Adhesive Qualities of Soybean Protein-Based Foamed Plywood Glues

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ABSTRACT: The potential of soy protein-based plywood glues for foam extrusion was evaluated. Standard glue mixes containing the soy flours Honeysoy 90, ISU-CCUR, Nutrisoy 7B, and defatted Soyafluff, and the soy concentrates Arcon F and Procon 2000 showed excellent foaming and adhesive qualities but did not have the ability to refoam. To improve refoaming capability, the formulations were modified by increasing the quantities of soy flour or concentrate so that they provided 3.48 g protein/100 g of glue mix. This was the amount of protein contributed by animal blood when it was used as the extender in the standard formulation for foamed glue. All the modified glues containing soy flour or concentrate had good refoaming properties and adhesive strengths that were at least equal to that of the control glue. Simple cost analysis also indicated that when soy flour was used, the modified formulations were cheaper to produce than the current blood-based glue.

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KEY WORDS: Adhesive qualities, animal blood protein, foam extrusion, foam stability, plywood glue, soy proteins.

Several studies on soybean-based plywood adhesives have reported that these glues provided satisfactory bonding strength to veneers (1–5). None of these studies, however, involved glues designed for foam extrusion, a method of applying glue to plywood in which the glue is foamed with air and then extruded into long strands having a diameter that will cover the entire veneer surface when pressed (6). Glues for foam extrusion contain a protein extender, which currently is spray-dried animal blood. Recently, however, concerns have been raised about handling or inhaling blood particulates that may contain possible disease agents. Animal blood also degrades rapidly and has a limited number of suppliers (Foucht, M., and T. Demaree, personal communication).

Soy protein appears to be a viable alternative to animal blood as an extender in foamed glues. Soy protein is available in a variety of forms that contain different levels of protein (meal, flour, concentrate, isolate) and can be obtained from several commercial processors. Soy meal and flour are also cheaper than animal blood (at present, $0.48/kg soy flour vs. $0.88/kg spray-dried animal blood). More importantly, soy proteins have excellent foaming properties (7), which were confirmed when we evaluated foamed glues containing soy protein products for their mixing and foaming performances (8). Our work identified the soy flours Honeysoy 90, Iowa State University-Center for Crops Utilization Research (ISU-CCUR), Nutrisoy 7B, and defatted Soyafluff, and the soy concentrates Arcon F and Procon 2000 as the products providing the desired mixing and foaming properties for foam extrusion.

The potential market for soy-based foamed plywood glues is enormous. The total domestic consumption of phenol-formaldehyde (PF) resin for plywood manufacture is about 910 million kg (2 billion lb)/yr (9), and foam extrusion accounts for 10–20% of this amount [or 91–182 million kg (200–400 million lb) of PF resins/yr applied to plywood veneer by foam extrusion] (6). The protein extender accounts for 3.5–5.5% of the total weight of foamed glue mixes (DiCarlo, D., personal communication), so there is a potential domestic market for soy protein in foamed plywood glues of approximately 3–10 million kg (7–22 million lb)/yr. This quantity will be produced from 180,000–564,000 bu (4.9–15.4 million kg) of soybeans/yr if soy flour is used in foamed glues [1 bu produces 17.7 kg (39 lb) of soy flour] or 350,000–1.1 million bu (9.5–30.0 million kg) of soybeans/yr if soy protein concentrate is used [1 bu produces 9.1 kg (20 lb) soy protein concentrate].

The bonding strengths of the standard glue mixes containing animal blood (control), soy flours, or soy protein concentrates were investigated. Modifications in the glue formulations to improve refoaming ability and comparisons of adhesion performances of the standard and modified soy protein-based foamed glues are described.

EXPERIMENTAL PROCEDURES

Materials. Spray-dried animal blood (APC 301) was obtained from American Protein Co. (Ames, IA). Honeysoy 90 soy flour was purchased from Cenex Harvest States (Mankato, MN). Nutrisoy 7B soy flour and Arcon F soy concentrate were provided by Archer Daniels Midland Co. (Decatur, IL). Soyafluff flour and Procon 2000 soy concentrate were provided by Central Soya Co., Inc. (Fort Wayne, IN), and ISU-CCUR soy flour was obtained from Iowa State University's Center for Crops Utilization Research (Ames, IA). GP 4445 PF resin (41.5% nonvolatiles) and Southern pine veneers were supplied by Georgia-Pacific Resins Inc. (Decatur, GA). Glu-X, wheat flour that is specific for plywood glues, was provided by The Robertson Corp. (Brownstown, IN).

Preparation of standard foamed glue mixes. The standard formulation for foamed plywood glues consisted of 22.0 g water, 6.0 g Glu-X, 3.5 g protein source, 65.1 g PF resin, 3.0

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g 50% NaOH, and 0.3 g foaming additive [Carsonol® SHS (sodium 2-ethylhexyl sulfate); Lonza Inc., Fairlawn, NJ] per 100 g glue mix. Ingredients were added individually in the order presented, with each addition followed by 2–7 min of mixing at slow speed (setting no. 2) using the flat paddle blade of a KitchenAid® mixer (model KSM 90). A 300-g sample of glue mix was prepared and allowed to stand overnight at room temperature prior to plywood processing. Viscosities of the glue mixes were measured by a Brookfield dial-reading viscometer before and after overnight standing to ensure that the values were no more than 1000 cP, the maximum viscosity allowed by foam extrusion equipment.

Plywood processing. Glues were tested on three-ply plywood using 25.4 × 25.4 cm (10 × 10 in.) Southern pine veneers. Two glue spreads were used: (i) a low spread value, which was calculated to be about 9 g for single glue-line application, and (ii) a high spread value, which was 20% greater than the low spread (11 g). Short (15 min) and long (60 min) assembly times were used. Three glue samples were prepared for testing a set of conditions, and duplicate three-ply boards were prepared per treatment.

The glue was applied in the required amount to the bottom and middle veneers by using a Black Bros. laboratory roll-coater model 22D-500-20. Veneers were oriented in the typical layup, in which the grain of the middle panel is perpendicular to the grain of the top and bottom panels. This point is the start of assembly time. Panels were cold-pressed at 140 psi (965 kPa) for 5 min, then placed on lab benches until assembly time was completed. Test panels were then cured at 163°C (325°F) and 200 psi (1,379 kPa) for 3.5 min in a two-opening, modified hand-pumped, hydraulic EEMCO® hot press. Cured panels were stored immediately in an insulated box.

Evaluation of adhesive quality. Test panels were cut into shear specimens according to the specifications described by the American Plywood Association (10), then subjected to the "vacuum/pressure soak" method to simulate accelerated aging before shearing (11). Specimens were placed in the chamber of a modified autoclave, which was then filled about halfway with water and placed under vacuum to −30 mm Hg for 30 min, followed by pressuring to 30 psi for another 30 min (12). After the water was drained, specimens were sheared immediately in a Globe Model Testing Machine and their wet tensile strengths were recorded. A value of at least 200 psi indicated a strong glue bond. The average strength per panel was calculated from 16 test specimens. Data were compared with those of specimens bonded by the blood-based control glue.

Modification and evaluation of soy protein-based formulations of foamed plywood glues. To improve the refoaming abilities of the soy-based foamed glues, the quantity of soy in the glue mix was increased to levels that provided 3.48 g protein/100 g glue, which was the amount of protein contributed by the blood-based protein extender in the original formulation [3.5 g extender × 0.993 (protein content, dry basis, of spray-dried animal blood)]. Duplicate samples of 1-kg glue mixes were prepared according to the protocol shown in Table 1 by using the KitchenAid mixer and then allowed to stand overnight at room temperature before being tested on the Oakes model 4MB1A mixer/foamer. Glue mix viscosities, minimum mixer speed, foam densities, refoaming performance, and foam strand qualities were recorded for all modified formulations.

TABLE 1
Typical Formulations for 1-kg Blood-Based and Modified Soy Protein-Based Glues (protein content-based replacement of animal blood)

	Protein source		
Ingredients (g)	Blood	Soy flour	Soy protein concentrate
Water	181	181	181
Protein extender	35	63[a]	50[a]
Glu-X	53.5	25.5	39
Resin	699	699	699
NaOH	29	29	29
Foamer	2.5	2.5	2.5

[a]These amounts were calculated based on 55% crude protein (dry basis) for soy flour and 70% crude protein for soy protein concentrate. The amount varied for each specific flour or concentrate depending on its actual crude protein content.

Modified soy-based glues were again tested on three-ply plywood using 25.4 × 25.4 cm (10 × 10 in.) Southern pine veneers. Samples of 200 g of glue were prepared according to the proportions given in Table 1. Plywood processing was done as described in previous sections, except that only the long assembly time (60 min) was used. Three replicates of each glue were prepared for testing a set of process conditions, and two boards were made for each treatment. The bonding strengths of the glues were determined by following the methods described earlier.

Statistical analyses. Statistical analyses were performed by using the SAS® Systems for Windows software (SAS Institute Inc., Cary, NC). Duncan's multiple range tests were performed on all data to determine significant differences among the various protein sources that were evaluated.

RESULTS AND DISCUSSION

Adhesive quality of standard foamed glue mixes. In the preceding phase of our research on soy protein-based foamed adhesives (8), we reported that glues containing the soy flours ISU-CCUR, Honeysoy 90, Nutrisoy 7B, and defatted Soyafluff, and the soy protein concentrates Arcon F and Procon 2000 possessed mixing and foaming properties desirable for foam extrusion and were comparable to those of the blood-based glue. Results from plywood testing indicated that soy protein-based foamed glues were equally as strong as the control glue under the processing conditions employed (Table 2). Tensile strengths of boards bonded by the soy-based adhesives were not significantly different from those of boards bonded by the blood-based control glue, despite some high values obtained for glues containing ISU-CCUR flour, Nutrisoy 7B flour, and Procon 2000 concentrate. Glue spread and assembly time were found to have no significant effects on the tensile strengths of plywood panels, which implied that lower

TABLE 2
Tensile Strengths of Plywood Made with Animal Blood or with Soy Protein-Based Standard Foamed Glues[a]

	Average tensile strength (psi)			
	Low spread (9 g)		High spread (11 g)	
Protein source[b]	Long assembly (60 min)	Short assembly (15 min)	Long assembly (60 min)	Short assembly (15 min)
Animal blood	232 ± 53	224 ± 44	254 ± 47	253 ± 38
Honeysoy 90 (F)	216 ± 49	248 ± 33	236 ± 20	215 ± 45
ISU-CCUR (F)	267 ± 13	191 ± 58	202 ± 29	220 ± 46
Nutrisoy 7B (F)	181 ± 36	264 ± 32	203 ± 34	218 ± 34
Soyafluff (F, defatted)	231 ± 25	233 ± 32	254 ± 39	239 ± 25
Arcon F (C)	218 ± 31	235 ± 51	238 ± 41	261 ± 28
Procon 2000 (C)	241 ± 36	262 ± 49	266 ± 39	311 ± 45

[a]Values represent mean ± SD of six plywood boards. Means were not significantly different among extenders within a given glue spread, or within extenders across glue spreads and assembly times ($P \leq 0.05$).
[b]F, flour; C, protein concentrate.

amounts of glue and shorter assembly times may be used when soy protein-based foamed glues are used to bond plywood.

Protein content-based replacement of animal blood in foamed glues. The soy protein-based foamed glues, however, had poor refoaming capabilities. Refoaming ability is important because during plywood processing, there are frequent starts and stops, and in those instances, unused foamed glue is mechanically defoamed, mixed back with the rest of the still-unfoamed glue, then refoamed when the operation resumes (6).

We attempted to improve this particular attribute by increasing the amount of soybean product in the glue mix to levels that provided 3.48 g protein/100 g glue, which was the amount of protein supplied by the animal blood when it was used as the protein extender in the standard formulation for foamed glues. The amounts of water and Glu-X were adjusted accordingly to maintain the total solids content of the mix at 27% and the final viscosity at around 1000 cP. Most of the soy protein-based foamed glues were within the recommended viscosities just after mixing and after overnight standing (Table 3). The exceptions were glues containing Soyafluff flour, Arcon F, and Procon 2000, which thickened considerably after overnight standing. Thicker glues are not desirable because they generally require higher motor speeds to generate the foamed strands. The foam extrusion equipment would be forced to use more energy to do its work, consequently adding to the production costs of the mill.

Foaming tests showed that for all glue samples, high speeds were needed for the Oakes mixer/foamer to form good-quality foam strands (Table 3). Researchers at PACO (Pacific Adhesives Co., Portland, OR), however, assured us that our values were nearly identical to those achieved in their foaming tests using the same equipment and that these values translated to acceptable mixer speeds when the pilot-scale foam extrusion system was used. The mixer speeds needed to foam the soy-based glues were similar to the speed used for the blood-based control glue (Table 3). The differences between mixer speeds for the control and soy protein-based glues were much greater when straight substitution of blood with soy was the approach used in the standard foamed glue formulations. All the glue samples required greater mixer speeds for refoaming, which was to be expected, but the mixer speeds for refoaming the soy-based glues were still close to the speed of the control (Table 3). Replacing animal blood with soy flour or concentrate on a protein-content basis significantly improved the refoaming performance of the soy protein-based glues.

Adhesive quality of modified foamed glue mixes. Plywood boards that were bonded by the modified formulations of soy protein-based glues were as strong as boards bonded by the control glue (Table 4). Their tensile strengths were not significantly different from those observed for the control boards. Increasing the amount of soy product in the foamed glue mix

TABLE 3
Mixing and Foaming Properties of Blood-Based and Modified Soy-Based Glues (protein content-based replacement of animal blood)

Mixing/foaming	Protein extender						
properties	Blood	ISU-CCUR	Nutrisoy 7B	Honeysoy 90	Arcon F	Procon 2000	DF[a] Soyafluff
Viscosity 1[b] (cps)	750	950	650	900	1100	975	1025
Viscosity 2[c] (cps)	825	750	1125	1100	1550	1300	1450
Minimum mixer speed (rpm)	750	850	800	825	900	850	850
Foam density (g/mL)	0.153	0.165	0.175	0.152	0.195	0.170	0.178
Minimum refoam mixer speed (rpm)	1100	1025	975	965	1150	1025	1060
Refoam density (g/mL)	0.177	0.144	0.160	0.135	0.210	0.165	0.188
Noodle appearance	Good	Smooth	Smooth	Smooth	Sputters	Some sputter	Thin but smooth

[a] DF, defatted (oil content = 0.21%, dry basis).
[b]Viscosity just after mixing.
[c]Viscosity after 24 h, just before foaming.

TABLE 4
Tensile Strengths of Plywood Test Specimens Bonded by Blood-Based and Modified Soy-Based Glues[a]

	Average tensile strength (psi) of plywood bonds			
	Low spread (9 g)		High spread (11 g)	
Protein source	Standard glue mix[b]	Modified glue mix[c]	Standard glue mix	Modified glue mix
Animal blood (control)	232 ± 53	235 ± 46	254 ± 47	210 ± 20
Honeysoy 90 (F)[d]	216 ± 50	242 ± 36	236 ± 20	224 ± 44
ISU-CCUR (F)	267 ± 13	231 ± 40	202 ± 29	218 ± 21
Nutrisoy 7B (F)	231 ± 36	247 ± 30	203 ± 34	250 ± 32
Soyafluff (F, defatted)	225 ± 25	231 ± 48	254 ± 39	257 ± 32
Arcon F (C)[d]	218 ± 31	215 ± 18	238 ± 41	237 ± 28
Procon 2000 (C)	241 ± 36	240 ± 36	266 ± 39	210 ± 48

[a]Values represent the mean ± SD of six plywood boards. There were no significant statistical differences detected among treatment means ($P \leq 0.05$).
[b]Involves straight substitution of blood with soy product (see Experimental Procedures section).
[c]Protein content-based substitution (see Table 1 for formulations).
[d]See Table 2 for abbreviations.

apparently had no detrimental effects on the glue's bond strength, but it did not make the bond stronger either (Table 4). Glue spread had no significant effects on tensile strengths of the foamed glues. However, significant interaction effects ($P \leq 0.05$) were found for type of glue (standard or modified) and glue spread only when Nutrisoy 7B flour was involved. This finding implies that using Nutrisoy 7B flour in the modified formulation and at the higher spread tended to produce higher tensile strength values. Changing the formulation by applying protein content-based substitution of animal blood with soy protein substantially improved the refoaming abilities of the glues while maintaining their excellent bond strengths. Georgia-Pacific Resins, Inc. has completed a mill trial on the soy flour-based glue formulations that we developed and is preparing for a second test run. Preliminary results indicate that the soy flour-based glues performed very well with respect to mixing, foaming, and adhesion under full-scale operating conditions in the plywood mill (Foucht, M., personal communication).

Cost comparisons of blood-based and soy-based modified glues. Cost estimates for the glues were based only on the protein extender and Glu-X because they were the components that changed amounts when the formulations were modified. The amounts of the other ingredients were unchanged from the basic glue recipe. Costs were computed based on 100 kg of glue mix.

Glue mixes that used soy protein concentrates were considerably more expensive than the control glue (Table 5). This is not surprising, given the cost of concentrates ($2.05/kg or $0.93/lb). Despite the excellent foaming and adhesive qualities of glues containing soy concentrate, cost is the major factor that will prevent them from being competitive with animal blood in foamed glues. Soy flour-based glues were cheaper than the control glue by $0.84/100 kg glue mix (Table 5), which means a considerable savings to the plywood milling industry annually if it adopts soy flour as an extender in the foamed glue mix.

These results show that soy flours have the strongest potential to replace animal blood as the extender in foamed glues. The soy flour-based glues are cost-competitive and possess mixing, foaming, and adhesive properties that match those of the plywood industry's current blood-based glue.

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TABLE 5
Cost Comparisons of Blood-Based and Soy-Based Foamed Glues (based on prices for extender and filler only)

Glue formulation	Extender/ filler	Unit cost ($/kg)[a]	Amount (kg)/ 100 kg glue	Cost ($)/ 100 kg glue	Total cost ($)/ 100 kg glue
Control glue	Blood	0.88	3.50	3.08	
	Glu-X	0.27	5.35	1.44	
					4.52
Protein content-based substitution of animal blood	Soy flour	0.48	6.15	2.95	
	Glu-X	0.27	2.71	0.73	
					3.68
	Arcon F	2.05	4.95	10.14	
	Glu-X	0.27	3.92	1.06	
					11.20

[a]Current prices, on per pound basis: spray-dried whole blood, $0.40; soy flour (Nutrisoy, Honeysoy 90), $0.22; soy concentrate (Arcon F), $0.93; Glu-X, $0.12. Prices were provided by product manufacturers.

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