# Mechanical and physical properties of air-formed wood-fiber/polymer-fiber composites

John A. Youngquist Andrzej M. Krzysik James H. Muehl Charles Carll

# Abstract

Little data are available on the physical and mechanical properties of nonwoven air-formed woodfiber and plastic-fiber webs that have been pressed into panels of varying density levels. This study establishes performance properties for panels with densities of 0.4, 0.7, 1.0, and 1.2 g/cm<sup>3</sup> and made from three formulations of wood and synthetic fibers (90% hemlock and 10% polyester; 90% hemlock and 10% polypropylene; and 80% hemlock, 10% polyester, and 10% phenolic resin). Nonwoven webs made from these three formulations were pressed into panels. Samples cut from these panels were then tested for physical and mechanical properties. With few exceptions, the physical and mechanical properties increased as panel density increased and as the formulation changed from hemlock and polyester to hemlock and polypropylene to hemlock, polyester, and phenolic resin. The results provide baseline information for tailoring product formulations and densities to industrial products.

Technology is evolving for combining wood fibers or fiber bundles with plastics to make an array of composite products. This technology provides a means of producing materials that take advantage of the properties of both wood and plastic. Advantages associated with these composite products include improved acoustic, impact, and heat reformability properties.

A variety of wood and synthetic fibers can be assembled into a web or mat using air-formed nonwoven web technology. The fibers are initially held together by mechanical interlocking. The web is then

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fused or thermoformed into panels or various shapes. Additional bonding of the fibers can be achieved by incorporating thermosetting resin in the web.

The processing flexibility inherent in nonwoven web technology gives rise to a host of natural and synthetic fiber products. These products can be produced in various thicknesses - from a material only a few millimeters thick to structural panels up to several centimeters thick. A variety of applications are possible because of the many alternative configurations of the products. Potential products include storage bins, furniture components. automobile and truck parts, and packages and filters.

Many patents have been issued, and numerous articles and technical papers have been written on the manufacture and use of nonwoven fiber webs containing combinations of textile and cellulosic fibers. Non-

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The authors are, respectively, Project Leader, Visiting Scientist, Forest Products Technologist, and Forest Products Technologist, USDA Forest Serv., Forest Prod. Lab., One Gifford Pinchot Dr.. Madison, WI 53705-2398. We are extremely grateful to Hunter Brooks, consultant, and Bill Surber and the General Motors Corporation for their assistance. Brooks provided valuable assistance and advice during equipment setup and experimentation. He continues to serve as a valuable resource to us as we move into new research areas. The General Motors Corporation and Bill Surber, Cadillac Motor Division, made it possible for the 12-inch Rando line, an air-forming line with unique capabilities, to be loaned to the Forest Products Laboratory for an extended period so an extensive research program in the area of wood-plastics could be developed. The use of firm or trade names is for reader information and does not imply endorsement by the USDA of any product or service. This paper was received for publication in October 1991.

woven web technology is particularly well known in the consumer products industry.

S. Hunter Brooks (3) reviewed the history of technology development for the production and use of moldable wood products and air-laid nonwoven mat processes and products. Moldable wood product processing technologies developed by Deutsche Fibrit in West Germany (3), Roberts (16, 17), and Caron and others (4-7, 10) in the United States involved the use of wood fibers and binder resins.

In the early 1970s, Brooks (3) developed a process for producing a very flexible mat using a thermoplastic fiber in combination with a thermosetting resin. Opportunities for combining wood with nonwood materials were reviewed by Youngquist and Rowell (23). Their paper included a discussion of the materials and properties of composites consisting of wood-biomass, wood-metals, wood-plastics, wood-glass. and woodsynthetic fibers.

In 1991, Krzysik and Youngquist (14) reported on the bonding of air-formed wood-polypropylene fiber composites, when maleated polypropylene was used as a coupling agent between the hydrophilic wood and the hydrophobic polyolefin materials.

Nonwoven web composites provide options for balancing mechanical and physical properties and material costs. The purpose of our research is to develop a database of mechanical and physical properties for panels made of three wood fiber and synthetic fiber formulations with densities of 0.4, 0.7, 1.0, and 1.2 g/cm<sup>3</sup>. The property results obtained provide information that materials scientists and product designers can use to develop an array of alternative products.

# Experimental design

Panels containing hemlock fiber and different types of synthetic fibers or phenolic resin are compared. Mechanical and physical properties were determined for panels containing 90 percent hemlock and 10 percent polyester (90H/10PE); 90 percent hemlock and 10 percent polypropylene (90H/10PP); and 80 percent hemlock, 10 percent polyester, and 10 percent phenolic resin (80H/ 10PE/ 10PR). Each formulation contained four density groups, 0.4, 0.7, 1.0, and 1.2 g/cm<sup>3</sup>, and was considered a replicated set that consisted of six individual panels. A total of 72 panels were made for this experiment.

The target densities were not precisely achieved. Because all properties depend strongly on density, these values were adjusted to the nominal densities by linear and quadratic regressions.

For each of the four target densities, a Scheffe multiple comparison test was performed to determine differences in the three formulations.

# Materials and methods

# Materials

Western hemlock (*Tsuga heterophylla*) wood fibers. obtained from Canfor, Ltd. (Vancouver, B.C.), were produced from 100 percent pulp-grade chips, steamed for 2 minutes at 0.759 MPa, disk refined, and flash dried at 160°C in a tube dryer. This processing sequence produced fibrous strands made of individual fibers, pieces of fiber, and fiber bundles. In this report, these fibrous strands are referred to as fibers. Two types of polyester fibers were obtained from E.I. Du-Pont deNemours, Inc., (Wilmington, Del.). When used alone with wood fibers, the polyester matrix fiber was a blend of 25 percent of a 3-denier  $(3.3 \times 10^{-7} \text{ kg/m})$ , 38.1-mm-long crimped polyester fiber with a bonding temperature of 155°C and 75 percent of a 15-denier  $(1.7 \times 10^{-6} \text{ kg/m})$ . 38.1-mm-long crimped polyester fiber with a melting temperature of 254°C. When polyester fibers were used as a matrix fiber in combination with a phenolic resin, they were 5.5 denier (6.1  $\times$  10<sup>-7</sup> kg/m). 38 mm long, crimped, with a bonding temperature greater than 2 15°C. The phenolic resin used had a solids content of 52 percent, a viscosity of 50 to 100 cps (0.05 to 0.1 Pa·s) at 25°C and a pH of 9.5 to 10.0. Polypropylene fibers, obtained from Hercules, Inc., (Norcross, Ga.), were 2.2 denier (2.4  $\times$ 10<sup>-7</sup> kg/m), 37 mm long, crimped, had a density of 0.910 g/cm<sup>3</sup>, and a melting point of 162°C.

# Process

The hemlock fibers were in tight clumps and were hammermilled to separate the clumps into fibers using a screen with a 12.7-mm-diameter hole pattern. When phenolic resin was used, the wood fibers were sprayed to give a 10 percent (dry-weight basis) resin content, based upon the total formulation weight.

The wood and plastic fibers were then mixed by passing them through a spiked drum, transferred through an air stream to a moving support bed, and subsequently formed into a continuous, low-density web of intertwined fibers contained between two thin layers of spun-bonded polyester fabric. The purpose of the spun-bonded fabric was to facilitate handling. The moisture content (MC) of the blended material was critical. If MC was much less than 10 percent, the static electricity produced resulted in erratic web formation. With material that contained phenolic resin, blended material having MC values greater than 12 percent resulted in plugging the former. This web then went through a needling process where barbedshank needles passed through the web thickness, and in so doing, resulted in an increased interlocking of the fibers. The webs were 330 mm wide and from 12.2 to 18.3 m long. The webs were then rolled for handling convenience. Panel-sized mats, 330 by 9 14 mm, were cut from each roll. For each panel, several panel-sized mats were selected according to their weight. The spun-bonded fabric was removed from each mat, and mats were stacked so as to construct multilayer mattresses of the target weight. The target density level of the panel influenced the selection of individual mats and the total number of mats in the stack.

A manually controlled, steam-heated press was used to press all panels; they were pressed at 190°C for 10 minutes. Press stops were used to produce panels 3.2 mm thick. From a production standpoint, the 10-minute press time is excessively long. However,

TABLE 1. - Experimental design a

			Total specimens
-	a	Specimens cut	per composite
Test	Specimen size	from each panel	formulation
	(mm)		
Static bending		2	48
MOR and MOE	51 by 127		
Cantilever beam		2	48
bending MOR	19 by 165		
Dynamic MOE	25 by 254	2	48
Tensile MOE and		2	48
MOR	51 by 254		
Internal bond	25 by 25	2	48
Impact energy	254 by 254	1	24
Dimensional stabilit	y		
24-hour water- soak	51 by 51	3	72
2-hour water boil	51 by 51	3	72
Linear expansion	76 by 305	2	48
Equilibrium MC	76 by 152	1	24

Six panels were used to test each density level in each composite formulation. MOE = modulus of elasticity; MOR = modulus of rupture.

we wanted to keep the press time constant for all three formulations, and the 90H/ 10PE formulation required 10 minutes to bond effectively. Depending upon the formulation, and generally at the higher density levels, different panel cooling procedures were used while the panel was still under pressure to reduce steam vapor pressure in the pressed panel. After processing, the panels were trimmed to 280 by 890 mm.

#### Tests

There were 6 replicate panels of each formulation at a given density level for a total of 72 panels. The panels of each set were tested for mechanical and physical properties including dimensional stability (Table 1).

Prior to mechanical and physical property testing at room temperature (about 23°C), the specimens were conditioned at 65 percent relative humidity (RH) and 20°C. Specimens had minimal exposure to ambient humidity during the time required to complete the testing. Three-point static bending modulus of elasticity (MOE) and modulus of rupture (MOR) and tensile MOE and MOR tests were performed in conformance with ASTM D 1037 using an Instron testing machine (2). Maximum cantilever beam bending MOR was determined on specimens in conformance with ASTM D747 using a Tinius Olsen stiffness tester with a loading rate of about 60 angular degrees/minute (1). Internal bond was determined using a Tinius Olsen testing machine with a loading rate of about 1 mm/ minute in conformance with ASTM D1037 (2). A dynamic MOE was determined with wave speed measurements using a Metriguard 239A tester according to published Metriguard procedures (15). Impact energy was measured in conformance with TAPPI standard T803 om-88 using a General Electric impact tester (21). For the thickness swell and water absorption measurements, specimens were immersed in water in a horizontal position for 24 hours at ambient temperature. Similar measurements were made for the 2-hour water boil test. These tests were performed

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 TABLE 2. – Properties of nonwoven web composite panels with a density of 0.4 g/cm<sup>3</sup>.

	Formulation <sup>a</sup>			
Property <sup>b</sup>	1: 90H/10PE	2: 90H/10PP	3: 80H/10PE/10PF	
Static bending MOR (MPa) Cantilever bending MOR (MPa)	2.4 2.0	4.0 3.3	5.5 4.6	
Static bending MOE (GPa)	0.11	0.37	0.46	
Dynamic MOE (GPa)	0.38	0.79	0.63	
Tensile MOR (MPa)	1.8	2.2	3.4	
Tensile MOE (GPa)	0.27	0.52	0.58	
Internal bond (MPa)	0.04	0.07	0.09	
Impact energy (J) Water-soak, 24 hour	12.2	5.5	16.6	
Thickness swell (%) Water-soak, 24 hour	40.3	23.9	16.0	
Water absorption (%) Water boll, 2 hour	304.3	229.6	219.8	
Thickness swell (%) Water boil, 2 hour	120.5	38.2	15.8	
Water absorption (%) Linear expansion – Ovendry to:	534.1	269.5	219.0	
30% ŘH (%)	0.46	0.29	0.29	
65% RH (%)	0.64	0.43	0.40	
90% RH (%)	0.84	0.68	0.60	
Equilibrium MC at: 30% RH (%)	3.5	3.3	3.3	
65% RH (%)	7.0	6.6	6.5	
90% RH (%)	15.2	14.4	15.0	

<sup>a</sup>Values connected by a solid line are not statistically different at a 0.05-significance level. 90H/10PE = 90 percent hemlock and 10 percent polyester; 90H/10PP = 90 percent hemlock and 10 percent polypropylene: 80H/10PE/10PR = 80 percent hemlock. 10 percent polyester, and 10 percent phenolic resin.

MOR = modulus of rupture: MOE = modulus of elasticity; RH = relative humidity.

in conformance with ASTM D1037 (2) and CAN-0188.0-M78 (8), respectively. Linear expansion test specimens were of the size specified in ASTM D 1037 (2). Length measurements were made at equilibrium at 30, 65, and 90 percent RH at 27°C. Specimens were then ovendried, and length measurements were made at an ovendry condition. Linear expansion values were calculated over the ranges: ovendry to 30 percent RH, ovendry to 65 percent RH, and ovendry to 90 percent RH. In addition, the MC of the specimens was determined at each of the RH conditions using the procedure outlined in ASTM D 1037 (2).

# **Results and discussion**

Mechanical and physical property data are presented in Tables 2 through 5. Results of Scheffe multiple comparison tests are included in these tables. The following discussions address the influence of panel densities and formulations on panel properties. Discussions regarding the influence of formulation focus on general trends as reflected by rank order of property values.

#### **Mechanical properties**

As density of panels increased, the mechanical. property values generally increased correspondingly. Analysis of the mechanical property data indicated a strong correlation of mechanical properties (MOE and MOR) with dynamic MOE and panel density. Presentation of this material is beyond the scope and length limitation of this paper.

Specimens of the 80H/10PE/10PR formulation generally had greater mechanical property values than did specimens of the other formulations at all density levels (Tables 2 to 6). Two exceptions to this trend, which can possibly be explained by random variability, were observed. The consistent superiority mechanical properties of specimens of the in 80H/10PE/10PR formulation indicates that wood/synthetic fiber composite materials can benefit from increased interfiber adhesion afforded by addition of binder resin. It also indicates that the adhesive

TABLE 3. – Properties of nonwoven web composite panels with a density of 0.7 g/cm<sup>3</sup>.

resin used, which was formulated for hardboard, was effective at improving interfiber bonding in a wood/ polyester fiber composite.

At density levels of 0.4, 0.7, and 1.0 g/cm<sup>3</sup>, specimens of the 90H/10PP formulation generally showed greater mechanical property values than did specimens of the 90H/10PE formulation. This general trend was reversed at the 1.2 g/cm<sup>3</sup> level. The exception to this trend was for impact energy values at all four density levels, and for tensile MOR at 1.0 g/cm<sup>3</sup>.

Relative impact resistance of specimens of the different formulations showed a consistent trend at all density levels. This trend was that specimens of the formulations containing polyester fibers had greater energy absorption values than did specimens from the formulation containing polypropylene fibers.

Static bending tests for the specimens in this experiment created shear deflections. This resulted in lower MOE values than those obtained by tensile or dynamic tests. During the static bending tests, significant relaxation and rearrangement between the con-

TABLE 4. – Properties of nonwoven web composite panels with a density of 1.0 g/cm<sup>3</sup>.

and the second s	Formulation <sup>a</sup>			
Property <sup>b</sup>	1: 90H/10PE	2: 90H/10PP 8	3: 30H/10PE/10PR	
Static bending MOR (MPa)	9.7	12.4	21.0	
Cantilever bending MOR (MPa)	8.0		19.4	
Static bending MOE (GPa)	0.93	1.57	1.59	
Dynamic MOE (GPa)	1.18	2.52	2.37	
Tensile MOR (MPa)	6.1	6.3	12.2	
Tensile MOE (GPa)	1.38	1.86	2.18	
Internal bond (MPa)	0.05	0.12	0.31	
Impact energy (J)	19.8	13.1	27.9	
Water-soak, 24 hour Thickness swell (%)	59.9	34.5	19.0	
Water-soak, 24 hour	150.0	101.0	07.1	
water absorption (%)	159.9	104.8	97.1	
Thickness swell (%)	238.2	59.4	22.0	
Water boll, 2 hour			101.1	
Water absorption (%)	445.8	150.4	104.4	
Ovendry to:				
30% RH (%)	0.24	0.14	0.40	
65% RH (%)	0.48	0.36	0.59	
90% RH (%)	0.81	0.74	0.70	
Equilibrium MC at:				
30% RH (%)	3.4	3.4	3.3	
65% RH (%)	6.9	6.8	6.8	
90% RH (%)	15.6	14.7	14.8	

<sup>a</sup> Values connected by a solid line are not statistically different at a 0.05-significance level. 90H/10PE = 90 percent hemlock and 10 percent polyester; 90H/10PP = 90 percent hemlock and 10 percent polypropylene; 80H/10PE/10PR = 80 percent hemlock, 10 percent polyester, and 10 percent phenolic resin.

<sup>b</sup>  $\dot{MOR}$  = modulus of rupture:  $\dot{MOE}$  = modulus of elasticity: RH = relative humidity.

	Formulation <sup>a</sup>			
Property <sup>b</sup>	1: 9011/10PE	2: 90H/10PP	3: 80H/10PE/10PR	
Static bending MOR (MPa)	23.3	25.5	49.3	
Cantilever bending MOR (MPa)		27.1	45.6	
Static bending MOE (GPa)	2.82	2.99	3.57	
Dynamic MOE (GPa)	4.75	5.27	5.52	
Tensile MOR (MPa)	13.5	12.5	27.7	
Tensile MOE (GPa)	3.87	4.20	5.07	
Internal bond (MPa)	0.14	0.28	0.81	
Impact energy (J)	26.7	21.5	34.3	
Thickness swell (%)	60.8	40.3	21.8	
Water-soak, 24 hour Water absorption (%)	85.0	54.7	45.1	
Water boil, 2 hour	0010			
Thickness swell (%)	260.1	77.5	28.2	
Water boll, 2 hour Water absorption (%)	301.6	99.5	55.7	
Linear expansion – Ovendry to:				
30% RH (%)	0.13	0.00	0.55	
65% RH (%)	0.38	0.25	0.76	
90% RH (%)	0.81	0.78	0.93	
Equilibrium MC at:				
30% RH (%)	3.4	3.4	3.4	
65% RH (%)	6.4	6.2	6.3	
90% RH (%)	15.6	14.9	14.1	

<sup>a</sup> Values connected by a solid line are not statistically different at a 0.05-significance level. 90H/10PE = 90 percent hemlock and 10 percent polyester: 90H/10PP = 90 percent hemlock and 10 percent polypropylene: 80H/10PE/10PR = 80 percent hemlock, 10 percent polyester, and 10 percent phenolic resin.

b MOR = modulus of rupture; MOE = modulus of elasticity; RH = relative humidity.

TABLE	5.	-	Properties of nor	nwoven	web	composite	panels	with	а
			density o	of 1.2	g/cm	3.			

	Formulation <sup>a</sup>			
Property <sup>b</sup>	1: 90H/10PE	2: 90H/10PP	3: 80H/10PE/10PR	
Static bending MOR (MPa)	36.5	36.8	76.4	
Cantilever bending MOR (MPa)	35.7	34.5	69.3	
Static bending MOE (GPa)	4.59	3.81	5.42 <sup>c</sup>	
Dynamic MOE (GPa)	7.85	7.68	8.51	
Tensile MOR (MPa)	20.2	17.8	42.2	
Tenstle MOE (GPa)	6.56	6.36	7.80	
Internal bond (MPa)	0.28	0.52	1.44	
Impact energy (J)	31.1	27.4	36.6 <sup>c</sup>	
Water-soak, 24 hour Thickness swell (%) Water-soak, 24 hour	57.1	42.7	23.6	
Water absorption (%) Water boll, 2 hour	57.5	37.5	28.4	
Thickness swell (%) Water boll, 2 hour	245.0	88.3	32.4	
Water absorption (%) Linear expansion –	227.3	79.6	38.6	
30% RH (%)	0.12	0.00	0.66	
65% RH (%) 90% RH (%)	0.33 0.81	0.20 0.81	0.86 1.13	
Equilibrium MC at: 30% RH (%)	3.4	3.5	3.4	
65% RH (%)	6.0	5.8	5.9	
90% RH (%)	15.5	15.0	13.6	

<sup>a</sup> Values connected by a solid line are not statistically different at a 0.05-significance level. 90H/10PE = 90 percent hemlock and 10 percent polyester: 90H/10PP = 90 percent hemlock and 10 percent polypropylene: 80H/10PE/10PR = 80 percent hemlock, 10 percent polyester, and 10 percent phenolic resin.

<sup>b</sup> MOR = modulus of rupture; MOE = modulus of elasticity; RH = relative humidity.

<sup>c</sup> Results for formulations 1 and 2 and 1 and 3 are not statistically different from each other; results for formulation 2 and 3 arc statistically different from each other.

stituents may have occurred, thus increasing the deflections observed and decreasing the MOE values. Time-dependent properties are not a consideration during dynamic testing. Even though differences between absolute static and dynamic MOE values existed, they were highly correlated (19,20).

# Physical and dimensional stability properties

Whereas mechanical property values were positively correlated with specimen density, physical and dimensional stability property values were sometimes positively correlated with density, sometimes negatively correlated with density, sometimes correlated with density differently for different formulations, and sometimes not correlated with density (Tables 2 to 5). The variable influence of density on physical and mechanical property values agrees with previous particleboard research (13).

Water absorption: 24-hour soak and 2-hour boil – In either the 24-hour soak or 2-hour boil test procedures, water absorption decreased as specimen density increased. This relationship between water absorption and density was also observed in particleboard studies by Roffael and Rauch (18) and by Vital et al. (22).

Formulation had a consistent influence on water absorption values. Specimens of the 80H/10PE/10PR formulation had the smallest water absorption, and specimens of the 90H/10PE formulation had the largest water absorption. The increased water absorption values for specimens from the 90H/10PE formulation were particularly noticeable after the boil exposure. For all formulations, larger water absorption values were observed after the 2-hour boil exposure than after the 24-hour soaking at ambient temperature.

Thickness swelling: 24-hoursoakand 2-hourboil. – In both the 24-hour soak and 2-hour boil test procedures, thickness swelling increased as specimen density increased. This is in direct contradiction to what we observed for water absorption, but is in agreement with what has been reported in literature for particleboard. Although high-density specimens absorb less water than do low-density specimens, high-density specimens contain more wood material and are more compact. This compaction can be relieved by exposure to very wet conditions, such as soaking or boiling (13). Increased thickness swelling properties as board densities increase was reported by Gatchell and others (9), Halligan and Schniewind (11), and Hse (12).

In our study, formulation had a consistent influence on thickness swelling values. Specimens of the 80H/10PE/10PR formulation had the smallest thickness swelling, and specimens of the 90H/10PE formulation had the largest. Significant differences were present among all formulations at all density levels. Thickness swelling for specimens from the 90H/10PE formulation was particularly evident after the 2-hour boil exposure. Boil exposure consistently resulted in increased thickness swelling values compared with the water-soak exposure at ambient temperature.

Linear expansion - The relationship between density and linear expansion was dependent upon formulation. For the 80H/10PE/10PR formulation. linear expansion values increased with board density. For the 90H/10PE formulation. the opposite trend was observed. For the 90H/10PP formulation, the relationship of linear expansion to board density appears to depend on the range of RH in which length measurements are made. In summary, the relationship between linear expansion and specimen density was not consistent. This is in agreement with a statement made by Kelly (13) regarding particleboard. Apparently, the phenomena that determine linear expansion during changes of RH for different board densities are more complicated than those that determine thickness swell or water absorption. Despite this, specimens of the 90H/10PP formulation had linear expansion values that were less than or equivalent to those of specimens of the other formulations at all board density levels. At densities of 0.7 g/cm<sup>3</sup> or more, specimens of the 80H/10PE/10PR formulation had greater than or equal linear expansion values than did specimens of the other formulations.

*Equilibrium MC.* – Generally, no trends were observed for equilibrium MC values at the 30, 65, and 90 percent RH levels for either the formulation or the density variations.

#### Conclusions

The information presented in this paper provides guidelines that materials scientists and product designers can use to make new products that balance material costs and mechanical and physical property requirements.

The mechanical property values for the 80H/ 10PE/10PR formulation at all four density levels were equal to or greater than corresponding property values of the other two formulations.

For bending and tensile MOR and MOE. no consistent trends were noted when comparing the 90H/10PE and the 90H/10PP formulations. For internal bond strength, the 90H/10PE formulation was significantly less than the 90H/10PP formulation only at densities of 0.7 and 1.0 g/cm<sup>3</sup>. Impact energy values at densities of 0.4, 0.7, and 1.0 g/cm<sup>3</sup> were less than the 90H/10PP formulation when compared to the other two formulations.

All water-soak properties for the 80H/10PE/10PR formulation at all four density levels were less than or equal to similar properties of the other two formulations.

Linear expansion values at 30,65, and 90 percent RH levels for the 80H/10PE/10PR formulation were significantly greater than were the other formulations at densities of 1.0 and 1.2 g/cm<sup>3</sup>. At a density of 0.4 g/cm<sup>3</sup>, the 80H/10PE/10PR and the 90H/10PP formulations were significantly less than was the 90H/10PE formulation. No consistent trends were observed at a density of 0.7 g/cm<sup>3</sup>.

Equilibrium MC values for all three formulations at the 30 and 65 percent RH conditions at all four density levels were equivalent. At the 90 percent RH condition, the 80H/10PE/10PR formulation was different from the other two formulations only at densities of 1.0 and 1.2 g/cm<sup>3</sup>.

From a material cost standpoint, the air-formed nonwoven web technology permits the use of a wide range of lignocellulosic and plastic fibers. The lignocellulosic components can range from wood materials to agricultural fiber products and can be chemically modified to improve the performance of the composite in adverse environments, as appropriate. Products can be made from 100 percent plastic fibers, 100 percent lignocellulosic fibers, or many different combinations of the two materials. Additionally, thermosetting resins can be either coated on the cellulosic fibers or added in powder form during web formation.

ALL MARKED AND AND AND AND AND AND AND AND AND AN	Mechanical property trend					
Property <sup>a</sup>	Panel density - 0.4 g/cm <sup>3</sup>	Panel density - 0.7 g/cm <sup>3</sup>	Panel density = 1.0 g/cm <sup>3</sup>	Panel density - 1.2 g/cm <sup>3</sup>		
Static bending MOR	80H/10PE/10PR >	80H/10PE/10PR >	80H/10PE/10PR >	80H/10PE/10PR >		
	90H/10PP >	90H/10PP >	90H/10PP >	90H/10PP >		
	90H/10PE	90H/10PE	90H/10PE	90H/10PE		
Cantilever bending MOR	80H/10PE/10PR >	80H/10PE/10PR >	80H/10PE/10PR >	80H/10PE/10PR >		
	90H/10PP >	90H/10PP >	90H/10PP >	90H/10PE >		
	90H/10PE	90H/10PE	90H/10PE	90H/10PP <sup>b</sup>		
Static bending MOE	80H/10PE/10PR >	80H/10PE/10PR >	80H/10PE/10PR >	80H/10PE/10PR >		
	90H/10PP >	90H/10PP >	90H/10PP >	90H/10PE >		
	90H/10PE	90H/10PE	90H/10PE	90H/10PP <sup>b</sup>		
Dynamic MOE	90H/10PP >	90H/10PP >	80H/10PE/10PR >	80H/10PE/10PR >		
	80H/10PE/10PR >	80H/10PE/10PR >	90H/10PP >	90H/10PE >		
	90H/10PE <sup>b</sup>	90H/10PE <sup>b</sup>	90H/10PE	90H/10PPb		
Tensile MOR	80H/10PE/10PR >	80H/10PE/10PR >	80H/10PE/10PR >	80H/10PE/10PR >		
	90H/10PP >	90H/10PP >	90H/10PE >	90H/10PE >		
	90H/10PE	90H/10PE	90H/10PP <sup>b</sup>	90H/10PP <sup>b</sup>		
Tensile MOE	80H/10PE/10PR >	80H/10PE/10PR >	80H/10PE/10PR >	80H/10PE/10PR >		
	90H/10PP >	90H/10PP >	90H/10PP >	90H/10PE >		
	90H/10PE	90H/10PE	90H/10PE	90H/10PP <sup>b</sup>		
Internal bond	80H/10PE/10PR >	80H/10PE/10PR >	80H/10PE/10PR >	80H/10PE/10PR >		
	90H/10PP >	90H/10PP >	90H/10PP >	90H/10PP >		
	90H/10PE	90H/10PE	90H/10PE	90H/10PE		
Impact energy	80H/10PE/10PR >	80H/10PE/10PR >	80H/10PE/10PR >	80H/10PE/10PR >		
	90H/10PE >	90H/10PE >	90H/10PE >	90H/10PE >		
	90H/10PP <sup>b</sup>	90H/10PP <sup>b</sup>	90H/10PP <sup>b</sup>	90H/10PP <sup>b</sup>		

TABLE 6. - Mechanical property trends of nonwoven web composite panels.

<sup>a</sup> MOR = modulus of rupture; MOE = modulus of elasticity.

<sup>b</sup> Does not follow general trend.

For example, assume that wood fiber costs \$0.15/lb., polyester fiber costs \$0.80/lb., polypropylene fiber costs \$0.48/lb., and phenolic resin costs \$0.50/lb. The material costs for each formulation used in this paper can be calculated as follows:

90H/10PE formulation = 0.215/lb. 90H/10PP formulation = 0.183/lb. 80H/10PE/10PR formulation = 0.270/lb.

Based upon these material costs for each formulation, the physical and mechanical requirements of the particular product(s) under consideration, and the data presented in Tables 2 through 5, it is possible to arrive at a formulation that will give the desired combination of end-use properties for a given composite in the most cost-effective manner.

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