

LAMINATING CREOSOTE-TREATED HARDWOODS

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ABSTRACT

A study was conducted to investigate the bondability of four selected hardwood species after being treated with creosote. A completely randomized block factorial design was employed. Experimental factors included five wood species (chestnut oak, red oak, red maple, yellow-poplar, and southern pine), five adhesive systems (elevated temperature cure phenol-resorcinol-formaldehyde, room temperature cure phenol-resorcinol-formaldehyde, resorcinol-formaldehyde, emulsion polymer isocyanate, and low-viscosity formulation emulsion polymer isocyanate) and two exposure levels (ambient room and vacuum/pressure/soak conditions). Exposure level effects on the different wood species resulted in highly variable adhesive system performance. Exposure level effects were most evident for the higher density oaks. Shear strength and percent wood failure results for all wood species revealed a general trend towards a higher performance for the two phenol-resorcinol-formaldehyde systems. Resorcinol-based adhesive systems had the highest shear strength values. Percent wood failure values were highest for the elevated temperature cure phenol-resorcinol-formaldehyde system for all species. Elevated temperature cure adhesive systems appeared to be required to successfully bond high-density creosote treated species. Successful bonding of medium-density species can be accomplished at room temperatures given proper adhesive system selection.

Keywords: Creosote-treated, lamination, red oak, red maple, chestnut oak, yellow-poplar, southern pine.

INTRODUCTION

Glulam research has concentrated on softwood species, and their use is the industry standard. However, interest is growing in the use of hardwoods as an efficient and economical alternative in the manufacture of glulam structural members. The oaks, red maple, and yellow-poplar have been targeted in part due to their excellent strength properties and/or underutilized status.

Researchers have reported on the perfor-

mance of hardwood glulam specimens that were treated with preservatives after fabrication (Freas and Selbo 1954; Selbo 1952, 1967; Shaffer et al. 1991). However, little information is available on the bondability of hardwood species treated before fabrication into glulam timbers. Almost no information exists regarding specific species/adhesive system interaction for underutilized hardwoods treated with creosote before being glued together into a structural member.

Interest in gluing treated wood began soon after modern, synthetic thermoset adhesive systems were developed in the 1940s. Much of this research was spurred on by the U.S. Naval Department's interest in using preservative-treated red oak in wooden minesweepers (Doskar and Knauss 1944; Kuenzel et al. 1953). Research efforts were later expanded to include other exterior applications such as bridges. Lindsley (1947, 1948) reported on the American Lumber and Treating Company's efforts to produce railroad bridge stringers from creosote-treated southern pine and Douglas-fir. These beams were manufactured using six different resorcinol adhesives and cured at 71.1°C for periods ranging from 5–12 hours. Shear block stress test (ASTM D905-49, 1988) and cyclic delamination test (similar to ASTM D1101-59, 1988) performance (Selbo and Angell 1955) exceeded the shear strength and wood failure standard (ANSI/AITC A190.1-83 AITC 1983) that southern pine glulam members must meet today and confirmed the viability of gluing creosote-treated wood (AITC 1987).

Henry and Gardner (1954) investigated the delamination resistance of red oak, white oak, southern pine, and Douglas-fir treated with nine different preservative systems, including creosote, prior to gluing with resorcinol-formaldehyde (RF) or phenol-resorcinol-formaldehyde (PRF) adhesive. Creosote-treated specimens averaged up to 0.8% delamination for the lower density softwoods and up to 5.1% delamination for the higher density oaks.

Selbo (1957) looked at the glue-line properties of Douglas-fir and southern pine treated with creosote prior to layup using RF and PRF adhesives cured at elevated (65.6°C) and room (26.7°C) temperatures. Shear strength and percent wood failure data indicated that the creosote treatment was affording adequate protection while not affecting the joint strength.

Selbo and Gronvold (1958) also investigated the glue-line properties of creosote-treated scotch pine using phenol-formaldehyde (PF), RF, and PRF resin systems cured at 15°C, 25°C, and 35°C. Specimens cured at the high-

est temperature had the greatest and most consistent shear strength and percent wood failure as a whole, although individual species/adhesive/curing temperature combinations also performed adequately.

Janowiak et al. (1990) investigated the glue-line properties of chestnut oak, red maple, yellow-poplar, and southern pine treated with an oil diluent pentachlorophenol preservative and glued following different surface enhancement treatments. Species/surface enhancement combinations bonded with an elevated cured PRF displayed the most consistent results, but individual combinations under other room temperature setting adhesive systems also performed adequately.

Room temperature setting adhesive systems are the glulam industry standard. Their use eliminates the need and expense associated with large drive-in ovens or other apparatus to elevate glue-line temperatures (Moult 1977).

Glue-laminated members intended for use in extreme exposure conditions require adhesives that are rated for structural use as well as being fully durable to repeated high moisture conditions. Those synthetic resins classified as fully durable to extreme moisture cycling include PF, RF, PRF, and malamine-formaldehyde (MF) (Blomquist 1983). Other thermoset resins, such as urea-formaldehyde, lack resistance to weathering, or have a tendency to creep under load, and as such, are not desired for glulam production. Of the previously mentioned resins, those most commonly used for glulam production are RF and resorcinol fortified PF systems (Moult 1977).

The purpose of this study was to investigate the bondability of four selected hardwood species treated with creosote. A completely randomized block factorial design was employed. Experimental factors included five wood species (chestnut oak, red oak, red maple, yellow-poplar, and southern pine), five adhesive systems (elevated temperature cure PRF, room temperature cure PRF, RF, emulsion polymer isocyanate (EPI), and low-viscosity formulation EPI) and two exposure levels (ambient and vacuum/pressure/soak-VPS).

EXPERIMENTAL PROCEDURES

Specimens

Wood species used for this study included chestnut oak (*Quercus prinus*), red oak (*Quercus rubra*), red maple (*Acer rubrum*), yellow-poplar (*Liriodendron tulipifera*), and southern pine (*Pinus* spp.). Southern pine was chosen to compare a species that is used extensively in glulam production today against the results obtained for the four hardwood species. The red oak, red maple, and yellow-poplar were kiln-dried at hardwood sawmills located in the northcentral and southeastern areas of Pennsylvania. The southern pine was obtained from a local building supplier. The chestnut oak was obtained through direct log procurement because this species is not differentiated from other species in the white oak group at commercial sawmills. These logs were processed into green five-quarter lumber and kiln-dried.

Individual boards were processed into 76.2 mm wide by 609.6 mm long by 20.6 mm thick billets. Approximately 80 billets per species were secured for creosote treatment.

Preservative treatment

Chestnut oak, red maple, yellow-poplar, and southern pine billets were treated in a laboratory retort through cooperation with Koppers Industries, Inc., in Harmarville, Pennsylvania. The target retention level was 160.2–192.2 kg/m³ of creosote. The preservative holding capacity for each species was determined so that the concentration of creosote in the treating solution necessary to achieve the target retention level could be reached. The creosote-to-toluene ratio was then adjusted to attain the correct concentration for each species. All samples were treated using the full-cell process, which included:

- 1) loading the samples and closing the cylinder door;
- 2) adding the treating solution;
- 3) pulling vacuum to 74.3 kPa Hg (minimum) and holding for 30 minutes;

TABLE 1. Initial and final average creosote retentions for four hardwood and one softwood species after a post-treatment streaming cycle.¹

Wood species	Average initial retention (kg/m ³)	Average final retention (kg/m ³)
Chestnut Oak	187.4	173.0
Red Oak	145.8	84.9
Red Maple	161.8	145.8
Yellow-poplar	150.6	145.8
Southern Pine	155.4	129.7

¹ Values reported are averaged from a sample of ten billets.

- 4) releasing the vacuum, pressurizing to 1034.3 kPa and holding for 1 hour;
- 5) slowly releasing the pressure to atmospheric (about 5 minutes); and
- 6) draining the treated solution and immediately weighing the samples.

Weight difference retentions were determined for a representative sample in each cylinder treatment charge using the volume of the billet and the weight gain from the treatment (Table 1). Assay extractions were also performed following the American Wood Preserver's Association (AWPA) A-6 method to provide an assay retention comparison (AWPA 1989).

The red oak billets were treated in a commercial facility through cooperation with Koppers Industries, Inc., Muncy, Pennsylvania treating plant. These billets were treated with a charge of red oak glued-laminated beams and red oak cross-ties. The treating cycle followed the empty-cell process and included:

- 1) loading the samples and closing the cylinder door;
- 2) pressurizing to 413.7 kPa;
- 3) filling the cylinder with creosote solution under pressure;
- 4) raising the temperature of the solution to 89.4°C and holding for 2 hours and 50 minutes;
- 5) pressurizing to 1310 kPa, increasing the temperature to 97.8°C and holding for 6 hours;
- 6) releasing the pressure and pumping back the solution (approximately 30 minutes);
- 7) pulling vacuum to 90.8 kPa Hg and holding for 2 hours; and

8) collecting drips and releasing the vacuum.

Weight difference retentions and assay extractions were performed and reported for individual billets in Kilmer (1992). A summary of the average retentions are listed in Table 1.

Adhesives

Adhesive systems used in this study included RF, PRF, and EPI resins. All systems were commercially available and rated for use in severe exposure environments. The first PRF (designated EPRF) was an elevated temperature cure system capable of providing strong, durable, waterproof bonds for marine service use. This adhesive system consisted of an alcohol-water solution of a partially condensed PRF resin mixed with a tan powder comprised of paraformaldehyde and walnut shell flour. Studies by Selbo (1950, 1957), Truax et al. (1953), and Freas and Selbo (1954) recommend using an elevated temperature setting adhesive system to achieve adequate bonding. This system was chosen for comparison purposes against the other, room temperature setting, systems. The other PRF (designated RPRF) was a room temperature setting formulation. Room temperature setting adhesive systems are the industry standard for glulam construction. The RPRF was also a two-part system with resin cure obtained through reaction with a definite proportion of a dry, powdered hardener. The RF was a two-component system capable of curing at room temperature and providing strong, waterproof bonds of the utmost durability. The EPI (designated EPI1 and EPI2) were room temperature setting systems as well. Both of these systems consisted of a reactive emulsion polymer mixed with an isocyanate crosslinker. The crosslinker was protected by a patented mechanism to prevent the isocyanate from immediately reacting with the water present in the emulsion. After spreading, the water and the protecting agent migrate from the glueline allowing the crosslinker to react with functional groups on the base polymer and the substrate. The level of crosslinker added to the emulsion

determined the level of durability for the cured joint.

Specimen preparation

All creosote-treated billets were steam-cleaned prior to laminating. The billets were placed on a rack in a stainless steel vessel and exposed to 115°C saturated steam at atmospheric pressure for one hour. A vacuum was then pulled to a level of 50.7 kPa Hg (minimum) and held for 30 minutes. Finally, the billets were placed on stickers and allowed to cool to room temperature.

Sample billet weights from each species group were measured to determine the amount of surface creosote removed during the steam-cleaning process. Each sample billet was weighed prior to placement in the steaming vessel and then weighed again immediately upon removal after the vacuum cycle. The initial and final weights for the sample billets were then averaged. This average was used to determine the average final retention level for each species group.

Individual billets were planed 1.6 mm immediately prior to layup. Double glueline applications were used throughout according to manufacturer's suggested spread rates. Open assembly time was kept to a minimum except for the chestnut oak/RPRF and red oak/RPRF combinations. Prior experimentation using untreated oak with this adhesive system indicated that a minimum 10-minute open assembly time was needed to fabricate joints capable of exceeding ANSI/AITC A190.1-83, performance standards (AITC 1983). Closed assembly time was also kept to a minimum and averaged approximately 15 minutes. The room setting billet pairs were placed in a clamping device and allowed to cure under 1034.3 kPa pressure for 16 to 18 hours. Elevated cure specimens were clamped in the same device, placed in a laboratory oven adjusted to a temperature of 76.7°C, and allowed to cure under 1034.3 kPa pressure for 14 hours.

Following layup, each billet pair was processed into shear specimens for subsequent

ASTM D905 testing (ASTM 1988). Eight specimens were taken from each of five billet pair replications resulting in a total sample of 40 specimens. Twenty specimens per species/adhesive combination were segregated at random for additional vacuum/pressure/soak (VPS) exposure testing. The remaining 20 specimens were stored and tested at ambient room conditions.

Testing

The vacuum/pressure/soak exposure level groups were subjected to two high moisture cycles designed to simulate extreme exposure conditions. All samples were tested using the following procedures:

- 1) fastening the samples to masonite pegboard strips and submerging in water to a minimum depth of 152.4 mm;
- 2) pulling vacuum to 50.7 kPa Hg and holding for 15 minutes;
- 3) releasing the vacuum, pressurizing to 517.1 kPa and holding for 2 hours;
- 4) repeating steps 2 and 3;
- 5) releasing the pressure, removing the samples from the cylinder and placing in a controlled environment chamber (set to 23.9°C and 66% RH) for 91 hours and 30 minutes; and
- 6) repeating the entire cycle.

All specimens were placed in the controlled environment chamber after the second VPS cycle and allowed to equilibrate to 12% moisture content prior to destructive testing.

Individual specimens were tested for shear strength parallel to the grain using a Tinius-Olsen universal testing machine equipped with a glueline shear tool. Destructive testing followed American Society for Testing and Materials D905 procedures (ASTM 1988). Length and width dimensions of each shear block were recorded to determine the area of glueline tested. Load at failure was also recorded for subsequent computation of shear strength. After each specimen was broken, the individual shear block halves were separated and evaluated for percent wood failure.

Data analysis

Analysis of variance (ANOVA) was conducted to detect if significant differences occurred in both shear strength and percent wood failure between main effect treatments and *n*'th order interactions at the 95th percentile over all species and on an individual species basis. Analysis of variance was also conducted to determine if exposure level differences were present on an individual species/adhesive system basis. Duncan's Multiple Range Test was conducted to compare the shear strength and percent wood failure means for differences due to adhesive system selection at the 0.05 significance level.

RESULTS AND DISCUSSION

Steam cleaning

Initial and final average retention results after a post-treatment steaming cycle are summarized in Table 1. The four species treated with the full cell process (chestnut oak, red maple, yellow-poplar, and southern pine) averaged only 15.2 kg/m³ less than the initial retention level. This is an indication that only the excess surface creosote was removed as intended. After cooling, the individual billet surfaces appeared "dry," with no further residual bleeding.

The red oak specimens, treated using the empty-cell process, lost an average of 60.9 kg/m³ during the steam cleaning cycle. These billets were treated using an initial air pressure of 413.7 kPa. Full-length red oak glulam beams, treated in the same charge, were observed to bleed at ambient temperatures two weeks after treatment, indicating that the initial air pressure was too high and that significant residual air pressure was still present in the specimens. The elevated temperatures present in the steam cleaning vessel probably increased this residual air pressure forcing more creosote to be removed through bleeding from the interior cell lumens than from the surface portions of the billet due to the scouring action of the steam as was intended. After cooling, and before gluing, some red oak bil-

TABLE 2. Average shear stress and percent wood failure for five species under five adhesive systems and two exposure levels.

Wood species	Exposure level ^b	Average shear strength and percent wood failure ^a									
		EPRF ^c		RPRF ^d		RF ^e		EPI1 ^f		EPI2 ^g	
		kPa	%	kPa	%	kPa	%	kPa	%	kPa	%
Chestnut Oak	Ambient	9,708	73	11,632	36	12,225	19	10,729	4	7,316	2
	VPS	16,286	70	16,645	60	7,619	8	8,633	2	5,220	2
Red Oak	Ambient	16,445	72	14,597	50	14,238	41	3,875	1	3,089	1
	VPS	17,017	74	12,342	62	6,771	7	621	0	600	0
Yellow-poplar	Ambient	12,659	98	12,928	82	13,080	92	12,342	76	9,336	27
	VPS	12,487	98	14,493	70	13,163	92	10,618	61	2,737	3
Red Maple	Ambient	15,776	81	15,928	80	13,921	65	15,059	60	12,770	63
	VPS	15,528	94	15,521	93	15,107	92	11,894	34	6,936	5
Southern Pine	Ambient	11,901	80	11,342	68	11,846	57	13,638	89	11,508	45
	VPS	10,777	80	11,666	69	8,522	59	12,494	48	8,460	24

^a Shear strength in kPa and wood failure in percent.

^b Ambient represents storage and testing at ambient room conditions and VPS represents moisture exposure.

^c PRF cured at elevated temperature.

^d PRF cured at room temperature.

^e RF cured at room temperature.

^f EPI cured at room temperature.

^g Low viscosity EPI cured at room temperature.

lets did bleed. This excess creosote was removed with a rag prior to application of adhesive.

Glueline bond quality

Average shear stress and percent wood failure values for the different species/adhesive/exposure level combinations are summarized in Table 2. Individual specimen data are given in Kilmer (1992). Consistently high shear strength and percent wood failure results were obtained for all five species under EPRF adhesive system. The RPRF and RF adhesive systems worked best with the lower density yellow-poplar, red maple, and southern pine species, but were unable to produce acceptable percent wood failure results for the higher density oak species. This trend was even more pronounced for the EPI1 adhesive system. In this case, acceptable bond quality was obtained for only the lowest density yellow-poplar and southern pine species. The EPI2 resin system produced unacceptable results for all species studied.

The shear strength performance comparison under the vacuum/pressure/soak exposure level is given in Table 2. The two PRF adhesive

systems after vacuum/pressure/soak conditions had comparable average shear strength values to the ambient exposure level specimens for the higher density oaks. The other three resin systems had lower average shear strength values after vacuum/pressure/soak conditions compared to ambient treatment conditions. All adhesive systems except the EPI2 had good average shear strength values for the three lower density species. The EPI2 resin failed to perform adequately with red maple and yellow-poplar after high moisture cycling.

The percent wood failure performance comparison under the no exposure condition level is given in Table 2. The elevated temperature cure EPRF system exceeded performance criteria for all species. In addition, this resin was the only system to produce consistently good percent wood failure values for the two oak species: The RPRF and RF systems had good average percent wood failure values for yellow-poplar, red maple, or southern pine. The EPI1 tended to have higher average percent wood failure values than EPI2 with yellow-poplar, red maple, and southern pine specimens. This variability reflects the sensitivity towards different wood species that these ad-

TABLE 3. Significant glue-line properties resulting from the various adhesives.

Variable	Species	Exposure level ¹	Adhesive to adhesive comparison for each exposure level ²				
			RFa	RPRFa	EPI1ab	EPRFbc	EPI2c
Shear strength	Chestnut Oak	Ambient	RFa	RPRFab	EPI1ab	EPRFbc	EPI2c
		VPS ¹	RPRFa	EPRFa	EPI1B	RFb	EPI2c
	Red Oak	Ambient	EPRFa	RPRFa	RFb	EPI1c	EPI2c
		VPS ¹	EPRFa	RPRFa	RFa	EPI1b	EPI2b
	Yellow-poplar	Ambient	RFa	RPRFa	EPRFa	EPI1a	EPI2b
		VPS ¹	RPRFa	RFb	EPRFb	EPI1c	EPI2d
	Red Maple	Ambient	RPRFa	EPRFa	EPI1ab	RFbc	EPI2c
		VPS ¹	EPRFa	RPRFa	RFa	EPI1b	EPI2c
	Southern Pine	Ambient	EPI1a	EPRFb	RFb	EPI2b	RPRFb
		VPS ¹	EPI1a	RPRFab	EPRFb	RFc	EPI2c
Wood failure	Chestnut Oak	Ambient	EPRFa	RPRFa	RFa	EPI1d	EPI2d
		VPS ¹	EPRFa	RPRFa	RFb	EPI1b	EPI2b
	Red Oak	Ambient	EPRFa	RPRFb	RFb	EPI1c	EPI2c
		VPS ¹	EPRFa	RPRFa	RFb	EPI2b	EPI2b
	Yellow-poplar	Ambient	EPRFa	RFab	RPRFbc	EPI1c	EPI2d
		VPS ¹	EPRFa	RFa	RPRFb	EPI1b	EPI2c
	Red Maple	Ambient	EPRFa	RPRFa	RFa	EPI2a	EPI1a
		VPS ¹	EPRFa	RPRFa	RFa	EPI1b	EPI2c
	Southern Pine	Ambient	EPI1a	EPRFab	RPRFbc	RFcd	EPI2d
		VPS ¹	EPRFa	RPRFab	RFbc	EPI1c	EPI2d

¹ Ambient represents storage and testing at ambient room conditions and VPS represents moisture exposure.

² Adhesives with same small letter have no significant differences.

hesive systems possess and makes prediction of glue-line bond quality across species difficult.

Table 2 lists the percent wood failure performance comparison under the vacuum/pressure/soak exposure level. The elevated temperature cure EPRF system again outperformed the other adhesive systems for all species studied.

For the lower density yellow-poplar, red maple, and southern pine, the trend towards individual species/adhesive system compatibility under the VPS exposure level continued for the room temperature cure RPRF and RF systems and both EPI systems.

Adhesive system effects

Table 3 summarizes the significance in glue-line properties resulting from the various adhesives on an individual species/exposure level basis. Analysis of variance was conducted to determine if shear strength and percent wood failure means were all equal under the null hypothesis. The rejection level was set at $P < 0.05$. Rejection of the null hypothesis led

to an analysis using Duncan's Multiple Range Test to test all of the possible hypotheses of the type $\mu_1 - \mu_2 = 0$ at the 0.05 rejection level (SAS Inst. 1985). The adhesives were then ranked accordingly from highest to lowest observed treatment value with nonsignificance denoted by a line below the pair(s).

For shear strength, a general trend is shown (Table 3) with the two PRF systems ranking higher than the RF and two EPI systems. One or the other PRF was either ranked highest or not significantly different than the highest ranked resin 65% of the time. At the lower end of the rankings, the EPI2 was either ranked last or not significantly different than the lowest ranked resin 90% of the time.

Other than these very general trends, however, no consistent patterns developed as far as rankings or significant differences for the other resin systems relative to observed mean shear strength. Overall, the adhesive systems displayed much variability in relative performance between the different species, indicating that adequate shear strength performance for any one particular species/adhesive system

TABLE 4. Significant shear strength and wood failure resulting from the different exposure conditions.

Species	Adhesive	Shear strength exposure to exposure comparison ¹		Percent wood failure exposure to exposure comparison ¹	
Chestnut Oak	EPRF	VPS	AMB	<u>AMB</u>	<u>VPS</u>
	RPRF	VPS	AMB	VPS	AMB
	RF	AMB	VPS	AMB	VPS
	EPI1	AMB	VPS	<u>AMB</u>	<u>VPS</u>
	EPI2	AMB	VPS	<u>AMB</u>	<u>VPS</u>
Red Oak	EPRF	<u>VPS</u>	<u>AMB</u>	<u>VPS</u>	<u>AMB</u>
	RPRF	AMB	VPS	<u>VPS</u>	<u>AMB</u>
	RF	AMB	VPS	AMB	VPS
	EPI1	AMB	VPS	AMB	VPS
	EPI2	AMB	VPS	<u>AMB</u>	<u>VPS</u>
Yellow-poplar	EPRF	<u>AMB</u>	<u>VPS</u>	<u>AMB</u>	<u>VPS</u>
	RPRF	VPS	AMB	<u>AMB</u>	<u>VPS</u>
	RF	<u>VPS</u>	<u>AMB</u>	<u>AMB</u>	<u>VPS</u>
	EPI1	AMB	VPS	<u>AMB</u>	<u>VPS</u>
	EPI2	AMB	VPS	AMB	VPS
Red Maple	EPRF	<u>AMB</u>	<u>VPS</u>	<u>VPS</u>	<u>AMB</u>
	RPRF	<u>AMB</u>	<u>VPS</u>	VPS	AMB
	RF	<u>VPS</u>	<u>AMB</u>	VPS	AMB
	EPI1	AMB	VPS	AMB	VPS
	EPI2	AMB	VPS	AMB	VPS
Southern Pine	EPRF	<u>AMB</u>	<u>VPS</u>	<u>AMB</u>	<u>VPS</u>
	RPRF	<u>VPS</u>	<u>AMB</u>	<u>VPS</u>	<u>AMB</u>
	RF	AMB	VPS	<u>VPS</u>	<u>AMB</u>
	EPI1	<u>AMB</u>	<u>VPS</u>	AMB	VPS
	EPI2	AMB	VPS	AMB	VPS

¹ Exposure levels underlined indicate no significant difference. VPS represents moisture exposure and ambient (AMB) represents storage and testing at ambient room conditions.

would be a poor predictor of shear strength for a different species glued with the same resin.

For the percent wood failure parameter, much stronger trends developed. The EPRF system was either ranked highest, or not significantly different than the resin ranked highest, for all cases. The RPRF system was either ranked second highest, or not significantly different than the second highest ranked adhesive system 90% of the time. The two PRF adhesive systems were consistently ranked above the RF and two EPI resins and registered either statistically significant differences or rankings at the top of gradients regardless of exposure condition. At the lower end of the rankings, the lower viscosity EPI2 either ranked lowest, or was not significantly different than the lowest ranked resin.

Exposure level effects

Table 4 summarizes the significance on glueline properties resulting from the two exposure levels (ambient and VPS) on an individual species/adhesive system basis. Analysis of variance was conducted to determine if shear strength and percent wood failure means were equal (null hypothesis) for the two exposure levels with the rejection level held at $P < 0.05$. The exposure levels were then ranked according to higher observed average bond quality performance. Nonsignificance was denoted by a line under the pair.

Glueline shear strength differences (Table 4) due to exposure condition level were significant with all adhesive systems for chestnut oak, and all adhesive systems except the EPRF for red oak. Higher density species are gen-

erally harder to bond, in part, because intimate contact between the adherends is difficult to obtain due to their stiffness. In addition, high moisture cycles are intended to maximize dimensional instability resulting in exaggerated glueline bond stresses. Weakly bonded joints are quickly uncovered by these methods.

Glueline shear strength differences (Table 4) due to exposure condition level for red maple, yellow-poplar, and southern pine were most evident under the EPI systems. Shear strength loss after VPS exposure testing averaged 17.5% (for yellow-poplar and red maple) under the EPI1 and 47.6% (for yellow-poplar, red maple, and southern pine) under the EPI2. The PRF and RF adhesive systems used with these species were less sensitive to exposure condition level for the shear strength parameter.

Sensitivity to the exposure condition level for the percent wood failure parameter (Table 4) was least evident for the EPRF. No significant differences between the ambient and the VPS exposure levels were present for any of the species studied. Elevated temperatures aid wetting of the adherend surfaces as well as complete polymerization between the PR reaction intermediates and the formaldehyde. This combination promotes superior bond development and thus maximum resistance to glueline bond stresses developed from high moisture cycling.

Exposure level sensitivity for the RPRF and RF was highly variable. Significant differences and rankings were strictly on an individual species/adhesive system basis.

The EPI systems performed poorly under the VPS exposure level. Nonsignificance between the exposure condition levels for the two oak species was due to extremely low percent wood failure values (less than 5%). Significant differences for the other three species reflected a high degree of sensitivity to the high moisture cycling. These adhesive systems require that the water present in the mix be removed, usually by soaking into the adherent, so that the polymer backbone miscelles and the isocyanate hardener can be brought close

enough together to react. The nonpolar creosote probably inhibited this moisture loss to a degree great enough to prohibit adequate bonding.

SUMMARY AND CONCLUSIONS

The EPRF system produced the highest and most consistent glueline shear strength and percent wood failure values. The RPRF system consistently produced joints with good shear strength values. The RPRF system produced good percent wood failure results under the VPS exposure level for chestnut oak, red oak, and red maple. The RF system had good average shear strength and percent wood failure values for yellow-poplar. It also produced bonds of comparable shear strength values under the ambient and VPS exposure levels for red maple. The EPI systems produced some of the lowest average percent wood failure performance values under the VPS exposure level. These resin systems would not be suitable for use in bonding creosote treated hardwood for structural applications.

Poor bonding, regardless of the adhesive system used, was probably a combination of improper wetting of the wood surfaces as well as inhibition of moisture absorption from the glue film by the creosote thus delaying, or preventing proper cure. Identification of compatible species/adhesive system combinations that cure under room temperatures is crucial for good glueline joint properties.

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