End Jointing Green Lumber with SoyBond

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Abstract

The possibility of bonding green wood offers the prospect of substantially increasing high value product recovery while at the same time reducing drying costs in the manufacture of lumber. Alkaline hydrolysis of protein-rich fractions from soybeans provides a material that, when combined with phenol-resorcinol-formaldehyde resins, forms a strong gel within seconds and that further polymerizes at room temperature to provide bonds with the strength and durability required for use in structural lumber. Because end-jointing randomizes the strength and grain pattern in wood, this process is especially significant because it offers a way to up-grade plantation grown timber for use in high-value added lumber products rather than use as pulp chips.

This paper describes some of the more important advantages offered through end jointing green lumber, soy protein hydrolysis conditions that have been successfully scaled up from laboratory to 378 liter (100 US gallons) reactions, and adhesive formulations that have been used to end-joint Douglas-fir, Hem-Fir, and Southern Pine lumber with only minor alterations of conventional lumber end-jointing lines used in the US. The same adhesive formulation can be used to bond dry, wet, or green material (and importantly wood with widely varying moisture content). No heat is required to cure the adhesive. Results of both laboratory and mill trial scale tests show that the strength and durability of the adhesive bonds meet requirements for use in structural lumber for either dry or wet use applications.

Why End Joint Green Lumber?

The conventional process for manufacture of lumber in the United States is to saw logs to various sized lumber, dry the material, and then sort the material by grade and size. This process results in short green end-trim that is made into pulp chips and a significant proportion of dry, defective, low-grade lumber only a small fraction of which is now upgraded by end-jointing and sold at a premium as compared with conventionally sawn lumber. In the process envisioned here, low quality defective lumber is scanned and cross cut to remove defects at the green end after which short green offcuts are combined with green end trim that are end jointed and then kiln dried to produce premium quality structural framing lumber. (Figure 1)

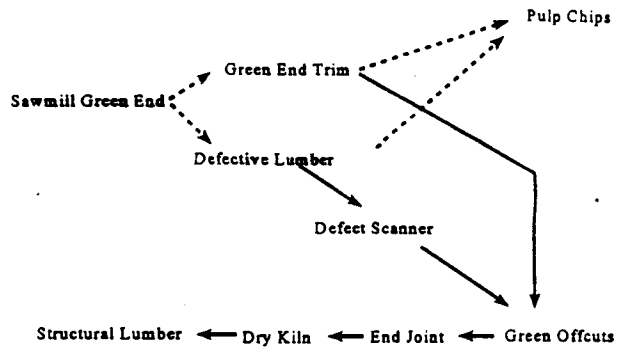


Figure 1. Schemes showing conventional (- - - -) and proposed green end joint line (------) for maximizing use of short defective material as structural lumber.

The object of this manufacturing scheme is to minimize the amout of material that is sold as pulp chips while maximizing the yield of structural lumber. The economic incentive for addition of a green end joint line to current lumber manufacturing processes becomes obvious when one compares the difference in value added between structural lumber and pulp chips. The market value for southern pine pulp chips in Louisiana is approximately $ 23/green US ton (2,000 lbs., 909 Kg.).[1] That volume of wood is equivalent to about 32 cubic feet (or 384 board feet) which, at a value of approximately $ 550/thousand board feet (Mbf), would have a market value of about $ 250 or about 10 times the market value as green pulp chips.

To provide some concept of the scale of the volume of residues from Southern U.S sawmills that are being sold as pulp chips, Koch[2] suggested an average of 1.6 tons (1,453 Kg) of green chips per Mbf (Doyle) of logs sawn and quotes another study showing the strong influence of scaling diameter on yield of pulp chips, suggesting that in current practice the figure may now be more like 2.5 green tons (2,270 Kg)/MBF of logs sawn. Because the amount of lumber actually produced from the various log scales is highly dependent on the scaling method used, the average log size and quality as well as their variability, estimates of the potential volume of green residue material that might be end jointed is so dependent on individual situations that each manufacturer would need to make that estimate. However, the calculations shown above suggest that if one

could divert even one fifth of the residue now going to pulp chips to manufacture of end jointed lumber, the increase in premium lumber recovery would be more than 20 percent.

End-jointed lumber sells at a premium over straight sawn lumber because the end jointed material is more uniform in strength properties and has less tendency to warp because the grain is randomized over the length of the piece. As harvest cycles for plantation grown trees decrease, differences in the properties of juvenile and mature wood become more important. The most important impact of juvenile wood centers on its comparatively low strength properties.[2,3] In a study of loblolly pine, McAlister and Clark[3] found that the modulus of elasticity of juvenile wood was only an average of 0.471 x 10^6 psi as compared with an average of 1.323 x 10^6 psi for mature wood. By end jointing to randomize the occurance of low strength wood, one can moderate these dramatic differences in strength properties.

There is some debate about the effect of the presence of high proportions of juvenile wood on warp. Koch[2] reviews work indicating that mature wood elongates by about 0.013 % while juvenile wood shrinks by about 0.001% resulting in a differential shrinkage of only 0.0135 inches over an 8 foot length. However, McAlister and Clark[4] found that the longitudinal shrinkage of juvenile wood was 0.47 percent as compared with 0.20 percent for mature wood which would suggest a differential shrinkage of 0.26 inches over an 8 foot span.

The advantage of end jointing for reducing warp lies in the strong relationship between the growth rate of the material and longitudinal shrinkage which ranges from typically less than 0.1 percent for slowly grown wood up to examples of over 1 percent for wood produced at 2 to 4 growth rings per inch. Also , because radial and tangential shrinkage average about 3.90 and 4.68 percent respectively for Southern pine,[4] and because lumber is never sawn perfectly flat grain, it would seem that the randomization of grain pattern is the most important feature of end jointing that leads to substantial reduction in warp (Table 1). Estimates of the reduction in warp resulting from such a randomization show that crook, which is most important for use of framing lumber, can be reduced by more than half by including one end joint in an eight foot piece of lumber.

Important advantages of the green end jointing process also rest in the kiln drying process. The most obvious advantage lies in the fact that energy is not used in drying defective wood that should not be used as sawn lumber because of its low quality. The amount of that material will vary widely depending on log grade and size and needs to be considered by each individual mill. However, use of an estimate of 20 percent of the lumber sawn would not seem unrealistic. By scanning the low grade material for defects and cross cutting to recover useble wood at the green end, one might expect to convert 75 percent of this low quality material into high-value end jointed lumber.

Table 1. Reduction of Crook through End-jointing of Lumber. If an 8 foot piece with a potential uniform crook of 0.5 or 1.0 inches is cut to 6 or 4 foot lengths and end-jointed randomly, the average crook of the reassembled 8 foot piece would be as shown.[5]

Section Length (feet)	End Joint/8 Foot	Crook (inches)		% Reduction
8	0	0.50	1.00	0
6	1	0.28	0.56	60
4	2	0.125	0.25	75

In addition, because kiln charges would be expected to be more uniform in length, an additional advantage would accrue from more efficient use of the kiln.

Reducing the amount of knots in Southern pine lumber will not only increase the quality of the product but will also reduce the amount of volatile organic compounds (VOCs) and blue haze from dry kilns.[5] The extent to which knots contribute to VOC emissions from drying Southern pine lumber is currently being studied.[6] A short preliminary study6 indicated that the amount of dichloromethane soluble extractives in knots was about 30 times higher than the amount in adjacent clear wood. GC-MS studies on the composition of knot extracts indicated that, while there were larger proportions of resins acids and stilbenes in these extracts, the proportion of volatile terpenes was still substantial. The composition of knot extracts differed significantly from extracts in the adjacent clear wood and from oleoresin collected by wounding the stem. If the relative proportions of volatile terpenes in wood and knot extracts are similar, approximately equal amounts of VOCs would come from the knots and clear wood if the volume of knots in the lumber was about 3 percent, a figure close to estimates of the proportion of knot tissue in southern pine wood.[2]

Bonding Requirements and the "Honeymoon" Adhesive System

Because of the high and variable moisture content of the wood substrate, as well as the need for a bonding process with comparatively low capital and maintenance costs, radio frequency systems are not applicable to green wood bonding. The high substrate moisture content also dictates that the adhesive reach a gel state rapidly to prevent over penetration and dilution so as to wash out the adhesive in the wet wood. At the same time, however, the adhesive must provide a reasonably long pot life and tolerance of variable assembly times. Once the joint is formed, the adhesive must reach sufficient strength to withstand the

handling stresses of movement from the point of application of end pressure to assembly into stacks of lumber suitable for kiln drying. Finally the adhesive must provide bond strength and water resistance as prescribed in applicable standards.

Chow[7] addressed the above contraints to end jointing green lumber in the mid-1970s and obtained a US patent for the concept of using heat to dry only the fingers and to use the heat retained in drying to drive the cure of a phenol-resorcinol-formaldehyde adhesive. Chow's concept was extended by Redekop and Barnes8 to whom a US Patent for the design of machinery to accomplish Chow's concept was granted in 1990. Interest in bonding green lumber accelerated when Parker and his coworkers9 developed their "Greenweld" technology. This stimulated our application of "Honeymoon" adhesive technology to the problem of bonding green wood.

The "Honeymoon" system for end jointing lumber was first described in 1974.[10] Following work by Pizzi,[11] who first applied Kreibich's idea in systems where condensed tannins were used as one component and phenol-resorcinol-formaldehyde resins were used as the second component, Kreibich and Hemingway[12-14] made a series of studies to advance the use of tannins available from North American forest and agricultural processing wastes in cold-setting lumber end jointing adhesive systems. That work included a demonstration that Vegetable Tannin/PRF combinations could be used to end-joint green lumber.[5] While technically feasible, questions about the availability and price of the tannin component stalled the development of that technology. Therefore, attention was focused on the possibility of using soy bean proteins as a component in a "Honeymoon" green lumber end jointing adhesive (Figure 2).

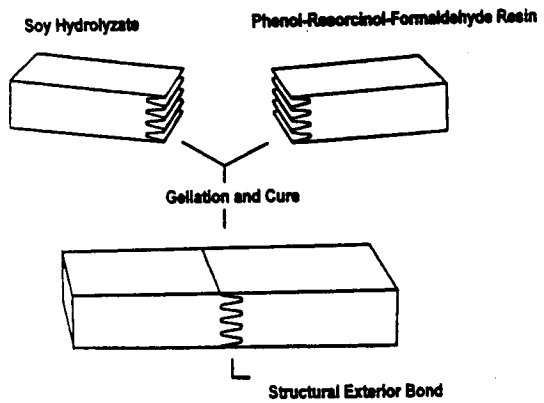


Figure 2. The "honeymoon" end joint system using soy protein hydrolyzate as one component.

The advantage of use of tannins in a "Honeymoon" end jointing system lies in their fast condensation and reactivity with PRF resins to rapidly form a polymer with sufficient molecular weight so as not to overpenetrate the substrate or to become excessively diluted in the water held in the substrate. Preliminary experiments showed that soy proteins hydrolyzed to a sufficiently low molecular weight so that they are pumpable and spreadable at solids contents of about 40 percent provide a gel even more rapidly than was obtained using vegetable tannins. Soy protein/PRF resins reacted at room temperature to achieve water-insoluble polymers with strong adhesion to wood.

The soy hydrolyzate, which importantly has unlimited pot life at ambient temperature and approximately 40 percent solids at a pH of approximately 9.0 to 10.0, is applied to one side of the joint. A PRF resin, also at 40 to 50 percent solids and carrying a formaldehyde doner catalyst with additional sources of formaldehyde to allow for polymerization of the protein, can be formulated to obtain a pot life of about 2 hours. This resin is applied to the opposite surface of the joint.

When the two polymers are mixed while mating the two surfaces, the adhesive rapidly gels to provide handling strength in only a few seconds to a few minutes depending on the formulation used (Figure 2). Importantly, the speed of that gel formation is not dependent on the moisture content of the substrate, so not only wood of high moisture content but also wood of widely varying moisture content can be used in the same joint (see Table 7 below). Another important feature of this "gellation" reaction is its comparative insensitivity to the temperature of the bond line. This initial gellation reaction has been studied over temperatures ranging from 0 °C to about 25 °C, so it is possible to pick up the strength due to the gell over wide range in temperatures, a feature important to manufacturers in locations with wide daily temperature swings.

Once formed, the adhesive will continue to cure even at ambient temperature. While it is important that sufficient drying of the bond line occur, these adhesives can provide high stength bonds if no external heat is applied. However, most applications of this technology would seem to be in end jointing lumber while green and then drying the material under normal kiln schedules used in lumber manufacture today. Results described below indicate that the rapid application of heat to dry the material enhances rather than degrades bond strength and durability.

Soy Protein Hydrolysis Conditions.

Although early experiments demonstrated the essential features of a Soy Protein/PRF "Honeymoon" adhesive system as described above, a number of different approaches were taken to the hydrolysis of high protein concentrates from soybeans. Most of this work was done using ARPRO 1100, a commercial product of Archer Daniels Midland.* Alkaline hydrolyses using either NaOH, Na_2CO_3, or NH_4OH were explored with the object of obtaining a hydrolyzate with a target viscosity of about 1,000 cps. Table 2 shows hydrolysis conditions, the viscosity of the product and the tensile strength and wood failure obtained

using each of these hydrolyzates as component A and Borden's* LT-75 with FM-260 and parapowder as the hardener as component B.

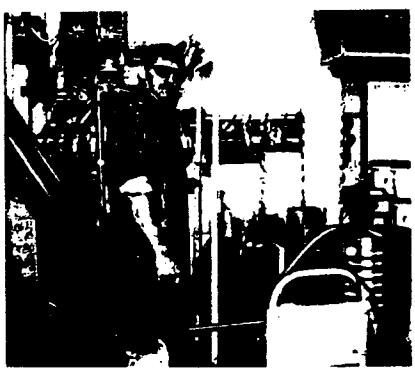
Promising results were obtained with all the hydrolyzates tested. Because of the simiplicity and low cost of using 50% NaOH, additional work was done using that catalyst with the target of reducing hydrolysis times to allow a full cook in an 8 hour shift. ARPRO 1100 (900 gms), water (1440 gms), and 50% NaOH (108 gms) were heated with stirring up to 120 °C over a period of 90 minutes and the temperature was held at 120 °C for an additional 5 hours (Figure 3). These conditions resulted in a head pressure of approximately 28 psi (190 kPa) that remained constant throughout the maximum temperature period. Adhesives made using this product gave excellent bonds. It was later determined that the addition of 3 to 5% of Na2CO3 during the cool down period to a NaOH catalyzed hydrolyzate seemed to improve bond properties

*Mention of trade names does not indicate endorsement by the US Department of Agriculture.

Table 2. Hydrolysis Conditions and Bond Properties Obtained from End Joints Bonded using Various Hydrolyzates in a Honeymoon System.

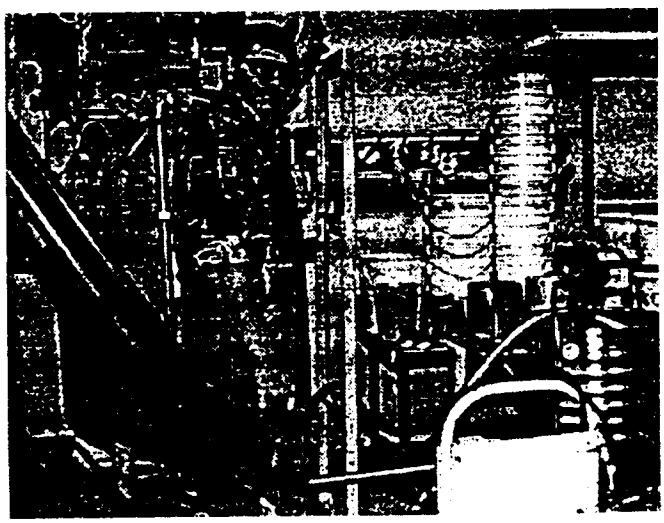
Formulation Parts by Weight					
ARPRO 1100		200	450	450	100
50% NaOH		24	—	—	—
30% NH_4OH		—	—	—	50
Na_2CO_3 (Anhydrous)		—	67	67	—
Water		320	720	720	490
Time at Temperature					
Hours		23	18	16	22
Temperature					
°C		96	95	94	90
Bond Tensile Strength (% Wood Failure)					
psi	Dry	5,790 (86)			
	VPS	4,146 (81)	4,096 (99)	4,187 (97)	3,806 (94)
kPa	Dry	39,950 (86)			
	VPS	28,607 (81)	28,262 (99)	28,890 (97)	26,260 (94)

Figure 3. Temperature and Pressure Profile of a ARPRO 1100 Hydrolysis with NaOH at 120 °C.



As work progressed from laboratory-scale tests to full-scale mill trials, it became necessary to make larger batches of the soy protein hydrolyzate which was accomplisted through a contract with the Food Protein Research and Development Center at Texas A&M University (Figure 4). The formulation used in two preparations was as follows: 251.4 liters (66.5 gallons) of water followed by 18.9 Kg (41.7 lbs) of 50% NaOH solution were added to the kettle. The temperature was increased to between 50 and 60 oC after which 157.7 Kg (347.3 lbs) of ARPRO 1100 were slowly added with stirring. It is important to add all the ARPRO 1100 before the temperature increases much above 60 °C because of the significant foaming that occurs early in the reaction. The kettle was sealed and the temperature was increased to 120 °C over approximately one hour as the mixture was stirred. The pressure within the kettle was approximately 28 psi and remained constant over the 5.5 hours of heating at 120 °C. The solution was then cooled to approximately 70 °C and the kettle vented to release some ammonia vapor. Sodium carbonate (21.5 Kg or 47.25 lbs) was then added and the solution was allowed to cool with stirring overnight. The product was cooled to about 35 °C overnight with stirring, drained into 19 liter (5 gallon) plastic containers, and the lids were sealed. The product had a pH of 9.0, a solids content of 37 percent, and a viscosity of 1,500 cps.

Figure 4. Dr. P.J. Steynberg preparing a Soy Hydrolyzate in the Reaction Kettle available at Texas A&M University.



Even though the hydrolyzate is stable for several months at ambient temperature, these products were stored in a walk-in freezer and samples were withdrawn randomly for various laboratory and full-scale mill trial tests. The scale up of these reactions from 1 to 378 liter reactions went smoothly. The only precaution involves the addition of the ARPRO 1100 to the caustic solution. While it is important to add the flour slowly so as to prevent lumps, it is also important not to let the temperature rise much about

60 °C during the addition because the material tends to foam during the heating period from about 75 to 100 °C, but that foaming subsides thereafter. As was experienced in laboratory scale reactions, the pressure increase does not exceed 30 psi throughout the cook.

Rate of Strength Development

The rate of strength development was measured using Weyerhaeuser Company's specially designed Novatech machine. Here nominal 2 X 2 inch specimens are mounted in rotating clamps. The machine closes the dry joint to define the position required to develop a predefined end pressure. The samples are then rotated out to a position for application of the adhesive and then back into a compression position at a specified end pressure. After selected time periods, the specimen is then pulled in tension and the load to failure is recorded.

Tests of bonding dry and wet (about 30 to 40 % moisture content) Douglas-fir and Hem-Fir using the sodium hydroxide catalyzed ARPRO 1100 hydrolyzate as component A and Borden's

LT-75 PRF resin with FM-260 and parapowder as a hardener as component B showed that gel strengths of 4,000 to 9,000 kPa (well within the requirements for handling of the end jointed lumber) are obtained within less than one minute after end pressure is applied (Figure 5).

Additional tests showed that this rapid pickup of strength is comparatively insensitive to substrate moisture content. The same adhesive formulation applied to green southern pine at moisture contents ranging for 60 to 106 % also gave rapid strength development (Figure 6).

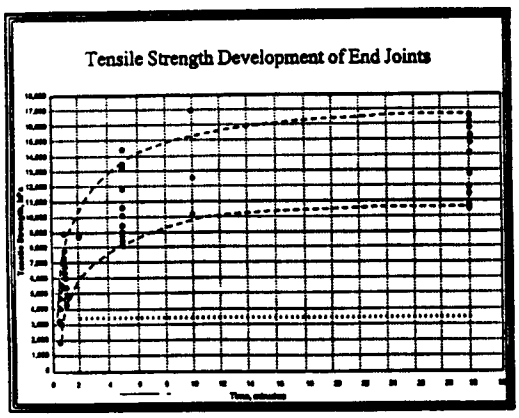


Figure 5. Rate of tensile strength development when end jointing Dougals-fir and Hem-Fir.

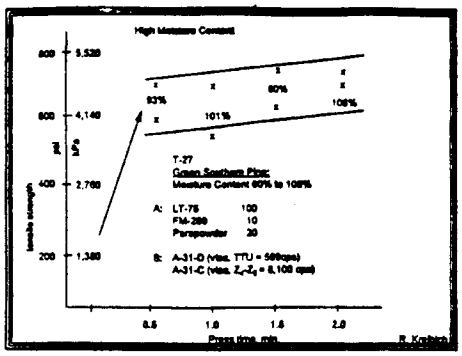


Figure 6. Tensile strength development in end jointing green Southern Pine.

Because questions were asked about use of this system for bonding "frozen" lumber, the Novatech machine was used to evaluate the rate of gel strength development at temperatures down to 0 °C. The rapid gel formation that results when the soy protein and PRF resins are mixed seems remarkably insensitive to the temperature of the bond line.

The initial gel formation is followed by a temperature and moisture content dependent cure of the adhesive. The adhesive will cure to a water insoluble polymer at room temperature, so it is not necessary to provide any heat to the bond line. However, the moisture content of the bond line and substrate must dry to around 15 percent moisture content to reach final strength and water resistance properties required of end jointed lumber for wet use. For most industrial applications, however, the end jointed lumber will be kiln dried following end jointing and here the heat used in drying the lumber also speeds the full cure of the adhesive as well as drying the substrate and bond line.

Strength and Durability of Final Bonds

Three groups of wood moisture content were examined. Dry wood is material that has previously been kiln dried and typically had a moisture content ranging from 5 to 12 percent. Wet wood is material that had previously been kiln dried but had been left out in the rain and moisture contents were typically in the range of 30 to 40 percent. Green wood is material that has never been dried. Moisture contents of that material ranged from a low of about 60 percent to as high as 160 percent moisture content. In some of the test results described below, the end jointed lumber was allowed to sit at room temperature for one to two weeks prior to testing. That material was designated as "room temperature cure." In an attempt to simulate the heat and drying that the joints would experience when kiln dried, most of the end jointed specimens were dried in an oven for 6 hours at 105 °C and then cut into strip tensile specimens. When testing end jointed "green" southern pine 2 X 4s, measurements of the moisture con-

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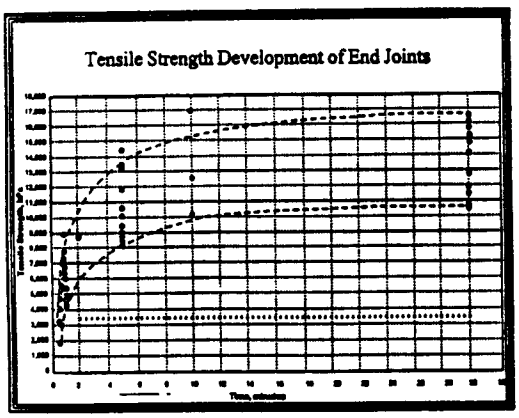

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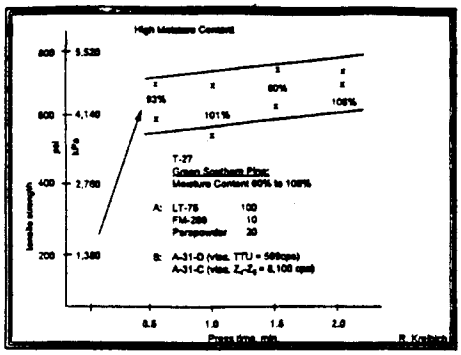

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tent of the "dried" wood at the time of test showed moisture contents ranging from 15 to 20 percent indicating that 6 hours at 105 °C was not sufficient time to represent kiln drying of that wood. Later tests in which the joints had been dried longer are indicated in the tables below.

End Jointing Western Conifers

Initial trials of the Soybond adhesive system were made using Douglas-fir and a mixture of western hemlock and true firs that are customarily grouped into lumber named Hem-Fir. These joints were made using the Novatech machine described earlier. Representative data obtained from bonding dry Doulas-fir with room temperature cure shown in Table 3 show the high strength and wood failure that can be obtained using this adhesive system for conventional dry wood end jointing.

Sample	Spec.		Thickness (inches)	Width (inches)	Load (lbs)	Tensile Strength (psi)	Wood Failure (%)
28-1		1-1	0.244	1.5	1,342	3,667	95
		1-2	0.234	1.5	1,280	3,647	98
		1-3	0.239	1.5	1,178	3,286	98
		1-4	0.230	1.5	1,012	2,933	98
28-6		1-1	0.231	1.5	1,278	3,688	98
		1-2	0.240	1.5	1,504	4,183	100
		1-3	0.237	1.5	1,419	3,992	100
		1-4	0.242	1.5	1,566	4,314	98
28-10		1-1	0.241	1.5	1,625	4,495	100
		1-2	0.238	1.5	1,595	4,468	100
		1-3	0.239	1.5	1,930	5,384	100
		1-4	0.233	1.5	1,780	5,093	98
29-1		1-1	0.242	1.5	1,771	4,879	90
		1-2	0.234	1.5	1,436	4,091	95
		1-3	0.237	1.5	1,493	4,200	95
		1-4	0.234	1.5	1,812	5,162	98
29-5		1-1	0.242	1.5	1,277	3,518	98
		1-2	0.233	1.5	1,141	3,265	100
		1-3	0.242	1.5	1,392	3,835	100
		1-4	0.230	1.5	1,074	3,113	100
29-8		1-1	0.243	1.5	1,561	4,283	92
		1-2	0.236	1.5	1,454	4,107	98
		1-3	0.242	1.5	1,687	4,667	100
		1-4	0.228	1.5	1,752	5,123	100
	Mean psi					4,141	98
	Mean kPa					28,572	

Table 3. Strength and Wood Failure after Room Temperature Cure of Douglas-fir Finger Joints Bonded with the Soybond Honeymoon Adhesive Using the Novatech Machine and Tested Wet after Vacuum/Pressure Water Soak According to ASTM D-4688

The success demonstrated in these and other laboratory-scale tests prompted a mill trial in which a mixture of "dry" and "wet" Hem-Fir was end jointed using the Soybond adhesive system with room temperature cure prior to testing according to ASTM D-4688 (Table 4). Testing these bonds while they are saturated with water obviously reduces the tensile strength so load values are not nearly as high as would be obtained from dry material. Most important here is the exceptionally high wood failure especially considering that the moisture content of the material bonded varied from less than 10 to over 30 percent.

Table 4. Finger Joint Mill Trial Tensile Strength and Wood Failure using a Mix of Dry and Wet Hem-Fir Wood with the Soybond Honeymoon Adhesive System Tested Wet after Vacuum/Pressure Water Soak according to ASTM D-4688. Specimens averaged 0.235 inches in thickness and 1.5 inches in width.

Sample	Specimen	Load (lbs)	Tensile Strength (psi)	Wood Failue (%)	Failure Code
57A	1	1,090	3,130	95	3
	2	1,206	3,816	95	3
	3	995	2,857	85	2
	4	1,055	3,029	90	3
	5	1,360	3,905	90	3
	6	1,300	3,733	90	3
	7	1,285	3,690	90	3
	8	1,100	3,158	90	3
	Mean	1,181	3,390	91	
	Std. Dev.	136	389	3	
	COV	11	11	4	

To further test the water resistance of these adhesive bonds, samples obtained from the above mill trial were subjected to 5.5 cycles of the ASTM D-4688 Boil/Oven Dry test. Here again the specimens are tested wet following the last cycle in order to rigorously test the water resistance of the bond (Table 5). Additional mill trials have been made to evaluate the use of this adhesive system for end jointing lumber with similar success.

Sample	Specimen	Thickness (in)	Width (in)	Load (lbs)	Tensile Strength (psi)	Wood Failure (%)
1-1	1	0.240	1.415	1,190	3,504	90
	2	0.233	1.415	1,140	3,458	90
	3	0.235	1.415	1,100	3,308	80
	4	0.231	1.415	1,290	3,947	85
	Mean			1,180	3,554	86
	Std. Dev.			82	275	5
	COV			7.0	7.7	5.6
1-2	1	0.229	1.357	1,260	4,055	100
	2	0.237	1.354	1,400	4,363	95
	3	0.234	1.343	1,790	5,654	95
	4	0.234	1.353	1,660	5,243	95
	Mean			1,528	4,829	96
	Std. Dev.			241	746	3
	COV			15.8	15.4	2.6

Table 5. Finger Joint Mill Trial Tensile Strength and Wood Failure using a Mix of Dry and Wet Hem-Fir Wood with the Soybond Honeymoon Adhesive System Tested Wet after 5.5 Cycles of ASTM D-4688 Boil/Oven Drying at 145 oF.

End Jointing Green Southern Pine

Because of the rapid expansion of the Forest Industry in the South and the need to increase use of plantation grown wood, opportunities for green end jointing technology are especially good. Early work centered on use of the above described soy hydrolyzates as component A in combination with Borden's phenol-resorcinol-formaldehyde (PRF) LT-75 resin and FM-260 hardener with additional paraformaldehyde as component B. The end joints were made using the Novatech machine described above and

tested according to ASTM D-4688. Southern pine wood at moisture contents ranging from 66 to 95 percent could be bonded to give ultimate tensile strenths over 3,000 psi and 89-99 percent wood failure.

Additional laboratory work directed to refining adhesive formulations based on the soy hydrolyzate and the LT-75 resin was done using a 3/4 inch long 5 tooth per inch profile on lumber from freshly felled trees where wood moisture contents ranged from 96 to 117 percent. Here the wood was allowed to dry at room temperature over a period of about 5 days and the resin was forced to cure without any heat. When tested according to ASTM D-3110-90 at final wood moisture contents of 11 to 18 percent, the bond strength and wood failure values met or exceeded the requirements for end jointed lumber in dry use conditions (Table 6) and the average wood failure after the VPS test was only marginally below requirements for wet use. Especially low wood failure values (average 23 percent) were found in one set of 13 samples that seemed especially resinous.

	Dry		VPS		3-Cycle Wet/dry		Bending	
	Ultimate Tensile Strength	Wood Failure	Ultimate Tensile Strength	Wood Failure	Ultimate Tensile Strength	Wood Failure	Modulus of Rupture	Wood Failure
Average of 56 tests	5,117	68	3,514	48*	4,549	83	7,300	88
Standard (Dry use)	2,000	60			1,000	30	2,000	
(Wet use	2,000	60	1,600	50			2,000	

Table 6. ASTM D-3110-90 Test Results for Green Southern Pine End Jointed with Soy Hydrolyzate and LT-75 PRF Resin and Allowed to Cure at Room Temperature.

The question of whether or not this same adhesive formulation could be used to bond dry to dry, dry to wet, and wet to wet southern pine lumber soon came to the forefront. Therefore experiments were made in which some of the lumber was dried to 10 percent moisture content and bonded wet to wet, wet to dry, or dry to dry using the same adhesive. First attempts were made using the soy hydrolyzate and LT-75 PRF resin system. The specimens were allowed to air dry to about 12 percent moisture content at room temperature prior to test (Table 7).

Efforts were then directed to determining if we could use another PRF resin (Borden's LT-5210 in combination with the FM-6210 slurry hardner with additional paraformaldehyde) as component B in a "Honeymoon" adhesive system with the soy hydrolyzate as component A. Freshly sawn southern pine lumber with a moisture content ranging between 42 and 146 percentwas end jointed using the PRF resin manufacturer's formulation for the PRF component and samples were tested according to ASTM D-3110-90. The results (Table 8) indicated that excellent bonds could be obtained using this PRF resin that is more commonly available. Because earlier test results were made on material that had been dried to only about 12 to 20 percent and water removal from the adhesive is important to full cure, an experiment on the effect of drying conditions on final bond properties was superimposed on this experiment. Additional drying to remove moisture from the glueline resulted in dramatic differences both in strength and the percent wood failure.

	Dry		VPS		3-Cycle Wet/dry		Bending	
	Ultimate Tensile Strength	Wood Failure	Ultimate Tensile Strength	Wood Failure	Ultimate Tensile Strength	Wood Failure	Modulus of Rupture	Wood Failure
Wet/Wet*	5,690	66	4,334	43	4,499	69	6,707	76
Wet/Dry*	5,178	93	4,248	93	4,083	91	6,159	88
Dry/Dry*	4,527	95	3,997	93	3,169	96	5,095	93
Standard (Dry use)	2,000	60			1,000	30	2,000	
(Wet use	2,000	60	1,600	50			2,000	

* Average moisture contents for wet to wet = 92 to 110, wet to dry = 111 to 10 and dry to dry = 10 to 10 percent. Test results are averages of eight joints at each moisture content combination.

Table 7. ASTM D-3110-90 Test Results for Dry and Green Southern Pine End Jointed with Soy Hydrolyzate and LT-75 PRF Resin and Allowed to Cure at Room Temperature.

	Dry		VPS		3-Cycle Wet/dry		Bending	
	Ultimate Tensile Strength	Wood Failure	Ultimate Tensile Strength	Wood Failure	Ultimate Tensile Strength	Wood Failure	Modulus of Rupture	Wood Failure
Wet/Wet	4,650 4,473	82 87	2,841 3,828	33a 71b			3,423 6,195 8,286	90 97 74
					3,984b 5,364b 4,513bc	93 65 83		
			2,982 3,293 2,861 3,067	56a 71d 19e 41f				
Wet/Dry					5,211b	90	7,145	70
Dry/Dry					2,862b	97	5,886	83
Standard (Dry use)	2,000	60			1,000	30	2,000	
(Wet use	2,000	60	1,600	50			2,000	

Table 8. ASTM D-3110-90 Test Results for Green Southern Pine End Jointed with Soy Hydrolyzate and LT-5210 PRF Resin Tested Following Different Drying Regimes.

The LT-5210 resin with the FM-6210 hardener performed at least as well as if not better than the LT-75 with the FM-260 hardener as the component B.

To determine if the amount of aldehyde in the FM-6210 was limiting the speed of the reaction with the hydrolyzate or if reaction temperature was most important in driving the reaction to complete cure, we examined the properties of end joints made using the standard soy hydrolyzate as component A and the standard LT-5210/FM-6210 formulation as component B. After drying the 2 x 4s in an oven, standard 1/4th inch tensile specimens were cut and then dried for an additional 24 hours at 105 °C. We compared those results with end joints that were made using twice the recommended amount of FM-6210 hardener and dried under the standard conditions (Table 8). Additional heat needed to drying the bond line to moisture contents of about 5 percent would help the bond properties.

Because most applications for this technology would require kiln drying the material following end jointing, the application of additional heat following the initial gellation of the resin would be expected under the envisioned

process. Good markets exits for this adhesive system in which it is not necessary to heat the bond line. High tensile strength can be obtained by only allowing the resin to cure at ambient temperature. However, wood failure values above 50 percent might not consistently be obtained when tested wet after a vacuum pressure water soak.

Because of the rapid development of a strong gel formation, a question arose about how tolerant this resin system would be of varying closed assembly times. The time between assembly of the finger joint and application of end pressure could vary significantly in an industrial setting. Green southern pine end joints were assembled with hand pressure and either 10, 20, or 30 seconds of delay was allowed prior to applying end pressure. The samples were tested dry after a 3 cycle water soak and oven drying treatment (Table 9). Results showed that there was not a consistent change in bond strength or wood failure after the 3 cycle test.

Table 9. Effect of closed assembly time on tensile strength and wood failure of green Southern pine end joints tested dry after a three cycle water soak and oven drying treatment.

Closed Assembly Time (seconds)		Tensile Strength (psi)	Wood Failure (%)
10		5,592	73
		5,531	96
		5,082	90
		4,889	75
	Mean	5274	84
20		5,032	76
		4,062	75
		3,942	83
		5,270	100
	Mean	4,577	84
30		5,333	85
		5,090	91
		3,431	83
		4,795	81
	Mean	4,662	85

Because of the importance of drying the bond line, particularly with regard to wood failure in the VPS test results as outlined in either ASTM D-3110-90 or ASTM D-5572-94, we also tested specimens that had been glued at green moisture contents and then dried under a proprietary "normal" southern pine lumber drying schedule.

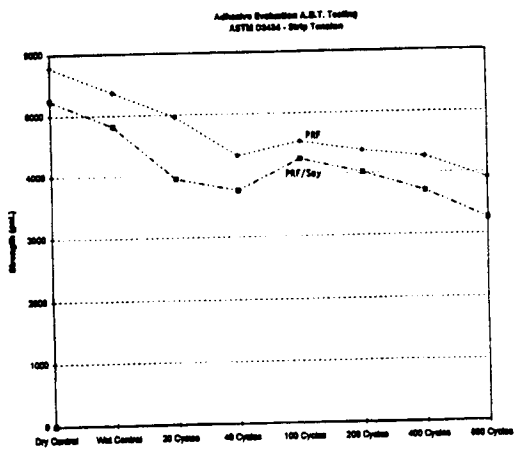
Table 10. Tensile Strength and Wood Failure of End Joints made with Green Southern Pine that was Kiln Dried and then Tested using ASTM D-5572-94

Sample No.	Moisture Content at gluing	Moisture Content after drying	Dry		VPS	
			Tensile Strength	Wood Failure	Tensile Strength	Wood Failure
1	148-142	8.5-8.5	4,092	96	3,558	82
2	148-166	8.5-8.5	4,228	96	3,543	68
3	166-142	8.5-8.5	4,046	97	3,088	61
4	156-148	8.5-8.5	4,695	87	3,570	72
5	156-127	8.5-8.5	4,128	98	3,925	57
Mean	156-140	8.5-8.5	4,238	95	3,537	68
Dry Use			2,000	60		
Wet Use			2,000	60	1,600	50

The results obtained from those tests (Table 10) showed that these end joints exceeded all requirements for use of this lumber under wet use conditions.

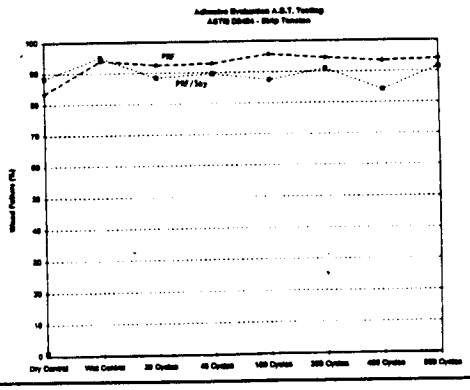
In an effort to predict the long-term durability of these adhesives, end joints were subjected to 800 cycles of boil-dry treatment and tested for strip tensile strength and wood failure according to ASM D-3434 in comparison with bonds made with 100% phenol-resorcinol-formaldehyde (PRF) bonded end joints. Alhough the tensile strengths of PRF/Soy bonds were marginally lower than those measured for the PRF resins, the deterioration of bond strength over hundreds of boil/dry cycles was not different and final bond strengths (Figure 5). After this severe treatment, the tensile strength of the PRF/Soy bond end joints exceeded ASTM requirements.

Figure 5. Srip tensile strength of PRF and SoyBond (PRF/Soy) bonded end joints through 800 boil/dry cycles (ASTM D-3434).



Wood failure values for the two adhesives were not significantly different remaining over 80% throughout the experiment (Figure 6). Therefore, changes in tensile strengh are due to degradation of wood strength and not loss of adhesives strength.

Figure 6. Wood failure of PRF and SoyBond (PRF/Soy) bonded end joints through 800 boil/dry cycles (ASTM D-3434).



The laboratory-scale results summarized above have been sufficiently good to prompt one manufacturer on the West Coast to enter into full-scale production and two major US manufacturers of southern pine lumber to conduct full-scale mill trials. Results of those experiments are proprietary information to each of those companies. What is heartening is the fact that at least two major manufacturers of southern pine lumber have seen the possible economic returns and have tested this adhesive in a real mill environment.

Conclusions:

Use of an alkaline hydrolyzate of a high protein fraction of soybeans as one component in combination with an equal weight of phenol-resorcinol-formaldehyde resins as the second component in honeymoon system adhesives for end jointing wood offers a way to substantially increase the recovery of structural lumber from trees. Because green wood can be bonded using this adhesive system, end trim and clear wood in slabs can be used for manufacture of lumber products with approximately ten times the value of their present use as pulp chips. Costs of drying wood and VOC emissions from wood driers can be reduced. Importantly, the SoyBond adhesive system is simple to use, requiring only the addition of a second glue applicator head to conventional end jointing systems in the United States. This adhesive system develops handling strength within seconds of mating at normal end pressures and no heat is required to cure the adhesive.

Both laboratory and mill trial scale testing of lumber made from dry, wet, and green wood and importantly, mixtures of wood of widely varying moisture content, have shown that these adhesives provide the bond strength and durability required for use as structural lumber in either dry or wet conditions. The "SoyBond" honeymoon adhesive system has now successfully been tested in five mill trials including three trials of applications to bonding of western conifers and two trials of bonding green southern pine. While the detailed results of those trials are proprietary, it can be said that the adhesive bond quality seen in laboratory tests were reproducible and the simplicity of use of this adhesive system was a major advantage in an industrial environment. Although tests have concentrated on the most important North American conifer species Douglas-fir, Hem-Fir, and Southern Pine, this adhesive system also has potential application in the bonding of hardwoods.

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