FINAL TECHNICAL REPORT

Project Title: Novel Isocyanate-Reactive Adhesives for Structural Wood-Based Composites

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Subcontractors: N A

Other Partners: National Starch and Chemical
TrusJoist - A Weyerhaeuser Business

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Project Objective: The development of novel moisture-curing polyurethane adhesives for the cold-press manufacture of laminated veneer lumber made from high moisture content wood.

Background: Realizing the project objective, stated above, will reduce energy consumption through the elimination of hot pressing and through the substantial reduction of wood drying. Reduced wood drying will also curtail VOC production.

This is the final project report. Herein results of dynamic mechanical analysis experiments of composite and plain wood specimens tested in creep mode are presented. The specimens used in this series were cut from polyurethane (HB222) and Phenol-formaldehyde (PF) bonded LVL boards. Specimens cut from southern yellow pine (SYP) wood functioned as control. A weathering cycle was conducted in order to reflect on adhesive degradation. Also included is the final report of the collaborative efforts between Weyerhaeuser and National Starch.

Status:

a) Dynamic Mechanical Analysis – Virginia Tech

In addition to previously conducted experiments with polyurethane-bonded LVL specimens tested in creep mode (for details see quarterly report 12_Q2_2007), phenol-formaldehyde LVL specimens were tested accordingly. The specimens with the following dimensions 35 mm x 15 mm x 3 mm (tangential x radial x longitudinal) had been cut from previously pressed lab-scale LVL boards (see quarterly report 4_Q2_2005). It is important to know that these boards were hot-pressed at 200°C for 9.5 min. A temperature profile throughout the board thickness was the consequence with 170, 120 and 110°C in bondlines 1, 3 and 5 of a 12-layer SYP LVL billet.

All specimens were tested with the single cantilever clamp set-up using stress control mode. The load was oriented along the grain axis of the wood and parallel to the bondlines.

Dynamic thermal scans

Dynamic thermal scans, alternating cooling and heating, were conducted between -150 and 160°C. The heating/cooling rate was set to 5°C/min. A stress of 0.1 MPa, which had been determined in stress sweep experiments to be the linear viscoelastic limit, was applied at a frequency of 1 Hz. The $\tan(\delta)$ of the first cooling and the subsequent first heating scan depart from all other scans conducted thereafter (Figure 1). This observation originates from the fact that the sample contains a small amount of moisture of approximately 0.5% when stored in a desiccator over P_2O_5 and under anhydrous nitrogen. After equilibration at 160°C the next cooling scan (2nd cooling) starts at lower $\tan(\delta)$ values. Furthermore, transitions shift to lower temperatures and appear more pronounced in the completely dry state. Recall that this specimen shows a high degree of complexity. The SYP wood consists of three different macromolecules, lignin, hemicelluloses, and celluloses, all in their glassy state. Additionally, the PF adhesive adds another compound.

Figure 1: Dynamic thermal scans PF-bonded LVL conducted in cooling and heating.

The following figures (Fig. 2 to Fig. 4) demonstrate the rheological behavior of PU- and PF-bonded LVL specimens as well as plain SYP specimens as a function of temperature. The first heating scan (Figure 2) shows four transitions for each specimen. Looking at the ($\tan(\delta)$) data, the first two transitions up to -50°C are similar in respect to their intensity (relaxation). The next transition which occurs at approximately 0°C show slightly higher $\tan(\delta)$ values for the PU-bonded LVL. At approximately 130°C the PU-bonded LVL show a major transition, which also is shifted to higher temperatures compared to the PF-bonded LVL and SYP.

Figure 2: Dynamic scans (1st heating) of PU- and PF bonded LVL specimens and SYP wood.

After a conditioning step at 160°C for 10 minutes a cooling scan was conducted with the results shown in Figure 3. Only three transitions can be observed. PU-bonded specimens already depart from the PF-bonded LVL and the SYP after the 1st transition at -120°C . All specimens show a relaxation at approximately -25°C . With increasing temperature the next transition occurs at 50°C for SYP, 100°C for PF-bonded LVL, and 140°C for the PU-bonded LVL specimens.

Figure 3: Dynamic scans (1st cooling) of PU- and PF bonded LVL specimens and SYP wood.

The 2nd heating scan, shown in Figure 4, shows similar results as the 1st cooling scan except that the temperature lag due to the 5°C cooling/heating rate shifts the transitions to higher temperatures.

Figure 4: Dynamic scan (2nd heating) of PU- and PF bonded LVL specimens and SYP wood.

Creep Experiments

A total of five replicates were tested. The experiments were carried out in creep mode using the single cantilever fixture on the DMA. A stress of 0.7 MPa, which had been determined in short time (1 min) creep segments, was the allowable force within the linear viscoelastic region (LVR). Creep steps of 17min alternated with conditioning steps

of 15min at pre-selected temperature intervals between 30 and 150°C. Prior to the experiment, the composites were kept in a desiccator under dry conditions of P_2O_5 and anhydrous nitrogen gas. Based on the experience of previous experiments the best data quality was obtained with a thermal conditioning step at the maximum temperature prior to the first creep segment. Furthermore, after cooling the specimen to 30°C at 5°C/min a mechanical conditioning step, creep and relaxation segment of 17 min, was conducted but disregarded in further analysis.

Figure 5 shows the creep compliance master curves after shifting single 17 min creep segments obtained at different temperatures along the time axis until they coincide. The overall compliance change in the temperature window from 30 to 150°C is very low but higher than in and the breadth spans almost 12 decades. Two transitions were observed at approximately 10^6 and 10^9 s. This deviated from previous PU-bonded LVL specimens.

Figure 5: Creep master curves (left) and resulting shift factors (right) of PF-bonded LVL specimens after a weathering procedure was applied.

Weathering of LVL and plain wood specimens

All previously tested PU- and PF-bonded LVL specimens underwent a weathering cycle in order to degrade the adhesive bond. Additionally the SYP plain wood specimens were weathered as control samples according to following test procedure:

1. Steaming cycle: Steaming over boiling water for 45 min
2. Drying cycle: Drying Oven at 65°C for 4 hours
3. Conditioning: Desiccator storage over P_2O_5 and under Nitrogen atmosphere for at least 4 days

The weathering cycle had two effects on the creep master curves of the PF-bonded LVL specimens (**Figure 6**); a slight increase of the creep compliance and a broadening of the master curve. It is also noticeable that the 2nd transition appears to be less pronounced compared to the un-weathered specimens.

Figure 6: Master curves of PF-bonded LVL after the weathering procedure.

The shift factors presented in **Figure 7** illustrate the breadth of creep master curves of un-weathered and weathered PF-bonded LVL specimens. No effect of the weathering procedure is obvious up to 90°C. However, above 90°C the weathered specimens show significant higher shift factors, which reflects on an increased molecular relaxation in comparison with the un-weathered specimens.

Figure 7: Un-weathered vs. weathered PF-bonded LVL specimens including a thermal conditioning step prior the creep experiment.

Figure 8 shows the creep compliance master curves of PU-bonded LVL after the weathering cycle. In the left graph the creep Procedure included a conditioning step at 120C whereas the right graphs represents the results of creep experiments subsequent to desiccator storage. The absolute compliance were not changed by the testing regime but the breadth of the master curves shows higher values when the specimens were taken out of the rheometer. Data quality was found to be superior when specimens underwent a conditioning cycle prior to the creep experiments.

Figure 8: Creep master curves of thermally conditioned PU-bonded LVL specimens (left) and after desiccator storage (right) after a weathering cycle was conducted.

Figure 9 shows the effect of the weathering procedure on the shift factors of the PU-bonded LVL specimens which were thermally conditioned prior to the creep procedure. A slight but significant decrease in the molecular relaxation can be observed for the weathered specimens which is inverse to the PU-bonded LVL.

Figure 9: Comparison of shift factors of un-weathered and weathered PU-bonded LVL specimens.

In Figure 10 creep master curves of SYP control specimens after the weathering procedure are shown. Again, the same specimens were tested in creep after a conditioning cycle at 120°C (left) and after desiccator storage over P_2O_5 and under anhydrous nitrogen (right) for at least 4 days. No significant difference can be observed in respect to the absolute compliance values. Specimens stored in the desiccator show less broad master curves than the thermally conditioned samples. The data quality of the thermally conditioned specimens was superior compared to the post-desiccator specimens. Although after the thermal conditioning a mechanical conditioning step was conducted prior to the actual creep experiment, slightly higher compliance values occurred within the first creep segment resulting in some inconsistency of the creep mastercurve.

Figure 10: Creep master curves of thermally conditioned SYP specimens (left) and after desiccator storage (right).

Figure 11 demonstrates the effect of a weathering procedure on the shift factor of SYP specimens. Weathered specimens show a significant decrease of the molecular relaxation over the entire temperature range. Again, in comparison with the PF-bonded specimens the SYP control specimens show the inverse effect of the weathering procedure on the shift factors.

Figure 11: Comparison of shift factors of un-weathered and weathered SYP specimens

Following on the next page is the report of the collaborative effort between Weyerhaeuser and National starch.

Weyerhaeuser

Date 20 March 2008

From Kristin Brandt

Location Boise, Idaho

Subject Final small scale results for testing PUR and EPI resins compared to PF using cold pressing for LVL (internal project #2030)

To Dr. Chip Frazier
Virginia Polytechnic Institute and State University

TITLE: Novel Isocyanate-Reactive Adhesives for Structural Wood-Based Composites (LVL) - test results for EPI, PUR and PF bonded billets

SUMMARY:

This project is funded by the U. S. Department of Energy and has been assigned DE-FC36-04GO14307 identification number. National Starch and Chemical, Virginia Tech, and Weyerhaeuser Company are the three participants.

The goal of this project was to develop a polyurethane based adhesive for the manufacture of laminated veneer lumber (LVL) that can be pressed at ambient temperature using veneer between 10% and 14% moisture content. Development of this process will:

- Reduce energy consumption during manufacturing
- Reduce volatile organic compound emissions during manufacturing
- Improve product durability

CONCLUSIONS:

The best overall performance from a trial adhesive is from the second EPI adhesive, 13102-143 A/B, denoted EPI-2007 throughout the report. For the tests performed, this adhesive performed equal to or better than the traditional PF resin.

Weyerhaeuser has provided assistance and resources to evaluate the LVL resins noted to assess their performance. Weyerhaeuser does not endorse or implicitly imply certification of final adhesive performance or meeting of any ASTM standard. To attain certification, a third party certification company should be utilized.

DISTRIBUTION TO TECHNICAL INFORMATION CENTER	LOCATION TIC	AUTHOR'S SIGNATURE	DATE 26 March 2008
Chip Frazier, Joe Fyie, Chuck Paul		AUTHOR'S NAME (Typed) Kristin Brandt	
PROJECT NO. 2030		APPROVED BY (Typed) Joe Fyie	DATE

Strictly Proprietary (Red): Disclosure strictly limited to persons on a managed list. Contact

Proprietary (Yellow): Disclosure limited to persons confidentially bound to Weyerhaeuser on a need to know basis.

Non-Proprietary (Green): Disclosure unlimited.

METHOD:

Test results discussed in this report include values for laminated veneer lumber (LVL) made with HB222 polyurethane (PUR) adhesive made by Purebond, SL 470 emulsion polymer isocyanate (EPI) adhesive made by National Starch and Company, 13102-143 A/B a novel EPI adhesive developed for this project by National Starch and Chemical and GP Resi-mix 004G27 Phenol Formaldehyde (PF) adhesive. This is the final report and is the only report that contains evaluation data for all four resins tested. For simplicity, the two EPI adhesives will be labeled with the test year; EPI-2006 is SL 470 and EPI-2007 is 13102-143 A/B.

Statistical tests were completed, but it should be noted that the PF samples sizes were very small. Larger sample sizes may change the outcome of the tests. All differences were determined using Tukey's HSD test.

In 2005, two sets of six PUR bonded LVL billets were made at Virginia Tech using 100% southern pine (SYP) and 100% yellow-poplar (YP) veneer. Two billets of each species were also made using PF resin for use as a control. Two additional sets of six EPI bonded billets were manufactured in 2006, one set using SYP and one using YP. Finally, in 2007 a second EPI formulation was used to manufacture both SYP and YP billets. The alternative resin LVL utilized veneer conditioned to 12% moisture content; the PF bonded billets were made with veneer conditioned to between 4% and 6% MC.

The following tests were conducted by Weyerhaeuser:

1. Internal bond per ASTM D 1037 – specimens were glued to the testing blocks using epoxy adhesive. Testing was performed at the Weyerhaeuser Technology Center in Federal Way, WA.
2. Trus Joist bending shear test (internal company method) – flatwise orientation with matched specimens tested in the dry condition and the wet condition at the Boise Technology Center in Boise, ID.
3. Adhesive durability test per ASTM D 5456-05: 6-cycle flatwise bending with matched specimens – control and cycled specimens tested dry at the Boise Technology Center in Boise, ID.
4. Product durability test per ASTM D 5456-05: single-cycle edgewise bending with matched specimens – control and cycled specimens tested dry at the Boise Technology Center in Boise, ID.

For the ASTM D-5456 tests, the control specimens were not cycled.

All test specimens were conditioned to equilibrium at 65% relative humidity and 21°C prior to testing. Density was determined at equilibrium conditions.

To keep consistency with Dr. Bill Boehner's previous report, boxplots are used to present the data analysis and give a sense of the range and variability in one graph. The bottom edge of the box represents the first quartile (Q1), while the top edge represents the third quartile (Q3).

RESULTS AND DISCUSSION:

Internal bond is not typically performed for LVL, however other tests that are used to evaluate bond-line integrity have deficiencies especially when a clear adhesive is used. The internal bond test could be a good compromise which might help in getting alternative adhesives accepted. The mean internal bond values are listed in Table 1. In addition to mean values, statistical groups were determined using analysis of variance and Tukey's HSD test. Density was tested as a covariate and was not significant at the 95% level. The PUR bonded billets were superior to the PF and both types EPI billets. The EPI-2007 billets were better than PF and either equivalent to or better than the EPI-2006 billets. Even though the EPI and PF internal bond strength values were lower than the PUR data, they were similar to typical values from pMDI bonded LSL composites. The internal bond strength and density data are shown graphically in Figure 1 and Figure 2, respectively.

Table 1: Mean internal bond and density values with statistical groups. Statistical differences are denoted by different letters.

Species	Density at 12% moisture content, pcf	Internal bond, psi	Statistical Groups
PF bonded LVL – ASTM D-1037 Internal bond			
Southern pine, n=12	40.6	136	A
Yellow-poplar, n=12	36.6	172	A B C
PUR bonded LVL – ASTM D-1037 Internal bond			
Southern pine, n=36	40.5	270	D
Yellow-poplar, n=36	34.6	304	E
EPI-2006 bonded LVL – ASTM D-1037 Internal bond			
Southern pine, n=36	40.0	159	A
Yellow-poplar, n=36	35.2	141	A B
EPI-2007 bonded LVL – ASTM D-1037 Internal bond			
Southern pine, n=36	40.1	183	B C
Yellow-poplar, n=36	33.1	204	C

Figure 1: Internal bond strength values for both species of LVL bonded using PF, PUR or EPI adhesives.

Figure 2: Density values for both species of LVL internal bond specimens bonded using PF, PUR or EPI adhesives.

The expected mode of failure for both the Trus Joist bending shear test and the ASTM D 5456 6-cycle flatwise bending test is horizontal shear. In a few instances the specimens did not fail in horizontal shear, but in bending. This is noted, but the data was not removed from the data set.

The Trus Joist bending shear 1-cycle data is shown in Table 2. Numerically, the best horizontal shear values were obtained when the LVL was bonded using the PUR. The worst values, only slightly less for SYP, but much less for YP were obtained when the LVL was bonded with the EPI-2006.

The Trus Joist flatwise bending shear test requires that the control specimens (dry) achieve 650-psi average shear value. The specimens tested wet after one aging cycle need an average value of 375-psi. All of the groups tested exceeded the dry specimen minimum; the YP average value for EPI-2006, 657-psi, was very near the limit and much lower than the PF, PUR and EPI-2007 mean values of 794-psi, 862-psi and 751-psi, respectively (Table 4). The SYP results were more closely grouped (Figure 3).

Neither species of the EPI-2006 bonded LVL met the wet strength requirement. While the PUR, PF and EPI-2007 bonded YP LVL passed, the SYP did not. However, discussions with several Technical Directors after the initial PUR adhesive analysis indicated that the 323-psi, 309-psi and 364-psi average values that were achieved by the PF, PUR and EPI-2007 bonded Southern pine LVL are acceptable. The average values of 313 and 298-psi from the SYP and YP EPI-2006 samples are in a similar range. This is based on the limited history of the wet strength test within Trus Joist, and the very small sample sizes in this study.

The large moisture content range for the wet PUR bonded yellow-poplar specimens cannot be readily explained (Figure 8). The measurement data and calculations were carefully reviewed, but no errors could be found.

Statistical groups are defined in Table 3 with the adjusted means. Density and MC were tested as covariates for all of the groups. MC was not significant with any group, but density was used for the YP specimens. Density variation is shown in Figure 5 and Figure 6, while MC variation is shown in Figure 7 and Figure 8. The best overall performance was attained by the EPI-2007, followed closely by the PUR, both of which are superior to the PF and EPI-2006.

Table 2: Trus Joist bending shear 1-cycle mean values, density, failure modes and moisture content at time of test.

Species	Density (pcf) at: 65% RH & 21°C	Control specimens				Cycled specimens			
		Peak load, lb	Horizontal shear, psi	Failure mode	MC at test, %	Peak load, lb	Horizontal shear, psi	Failure mode	MC at test, %
PF bonded LVL - n=4									
SYP	41.1	2003	672	4 HS	10.8	1093	323	4 HS	116
YP	36.3	2514	794	4 HS	10.3	1400	385	4 HS	138
PUR bonded LVL - n=12									
SYP	39.6	2611	758	7 HS	11.1	1157	309	12 HS	110
YP	33.7	2685	862	12 HS	10.1	1516	415	10 HS	146
EPI-2006 bonded LVL - n=12									
SYP	40.0	2271	682	12 HS	12.0	1144	313	12 HS	127
YP	35.4	2272	657	12 HS	11.5	1135	298	12 HS	115
EPI-2007 bonded LVL - n=12									
SYP	40.1	2452	750	9 HS	11.7	1305	364	12 HS	112
YP	33.3	2365	751	11 HS	10.9	1401	410	12 HS	120

Table 3: Statistical tests and adjusted means for Trus Joist bending shear tests. Analysis of variance was used for all tests with Tukey's HSD. Density was a significant covariate for both sets of YP product.

Control Specimens (not cycled)				
SYP			YP	
Binder	Peak Load (psi)	Statistical Group	Peak Load (psi)	Statistical Group
PF	2003	A	2283	C
PUR	2611	C	2764	D
EPI-2006	2271	A B	2145	C
EPI-2007	2452	B C	2490	D
Cycled Specimens				
SYP			YP	
Binder	Peak Load (psi)	Statistical Group	Peak Load (psi)	Statistical Group
PF	1093	A	1292	A B
PUR	1157	A	1543	B C
EPI-2006	1144	A	1166	A
EPI-2007	1305	B	1461	C

Figure 3: Trus Joist bending shear test results for SYP LVL made with PF, PUR, and EPI adhesives.

Figure 4: Trus Joist bending shear test results for YP LVL made with PF, PUR, and EPI adhesives.

Figure 5: Density of SYP Trus Joist bending shear test specimens made with PF, PUR, and EPI adhesives.

Figure 6: Density of YP Trus Joist bending shear test specimens made with PF, PUR, and EPI adhesives.

Figure 7: Moisture content of control Trus Joist bending shear test specimens made with PF, PUR, and EPI adhesives.

Figure 8: Moisture content of cycled Trus Joist bending shear test specimens for both species made with PF, PUR, and EPI adhesives.

The average peak load is graphically shown in Figure 9 and Figure 10. In addition, the average values are included in Table 4. Also in Table 4 is density, MC at testing and a failure mode report. The ASTM D 5456-05 6-cycle flatwise bending (A4.2) method requires that the average strength retention be at least 50%; this was achieved by all tests (Figure 11 and Table 5). Note that the y-axis in Figure 11 increased compared to earlier updates from 100% to 120% with the addition of EPI-2007.

Table 4: ASTM D 5456-05, 6-cycle flatwise bending values, density, failure modes and moisture content at time of test.

Species	Density (pcf) at: 65% RH & 21°C	Control specimens			Cycled specimens		
		Peak load, lb	Failure mode	MC at test, %	Peak load, lb	Failure mode	MC at test, %
PF bonded LVL - n=4							
SYP	41.1	2108	4 HS	10.9	1822	3 HS	10.4
YP	35.7	2376	4 HS	10.3	2191	4 HS	11.2
PUR bonded LVL - n=12							
SYP	39.4	2737	10 HS	11.2	2219	11 HS	13.7
YP	33.6	3000	12 HS	10.3	2511	12 HS	14.1
EPI-2006 bonded LVL - n=12							
SYP	39.6	2493	11 HS	12.0	1762	12 HS	11.8
YP	35.2	2417	11 HS	11.5	1822	12 HS	12.8
EPI-2007 bonded LVL - n=12							
SYP	40.0	2603	11 HS	11.8	2436	11 HS	11.0
YP	33.3	2382	12 HS	10.9	2244	12 HS	11.6

Results of analysis of covariance are reported for the 6-cycle edge bending tests in Table 5. The average values reported are adjusted means and if significant covariates were identified the means were normalized using those factors. Each statistical test was run for a single species and test combination, e.g. peak load for SYP control specimens. The best overall performance was measured on the billets bonded with the PUR adhesive, which out-performed EPI-2007 in only one test: peak load of the control YP.

Table 5: Statistical results for 6-cycle ASTM 5456 data analyzed using analysis of covariance. Significant covariates for each test are listed with the species. Letters denote statistical groups.

Control Specimens (not cycled) – Peak Load				
Binder	SYP – no covariate		YP – density as covariate	
	Peak Load (psi)	Statistical Group	Peak Load (psi)	Statistical Group
PF	2109	A	2231	C
PUR	2737	B	3060	E
EPI-2006	2493	B	2308	C D
EPI - 2007	2603	B	2479	D
Cycled Specimens – Peak Load				
Binder	SYP – no covariate		YP – density as covariate	
	Peak Load (psi)	Statistical Group	Peak Load (psi)	Statistical Group
PF	1823	F	1952	I
PUR	2219	G	2613	J
EPI-2006	1762	F	1653	H
EPI-2007	2436	G	2391	J
Cycled Specimens (not cycled) – Percent Strength Retention				
Binder	SYP – no covariate		YP – no covariate	
	Strength Retention (%)	Statistical Group	Strength Retention (%)	Statistical Group
PF	86.8	B C	91.8	B C
PUR	81.4	B	83.8	A B
EPI-2006	70.8	A	76.0	A
EPI-2007	94.0	C	94.6	C

Figure 9: ASTM 5456-05 SYP 6-cycle flatwise bending test results for PF, PUR, and EPI adhesives.

Figure 10: ASTM 5456-05 YP 6-cycle flatwise bending test results for PF, PUR, and EPI adhesives.

Figure 11: Percent strength retention ASTM 5456-05 6-cycle flatwise bending test specimens for both species made with PF, PUR, and EPI adhesives.

Figure 12: Density results for ASTM 5456-05 SYP 6-cycle flatwise bending test specimens for control and cycled specimens made with PF, PUR, and EPI adhesives.

Figure 13: Density results for ASTM 5456-05 YP 6-cycle flatwise bending test specimens for control and cycled specimens made with PF, PUR, and EPI adhesives.

Figure 14: Moisture content results for SYP ASTM 5456-05 6-cycle flatwise bending test specimens for control and cycled specimens made with PF, PUR, and EPI adhesives.

Figure 15: Moisture content results for YP ASTM 5456-05 6-cycle flatwise bending test specimens for control and cycled specimens made with PF, PUR, and EPI adhesives.

For the ASTM D 5456-05 single-cycle test, average peak load values are listed in Table 6 with density, failure mode and MC at the time of the test. Variability of peak load, density and MC are illustrated in Figure 16, Figure 17, Figure 19, Figure 20, Figure 21 and Figure 22. The ASTM D 5456-05 single-cycle edgewise bending (A4.3) method requires that the average strength retention be at least 75%. All of the test groups passed this requirement (Figure 18). The lowest values, measured on the PUR bonded billets, achieved an average of 89% and 87% strength retention for the SYP and YP boards, respectively.

Table 6: ASTM D 5456-05, 1-cycle edgewise bending values, density, failure modes and moisture content at time of test.

Species	Density (pcf) at: 65% RH & 21°C	Control specimens			Cycled specimens		
		Peak load, lb	Failure mode	MC at test, %	Peak load, lb	Failure mode	MC at test, %
PF bonded LVL - n=4							
SYP	41.4	1452	4 BT	9.7	1510	4 BT	7.8
YP	36.2	1635	3 BT	9.4	1538	2 BT	10.8
PUR bonded LVL - n=12							
SYP	39.9	1709	12 BT	10.9	1510	12 BT	13.1
YP	34.1	1633	12 BT	10.1	1415	12 BT	12
EPI-2006 bonded LVL - n=12							
SYP	40.2	1903	12 BT	11.2	1978	12 BT	9.4
YP	35.4	1695	12 BT	11.0	1564	12 BT	11.6
EPI-2007 bonded LVL - n=12							
SYP	40.6	1936	12 BT	10.8	1922	12 BT	10.0
YP	33.3	1554	12 BT	10.4	1467	12 BT	10.4

Results from analysis of covariance tests using Tukey's HSD test for the 1-cycle edge bending are reported in Table 7. Boards bonded with the EPI-2007 had the best performance and the PF bonded boards had the worst.

Table 7: Statistical results for 1-cycle ASTM 5456 data analyzed using analysis of covariance. Significant covariates for each test are listed with the species. Letters denote statistical groups. Values reported are adjusted means.

Control Specimens (not cycled) – Peak Load				
Binder	SYP – density as covariate		YP – density as covariate	
	Peak Load (psi)	Statistical Group	Peak Load (psi)	Statistical Group
PF	1365	A	1507	D
PUR	1743	B	1661	E
EPI-2006	1913	B C	1630	E
EPI-2007	1921	C	1633	E
Cycled Specimens – Peak Load				
Binder	SYP – density as covariate		YP – density and MC as covariates	
	Peak Load (psi)	Statistical Group	Peak Load (psi)	Statistical Group
PF	1447	F	1414	H
PUR	1536	F	1471	I
EPI-2006	1995	G	1534	I
EPI-2007	1901	G	1482	I
Cycled Specimens (not cycled) – Percent Strength Retention				
Binder	SYP – density as covariate		YP – MC as covariate	
	Strength Retention (%)	Statistical Group	Strength Retention (%)	Statistical Group
PF	104.0	K	92.6	L
PUR	89.2	J	89.5	L
EPI-2006	104.3	K	93.4	L
EPI-2007	98.9	K	91.3	L

Figure 16: ASTM 5456-05 SYP single-cycle edgewise bending test results for PF, PUR, and EPI adhesives.

Figure 17: ASTM 5456-05 YP single-cycle edgewise bending test results for PF, PUR, and EPI adhesives.

Figure 18: Percent strength retention ASTM 5456-05 single-cycle edgewise bending test specimens for both species made with PF, PUR, and EPI adhesives.

Figure 19: Density results for SYP ASTM 5456-05 single-cycle edgewise bending control and cycled test specimens made with PF, PUR, and EPI adhesives.

Figure 20: Density results for YP ASTM 5456-05 single-cycle edgewise bending control and cycled test specimens made with PF, PUR, and EPI adhesives.

Figure 21: Moisture content results for ASTM 5456-05 SYP single-cycle edgewise bending test specimens for control and cycled specimens made with PF, PUR, and EPI adhesives.

Figure 22: Moisture content results for ASTM 5456-05 YP single-cycle edgewise bending test specimens for control and cycled specimens made with PF, PUR, and EPI adhesives.

Milestone Status Table as of December, 2006:

ID Number	Task / Milestone Description	Planned Completion	Actual Completion	Comments
1.1.1	VT: Install hydraulic fluid cooling system on pilot-scale hot-press	Jan 05	Jan 05	
1.1.2	VT: Install new Rheometer system	Dec 04	Jan 05	
1.1.3	VT: Develop small-scale LVL manufacture protocol.	Feb 05	Jan 05	
1.1.4	NS: Install autoclave for ASTM D2559 testing	Dec 04	Feb 05	
1.1.5	NS: Initiate ASTM D2559 testing for phase I adhesives	Jan 05	March 05	
1.2.1	VT: Install RH control system	Jan 05	Feb 05	
1.2.2	VT: Initiate development of isothermal /iso-humid cure analysis	Feb 05	March 05	
1.2.3	VT: Manufacture SYP-LVL	Feb 05	June 05	
1.2.4	VT: Manufacture SP-LVL	March 05	June 05	
1.2.5	NS: Complete ASTM D2559 testing	Feb 05	June 05	
1.2.6	NS: Conduct adhesive thermal, swelling etc. analysis	Jan 05	May 05	
1.2.7	TJ: Initiate small-scale LVL-testing	Feb 05	March 05	
1.3.1	VT: Complete development of isothermal/iso-humid rheometer cure analysis.	April 05	May 05	
1.3.2	VT: Initiate crosslink density (Rheometer) measurements of neat phase I adhesives in parallel plate mode.	May 05	Sept 05	
1.3.3	VT: Initiate development of crosslink density measurements of bonded-wood samples in parallel plate mode	June 05	Oct 05	
1.3.4	NS: Compile and review phase I results.	June 05	June 05	
1.3.5	NS: Devise phase II adhesive synthesis/formulation strategy.	June 05	July 05	
1.3.6	TJ: Complete phase I small-scale LVL mechanical testing.	May 05	July 05	
1.4.1	NS: Prepare phase II adhesives.	Aug 05	Aug 05	
1.4.2	NS: Conduct ASTM D2559 testing for phase II adhesives.	Sept 05	Sept 05	
1.4.3	NS: Conduct adhesive thermal, swelling, pot-life, etc. analyses.	Sept 05	Sept 05	
1.4.4	VT: Manufacture southern pine LVL; 6 billets for phase II adhesive (+2 billets for PF control).	Sept 05	May 06	
1.4.5	VT: Manufacture yellow-poplar LVL; 6 billets for phase II adhesive (+2 billets for PF control).	Sept 05	May 06	
Year 2:				
2.1.1	TJ: Conduct phase II small-scale LVL mechanical testing.	Dec 05	Sept 06	

ID Number	Task / Milestone Description	Planned Completion	Actual Completion	Comments
2.1.2	VT: Conduct phase II adhesive cure & crosslink density studies.	Dec 05	Nov 06	
2.1.3	NS: Compile and review phase II results.	Nov 05	Nov 06	
2.1.4	NS: Devise phase III adhesive synthesis/formulation strategy	Dec 05	July 06	
2.1.5	NS: Organize phone conference (Milestone #1)	Dec 05	Sept 05	Project group meeting held in Blacksburg, VT
2.2.1	NS: Prepare phase III adhesives	Jan 06	August 06	
2.2.2	NS: Conduct ASTM D2559 testing for phase III adhesives	Feb 06	September 06	
2.2.3	NS: Conduct adhesive thermal, swelling, pot-life, etc. analyses	March 06	October 06	
2.2.4	VT: Manufacture southern pine LVL; 6 billets for phase III adhesives (+2 billets for PF control)	March 06	May 07	
2.2.5	VT: Manufacture yellow-poplar LVL. 6 billets for phase III adhesives (+2 billets for PF control).	March 06	May 07	
2.3.1	TJ: Conduct phase III small-scale LVL mechanical testing.	June 06		July 07
2.3.2	VT: Conduct phase III adhesive DMA cure & crosslink density studies.	May 06		July 07
2.3.3	NS: Compile and review phase III results.	May 06		August 07
2.3.4	NS: Devise phase IV adhesive synthesis/formulation strategy.	June 06		
2.3.5	NS: Organize phone conference (Milestone #2).	June 06		Project group meeting held in Blacksburg, VT
2.4.1	NS: Prepare phase IV adhesive.	July 06	May 07	A total of seven adhesives were synthesized and tested according to ASTM D2559 at National Starch. None of the adhesives passed the required value on SYP. Specimens were shipped to VT for bondline analysis employing fluorescent microscopy.
2.4.2	NS: Conduct ASTM D2559 testing for phase IV adhesives.	Aug 06	May 07	
2.4.3	NS: Conduct adhesive thermal, swelling, pot-life, etc. analyses.	Sept 06	May 07	
2.4.4	VT: Manufacture southern pine LVL; 6 billets for phase IV adhesive (+2 billets for PF control).	Sept 06	Sept 06	
2.4.5	VT: Manufacture yellow-poplar LVL; 6 billets for phase IV adhesive (+2 billets for PF control).	Sept 06	Sept 06	
Year 3:				
3.1.1	TJ: Conduct phase IV small-scale LVL mechanical testing.	Nov 06		
3.1.2	VT: Conduct phase IV adhesive cure & crosslink density studies.	Nov 06		
3.1.3	NS: Compile and review phase IV results.	Nov 06		

ID Number	Task / Milestone Description	Planned Completion	Actual Completion	Comments
3.1.4	NS: Devise phase V adhesive synthesis/formulation strategy.	Dec 06		
3.1.5	NS: Organize research review at TJ Technology Center, Boise ID (Milestone #3).	Dec 06		
3.2.1	NS: Prepare phase V adhesives.	Jan 07		
3.2.2	NS: Conduct ASTM D2559 testing for phase V adhesives	May 07		Tim Ramsey had requested that we list the demonstration of passing the delam test as one of VT activities. However, delam testing is conducted by National Starch, not VT. We hope to demonstrate this, and perhaps we will.
3.2.3	NS: Conduct adhesive thermal, swelling, pot-life, etc. analyses.	May 07		
3.2.4	TJ: Manufacture large-scale southern pine LVL; 2 billets for phase V adhesive (+2 billets for PF control)	Feb 07		Was scheduled for January 2007. 18 billets of SYP bonded with polyurethane adhesive (HB222). The manufacture of LVL did not occur. A phone conference (VT, NSC and Weyerhaeuser was held
3.2.5	TJ: Manufacture large-scale yellow poplar LVL; 2 billets for phase V adhesive (+2 billets for PF control)	Feb 07		
3.2.6	TJ: Conduct phase V large-scale LVL mechanical testing	March 07		
3.2.7	TJ: Analyze mill trial feasibility.	March 07		
3.2.8	VT: Conduct phase V adhesive cure & crosslink density studies.	March 07	Sept 07	
3.3.1	NS: Compile and review phase V results.	April 07		
3.3.2	NS: Devise phase VI adhesive synthesis/formulation strategy.	April 07	Oct 07	
3.3.3	NS: Organize phone conference (Milestone #4).	June 07	Oct 07	
3.3.4	NS: Prepare phase VI adhesive.	May 07	Dec 07	
3.3.5	TJ: Manufacture large-scale southern pine LVL; 2 billets for phase VI adhesives (+2 billets for PF control).	May 07	Jan 08	
3.3.6	TJ: Manufacture large-scale yellow-poplar LVL; 2 billets for phase VI adhesives (+2 billets for PF control).	May 07	March 08	
3.3.7	TJ: Conduct phase VI large-scale LVL mechanical testing	June 07	March 08	
3.3.8	VT: Conduct phase VI adhesive cure & crosslink density studies.	June07	NA	Deemed unnecessary

ID Number	Task / Milestone Description	Planned Completion	Actual Completion	Comments
3.4.1	NS: Conduct ASTM D2559 testing for phase VI adhesive	July 07		
3.4.2	NS: Conduct adhesive thermal, swelling, pot-life, etc. analyses.	Aug 07		
3.4.3	NS: Compile and review phase VI results.	Sept 07		
3.4.4	NS: Organize research review and planning session (Milestone #5).	Sept 07		

Project Spending and Estimate of Future Spending							
Quarter	From	To	Estimated Federal Share of Outlays*	Actual Federal Share of Outlays	Estimated Recipient Share of Outlays*	Actual Recipient Share of Outlays	Cumulative
4Q04	Start(10/15/04)	12/31/04	\$98,000	\$40,216.50	\$18,240.75	\$1,395.00	0
1Q05	1/1/05	3/31/05	\$25,000	\$116,993.83	\$18,240.75	\$2,894.00	
2Q05	4/1/05	6/30/05	\$25,000	\$19,421.99	\$18,240.75	\$18,736.00	
3Q05	7/31/05	9/30/05	\$30,578	\$24,690.00	\$18,240.75	\$29,142.25	
4Q05	10/1/05	12/31/05	\$25,000	\$19,643.15	\$22,990.75	\$15,364.00	
1Q06	1/1/06	3/31/06	\$36,671.63	\$19,151.00	\$22,990.75	\$8,445.00	
2Q06	4/1/06	6/30/06	\$36,671.63	\$25,834.15	\$22,990.75	\$8,612.00	
3Q06	7/1/06	9/30/06	\$36,671.63	\$23,272.26	\$22,990.75	\$13,012.50	
4Q06	10/1/06	12/31/06	\$36,671.63	\$20,630.06	\$14,674.25	\$19,476.00	
1Q07	1/1/07	3/31/07	\$36,671.63	\$22,778.25	\$14,674.25	\$21,637.50	
2Q07	4/1/07	6/30/07	\$36,671.63		\$14,674.25		
3Q07	7/1/07	9/30/07	\$36,671.63		\$14,674.25		
4Q07	10/1/07	12/31/07	\$24,351.63				
Totals			\$479,053	\$332,630.54	\$223,623	\$ 138,715	0