Effects of the Steam Test on Bonding Strength of Laminated Veneer Lumbers Manufactured by Using Different Adhesives

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ABSTRACT: Failures in adhesion of wood particles or fiber in a composite board can result from several factors. Poor chemical and physical interfacial interactions between the wood surface and the resin and dissimilar swelling of resin and wood resulting from moisture sorption are two of the most important mechanisms of bond failure. This study was performed to determine how the adhesives affect shear strength of laminated veneer lumbers (LVL) manufactured from poplar, beech, pine, black sea fir, and quercus veneers, with phenol–formaldehyde (PF), poly(vinyl acetate) (PVAc), Desmodur-VTKA (D-VTKA), and urea–formaldehyde (UF) adhesives. The shear strength tests were done (based on BS EN 205) on the LVL, after being exposed to steam for 96-h period, according to the procedure of the Turkish Standards (TS) 3639. From the shear strength test, it was found that the highest shear strength was obtained in beech control samples (not exposed to steam) with PVAc adhesive (15.8 N/mm^2) and the lowest shear strength was obtained in poplar LVL with UF adhesive (4.24 N/mm^2). Beech wood and VTKA and PVAc adhesives could be proposed for manufacturing of LVL used in wet conditions and exposed to shear strain. © 2006 Wiley Periodicals, Inc. J Appl Polym Sci 99: 2973–2977, 2006

Key words: adhesives; composites; shear; strength; swelling

INTRODUCTION

The demand for engineered wood products (such as oriented strand board, glulam, and laminated veneer lumber—LVL) has increased because of a constant increase in the global population. The grain of each layer of veneer assembled into LVL runs parallel with each adjacent ply.[1] Being homogeneous and dimensionally stable building material, LVL can be used where strength and stability are required.[2] Modern production of structural laminated wood for exterior use dates back to the development of resorcinol and phenol–resorcinol adhesives about 60 years ago,[3–4] and researchers have reported on the performance of softwood and hardwood glulam specimens.

Today, synthetic resins are being produced according to the wood materials used on dry and damp conditions. They are also convenient to use in the workshops and nonstop manufacturing. To prevent material scraps and increase the quality, research studies have been carried on the development of glue and its new application areas.[5]

There is an expectation that the formation of an interpenetrating network between wood and glue will lead to higher bond stability, in the sense of resistance to hydrolysis and lifetime.[6,7] However, the effect of interpenetration on the stability of bond-lines in a mechanical sense has to be considered as well.

LVL panels, like plywood, are manufactured using different synthetic resins depending on where they are used. Phenol–formaldehyde (PF) resins are generally used as a binder for exterior grade panel production. Melamine– urea–formaldehyde (UF) resins are also used for panels evaluated in damp conditions. However, it was stated that the panel bonded with urea–UF resins under exterior conditions was not as resistant as the panel bonded with PF resin.[8] To increase water repellence, the addition of melamine to a UF glue mixture was found to be quite effective by Cremonini et al.[9] and Cremonimi and Pizzi,[10] and a better shear strength results were obtained from the UF glue mixture.

The effects of adhesive types on bonding of LVL after being exposed to the steam were not studied properly. Therefore, the aim of this study was to compare the shear strength of LVL bonded with PF, poly(vinyl acetate) (PVAc), Desmodur-VTKA (D-VTKA), and UF adhesives, after being exposed to the steam.

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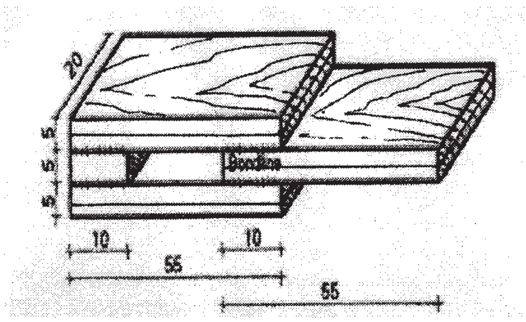

Figure 1 The test sample (sizes given in mm).

MATERIALS AND METHODS

Wood species

The woods of poplar (*Populus euramericana cv*), beech (*Fagus orientalis* lipsky), pine (*Pinus sylvestris* L.), black sea fir (*Abies nordmanniana*), and quercus (*Quercus petraea*) were chosen randomly from timber merchants of Ankara, Turkey. A special emphasis is put on the selection of the wood material. Accordingly, nondeficient, proper, knotless, normally grown (without zone line, reaction wood, decay, insect and mushroom damages) wood materials are selected.

Adhesives

The following adhesives were used in this experiment. PVAc is an odorless, nonflammable adhesive. It can be used in cold temperatures and solidifies quickly. The application of this adhesive is very easy and it does not damage the tools during the cutting process. However, mechanical resistance of PVAc adhesive decreases with increasing temperature. PVAc adhesive loses its bonding resistance capacity when the temperature is over 70°C. Using 150–200 g/m^2 adhesive to only one surface seems to be suitable.[11]

The density of PVAc was 1.1 g/cm^3, the viscosity 16.000 ± 3.000 mPa s, pH value 3–7, and ash ratio should be 3% (m/m) at 20°C. The solid content of PVAc is 40% (m/m). A pressing time of 20 min for the cold pressure and 2 min for the hot process (80°C) are recommended for the jointing process, with 6–15% humidity. After a hot-pressing process, the materials should be stored until it fits to its environment.[12] PVAc adhesive was supplied by Polisan (İzmit, Turkey).

According to the manufacturer[13] D-VTKA adhesive is a one-component polyurethane-based adhesive and widely preferred for the assembly process in the furniture industry. It is used for gluing wood, metal, polyester, stone, glass, ceramic, PVC and various plastic materials. Its application is specially recommended in locations subjected to high-level humidity. The gluing process was carried out at 20°C and 65% relative humidity. According to the manufacturer's instructions, 180–190 g/m^2 of adhesive was applied to the surfaces. Its viscosity was 14 000 ± 3000 mPa s at 25°C, density 1.11 ± 0.02 g/cm^3 at 20°C, and it has resistance against the cold air. The solid content of D-VTKA adhesive is 35–40% (m/m), pH value is 5, and ash ratio is maximum 3% (m/m).

UF is an amine resin made from the polycondensation of urea (carbamide) with formaldehyde. It is shipped to engineered wood product plants as a colloidal aqueous solution with a solid content of about 65%. About 100–150 g/m^2 of adhesive is usually applied to the surfaces. If cold pressure is applied at 20°C, the period of pressing is 3–5 h. In hot pressing this period decreases to 3–5 min. According to the manufacturer, this adhesive is opaque, the density is between 1.270 and 1.275 kg/m^3 at 20°C, the viscosity is 300–500 cP s at 20°C, jel time is 30–35 s, pH value is 7.5–8.5. UF adhesive was supplied by Polisan.[14]

When shipped, the PF liquid, just like UF, is partially polymerized and cross-grained. In the present PF solution, phenol and formaldehyde are available at a molar ratio of about 2.2. The free formaldehyde released during the pressing is about the same level as that released during the pressing of UF. According to the manufacturer, this adhesive is red, the density is between 1.195 and 1.205 kg/m^3 at 20°C, the viscosity is 250–500 cP s at 20°C, jell time is 10–20 s, pH value is 10.5–13. PF adhesive was supplied by Polisan.[11]

TABLE I
Air Dry Density of LVL and Control Samples (g/cm^3)

	Wood species				
	Poplar	Beech	Scotch pine	Black sea fir	Quercus
Control	0.4	0.71	0.52	0.43	0.73
LVL with PVAc	0.51 [0.11] (0.28)	0.92 [0.21] (0.30)	0.59 [0.07] (0.13)	0.50 [0.07] (0.16)	0.93 [0.20] (0.27)
LVL with VTKA	0.59 [0.19] (0.48)	0.93 [0.22] (0.28)	0.57 [0.05] (0.09)	0.48 [0.05] (0.10)	0.95 [0.22] (0.30)
LVL with UF	0.54 [0.14] (0.35)	0.89 [0.18] (0.25)	0.68 [0.16] (0.30)	0.58 [0.15] (0.34)	0.91 [0.18] (0.24)
LVL with PF	0.55 [0.15] (0.38)	0.89 [0.18] (0.25)	0.65 [0.13] (0.25)	0.55 [0.12] (0.27)	0.91 [0.18] (0.25)

Values in brackets indicate increase in density with respect to control, and values in parentheses indicate fractional increase (in %) over the control densities.

TABLE II
Average Shear Strength According to the Types of Materials

Control and LVL	Adhesives	Shear strength	N
Poplar control LVL	PVAc	4.3100 ± 0.2025[a]	10
	VTKA	4.4700 ± 0.4029	10
	UF	4.2400 ± 0.06992	10
	PF	4.2600 ± 0.1265	10
	Total	4.3200 ± 0.2452	40
Poplar LVL	PVAc	4.0000 ± 0.2828	10
	VTKA	3.5600 ± 0.8343	10
	UF	4.9400 ± 0.7412	10
	PF	8.5200 ± 0.1874	10
	Total	5.2550 ± 2.0526	40
Beech control LVL	PVAc	15.8000 ± 0.5676	10
	VTKA	15.1600 ± 1.2730	10
	UF	10.9000 ± 0.9393	10
	PF	10.3100 ± 1.3544	10
	Total	13.0425 ± 2.6956	40
Beech LVL	PVAc	9.7400 ± 1.6091	10
	VTKA	11.8600 ± 1.4946	10
	UF	9.8300 ± 2.6821	10
	PF	8.1600 ± 0.5542	10
	Total	9.8975 ± 2.1478	40
Pine control LVL	PVAc	4.8750 ± 0.01354	10
	VTKA	7.0650 ± 1.0499	10
	UF	6.4590 ± 0.5520	10
	PF	6.3300 ± 0.3940	10
	Total	6.1823 ± 1.0118	40
Pine LVL	PVAc	4.1500 ± 0.8311	10
	VTKA	5.5580 ± 0.8580	10
	UF	4.9260 ± 0.3930	10
	PF	5.6900 ± 0.1632	10
	Total	5.0810 ± 0.8677	40
Black sea fir control LVL	PVAc	4.5870 ± 0.07334	10
	VTKA	4.5380 ± 0.4645	10
	UF	3.9180 ± 0.2270	10
	PF	3.9550 ± 0.2533	10
	Total	4.2495 ± 0.4227	40
Black sea fir LVL	PVAc	4.3270 ± 0.06701	10
	VTKA	4.2800 ± 0.1526	10
	UF	3.7920 ± 0.5893	10
	PF	3.6050 ± 0.08276	10
	Total	4.0010 ± 0.4321	40
Quercus control LVL	PVAc	8.6800 ± 0.2860	10
	VTKA	12.3100 ± 0.8306	10
	UF	8.9400 ± 0.2914	10
	PF	6.0000 ± 0.3127	10
	Total	8.9825 ± 2.3160	40
Quercus LVL	PVAc	8.0200 ± 0.3048	10
	VTKA	4.7800 ± 0.7927	10
	UF	6.0600 ± 0.7648	10
	PF	5.5300 ± 0.3974	10
	Total	6.0975 ± 1.3467	40

[a] Values are expressed as means ± SD.

Preparation of the test samples

The veneers, which had 2 ± 0.5 mm thickness, were used to manufacture of panels. The test samples were cut in the dimension of 5 × 100 × 100 mm^3 (thick × width × length), according to the procedure of BS EN 204[15], for shear strength test. Afterwards, according to TS 5430,[16] approximately 180 g/m^2 of the adhesives were applied to the bonding surfaces of samples. A single daylight press was used for hot pressing. Press pressure and duration were 1.2 N/mm^2 and 7 min, respectively. Press temperatures were 110°C for UF and 140°C for PF adhesive, by taking the general curing temperatures recommended by their manufacturers into consideration. The perspectives of the test specimen are shown in Figure 1.

Density

Ten samples were prepared for each control samples and laminated materials having 20 × 20 × 20 mm^3 dimensions. They were stored at 20 ± 2°C and 65 ± 5% relative humidity until constant weight was reached. Then the samples were weighted in a balance of 0.01 g sensitivity, and volumetric measurement was made with a micrometer of ±0.01 mm sensitivity. The density of the samples was calculated according to the following equation:

$$\delta_{12} = m_{12}/v_{12} \text{ g/cm}^3 \quad (1)$$

Execution of the test

The test samples were kept in test equipment having a 60-cm diameter and 120-cm length, at 49 ± 2°C and 85 ± 3% relative humidity, according to the procedure of TS 4084.[17] The test samples were kept at steam conditions for 96 h in test equipment and climatized until they were stable at 20 ± 2°C and 65 ± 5% relative humidity in climatization room.

The shear strength test was carried out in a universal test machine, according to the procedure of BS EN 205 standards.[18] The loading speed was 50 mm/min. The loading was carried on until a break or separation occurred on the surface of the test samples. The shear strength (σ_k) was calculated using the observed load (F_{max}) and bonding surface of sample (A, mm^2) as follows:

$$\sigma_k = \frac{F_{max}}{2A} = \frac{F_{max}}{2(ab)} \text{ N/mm}^2 \quad (2)$$

where a is the width of glued face (10 mm) and b is the length of glued face (20 mm).

Data analyses

By using 4 different types of adhesive, 5 different species of laminated wood, and 50 control samples as parameters, a total of 250 samples (4 × 5×10 + 50)

TABLE III
Multivariance Analysis with Shear Strength of LVL and Control Samples, after being Exposed to Steam

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	3967.711	39	101.736	163.595	0.000
Intercept	18014.337	1	18014.337	28967.650	0.000
Control and LVL	3198.166	9	355.352	571.417	0.000
Adhesive	75.979	3	25.326	40.726	0.000
Control and LVL*Adhesive	693.566	27	25.688	41.307	0.000
Error	223.876	360	0.622		
Total	22205.924	400			
Corrected Total	4191.587	399			

[a] $R^2 = 0.947$ (adjusted $R^2 = 0.941$).

were prepared for shear strength test with 10 samples for each parameter. Multiple variance analysis was used to determine the differences among the LVL. By Duncan test, it was found that there is a significant difference among the groups.

RESULTS AND DISCUSSION

Density

Air-dry density of LVL produced by using different adhesives is indicated in Table I.

The density of wood species increased by the effects of adhesives and the pressure applied during the production of LVL. The highest increase was found for LVL with VTKA adhesive in both samples. The highest density increase for quercus LVL with VTKA adhesive was determined to be 0.95 g/cm^3.

The average values of shear strength obtained for LVL and control samples are given in Table II. The multivariance analysis with shear strength of LVL and control samples, after being exposed to steam, are also given in Table III.

The differences among the groups regarding the effect of variance sources on shear strength are significant (5%). Duncan test results used to determine the importance of the differences among the groups are given in Table IV.

According to the mean comparisons, the highest shear strength was obtained in beech control samples with PVAc adhesive (15.8 N/mm^2) and the lowest

TABLE IV
Duncan Shear Strength Test Results of LVL (p < 0.05)*

Source of variance			Shear strength (N/mm^2)					
	Adhesive	N	1	2	3	4	5	6
Duncan[a,b]	PF	100	6.2360					
	UF	100	6.4005					
	PVAc	100		6.8489				
	VTKA	100			7.3581			
	Sig.		0.140	1.000	1.000			
	Control and LVL							
	Fir LVL	40	4.0010					
	Fir control	40	4.2495					
	Poplar control	40	4.3200					
	Pine LVL	40		5.0810				
	Poplar LVL	40		5.2550				
	Quercus LVL	40			6.0975			
	Pine control	40			6.1823			
	Quercus control	40				8.9825		
	Beech LVL	40					9.8975	
	Beech control	40						13.0425
	Sig.		0.087	0.324	0.631	1.000	1.000	1.000

Means for groups in homogeneous subsets are displayed. Based on Type III sum of squares. The error term is mean square (error) = 0.622.
[a] Uses harmonic mean sample size = 100.000.
[b] $\alpha = 0.05$.

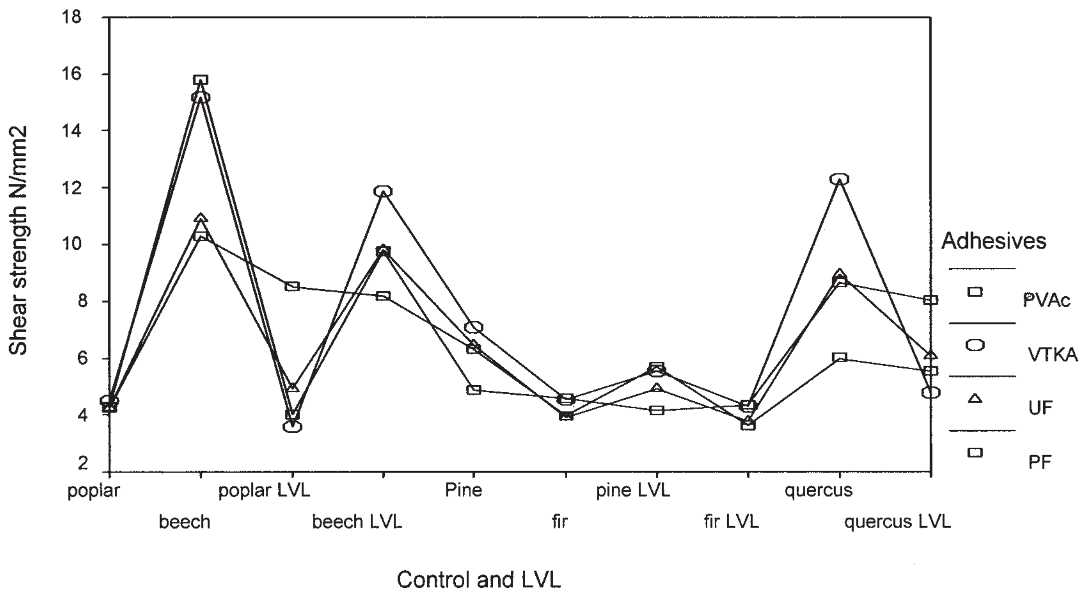

Figure 2 The effects of 96-h exposure to steam on shear strength of control and LVL samples.

shear strength was obtained in poplar LVL with VTKA adhesive (3.56 N/mm^2). The shear strengths, according to the LVL type and adhesive type, are shown in Figure 2.

CONCLUSIONS

The density of wood species increased by the effects of adhesives and the pressure applied during the production of LVL. The highest density increase for quercus LVL with VTKA adhesive was determined to be 0.93 g/cm^3. The highest fractional increase over control density was determined for poplar LVL with VTKA adhesive as 48%. On the contrary, the lowest fractional increase over control density was determined for Scotch pine with VTKA adhesive as 0.09%.

The highest shear strength was obtained in beech control samples with PVAc adhesive (15.8 N/mm^2) and the lowest shear strength was obtained in poplar LVL with VTKA adhesive (3.56 N/mm^2). In this respect, the range from higher to lower shear strength was beech control, beech LVL, poplar LVL, poplar control, respectively, among wood species, as well as VTKA, PVAc, PF, and UF, respectively, among adhesive types. Normal polymerization of an acidic adhesive, such as UF, can be retarded by an alkaline wood surface, which would compromise the integrity of the adhesive film and bond.[18] Beech wood gives smoother surfaces because it has more homogeneous structure, and smoother surfaces increase the bonding strength. The acidity of extractives of oak species can interfere with the chemical cure of adhesives.[19]

Consequently, an evaluation of the shear strength indicates that beech among wood species; VTKA and PVAc among adhesives give better results in the test samples. Thus, beech wood and VTKA and PVAc adhesives could be proposed for manufacturing of LVL used in wet conditions and exposed to shear strain.

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