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Properties of laminated veneer lumber (LVL) made with low density hardwood species: effect of the pressure duration

S. R. Shukla · D. Pascal Kamdem

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Abstract Cross-linked polyvinyl acetate (PVAc) adhesive and thin veneers of three low density wood species, namely silver maple, yellow poplar and aspen, were used to produce LVL engineered wood products using different press durations. Density, water absorption, thickness swelling, flexural strength and surface hardness were evaluated. Internal bond strength, tensile shear and block shear strengths were tested in dry, accelerated (boiling and dry) and cyclic (wet and dry) conditions. LVL made using cross-linked polyvinyl acetate and silver maple with a platen temperature of 38 °C for 5 minutes exhibited the best properties. LVL of silver maple veneers showed improved properties as compared to yellow poplar and aspen. Silver maple can be used suitably in laminated veneer flooring.

Eigenschaften von Furnierschichtholz (LVL) aus Laubholz geringer Dichte: Einfluss der Pressdauer

Zusammenfassung Aus vernetztem Polyvinylacetat (PVAc) und dünnen Furnieren dreier Holzarten von geringer Dichte, Silberahorn, Amerikanischem Tulpenbaum und Espe, wurden unter Verwendung von unterschiedlichen Presszeiten Furnierschichtholzprodukte hergestellt. Dichte, Wasserabsorption, Dickenquellung, Biegefestigkeit und Oberflächenhärte wurden bestimmt. Querzugfestigkeit, Zugscher- sowie Blockscherfestigkeit wurden unter trockenen Bedingungen sowie nach schneller Bewitterung (kochen und trocknen) sowie zyklischer klimatischer Beanspruchung (nass und trocken) geprüft. Dabei wies Furnierschichtholz aus vernetztem Polyvinylacetat und Silberahorn bei einer Presstemperatur von 38 °C und einer Pressdauer von 5 Minuten die besten Eigenschaften auf. LVL aus Silberahorn könnte beispielsweise gut als Bodenbelag aus Furnierschichtholz eingesetzt werden.

S. R. Shukla · D. P. Kamdem (✉)
Laboratory of Wood Science and Technology,
Department of Forestry, 126, Natural Resources Building,
Michigan State University,
East Lansing, MI 48824, USA
e-mail: kamdem@msu.edu

1 Introduction

In view of the increasing awareness of society concerning the natural environment, the acceptance of wooden building materials in form of solid wood and wood-based composites has increased substantially during the past few decades. The main advantages of these materials are availability, renewability, lower processing costs and simplicity of dismounting and disposal at the end of their service life. Researchers are showing increased interest in the benefits of composite technology for wood-based materials for structural and non-structural usage (Fridley 2002). One of the objectives of composite technology is to produce a product with acceptable performance characteristics using low quality raw materials combining beneficial aspects of each constituent. New composites are produced with the aim to reduce the costs and to improve performance (Schuler and Adair 2003).

Wooden flooring is one of the high value products from wood or wood composites, widely used in residential houses as well as industrial units. Engineered wood flooring (EWF) is generally made of plywood with a thin hardwood species veneer bonded onto the face of the composite plywood. Subsequently, a thin coating is applied to this fancy veneer (Kim and Kim 2006). In the North American market, the demand of engineered wood flooring products has been increased many fold in the last 15 years (Blanchet et al. 2005, 2006) for its usage in different applications. Laminated veneer lumber (LVL), cross-laminated plywood and other wood-based composites have been manufactured by using appropriate adhesives, processing conditions, veneers from different wood species at different orientations. LVL has the potential to be used in structural and non-structural applications such as construction and furniture industry, material for flooring and numerous other areas (Eckelman 1993, Hayashi and Oshiumi 1993, Wong et al. 1996, Ozarska 1999, Lam 2001). A variety of low-grade plantation species has been studied for the production of LVL (Hesterman and Gorman 1992, Feng et al. 1999). Effects of different processing variables on processing behavior, strength and stiffness of aspen LVL were investigated (Wang and Dai 2005). Static bending properties of aspen LVL made using low grade veneers were found to be comparable to pine and spruce commercial LVL (Hsu 1988). For producing engineered wood products, different thermoplastic and thermosetting adhesives have been used (Sellers et al. 1988, Sellers 2001). Polyvinyl acetate (PVAc) is one of such thermo-plastic adhesive that is mostly used as an emulsion.

Due to associated health hazards in formaldehyde emissions from formaldehyde-based adhesives, there is growing interest in the usage of PVAc-based composites in furniture, residential construction, paper, textile and other adhesive industry (Kim and Kim 2006). In order to improve the performance in adverse climatic conditions, PVAc adhesives are generally modified with cross-linking agents such as polymeric diphenylmethane isocyanate (pMDI) and other vinyl monomers during polymerization (Qiao et al. 2000a, 2002). Cross-linked PVAc are rigid, better heat and moisture resistant. A comparative study on using four different adhesives for producing engineered wood parquet flooring was reported by Blanchet et al. (2003). Out of these four adhesives, the best adhesive for bonding EWF layer was found to be polyurethane (PU) for stability of the glue line strength following aging cycles. PVAc adhesive was not found suitable for EWF. Kilic et al. (2006) have reported the results on some physical and mechanical properties of laminated veneer lumber made from black alder (*Alnus glutina*) glued with PVAc and PU adhesives. PVAc adhesive was found to yield much better properties as compared with PU adhesive. Studies on shear strength of Calabrian pine (*Pinus brutia* Ten.) wood bonded with PVAc and PU adhesives were reported by Burdurlu et al. (2006). Highest shear strength was exhibited for specimens glued with PVAc adhesive as compared to those glued with PU adhesive.

Michigan forests of the United States are known to contain several hardwood species that are underutilized due to their lower density and poor mechanical and physical properties. High value products may be developed using appropriate processing technology. LVL is one of the most favourable technologies that can be applied to manufacture high value products from less utilized species of Michigan forest. The proposed research is therefore aimed to explore the possibility of developing three-ply LVL high value engineered wood product using low value wood species such as silver maple, yellow poplar and aspen. A commercially available cross-linked PVAc adhesive obtained from National Casein Company, Chicago, USA will be used as adhesive. Such scientific and technical information is very much required by the forest products industry to meet and develop future market demands in high value products such as flooring, kitchen cabinets, molding, etc.

2 Materials and methods

2.1 Wood veneers

Silver maple (*Acer saccharinum*), yellow poplar (*Liriodendron tulipifera*) and aspen poplar or aspen (*Populus tremuloides*), three hardwood species growing in Augusta, Michigan in natural site of W. Kellogg Experimental Forest managed by the Department of Forestry, Michigan State University, were harvested. The logs were about 1.83 meter long and were rotary peeled into veneers at Dimension Veneers, Edon, Ohio. Veneers, 610 mm long by 510 mm wide by 3.0 to 3.5 mm thickness, were used for making 3-ply laminated veneer lumber. The average moisture content of the dried veneers varied between 6%–8%.

2.2 Adhesive

One-part type II cross-linked (poly)vinyl acetate (PVAc) adhesive (PC-2002 from National Casein Company, Chicago, USA) was used for producing these three-ply LVL boards in duplicate. The ready-to-use adhesive has a viscosity of 5000 cp at 25 °C, pH 3.0 and a density of 1.08 kg per liter. The adhesive was spread at the rate of about 200–220 g/m^2 on single bonding surface of the veneers (single glue line) as recommended by the manufacture. Glue was spread uniformly on the veneers by manually hand brushing.

2.3 Process

The boards were pressed at a pressure of 1.38 MPa for different durations, varying between 2, 5, 15 and 30 minutes in a microprocessor-controlled thermo-oil hydraulic hot press made by Erie Mill & Press Company Inc., USA having two steel platens measuring 685 mm by 610 mm. For the first three press durations, the press temperature was set to 38 °C for all the three species. Furthermore, the press was operated at room temperature (21 °C) for 30 minutes with the silver maple veneers. Two sets of LVL boards were made for all pressing durations using veneers of only single wood species. The pressed boards were trimmed of all edges of about 25 mm and stacked in a conditioning chamber with a temperature of 21 °C and a relative humidity of 65% for more than three weeks until further testing.

2.4 Physical, mechanical and adhesive testing methods

Density, water absorption, thickness swelling, static bending modulus of rupture, modulus of elasticity, surface hardness, internal bond strength, tensile shear strength and block shear strength were tested. The strength and adhesive properties were evaluated using a computer controlled Instron testing machine (model 4206) according to ASTM standards with slight modifications as described below.

2.4.1 Density and moisture content

About 17 to 20 specimens, 50.8 mm long by 50.8 mm wide by 9.5 mm thick, were used to determine the density and moisture content of each board type. The moisture content was determined by weighing the samples and then placing them in an oven set at 103 ± 2 °C for 24 hours. The air-dry and oven-dry densities were computed based on the air- or oven-dry weights divided by the volume of the samples in air-dry condition. These properties were also computed for the specimens used for static bending and surface hardness tests.

2.4.2 Thickness swelling and water absorption

For thickness swelling and water absorption tests, average sample size used was 152.4 mm long by 50.8 mm wide by 9.5 mm thick. Four replicates were taken for each type of boards. The specimens were submerged such that the top face of each specimen was about 2.5–3.0 cm from the surface of water. Due care was taken such that specimen faces were not resting against the flat surface of the container. No coating or water seals were applied on the edges of the samples during water dipping. After 2 hours, the specimens were removed; extra water at the surface was wiped off with tissue paper and measurements were taken of weight and dimensions. Finally, after 24 hours, the same procedure was repeated and samples were in the air for 15 hours before oven drying. After oven drying, thickness and weight measurements were once again repeated quickly. According to ASTM D 1037, thickness swelling was computed using the formula $\text{TS}(\%) = ((T_\text{f} - T_\text{i})/T_\text{i}) \times 100$, where T_f is wet thickness of specimen after water saturation for 2 hours and 24 hours, and T_i is the oven-dry thickness of specimens. Similarly, water absorption (WA) in percentage was computed from the oven-dry weight (W_i) and wet weights after 2 hours and 24 hours water saturation (W_f) using the formula: $\text{WA}(\%) = [((W_\text{f} - W_\text{i})/W_\text{i}) \times 100]$.

2.4.3 Flexural Properties

Flat wise three-point flexural (static bending) test was performed on the conditioned samples of size 152.4 mm by 25.4 mm by thickness of LVL and the crosshead loading speed was kept at 1 mm/min. Number of specimens tested for each LVL board type was six. In order to conduct this test, guidelines were taken from ASTM D 5456-06 with a slightly smaller span-to-depth ratio of 15. The recommended minimum span-to-depth ratio for three-point loading is 17.

2.4.4 Surface Hardness (Static Indentation)

Sample size for the surface hardness test was 101.6 mm long by 25.4 mm wide by twice the thickness of LVL as two pieces were stacked together during testing. Four replicates were taken for each type of boards. The crosshead loading speed was kept at 6 mm/min according to ASTM D 1037.

2.4.5 Internal bond (IB) strength

The sample size was 50.8 mm long by 50.8 mm wide by thickness of LVL and the crosshead loading speed was kept at 0.08 cm/cm of thickness of specimen per minute. Four to five samples were tested for each type of boards. The tensile strength perpendicular to the surface test was carried out using the samples glued to metal testing blocks with a high strength hot melt epoxy adhesive and conditioned before testing. According to ASTM D 1037, the tensile strength perpendicular to the surface test was carried out.

2.4.6 Tensile shear strength (TSS)

Sample size for this test was 76.2 mm long by 25.4 mm wide by the thickness of LVL and the glue shearing area was kept 25.4 mm long by 25.4 mm wide. Two grooves, 3.2 mm wide, were made on either side to a depth of two-plies. Number of specimens per board type varied from four to five. Crosshead loading speed was kept at 1.5 mm/min according to ASTM D 906-98.

2.4.7 Block shear strength (BSS)

The samples measuring 50.8 mm by 50.4 mm by the thickness of LVL were used for the BSS or glue-line shear strength test. The crosshead loading speed was kept at 0.6 mm/min and steps for applying shearing force in the samples were prepared according to ASTM D 1037. Number of replicates taken for each type of board varied from four to five. In order to avoid buckling of the back thin layer, a piece of metal was bonded using high strength hot melt epoxy glue as mentioned by Blanchet et al. (2003).

In addition to dry condition, the adhesive bond properties, viz., IB strength, TSS and BSS of the LVL, were also tested in the following two conditions:

(i) **Cyclic condition (repeated water soaking test)**: Samples were immerged completely in water at 22 °C ± 2 °C for a period of 24 hours followed by 24 hours of open air-drying and subsequently oven drying at 60 °C ± 2 °C for 20 to 24 hours and then cooled in the oven. All the samples were transferred to the conditioning room maintained at 21 °C and 65% relative humidity and kept there for 6 to 7 days before repeating the wetting cycle. Three such cycles were repeated for this treatment giving a total water submersion time of 72 hours.
(ii) **Accelerated condition (boiling water test)**: Samples were immerged in water at 22 °C ± 2 °C and water was brought to boiling and kept continuously boiling for 2 hours. Samples were then cooled in the water to 27 °C ± 2 °C followed by 24 hours of open air-drying and subsequently oven drying at 60 °C ± 2 °C for 24 hours. All the samples were transferred to the conditioning room maintained at 21 °C and 65% relative humidity and kept there for 12 to 15 days before testing.

3 Results and discussion

3.1 Physical properties

3.1.1 Density and moisture content

The density of wood and wood composites is one of the most important physical parameters and generally considered as the predictor of strength properties. In wood composites, the density is determined by the type and condition of wood species, form of the wood element used for producing the composite, type of glue applied and several processing parameters such as pressure, temperature, pressure duration, etc. The average values of air-dry density and oven-dry density of LVL from silver maple, yellow poplar and aspen are summarized in Table 1. For the sake of comparison, the air-dry density values of the neat wood veneers of these species were also calculated and given in Table 1. Silver maple wood composites have shown slightly improved values of air-dry density as compared to solid wood veneers followed by aspen and yellow poplar wood composites. The pressing duration of 5 minutes at a moderate temperature of 38 °C exhibited higher values of density of 605 ± 8 kg/m^3 for silver maple LVL. This corresponds to about 12% increase in the air-dry density value compared to solid wood veneers (Table 1). Silver maple LVL pressed at room temperature (21 °C) for a comparatively long duration of 30 minutes showed a density improvement of about 13%. Aspen and yellow poplar composites have shown slightly lower increments of 11% each compared to the respective solid wood veneers at a press duration of 15 minutes. The oven-dry density values have also shown almost similar behavior. The total range of improvement in the air-dry density of the LVL pressed for different durations was found to be about 6%–13% higher than the corresponding density of the solid wood veneers. This may correspond to only a slight densification of the LVL during processing. All the specimens were in a conditioning chamber maintained at a temperature of 21 °C and relative humidity 65% for more than a month prior testing. The equilibrium moisture content of the LVL samples was found in the range of 8.3 ± 0.3% to 9.1 ± 0.3%. For hardwood flooring application, one of the recommended species is sugar maple (*Acer saccharum*) (Luzadis and Gossett 1996). Values of some of the physical and mechanical properties of sugar maple solid wood with a moisture content of 12% are taken for comparison. The density of sugar maple wood is 676 kg/m^3 (sp.gr. 0.63) (Anon 2001). Density values greater than 600 kg/m^3 were shown by the silver maple LVL pressed for 5 minutes and 30 minutes. Processing wood composites at 21 °C room temperature may require longer press periods to yield the density values comparable or similar to those obtained at a very moderate temperature of 38 °C. These results will be used to optimize the processing parameters of the manufacture of three-ply LVL using low density hardwood species and cross-linked PVAc wood adhesive.

3.1.2 Thickness swelling and water absorption

The values of the dimensional stability: thickness swelling (TS) and water absorption (WA) for different press durations of silver maple, yellow poplar and aspen LVL are listed in Table 2. The LVL samples made from silver maple veneers and pressed for more than 5 minutes have shown least thickness swelling after 2 hours and 24 hours of water immer-

Table 1 Density values of solid wood veneers and three-ply LVL **Tabelle 1** Dichte der Furniere von dreilagigem Furnierschichtholz

Wood species	Solid veneers (kg/m^3)	Air-dry density (kg/m^3)				Oven-dry density (kg/m^3)			
Press duration		2 min	5 min	15 min	30 min	2 min	5 min	15 min	30 min
Silver maple	542 ± 9	588 ± 41	605 ± 8	572 ± 54	623 ± 26	538 ± 41	556 ± 7	521 ± 54	573 ± 26
Yellow poplar	492 ± 21	539 ± 13	536 ± 15	546 ± 28	–	496 ± 14	494 ± 14	517 ± 24	–
Aspen	498 ± 18	545 ± 18	548 ± 26	558 ± 21	–	507 ± 12	518 ± 24	518 ± 19	–

Table 2 Physical and mechanical properties of LVL pressed for different durations
Tabelle 2 Physikalische und mechanische Eigenschaften von mit vernetztem PVAc verklebtem, dreilagigem Furnierschichtholz (LVL) in Abhängigkeit der Presszeiten

Property	Silver maple				Yellow poplar			Aspen		
Press duration	2 min	5 min	15 min	30 min	2 min	5 min	15 min	2 min	5 min	15 min
Avg. dry thickness (mm)	9.75± 0.15	9.58± 0.07	9.56± 0.06	9.65± 0.07	9.49± 0.07	9.38± 0.09	9.32± 0.15	9.32± 0.15	9.21± 0.12	9.40± 0.08
Water Absorption (%) – 2 hours dipping	34.11± 2.10	29.52± 1.04	32.53± 1.58	29.02± 1.23	23.61± 0.18	26.55± 3.45	24.51± 2.09	32.58± 2.28	28.91± 1.62	30.19± 1.94
24 hours dipping	67.51± 4.18	60.92± 1.55	66.75± 0.57	60.12± 4.28	42.05± 1.35	47.36± 3.53	44.31± 2.72	64.38± 4.02	56.96± 5.10	54.71± 2.90
Thickness Swelling (%) – 2 hours dipping	2.26± 0.47	1.42± 0.67	1.50± 0.73	1.58± 0.30	2.22± 0.50	3.40± 1.40	2.36± 0.79	2.48± 0.31	1.74± 0.36	1.71± 0.83
24 hours dipping	3.38± 0.71	3.51± 1.32	3.13± 0.38	2.43± 1.01	4.16± 0.81	5.29± 0.25	4.77± 0.52	4.48± 0.34	3.04± 0.82	3.49± 0.73
Surface Hardness (kN)	4.92± 0.15	5.03± 0.31	5.31± 0.22	4.94± 0.12	3.74± 0.29	3.18± 0.86	3.60± 0.24	3.59± 0.30	3.83± 0.50	4.14± 0.21

sion, while yellow poplar LVL has shown the highest value of 3.4% after 2 hours of dipping. Average values of percentage of water absorption are also presented in Table 2. After 2 hours of dipping, minimum value of water absorption was obtained with yellow poplar LVL compared to silver maple and aspen LVL. Silver maple LVL pressed for 5 and 30 minutes has shown values in the range of 29%–30%. After 24 hours of dipping, highest values in the range of 60%–67% were obtained for silver maple LVL followed by aspen LVL. No trend was observed as a function of pressure duration. The average values of air-dry thickness of LVL are listed in Table 2. There was no significant difference in the average thickness of the LVL boards pressed for different durations. As low pressure level of 1.38 MPa was used, no spring back was observed in the processing of the LVL.

3.2 Strength properties

3.2.1 Flexural properties: MOR and MOE

Figs. 1 and 2 illustrate the effect of press duration on flat wise flexural modulus of rupture (MOR) and modulus of elasticity (MOE) of silver maple, yellow poplar and aspen three-ply LVL, respectively. The silver maple LVL has shown higher values of both flexural MOR and MOE in the range of 108.24–112.57 MPa and 9.82–9.96 GPa, respectively. These values were not affected by the press duration. LVL made from yellow poplar veneers have exhibited slightly better stiffness in the range of 8.52–9.04 GPa compared to aspen LVL (7.90–8.37 GPa). The press duration has not affected the pattern of MOE between these species

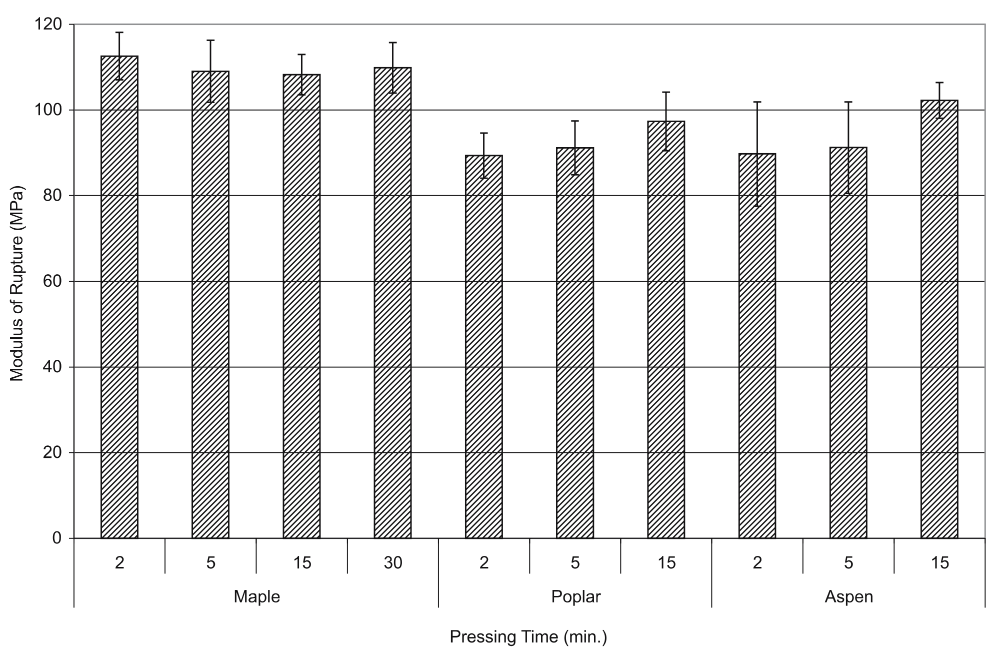

Fig. 1 Effect of press time on modulus of rupture (MOR) of PVAc glued 3-ply LVL from silver maple, yellow poplar and aspen
Abb. 1 Einfluss der Presszeit auf die Biegefestigkeit (MOR) von mit vernetztem PVAc verklebtem dreilagigem Furnierschichtholz aus Silberahorn, Amerikanischem Tulpenbaum und Espe

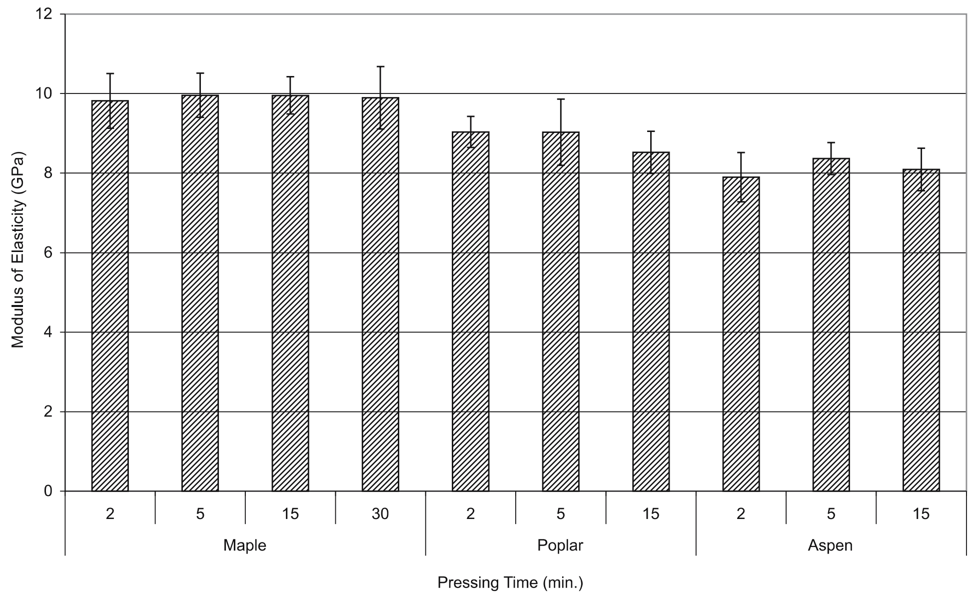

Fig. 2 Effect of press time on modulus of elasticity (MOE) of PVAc glued 3-ply LVL from silver maple, yellow poplar and aspen
Abb. 2 Einfluss der Presszeit auf den E-Modul (MOE) von mit PVAc verklebtem, dreilagigem Furnierschichtholz aus Silberahorn, Amerikanischem Tulpenbaum und Espe

composites (Fig. 2). In case of MOR, the longer press duration of 15 minutes yielded higher values in yellow poplar and aspen veneer composites as compared with 2 and 5 minutes press durations. Values of static bending MOR and MOE at 12% moisture content for sugar maple and silver maple solid wood are reported to be (109 MPa, 61 MPa) and (12.6 GPa, 7.9 GPa), respectively (Anon 2001). MOR values obtained for the 3-ply silver maple LVL are comparable to sugar maple solid wood values; however, MOE values are lower than the value reported for sugar maple. The comparison with values of silver maple solid wood showed that both MOR and MOE of these composites are much greater than that of solid wood. Lee et al. (1999) reported that PF-glued yellow poplar LVL with crushed-lap veneer joints and also without joints showed almost similar values of edgewise static bending strength (MOR) in the range of 80.94–81.47 MPa. LVL members with scarf veneer joints had relatively lower mechanical properties. According to Ozarska (1999), the study carried out on aspen LVL by Durand-Raute Industries Ltd (1988) indicated that LVL made from aspen tends to have higher bending strength (MOR) but lower stiffness (MOE) than LVL made from southern yellow pine. In the present study also it was found that MOE of aspen LVL was influenced by the press duration, particularly when pressed for a longer duration as compared to yellow poplar composites.

3.2.2 Surface hardness (static indentation)

Surface hardness (indentation) is considered as an indicator of the resistance to abrasion of wood composite which may be used in veneer laminated flooring. The surface hardness data presented in Table 2 shows that silver maple LVL samples have much higher values as compared to LVL made from aspen and yellow poplar. The hardness values were found to increase with the press duration from 2 minutes to 15 minutes for all the species except for yellow poplar. In the case of silver maple composites, longer pressing of 30 minutes at room temperature did not improve the hardness. The reported values of side hardness at 12% moisture content for sugar maple and silver maple solid wood are 6.4 kN and 3.1 kN, respectively (Anon 2001). Percentage of increase in hardness was found in the range of 58%–71% for the silver maple LVL above the solid wood. The gluing process thus helped in improving the surface hardness of the silver maple LVL significantly.

3.3 Adhesive properties

3.3.1 Tensile shear strength (TSS)

The effect of press duration on tensile shear strength is summarized in Table 3. In most of the cases, silver maple and aspen composites, tensile shear strength of 4.56 MPa was obtained for silver maple composites pressed for 5 minutes. Higher values of TSS after boiling in water were obtained due to cross linking effect of the PVAc adhesive. In some of the cases, after accelerated treatment, the average tensile shear strength of PVAc adhesive was increased slightly or remained almost constant. This was likely due to post-curing of the adhesive during accelerated treatment. It shows that the cross-linked PVAc adhesive maintained and exhibited a good bonding behavior in boiling water treatments. Qiao et al. (2000b) reported that MDI hardened PVAc emulsions as structural adhesives showed excellent performance against cold soaking and boiling water. They also observed

Table 3 Adhesive (bonding) properties of cross-linked PVAc-glued three-ply LVL
Tabelle 3 Zugscher- und Querzugfestigkeiten von mit vernetztem PVAc verklebtem, dreilagigem Furnierschichtholz (LVL)

Property	Silver maple				Yellow poplar			Aspen		
Press duration	2 min	5 min	15 min	30 min	2 min	5 min	15 min	2 min	5 min	15 min
Tensile Shear Strength (MPa) – Air-dry	4.09± 1.14	3.37± 0.19	3.21± 0.16	3.62± 0.31	2.99± 0.43	2.95± 0.05	2.70± 0.40	2.07± 0.59	2.60± 0.50	3.04± 1.01
Accelerated	4.15± 0.51	4.56± 0.86	3.37± 0.02	3.19± 0.63	2.58± 0.54	2.75± 0.10	2.15± 0.20	2.79± 0.93	2.25± 1.52	3.16± 0.58
Internal Bond. (IB) Strength (MPa) – Air-dry	2.84± 0.05	2.95± 0.47	2.24± 0.40	2.73± 0.79	1.86± 0.51	2.09± 0.70	2.19± 0.76	1.73± 1.27	2.15± 0.71	2.64± 0.94
Cyclic	2.69± 1.39	3.16± 1.08	2.52± 0.40	3.02± 0.71	1.93± 0.24	2.80± 0.79	1.84± 0.36	2.23± 0.19	2.76± 0.36	2.23± 0.53
Accelerated	2.38± 0.70	2.43± 0.34	2.26± 0.80	2.76± 0.77	2.60± 0.91	2.70± 0.91	1.87± 0.60	1.12± 0.61	1.65± 0.75	1.52± 0.87

higher values of shear strengths of wood joints with some of the PVAc-based emulsions tested after water soaking and boiling water treatments as compared with dry condition. Similar observations were reported by Umemura et al. (2003) while working with urea formaldehyde resin glued three-ply wood composites. While studying the bonding behavior of some fast growing tropical Indonesian hardwood tree species, Alamsyah et al. (2007) have also observed a similar behavior of *P. merkusii* laminated wood bonded with UF adhesive.

3.3.2 Internal bond (IB) strength

Table 3 gives the average values of the internal bond (IB) strength of cross-linked PVAc glued 3-ply silver maple, yellow poplar and aspen LVL tested in dry, cyclic and accelerated conditions. The silver maple LVL pressed for 5 minutes shows maximum IB strengths of 2.95 MPa and 3.16 MPa in air-dry and cyclic conditions, respectively. Yellow poplar and aspen LVL pressed for 2 minutes showed IB strength values less than 2.0 MPa in dry condition. The cyclic and accelerated values were not found consistent to follow a pattern. In the evaluation of overall performance of the cross-linked PVAc adhesive with these wood species, better IB strength values were found with silver maple wood compared to yellow poplar and aspen wood.

3.3.3 Block shear strength (BSS)

Figure 3 shows average values of the block shear strength (BSS) evaluated for LVL under three conditions. As in the case of IB strength, almost similar behavior was exhibited for BSS. Silver maple boards pressed for 2 and 5 minutes at 38 °C and 30 minutes at 21 °C showed the air-dry BSS

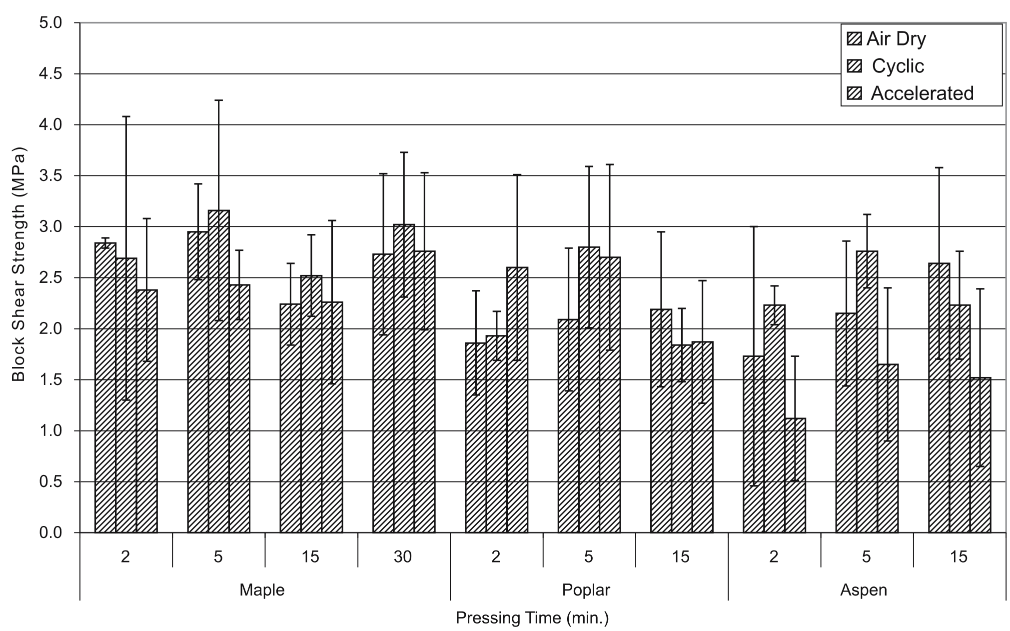

Fig. 3 Effect of press time on block shear strength of PVAc glued 3-ply LVL from silver maple, yellow poplar and aspen in air-dry, cyclic and accelerated conditions
Abb. 3 Einfluss der Presszeit auf die Blockscherfestigkeit von mit PVAc verklebtem, dreilagigem Furnierschichtholz aus Silberahorn, Amerikanischem Tulpenbaum und Espe unter lufttrockenen, zyklischen und schnell bewitterten Bedingungen

values in the range of 5.88 to 6.19 MPa. Cross-linked PVAc glued silver maple composites pressed for 5 minutes showed higher values when tested after cyclic and accelerated treatments. Comparatively, yellow poplar and aspen LVL yielded lower values of BSS in all the three conditions except in the case of silver maple laminates pressed for 15 minutes. As explained above, the average IB strength or BSS of PVAc adhesive was increased slightly or remained almost the same as the dry bond strength after cyclic or accelerated treatment with water and drying in the oven. It has to be noted that during preparation of sample for these tests, the specimens were also given a mild heat treatment just before applying the hot-melt epoxy adhesive to adhere the specimens with the metal blocks strictly. In the case of very strong samples, the epoxy glue failed and was applied again. This process could likely be given extra post-curing to the cross-linked PVAc adhesive as discussed above (Qiao et al. 2000b, Umemura et al. 2003, Alamsyah et al. 2007). These tests also demonstrated that even after repeated water immersion or short-term boiling water treatments, the cross-linked PVAc adhesive showed a good bonding property and water resistance and can be used in the production of structural and non-structural wood products.

4 Conclusions

Laminated veneer lumber (LVL) boards were successfully produced from thin veneers of three low density wood species namely silver maple, yellow poplar and aspen and cross-linked polyvinyl acetate (PVAc) adhesive. The effect of press duration (closed assembly time) on different physical, mechanical and adhesive properties was investigated. This study showed that three-ply silver maple LVL pressed under moderate temperature of 38 °C for 5 minutes using cross-linked PVAc adhesive yielded acceptable properties as compared to longer press duration at room temperature. LVL made from silver maple also exhibited improved strength properties: strength, stiffness, surface hardness as compared with the silver maple solid wood. The thickness swelling shown by silver maple composites was about 1.4% and 3.1% for 2 and 24 hours of water dipping, respectively. The flexural MOR of silver maple LVL was found comparable to sugar maple, while surface hardness and MOE were found lower than sugar maple wood. The adhesive properties of silver maple LVL made using cross-linked PVAc in the cyclic and accelerated conditions were found comparable with dry state showing better water resistance. When compared with LVL made from yellow poplar and aspen veneers, silver maple LVL has shown overall better properties. With improved strength and adhesive properties under stringent conditions with cross-linked PVAc, LVL made from silver maple can be a good alternative choice for nonstructural applications like laminated engineered wood flooring.

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