Tukey's test at $\alpha = 0.05$. The values in parentheses represent one standard deviation.				
¹ Contact angle at 46 s				
² Bond strength taken after 180 s of pressing				

Cooling the logs prior to peeling had no effect on the surface roughness, as measured by stylus (Table 1). The roughness parameters were similar on both surfaces, and there was no statistical difference between veneer surfaces that were peeled after cooling or when hot. The R_a values on the cold- and hot-peeled surfaces were 9.30 μm and 9.64 μm , respectively.

Peeling logs at a higher temperature decreases the roughness of 2-mm-thick spruce (*Picea orientalis* L.) veneer, measured using the stylus method (Aydin *et al.* 2006). The results of the current study, however, did not corroborate this finding, most likely due to the thickness of the veneer and the different wood species studied.

SEM micrographs (Fig. 1) show similar features on both hot- and cold-peeled veneer surfaces, and significant differences were not observed. Unfortunately, SEM could not identify any quantitative differences on these surfaces. It is likely, however, that a slightly greater quantity of very fine particles was present on the surface of the veneer that was peeled from hot logs. This contention was supported by the integrity test results, where the number of loose particles was slightly greater on the veneer peeled hot than on veneer peeled after cooling (Fig. 2).

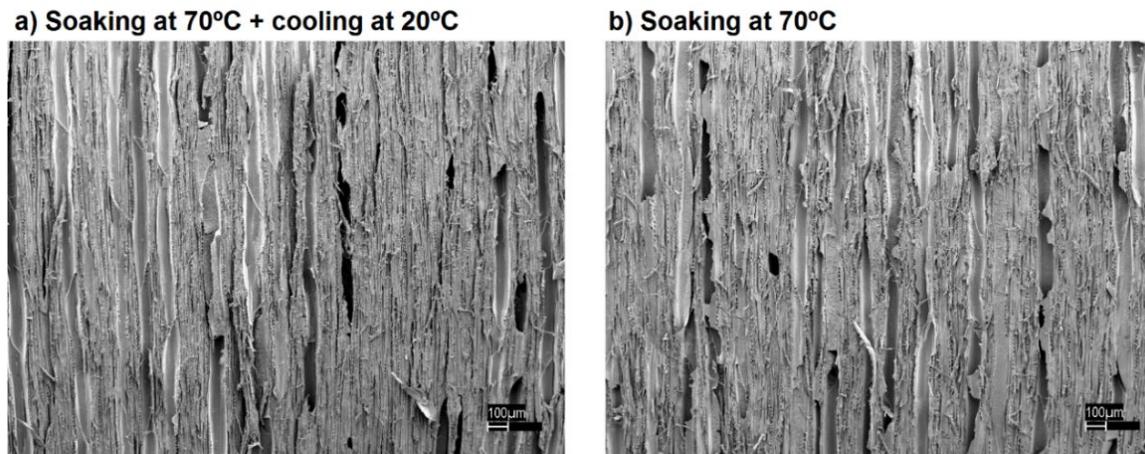


Fig. 1. Representative SEM micrographs of veneer surfaces a) cold-soaked at 70 °C and cooled at 20 °C prior peeling, b) hot-soaked at 70 °C and peeled at 70 °C

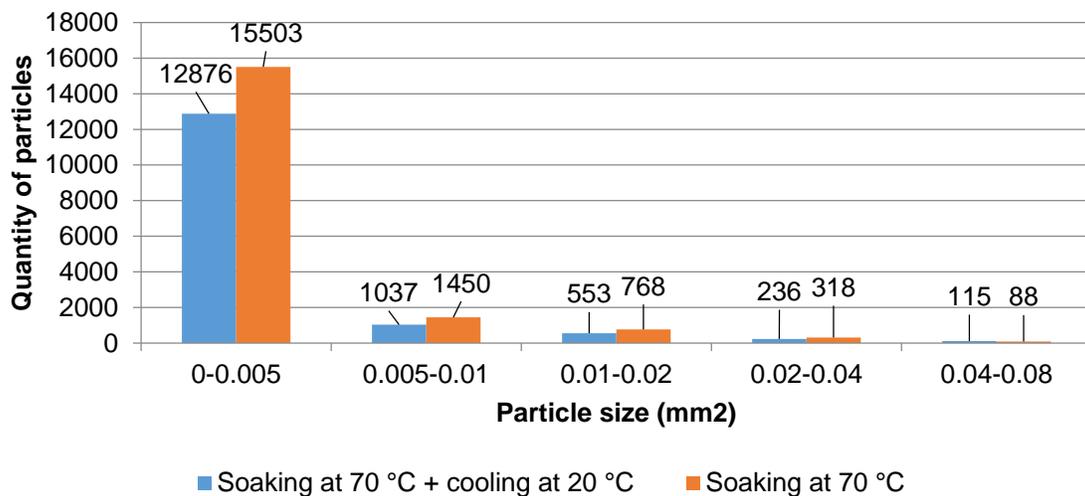


Fig. 2. Effect of log heating on loosely attached particle quantity and size on veneer surface

It is generally well known that for good bonding, effective wetting is essential to establish close contact between adhesive and the bonded surface. Wetting was investigated with the contact angle measurements. Contact angle measurements of surface wettability indicated clear differences between hot- and cold-peeled veneer surfaces; the results were 31.2° and 54.5° , respectively (Table 1). Both curves showed clear differences at all times from 0 to 46 s (Fig. 3a), and the differences were statistically significant (Table 1). Moreover, the contact angle on veneers obtained from cooled logs was lower (54.5°) than the contact angle of 101.3° reported by Rohumaa *et al.* (2014) from veneers produced in similar manner, except that the logs were soaked and peeled at 20°C . These results clearly show that the wettability of veneer surfaces in which the material was soaked at 70°C and peeled at either 20°C or 70°C (hot and cold) is much better than when the veneer surfaces are produced from logs soaked and peeled at 20°C . Furthermore, the differences in contact angles between hot and cold were statistically significant, suggesting that there were also differences in bond strength.

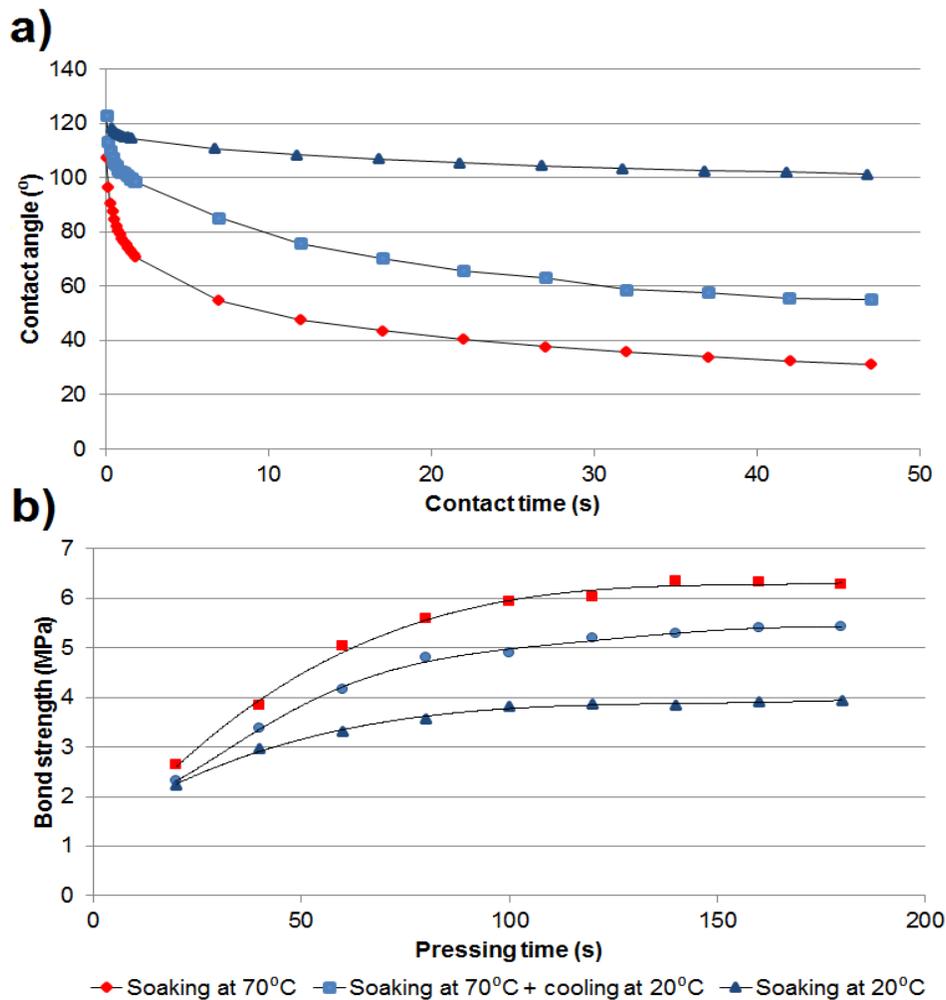


Fig. 3. Effect of log heating on a) wettability and b) bond strength development; the data from logs soaked at 20°C were adapted from the study conducted by Rohumaa *et al.* (2014)

The bond strength values decreased slightly on veneers that were peeled from the cooled logs (Fig. 3b), but the results were still much higher (5.43 MPa) than those obtained by Rohumaa *et al.* (2014), where the average bond strength was only 3.94 MPa after 180 s pressing using veneers that were soaked and peeled at 20 °C. Surface analyses of roughness, color, contact angle, and integrity showed that the cooled surface was much more similar to the surface obtained from logs soaked at 70 °C and peeled hot than the surface that was obtained from logs soaked only at 20 °C (Rohumaa *et al.* 2014).

The results of this study show that the temperature history of a birch log prior to peeling is an important factor that contributes to veneer properties and bond strength. The results also demonstrate that the peeling temperature has much less of an effect on bond strength than was expected and that material softening arising from the elevated peeling temperature did not have a sizeable effect on the surface roughness or topography of the tight side of the veneer. The results suggest that soaking temperature not only causes softening of the material in the peeling process, but also causes irreversible chemical changes in wood material that subsequently affect bond strength development. The present study also corroborates the assertion that contact angle measurement is a useful method for evaluating the surface properties affecting bond development, though it is impossible to separate the surface physical properties from the chemical properties that affect bond formation using this technique. This study also confirms that the integrity test was much more valuable than the roughness measurement test for predicting the bonding quality of the veneer-adhesive assembly. The advantage of the integrity test is that it evaluates the particles loosely attached to the surface, which have arisen as a result of the wood cutting process and cannot be evaluated using roughness techniques.

CONCLUSIONS

1. The results show that logs soaked at 70 °C and peeled at 20 °C had roughness, color, integrity, bond strength, and wetting properties much more similar to logs soaked and peeled at 70 °C than those soaked and peeled at 20 °C.
2. The study indicates that the effect of the peeling temperature on veneer properties was minor compared with the effect of soaking temperature. The temperature history of the log prior to peeling is an important factor that contributes to veneer properties and bond strength. Soaking results in the softening of wood, but it also causes irreversible changes in the wood material, which have a measurable effect on bond strength development.
3. The integrity test proved to be more valuable for predicting the bonding quality than roughness measurements because of its advantage of evaluating particles loosely attached to surface.

ACKNOWLEDGMENTS

The authors would like to acknowledge the financial assistance provided by the Finnish Funding Agency for Technology and Innovation (Tekes). Additionally, warm thanks are extended to the staff at the U. S. Forest Service Forest Products Laboratory in Madison, WI, USA.

REFERENCES CITED

- Aydin, I., Colakoglu, G., and Hiziroglu, S. (2006). "Surface characteristics of spruce veneers and shear strength of plywood as a function of log temperature in peeling process," *Int. J. Solids Structures* 43(20), 6140-6147. DOI: 10.1016/j.ijsolstr.2005.05.034
- Bailleres, H., Denaud, L., Butaud, J., and McGavin, R. L. (2015). "Experimental investigation on rotary peeling parameters of high density coconut wood," *BioResources* 10(3), 4978-4996. DOI: 10.15376/biores.10.3.4978-4996
- Dupleix, A., Denaud, L., Bleron, L., Marchal, R., and Hughes, M. (2013). "The effect of log heating temperature on the peeling process and veneer quality: Beech, birch, and spruce case studies," *Eur. J. Wood Prod.* 71(2), 163-171. DOI: 10.1007/s00107-012-0656-1
- Kontinen, P., Kivistö, A., Söyriälä, P., and Usenius, A. (1992). *Automation of Plywood Manufacturing*, VTT Publications, Espoo, Finland.
- Marchal, R., Mothe, F., Denaud, L., Thibaut, B., and Bleron, L. (2009). "Cutting forces in wood machining – Basics and applications in industrial processes. A review COST Action E35 2004-2008: Wood machining - micromechanics and fracture," *Holzforschung* 63(2), 157-167. DOI: 10.1515/HF.2009.014
- Marra, A. A. (1992). *Technology of Wood Bonding*, Van Nostrand Reinhold, New York, NY, USA.
- Mayer, I., and Koch, G. (2007). "Element content and pH value in American black cherry (*Prunus serotina*) with regard to colour changes during heartwood formation and hot water treatment," *Wood Sci. Technol.* 41(6), 537-547. DOI: 10.1007/s00226-007-0144-7
- Meriluoto, J. (1965). *The Influence of Raw Material Factors on the Quantity and Quality of Rotary Cut Brick Veneer*, Uudenmaan Kirjapaino Oy, Helsinki, Finland.
- Rohumaa, A., Hunt, C. G., Hughes, M., Frihart, C. R., and Logren, J. (2013). "The influence of lathe check depth and orientation on the bond quality of phenol-formaldehyde-bonded birch plywood," *Holzforschung* 67(7), 779-786. DOI: 10.1515/hf-2012-0161
- Rohumaa, A., Hunt, C. G., Frihart, C. R., Saranpää, P., Ohlmeyer, M., and Hughes, M. (2014). "The influence of felling season and log-soaking temperature on the wetting and phenol formaldehyde adhesive bonding characteristics of birch veneer," *Holzforschung* 68(8), 965-970. DOI: 10.1515/hf-2013-0166
- Rohumaa, A., Antikainen, T., Hunt, C. G., Frihart, C. R., and Hughes, M. (2016). "The influence of log soaking temperature on surface quality and integrity performance of birch (*Betula pendula* Roth) veneer," *Wood Sci. Technol.* DOI: 10.1007/s00226-016-0805-5
- Salmen, L. (1982). *Temperature and Water Induced Softening Behaviour of Wood Fiber Based Materials*, Royal Institute of Technology, Stockholm, Sweden.
- Sellers, T. (1985). *Plywood and Adhesive Technology*, Marcel Dekker Inc., New York, NY, USA.
- SFS-EN ISO 4288. (1998). "Geometrical product specifications (GPS). Surface texture: Profile method. Rules and procedures for the assessment of surface texture," Finnish Standards Association (SFS), Helsinki, Finland.

- SFS-EN ISO 3274. (1998). “Geometrical product specifications (GPS). Surface texture: Profile method. Nominal characteristics of contact (stylus) instruments,” Finnish Standards Association (SFS), Helsinki, Finland.
- Yamamoto, A., Rohumaa, A., Kontturi, E., Hughes, M., and Vuorinen, T. (2015a). “The effect of hydrothermal treatment on the color stability and chemical properties of birch veneer surfaces,” *BioResources* 10(4), 6610-6623. DOI: 10.15376/biores.10.4.6610-6623
- Yamamoto, A., Rohumaa, A., Kontturi, E., Hughes, M., and Vuorinen, T. (2015b). “Chemical characteristics of squeezable sap of hydrothermally treated silver birch logs (*Betula pendula*): Effect of treatment time and the quality of the soaking water in pilot scale experiment,” *Wood Sci. Technol.* 49(2), 289-302. DOI: 10.1007/s00226-014-0693-5
- Yamamoto, A., Rohumaa, A., Kontturi, E., Hughes, M., and Vuorinen, T. (2015c). “The chemical characteristics of squeezable sap from silver birch (*Betula pendula*) logs hydrothermally treated at 70 °C: The effect of treatment time on the concentration of water extracts,” *Wood Sci. Technol.* 49(6), 1295-1306. DOI: 10.1007/s00226-015-0758-0

Article submitted: February 15, 2016; Peer review completed: April 10, 2016; Revised version received and accepted: April 27, 2016; Published: May 11, 2016.
DOI: 10.15376/biores.11.3.5829-5838