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The influence of felling season and log-soaking temperature on the wetting and phenol formaldehyde adhesive bonding characteristics of birch veneer

Abstract: Most adhesive studies employing wood veneer as the substrate assume that it is a relatively uniform material if wood species and veneer thickness are constant. In the present study, veneers from rotary cut birch (*Betula pendula* Roth) were produced from logs harvested in spring, autumn and winter, and soaked at 20°C and 70°C prior to peeling. Firstly, veneers produced from logs felled in autumn were dried at 103°C for 24 h and subsequently half of these veneers were heat-treated at 180°C for 3 h. In addition, veneers produced from logs felled in all three seasons were dried at 160°C for 3.5 min to simulate industrial drying. The wettability of veneers was evaluated goniometrically, and bonding strength was evaluated with an automated bonding evaluation system (ABES). The results show that soaking birch logs at 70°C rather than at 20°C before peeling, or harvesting trees in the spring rather than in the autumn or winter, gives rise to veneers with enhanced wettability and higher bond strengths with a phenol-formaldehyde adhesive. Changes in the preparation and history of a veneer surface may have a profound effect on the development of adhesive bonds.

Keywords: automated bonding evaluation system (ABES), bond strength, felling season, heat-treatment, soaking temperature, veneer, wettability

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Introduction

Understanding and controlling wood bonding is a challenging task because of material heterogeneity and variability. The influence of the surface properties of veneer on adhesive bond strength is particularly difficult to evaluate, because: a) standard testing methods are laborious and time consuming, and b) there are many material and process parameters that influence bond strength (Marra 1992). Some of these parameters and process stages, such as veneer drying and its effect on the surface properties of veneer, have been well studied (Christiansen 1990, 1991; Šernek et al. 2004). However, the effects of felling season and log soaking/heating prior to peeling, have received little attention. A better understanding of their effect on the veneer surface and the resulting bond properties is needed in the development of more durable wood-based materials.

Several researchers have reported that felling season affects the chemistry of the wood surface in silver birch (*Betula pendula* Roth) by influencing the concentration of phenolic compounds and other compounds with low molar mass (Mononen et al. 2004; Yamamoto et al. 2013). As these compounds reduce surface wettability and bond strength (Plomley et al. 1976), the felling season might affect bonding. The density of silver birch varies slightly (by 5–6%) from season-to-season because of the variation in the total amount of extractives (Möttönen and Luostarinen 2006). According to the quoted author, this parameter has insignificant effect on physical and mechanical properties of wood and probably it also has negligible effect on failure modes in adhesive bond testing.

Logs are heated prior to peeling or slicing to produce smoother and 'tighter' veneer, with less wear and damage to the knife (Lutz 1960, 1977; Corder and Atherton 1963; Salmén 1982; Placet et al. 2007). Besides softening, the treatment temperature has an effect on the wettability of the veneer produced (Aydin et al. 2006). The wettability of wood surfaces is usually tested by contact angle (CA) measurements (Collett 1972; De Meijer et al. 2000; Nussbaum and Sterley 2002; Wålinder 2002; Sinn et al. 2009). The permeability and surface energy of wood influences adhesive penetration and spreading, which in turn affects the durability of the bond formed (Marian and Stumbo 1962; Frihart 2004; Kamke and Lee 2007).

Standard shear strength tests on plywood specimens are time consuming and require a lot of test material. Less material is needed for the automated bonding evaluation system (ABES), where the adhesive is cured under controlled conditions in an integrated miniature hot-press, while the lap-shear bond strength is measured within the same unit after pressing (Humphrey 1993). The advantages of the ABES are that small and smooth veneer specimens are tested with a small overlap area, and in the parallel-ply assembly the orientation of checking cannot cause differences in the failure modes or the quantitative data (wood failure percentage) (Rohumaa et al. 2013). ABES was used successfully in studies on the development of the adhesive bond for modelling the hot-pressing process of panel products (Humphrey 1997; Stöckel et al. 2010) and in the optimisation of resin formulations (He et al. 2012). The effect of the chemical modification of wood upon bond strength development was also tested by ABES (Chowdhury and Humphrey 1999).

How variations in veneer processing operations affect bond strength development have not yet been tested by the ABES method. The aim of the present work was to gain more insight into the complex process of plywood production. In particular, the felling season of the trees and process parameters, such as the log soaking and veneer drying temperatures, were evaluated by means of the reliable ABES method.

Materials and methods

Silver birch *(Betula pendula* Roth*)* trees were felled at the end of February, May and September in Rusutjärvi, Southern Finland. Material without visual defects was selected. The average diameter of the logs was 244 mm, the average density of the wood material was 510 kg m^{-3} and the initial moisture content (MC) before drying was 72.5%.

Experimental set no. I focusing on soaking temperature and heat-treatment: A fresh tree felled in autumn was sectioned into logs nominally 1.2 m in length and completely immersed in water tanks heated to either 20°C or 70°C. The core temperature of the logs was monitored by embedded thermocouples. The logs were kept at the target temperature at least 12 h. Then the logs were 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 were cut from the veneer ribbon with dimensions of approximately 350 mm by 400 mm, free from obvious defects such as knots or sloping grain. The specimens were subsequently dried for 24 h in a fan assisted oven (Model TS 8136, Termaks AS, Bergen, Norway) at 103°C to achieve 0% MC. Selected dried specimens were then 'heat-treated' for 3 h at 180°C in the same oven. Prior to all testing, the specimens were conditioned at 20°C and 65% RH, until constant mass was achieved.

Experimental set no. II focusing on felling season and soaking temperature: Fresh trees felled in winter, spring and autumn were cut to a nominal length of 1.2 m and completely immersed in water tanks heated to either 20°C or 70°C. The logs were processed in the same manner as in the first experimental set, except that the veneers were dried at 160°C for approx. 3.5 min in a laboratory scale veneer dryer (Raute Oyj, Lahti, Finland) to achieve an average MC of 6%. Prior to all testing, the veneers were conditioned to constant mass at 20°C and 65% RH.

Bond formation: Matched specimens, 20×117 mm^2, were cut from the conditioned veneer sheets. A liquid phenol formaldehyde (PF) resin (Prefere 14J021, Dynea Chemicals Oy, Hamina, Finland), with 49% solids content was applied to an area of 5×20 mm^2 at one end of the veneer specimens to give a resin spread rate of ~200 g m^{-2} in experimental set I and ~100 g m^{-2} in the experimental set II. For experimental set I, the adhesive was applied manually with a brush and for experimental set II by a micropipette (HandyStep electronic, BRAND GMBH + CO KG, Wertheim, Germany). It was difficult to apply resin accurately by brush at a spread rate of <200 g m^{-2} and it was also noticed that excess resin was squeezed out from the bond-line. After adhesive application, the veneer-resin assembly was placed in the ABES equipment (Adhesive Evaluation Systems, Incorporated, Corvallis, OR, USA) and hot pressing started almost immediately. The assembly time for specimens was approx. 5 s. Shear strength was measured after various pressing times ranging from 20 to 200 s. The platen temperature was 130°C and press pressure was 2.0 MPa. The bonds were not cooled prior to strength testing. At least seven bonded specimens were tested for each substrate type and pressing time.

Contact angle (CA) measurements were performed on a CAM 200 Goniometer (KSV NIMA, Espoo, Finland) with de-ionised water. The water droplet volume was ~10 µl. CA was measured at intervals of 120 ms for the 1st s and every 5 s thereafter up to 70 s. At least 30 CA determinations were made at different locations on the veneer surface for each specimen representing the combinations felling season, soaking temperature, and drying temperature.

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

Results and discussion

Effects of soaking temperature and heat-treatment

The veneer process parameters and bond strength values after 120 s pressing (expected complete cure) are summarised in Table 1. Statistically significant differences

Table 1 Data of logs felled in autumn. Average bond strength was determined after 120 s pressing time at 130°C. Average contact angle is determined after 70 s contact with the surface.

Sample codes	Soaking temp. (°C)	Drying temp. (°C)	Avg. Bond strength (MPa)	Group homogeneity[a]	Avg. Contact angle (°)	Group homogeneity[a]
s20/d103	20	103	5.34±0.28	B	77.6±5.3	B
s20/d103+180	20	103+180	4.34±0.21	C	118.2±8.0	D
s70/d103	70	103	6.14±0.66	A	24.0±10.1	A
s70/d103+180	70	103+180	3.66±0.46	D	108.9±8.9	C

[a]A, B, C and D represent segregation among the average values, describing that all groups are different form one another.

exist between all means after 120 s pressing time. The higher soaking temperature leads to higher bond strength (Table 1), with the average value rising from 5.34 MPa (s20/d103) to 6.14 MPa (s70/d103). Even after heat-treatment at 180°C for 3 h, the effect of log soaking temperature is still noticeable, with clear differences in the bond strengths being seen after 120 s pressing time. The effect of drying conditions on bonding was as expected: all the heat-treated veneers displayed lower ultimate strength values after 120 s pressing than those dried at 103°C (Table 1).

Figure 1 shows that there are clear differences in the rate of strength development and in the final bond strength values. Comparing the initial (20 s pressing time) portions of the cure curves (Figure 1), there was some evidence that heat-treatment results in higher initial bond strength values, but after 40 s of pressing bond strength reaches a plateau, whereas the strength of samples dried at 103°C were still increasing. Further work is necessary to understand this observation.

Table 1 summarises the effect of the log soaking temperature and drying conditions on CA. The 70°C soaking temperature coupled with the 103°C drying temperature led to the lowest CA, whereas 20°C soaking temperature and 103°C+180°C heat-treatment led to the highest CA values, indicating reduced wettability. ANOVA with Tukey's test shows that the CA differences are significant (Table 1).

The CA as a function of time is illustrated in Figure 2. Each curve represents the average of all CA determinations (minimum n=30) taken on each surface type. After drying at 103°C, there was a distinct difference between the wetting behaviour of veneer s20/d103 and s70/d103. After a rapid decrease in CA during the first 5 s to 10 s in contact with the veneer surface, CA continued to decrease, indicating further spreading/absorption on the substrate. After 70 s, the mean CA value of veneers s70/d103 was 24° and veneers s20/d103 was 78°, although equilibrium had not been reached (Figure 2). Log soaking temperature clearly has a marked effect upon the wetting behaviour of the veneer surface when dried at 103°C and though the cause is not yet fully understood, both physical and chemical changes were thought to play a part.

The wetting behaviour of heat-treated veneers s20/d103+180 and s70/d103+180 is significantly different to those dried at 103°C with little change in CA after 10 s indicating that the surface has been 'inactivated'. After 70 s contact with the surface (Figure 2), the heat-treated veneers s20/d103+180 had a CA of 118° and veneers s70/d103+180 had a CA of 109°. The effect of log soaking temperature on CA is still noticeable even after heat-treatment,

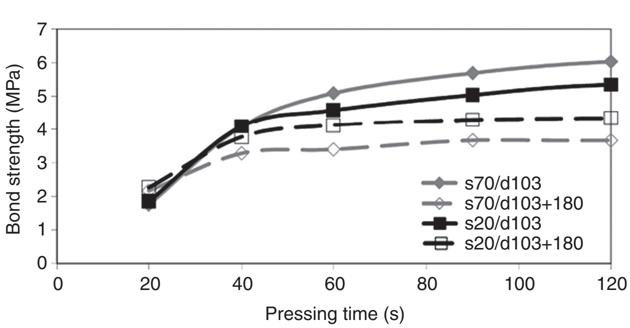

Figure 1 Bond strength development as detected by ABES. In the codes, s is for soaking and d for drying; the numerals are temperatures (°C). In all samples the time for drying was 24 h; the additional drying temperature (+180°C) was maintained for 3 h.

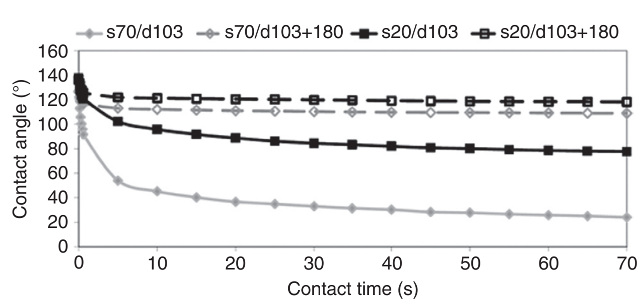

Figure 2 Contact angle of water droplet on wood surface as a function of contact time. In the codes, s is for soaking and d for drying; the numerals are temperatures (°C). In all samples the time for drying was 24 h; the additional drying temperature (+180°C) was maintained for 3 h.

that may well account for the differences in the observed bond strength.

Effect of felling season

The effect of soaking is clearly visible in the plots of bond strength vs. pressing time (Figure 3). Veneers prepared at 70°C have higher bond strength over the whole range of pressing times. Figure 4a shows that felling season has an effect on strength when logs are soaked at 20°C, but that soaking at 70°C leads to more uniform strength results overriding the effects of felling season. Winter felled logs are most susceptible to the effects of soaking temperature. ANOVA combined with Tukey's test shows that the seasonal differences were only significant within the material soaked at 20°C. Also the CAs of veneers from logs soaked at 70°C was more uniform (Figure 4b) independent of the felling season. There is a strong correlation (-0.81) between CA and bond strength. The reason for this very strong correlation might be partly due to the fact that the assembly time was short; hot-pressing started immediately after adhesive application and the adhesive did not have time to penetrate into the surface as in industrial applications.

The different wetting behaviour and bond strengths obtained from material felled at different seasons was likely due to the changing quantity and character of metabolites in different seasons. In autumn and winter felled birch, the material contains more starch and other extractives as an energy reserve (Piispanen and Saranpää 2001; Mononen et al. 2004). Extractives can migrate to the wood surface during the drying process leading to a reduction in wettability; over-drying can exacerbate the effect leading to a further decrease in wetting, resulting in poor bonding as noted by Christiansen (1990, 1991) and Šernek et al. (2004). More severe treatment, such as the heat-treatment applied in the present study, has also been found to decrease bond strength with PF resin (Kariz and Šernek 2010) and significantly increase the hydrophobicity of wood (Pétrissans et al. 2003; Esteves and Pereira 2009).

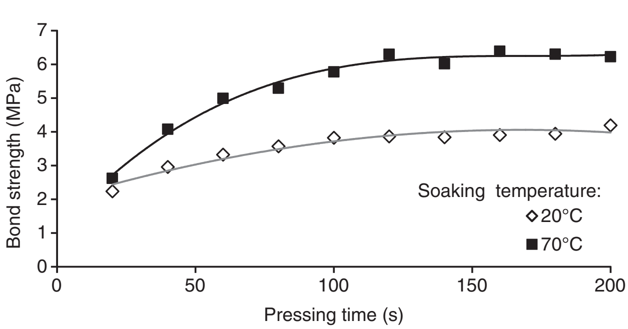

Figure 3 The effect of soaking temperature on bond strength development as determined by ABES for veneers prepared from winter-felled birch, which were dried at 160°C for 3.5 min.

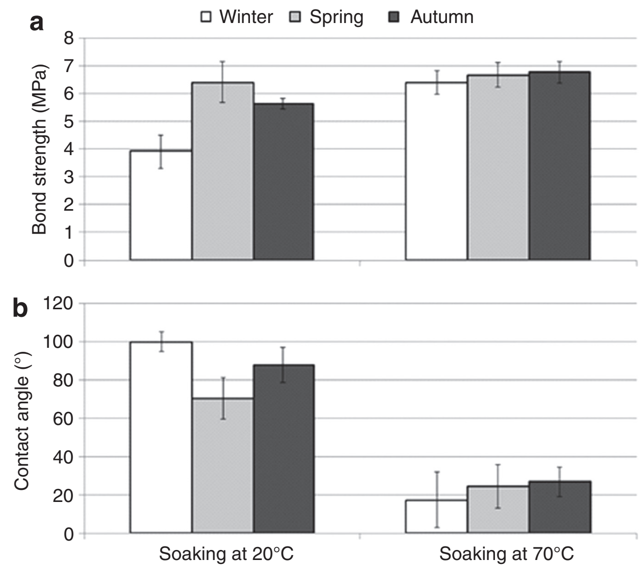

Figure 4 The effect of felling season and soaking temperature on bond strength development (a) and contact angle (b). Bond strength a) was measured after 160 s of pressing by means of ABES. The contact angle b) of a water droplet was measured after 70 s contact time (veneers were dried before at 160°C for 3.5 min).

In the present study, 103°C or 160°C drying temperatures do not have a significant effect on bond strength because the heat of vaporisation cools the surface as long as the MC of the veneer is above fibre saturation point (Keylwerth 1953). The short drying process at 160°C (3.5 min) certainly did not cause overheating of the veneers.

The results clearly demonstrate that felling season can have a significant influence on bond strength, depending upon the soaking temperature employed, if the ABES method is used for evaluation. For reliable measurements, there is a need to know the origin and processing history of the veneers. In most reported studies based on ABES, the origin of the material and preparation process is unknown or not mentioned, which casts doubt on the comparability of the findings.

Conclusions

In this study, the effect of felling season and log soaking temperature on the wetting characteristics and adhesive bonding in birch veneer was investigated. Both felling season and log soaking temperature were found to significantly affect wettability and adhesive bond strength with a PF resin. Furthermore, the interpretation of adhesion data obtained by ABES should be treated with caution in situations where the veneer properties and history are not fully known. Assuming that veneer is a homogenous substrate might lead to a misinterpretation of results. Despite the aforementioned reservations, ABES was found to be useful for evaluating the impact of veneer production variables or the wood properties on the bonding process.

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