# Properties of wood fiber and polymer fiber composites

*John A. Youngquist, Project Leader, Andrzej M. Krzysik Visiting Scientist, James H. Muehl, Forest Products Technologist, and Charles Carll, Forest Products Technologist, USDA Forest Service Forest Products Laboratory, Madison, Wsconsin*

**Abstract**

Little data are available on the physical and mechanical properties of nonwoven air-formed wood fiber 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$^3$ and made from three formulations of wood and synthetic fibers (90% hemlock/10% polyester, 90% hemlock/10% polypropylene, and 80% hemlock/10% polyester/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/polyester to hemlock/polypropylene to hemlock/polyester/phenolic resin.Theresults provide baseline information for tailoring product formulations and densities to industrial products.

## Introduction

Promising technology is evolving for using wood fibers or fiber bundles blended with plastics to make an array of high-performance, reinforced composite products. This technology provides a strategy for producing materials that take advantage of the enhanced properties of both wood and plastic. In addition to being lightweight, 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-forming or nonwoven web technology. The fibers are initially held together by mechanical interlocking. The web is then fused or thermoformed into panels or various shapes. To provide additional bonding of the fibers, a thermosetting resin is incorporated in the web.

The increased 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 the following

1. Storage bins for crops or other commodities.
2. Temporary housing structures.
3. Furniture components, including flat and curved surfaces.
4. Automobile and truck components.
5. Paneling for interior wall sections, partitions, and door systems.
6. Floor, wall, and roof systems for light-frame construction.
7. Packages, containers, cartons, and pallets.
8. Filters for air and liquids.

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. The following discussion is not intended as a comprehensive review of the literature. Our intent is to illustrate the effects of some important composition and processing variables on these composite systems. Nonwoven web technology is particularly well known in the consumer products industry. For example, Sciaraffa and others (16) were issued a patent for producing a nonwoven web that has both fused spot bonds and patterned embossments for use as a liner material for disposable diapers. Bither (3) found that polyolefin pulps can serve as effective binders in nonwoven products.

S. Hunter Brooks (4) reviewed the history of technology development for the production and use of moldable wood products and air-laid nonwoven mat processes and products. The first moldable wood product using the wet slurry process was developed in 1946 by Deutche Fibrit in Krefeld, Germany (4). A moldable cellulose composition containing pinewood resin was patented in 1955 by Roberts (4), and a process for producing molded products from this composition was patented in 1956 by Roberts (15). This composition is a mixture of comminuted cellulose material and at least 10 percent of a thermoplastic pinewood resin derived from the solvent refining of crude rosin. Both patents were assigned to the Weyerhaeuser Company.

From 1966 to 1968, a series of five patents were issued

to P.E. Caron and others (5-8,10) and assigned to the Weyerhaeuser Company. These patents cover the use of a wood fiber and thermoplastic resin system in conjunction with a thermosetting resin system.

In the early 1970s, Brooks (4) developed a process that produced a very flexible mat using a thermoplastic Vinyon fiber in combination with a thermosetting resin system. The mat is fed through an oven to melt and set the Vinyon fiber without effecting the setting of the thermosetting resin component. This process was patented in 1984 by R. Doerer and J. Karpik (10) and assigned to the Van Dresser Corporation.

opportunities for combining wood with nonwood materials were reviewed by Youngquist and Rowell (18). This paper included a discussion of the materials and properties of composites consisting of wood-biomass, wood-metals, wood-plastics, wood-glass, and wood-synthetic fibers.

In 1990, Youngquist and others (19) reported on the mechanical and physical properties of wood-plastic fiber composites made with air-formed dry-process technology. This paper reported on the effect of species, the ratios of wood fiber to polypropylene, and the type of plastic fiber or plastic fiber and thermosetting resin blends on pressed panels having a density of 1.0 g/cm$^3$.

Krzysik and Youngquist (12) 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 was 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$^3$. 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$^3$, 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 Scheffé 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., Canada), 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. Polyester fibers, obtained from E.I. DuPont deNemours, Inc. (Wilmington, Dela.), were of two types. When used alone with wood fibers, the polyester matrix fiber was a blend of 25 percent of a 3-denier ($3.3 \times 10^{-7}$ kg/m), 38.1-mm-long crimped polyester fiber with a bonding temperature of 155°C and 75 percent of a 15-denier ($1.7 \times 10^{-6}$ 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 ($6.1 \times 10^{-7}$ kg/m), 38 mm long, crimped, with a bonding temperature greater than 215°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 ($2.4 \times 10^{-7}$kg/m), 37 mm long, crimped, had a density of 0.910 g/mL, and a melting point of 162°C.

### Process

The hemlock fibers were then hammermilled 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 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 fishhook-type 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 in length. The webs were then rolled for handling convenience, Panel-sized mats, 330 by 914 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 maintain the same machine direction orientation and the same weight in each stack. 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 control panel thickness. From a production standpoint, the 10-minute press time is excessively long. However, 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 and were 3.2 mm thick.

### Tests

Each formulation at a given density level was considered a replicated set, consisting of 6 individual panels, for a total of 72 panels for the entire experiment. 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 D 747 using a Tinius Olsen stiffness tester with a loading rate of about 60 angular degrees per minute (1). Internal bond was determined using a Tinius Olsen testing machine with a loading rate of about 1 mm per minute in conformance with ASTM D 1037 (2). A dynamic MOE was determined with wave speed measurements using a Metriguard 239A tester according to published Metriguard procedures (13). Impact energy was measured in conformance with TAPPI standard T803 om-88 using a General Electric impact tester (17). For the dimensional stability 24-hour water soak test at ambient temperature, thickness swell and water absorption properties were measured. Similar measurements were made for the dimensional stability 2-hour water boil test. These tests were performed in conformance with ASTM D 1037 (2) and CAN-0188.0-M78 (9), respectively. Linear expansion was determined in conformance with ASTM D 1037 for specimens conditioned to equilibrium at 30,65, and 90 percent RH using an apparatus constructed at the Forest Products Laboratory (2). MC was determined for specimens conditioned to equilibrium at 30, 65, and 90 percent RH using the procedure outlined in ASTM D 1037 (2).

Table 1. — *Experimental design.*

| Test | Specimen size | Specimens cut from each panel | Total specimens per composite formulation |
|---|---|---|---|
| Static bending MOR and MOE | 51 by 127 | 2 | 48 |
| Cantilever beam bending MOR | 19 by 165 | 2 | 48 |
| Dynamic MOE | 25 by 254 | 2 | 48 |
| Tensile MOE and MOR | 51 by 254 | 2 | 48 |
| Internal bond | 25 by 25 | 2 | 48 |
| Impact energy | 254 by 254 | 1 | 24 |
| Dimensional stability | | | |
| 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 |
| EMC | 76 by 152 | 1 | 24 |

[a] Six panels were used to test each density level in each composite formulation.

## Results and discussion

Results of each test are presented in Tables 2 to 5. Values connected by a solid line are not statistically different at a 0.05 significance level.

### Mechanical properties

As the density of the panel increased, the level of magnitude of the mechanical properties generally increased cor-

Table 2. — *Properties of nonwoven web composite panels, density 0.4 g/cm³.*

| Property | Formulation[a] | | |
|---|---|---|---|
| | 90H/10PE | 90H/10PP | 80H/10PE/10PR |
| Static bending MOR (MPa) | 2.4 | 4.0 | 5.5 |
| Cantilever bending MOR (MPa) | 2.0 | 3.3 | 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) | 12.2 | 5.5 | 16.6 |
| Water soak 24-hour thickness swell (%) | 40.3 | 23.9 | 16.0 |
| Water soak 24-hour water absorption (%) | 304.3 | 229.6 | 219.8 |
| Water boil 2-hour thickness swell (%) | 120.5 | 38.2 | 15.8 |
| Water boil 2-hour water absorption (%) | 534.1 | 269.5 | 219.0 |
| Linear expansion | | | |
| at 30% RH (%) | 0.46 | 0.29 | 0.29 |
| at 65% RH (%) | 0.64 | 0.43 | 0.40 |
| at 90% RH (%) | 0.84 | 0.68 | 0.60 |
| EMC | | | |
| at 30% RH (%) | 3.5 | 3.3 | 3.3 |
| at 65% RH (%) | 7.0 | 6.6 | 6.5 |
| at 90% RH (%) | 15.2 | 14.4 | 15.0 |

[a] Values connected by a solid line are not statistically different at a 0.05-significance level.

respondingly. For this reason, mechanical properties are reviewed by density grouping. For ease of discussion and comparison, the 90H/10PE formulation is used as the basis to which the 90H/10PP and 80H/10PE/10PR formulations are compared.

*Density 0.4g/cm³.* — Products (filters, sound absorbers, landscape mulching) made from low-density composites usually require mechanical properties that are quite different from the properties we expect from high-density composites, which are used in a variety of structural applications. A comparison of all the mechanical property results of panels with 0.4 g/cm³ density clearly shows that, in most cases, the 80H/10PE/10PR and 90H/10PP formulations had greater values than did the 90H/10PE formulation, with the 80H/10PE/10PR formulation generally exhibiting greater values than did the 90H/10PP formulation (Table 2). The one exception to the observed increasing trend in mechanical properties was previously noted.

For the impact energy test, the results of the 90H/10PP formulation were 55 percent less than those of the 90H/10PE basis formulation, whereas results of the 80H/10PE/10PR formulation were 36 percent greater than the 90H/10PP formulation.

For the bending MOR and impact energy tests, all properties were significantly different from each other for the three formulations.

The analyses for the static bending, dynamic, and tensile MOE values showed no statistical difference between the 90H/10PP and 80H/10PE/10PR formulations. However, statistically significant differences were observed when these two formulations were compared to the basis formulation.

The opposite trend occurred for cantilever bending and tensile MOR tests. For both properties, the 90H/10PP and 90H/10PE formulations did not produce a statistically significant difference.

The differences in internal bond values were not statistically significant for all three formulations.

*Density 0.7g/cm³.* — Results from panels with 0.7g/cm³ density are given in Table 3.

For the static bending MOR tests, the 90H/10PP and 80H/10PE/10PR formulations exhibited increases of 28 and 110 percent, respectively, when compared to the basis formulation.

For the cantilever bending MOR and static bending MOE tests, the 90H/10PP and 80H/10PE/10PR formulations did not produce statistically different results from each other. This allowed the use of an average value when making a comparison to the basis formulation. For the cantilever bending MOR test, the average result was 116 percent greater, and for the static bending MOE test, 70 percent greater than the basis formulation.

Table 3. — *Properties of nonwoven web composite panels, density 0.7 g/cm³.*

| Property | Formulation[a] | | |
|---|---|---|---|
| | 90H/10PE | 90H/10PP | 80H/10PE/10PR |
| Static bending MOR (MPa) | 9.7 | 12.4 | 21.0 |
| Cantilever bending MOR (MPa) | 8.0 | 14.2 | 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 water absorption (%) | 159.9 | 104.8 | 97.1 |
| Water boil 2-hour thickness swell (%) | 238.2 | 59.4 | 22.0 |
| Water boil 2-hour water absorption (%) | 445.8 | 150.4 | 104.4 |
| Linear expansion | | | |
| at 30% RH (%) | 0.24 | 0.14 | 0.40 |
| at 65% RH (%) | 0.48 | 0.36 | 0.59 |
| at 90% RH (%) | 0.81 | 0.74 | 0.70 |
| Equilibrium moisture content | | | |
| at 30% RH (%) | 3.4 | 3.4 | 3.3 |
| at 65% RH (%) | 6.9 | 6.8 | 6.8 |
| at 90% RH (%) | 15.6 | 14.7 | 14.8 |

[a] Values connected by a solid line are not statistically different at a 0.05-significance level.

Table 4. — *Properties of nonwoven web composite panels, density 1.0 g/cm³.*

| Property | Formulation[a] | | |
|---|---|---|---|
| | 90H/10PE | 90H/10PP | 80H/10PE/10PR |
| Static bending MOR (MPa) | 23.3 | 25.5 | 49.3 |
| Cantilever bending MOR (MPa) | 21.1 | 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 |
| Water soak 24-hour thickness swell (%) | 60.8 | 40.3 | 21.8 |
| Water soak 24-hour water absorption (%) | 85.0 | 54.7 | 45.1 |
| Water boil 2-hour thickness swell (%) | 260.1 | 77.5 | 28.2 |
| Water boil 2-hour water absorption (%) | 301.6 | 99.5 | 55.7 |
| Linear expansion | | | |
| at 30% RH (%) | 0.13 | 0.00 | 0.55 |
| at 65% RH (%) | 0.38 | 0.25 | 0.76 |
| at 90% RH (%) | 0.81 | 0.78 | 0.93 |
| Equilibrium moisture content | | | |
| at 30% RH (%) | 3.4 | 3.4 | 3.4 |
| at 65% RH (%) | 6.4 | 6.2 | 6.3 |
| at 90% RH (%) | 15.6 | 14.9 | 14.1 |

[a] Values connected by a solid line are not statistically different at a 0.05-significance level.

A similar trend occurred for the dynamic and tensile MOE tests, with lack of statistical differences between the 10H/10PP and 80H/10PE/10PR formulations. The average of these two formulations produced a statistically significant increase of 107 and 46 percent respectively, compared to the basis formulation.

For the tensile MOR test, the 80H/10PE/10PR formulation exhibited an increase of 100 percent compared to the basis formulation. No statistical differences resulted from the values of the two other formulations.

The differences in internal bond values were statistically significant for all three formulations. The 90H/10PP formulation was 140 percent greater and the 80H/10PE/10PR formulation was 520 percent greater than the basis formulation. Note that all values for the internal bond test were relatively low compared to internal bond values found in medium-density hardboard products.

Similar trends were observed for impact energy at 0.7 g/cm$^3$ density as in 0.4g/cm$^3$ density. Compared to the basis formulation, the 90H/10PP formulation decreased in impact energy by 34 percent, and the 80H/10PE/10PR formulation increased by 41 percent.

Table 5. — Properties of nonwoven web composite panels, density 1.2 g/cm$^3$.

| Property | Formulation[a] | | |
|---|---|---|---|
| | 90H/10PE | 90H/10PP | 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[b] |
| Dynamic MOE (GPa) | 7.85 | 7.68 | 8.51 |
| Tensile MOR (MPa) | 20.2 | 17.8 | 42.2 |
| Tensile 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[b] |
| Water soak 24-hour thicknessss swell (%) | 57.1 | 42.7 | 23.6 |
| Water soak 24-hour water absorption (%) | 57.5 | 37.5 | 28.4 |
| Water boil 2-hour thickness swell (%) | 245.0 | 88.3 | 32.4 |
| Water boil 2-hour water absorption (%) | 227.3 | 79.6 | 38.6 |
| Linear expansion | | | |
| at 30% RH (%) | 0.12 | 0.00 | 0.66 |
| at 65% RH (%) | 0.33 | 0.20 | 0.86 |
| at 90% RH (%) | 0.81 | 0.81 | 1.13 |
| Equilibrium moisture content | | | |
| at 30% RH (%) | 3.4 | 3.5 | 3.4 |
| at 65% RH (%) | 6.0 | 5.8 | 5.9 |
| at 90% RH (%) | 15.5 | 15.0 | 13.6 |

[a] Values connected by a solid line are not statistically different at a 0.05-significance level.

[b] Results for formulation 1 and 3 are not statistically different from each other; results for formulation 2 and 3 are statistically significant.

*Density 1.0g/cm$^3$.* — Results from panels with 1.0g/cm$^3$ density are given in Table 4.

For the static bending and cantilever bending MOR tests, the 90H/10PP and 90H/10PE formulations did not produce a statistically significant difference. In these two tests, the 80H/10PE/10PR formulation produced statistically significant increases of 112 and 116 percent, respectively.

For the static bending MOE test, only the 80H/10PE/10PR formulation produced a statistically significant improvement of 27 percent, compared to the basis formulation. The dynamic MOE values showed no statistical difference between the 90H/10PP and 80H/10PE/10PR formulations. However, a small statistically significant increase of 14 percent was noted when the average of these two formulations was compared to the basis formulation. For dynamic MOE, as determined by either method of measurement, improvements were small; however, they were statistically significant.

An interesting pattern occurred when analyzing the tensile MOR and MOE test results. The 90H/10PP and the 90H/10PE formulations did not produce a statistically significant difference. However, for tensile MOR, the 80H/10PE/10PR result was 105 percent greater than the basis formulation. The results for tensile MOE for all three formulations were not statistically different from each other.

The differences in internal bond values were statistically significant for all three formulations. The 90H/10PP formulation was 100 percent greater and the 80H/10PE/10PR formulation was 479 percent greater than the basis formulation. As noted for the panels at 0.7 g/cm$^3$ density, which had very low values, a similar trend was repeated for panels at 1.0 g/cm$^3$ density.

Relative to the basis formulation, impact energy at the 90H/10PP formulation decreased by 19 percent, whereas the 80H/10PE/10PR formulation increased by 28 percent.

*Density 1.2g/cm$^3$.* — Results from panels with 1.2 g/cm$^3$ density are given in Table 5.

Tests results for static bending MOR and cantilever bending MOR show no statistical difference between the 90H/10PP and the 90H/10PE formulations. Significant increases of 109 percent for static bending MOR and 94 percent for cantilever bending MOR were observed for the 80H/10PE/10PR formulation.

Except for a statistically significant improvement of 42 percent for static bending MOE between 80H/10PE/10PR and 90H/10PP formulations, all other values obtained for this property were not significantly different.

For the tensile MOR test, the 80H/10PE/10PR formulation exhibited an increase of 109 percent, compared to the basis formulation, with no differences found for the other two formulations. The tensile MOE values were not statistically significant for all three formulations.

For the internal bond test, the 80H/10PE/10PR formulation was 414 percent greater than the basis formulation.

No statistical differences were found in the values of the two other formulations.

Impact energy values exhibited a statistically significant increase of 34 percent when compared to the 80H/10PE/10PR and 90H/10PP formulations. Impact energy values for the 90H/10PP and the 90H/10PE formulations were not statistically different from each other.

**Physical and dimensional stability properties**

Unlike the increasing trends noted in the mechanical property data, the dimensional stability property levels for each of the three formulations did not exhibit consistent improvements as densities increased. For this reason, the discussion in this section is based upon the trends in results obtained on the various tests conducted. The data discussed in this section are included in Tables 2 to 5 for the 0.4,0.7, 1.0, and 1.2 g/cm$^3$ density levels, respectively.

*24-hour water soak/thickness swell.* — Thickness swell properties for all formulations at 0.4,0.7,1.0, and 1.2 g/cm$^3$ densities had decreasing values from the 90H/10PE, to the 90H/10PP, to the 80H/10PE/10PR formulations, and all formulations at each density level were significantly different from each other. For example, at 0.7 g/cm$^3$ density, the 90H/10PE formulation had the greatest thickness swell, followed by the 90H/10PP, and then by the 80H/10PE/10PR formulation. The same pattern was found for all density levels.

*24-hour water soak/water absorption.* — Water absorption results for 0.4 and 0.7 g/cm$^3$ densities exhibited similar trends for all three formulations. The 90H/10PE formulation had significantly greater water absorption properties compared to the other two formulations, which were not significantly different from each other. Note that for 0.4 and 0.7 g/cm$^3$ densities, this property was not further improved when the formulation was changed from 90H/10PP to 80H/10PE/10PR. At 1.0 and 1.2 g/cm$^3$ densities, all three formulations produced results that were statistically different from each other. For both density levels, the values obtained for 90H/10PE and 90H/10PP formulations were greater than values obtained in the 80H/10PE/10PR formulation. In general, water absorption values decreased for all three formulations as the density increased from 0.4 to 0.7 to 1.0 to 1.2 g/cm$^3$.

*2-hour water boil/thickness swell.* — As in the 24-hour water soak/thickness swell test, a similar trend occurred for the 2-hour water boil/thickness swell test. Thickness swell properties for all formulations at 0.4,0.7,1.0, and 1.2 g/cm$^3$ densities had decreasing values from the 90H/10PE, to the 90H/10PP, to the 80H/10PE/10PR formulations, and all formulations at each density level were significantly different from each other. Because the 2-hour water boil test is very harsh, the thickness swell values are 2 to 4 times greater than the commonly used 24-hour water soak test.

*2-hour water boil/water absorption.* — Water absorption properties for all formulations at 0.4,0.7,1.0, and 1.2 g/cm$^3$ densities had decreasing values from the 90H/10PE, to the 90H/10PP, to the 80H/10PE/10PR formulations, and all formulations at each density level were significantly different from each other.

*Linear expansion.* — A linear expansion test was conducted to measure the dimensional stability of a composite with changes in MC. This test was conducted at 30,65, and 90 percent RH levels at 27°C. The values reported in Tables 3 to 5 are the percentage change in length of these samples when exposed to these various conditions. The results are based on an ovendry, O percent MC condition.

At 30 percent RH, all formulations at the four levels of density exhibited linear expansion values ranging from 0.00 to 0.66 percent. At the 0.4 g/cm$^3$ density level, the 90H/10PP and 80H/10PE/10PR formulations were not statistically different. An interesting pattern occurred when analyzing 0.7 and 1.2 g/cm$^3$ densities. The 90H/10PP and 90H/10PE formulations did not produce a statistically significant difference; however, the 1.0 density produced a statistical difference in all properties. At 1.0 and 1.2 g/cm$^3$ densities, the 80H/10PE/10PR formulation had much greater linear expansion values than did either the 90H/10PP or the 90H/10PE formulations.

At 65 percent RH, all formulations at the four levels of density showed linear expansion values ranging from 0.20 to 0.86 percent. At this RH level, all formulations were significantly different from one another, with one exception. At the 0.4 g/cm$^3$ density level, the 90H/10PP and the 80H/10PE/10PR formulations were not statistically different from each other. At 1.0 and 1.2 g/cm$^3$ densities, the 80H/10PE/10PR formulation had much greater linear expansion values than did either the 90H/10PP or the 90H/10PE formulations.

At 90 percent RH, linear expansion values ranged from 0.60 percent to 1.13 percent. At a density of 0.4 g/cm$^3$, the 90H/10PE formulation was statistically different from the two other formulations, which did not produce a statistically significant difference from each other. At the 0.7 g/cm$^3$ density level, the values were not statistically different for all three formulations. Note that at 1.0 and 1.2 g/cm$^3$ densities, the 80H/10PE/10PR formulation produced statistically different results. These values were greater than those for the other two formulations and were not significantly different from each other.

*Equilibrium moisture content (EMC).* — EMC is the MC at which a material neither gains nor loses moisture when surrounded by air at a given relative humidity and temperature. This test was run at 30,65, and 90 percent RH levels at 27°C. Tables 3 to 5 give the MC values of these samples when exposed to these conditions. These values are based on an ovendry, O percent MC condition.

At 30 percent RH, all formulations at the four densities exhibited MC values ranging from 3.3 to 3.5 percent, and

no significant differences were noted for all three formulations.

At the 65 percent RH, all formulations at the four densities had MC values ranging from 5.8 to 7.0 percent, and no significant differences were noted for all three formulations.

At 90 percent RH, MC values ranged from 13.6 to 15.6 percent. At 0.4 and 0.7 g/cm$^3$ densities, no statistical differences were observed for all three formulations. At 1.0 and 1.2 g/cm$^3$ densities, the 80H/10PE/10PR formulation produced statistically different results, compared to the two other formulations, which were not different from each other.

Generally, no definite trends were observed for EMC values at the 30, 65, and 90 percent RH levels for either the formulation or the density variations.

## Concluding remarks

Three distinct composite formulations were extensively tested. As panel density levels increased, the 90H/10PE and 80H/10PE/10PR formulations maintained a discontinuous polyester fiber matrix throughout the composite because these synthetic fibers melt at temperatures greater than those used to bond the panels. In contrast to this, the polypropylene component of the 90H/10PP composite does not maintain a fibrous matrix because it softens at the bonding temperatures used and flows as press pressures are increased, The data presented show that these different composite formulations can be either an advantage or a disadvantage, depending upon the properties needed to produce a competitive product. 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 properties for the 80H/10PE/10PR formulation at all four density levels were equal to or greater than corresponding properties 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 0.7 and 1.0 g/cm$^3$ densities. Impact energy values at 0.4, 0.7 and 1.0 g/cm$^3$ densities were less than the 90H/10PP formulation when compared to the other two formulations.

AU 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.

In contrast to the mechanical property data, linear expansion values at 30, 65 and 90 percent RH levels for the 80H/10PE/10PR formulation were significantly greater than the other formulations at 1.0 and 1.2 g/cm$^3$ densities. At 0.4 g/cm$^3$ density, the 80H/10PE/10PR and the 90H/10PP formulations were significantly less than the 90H/10PE formulation. No consistent trends were observed at 0.7 g/cm$^3$ density,

EMC values for all three formulations at the 30 percent RH condition at all four density levels were equal to each other. The same pattern occurred at the 65 percent RH condition. At the 90 percent RH condition, the 80H/10PE/10PR formulation was different from the other two formulations only at 1.0 and 1.2 g/cm$^3$ densities.

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.

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 3 to 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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## Literature cited

1. American Society for Testing and Materials. 1986. Standard test method for apparent bending modulus of plastics by means of cantilever beam. ASTM D 747-84a. ASTM, Philadelphia, Pa.
2. _____. 1987. Standard methods of evaluating the properties of wood-base fiber and particle panel materials. ASTM D 1037-87. ASTM, Philadelphia, Pa.

3. Bither, P. 1980. Polyolefin pulps as nonwoven binders. *In:* Proc. Air-laid and Advanced Forming Conf. Publication available from Marketing/Technology Serv., 3125 West Main St., Kalamazoo, MI 49007.
4. Brooks, S.H. 1990. Air lay non woven moldable mat process and products produced by using this mat process. *In:* Proc. 1990 TAPPI nonwovens conference. pp. 87-108.
5. Caron, P.E. and G.D. Allen. 1968. Reinforced moldable wood fiber mat and method of making the same. U.S. Pat. 3,367,820. U.S. Pat. Off., Washington, D.C.
6. _____ and G.A. Grove. 1966. Method of die-baking moldable wood fiber parts. U.S. Pat. 3,265,791. U.S. Pat. Off., Washington, D.C.
7. _____ and _____. 1966. Process for manufacturing moldable fibrous panels. U.S. Pat. 3,230,287. U.S. Pat. Off., Washington, D.C.
8. _____ and _____. 1966. Production of hot-pressed three dimensional fiber articles. U.S. Pat. 3,261,898. U.S. Pat. Off., Washington, D.C.
9. Canadian Standards Association. 1978. Standard test methods for mat-formed wood particleboards and waferboard. CAN-0188.0-M78. CSA, Ont., Canada.
10. Doerer, R.P. and J.T. Karpik. 1984. Moldable fibrous mat and product molded therefrom. U.S. Pat. 4,474,846. U.S. Pat. Off., Washington, D.C.
11. Grove, G.A. and P.E. Caron. 1966. Method of making a moldable wood fiber mat with metal insert. U.S. Pat. 3,279,048. U.S. Pat. Off., Washington, D.C.
12. Krzysik, A.M. and J.A. Youngquist. [In press]. Bonding of air-formed wood-polypropylene fiber composites. Inter. J. of Adhesion and Adhesives. Butterworth-Heinemann, Ltd., Guildford, Surrey, U.K.
13. Metriguard. 1986. Metriguard Model 239A. Stress wave timer manual. Care and instruction. Theory and data reduction. Metriguard, Inc., Pullman, Wash.
14. Roberts, J.R. 1955. Moldable cellulose composition containing pinewood resin and molded product therefrom. U.S. Pat. 2,714,072. U.S. Pat. Off., Washington, D.C.
15. _____. 1956. Process of forming molded cellulose products. U.S. Pat. 2,759,837. U.S. Pat. Off., Washington, D.C.
16. Sciaraffa, M.A., D.G. Thome, and C.M. Bogt. 1982. Soft, bulky, lightweight nonwoven web and method of producing: the web has both fused spot bonds and patterned embossments. U.S. Pat. 4,333,979. U.S. Pat. Off., Washington, D.C.
17. TAPPI. 1989. TAPPI test methods. Puncture test of containerboard. TAPPI T803 om-88, Vol. 2. TAPPI, Atlanta, Ga.
18. Youngquist, J.A. and R.M. Rowell. 1989. Opportunities for combining wood with nonwood materials. *In:* Proc. 23rd Washington State Univ. Inter. Particleboard/Composite Materials Symp., T. Maloney, ed. Washington State Univ., Pullman, Wash. pp. 141-157.
19. _____, J. Muehl, A. Krzysik, and T. Xin. 1990. Mechanical and physical properties of wood/plastic fiber composites made with air-formed dry-process technology. *In:* Proc. 1990 Joint Inter. Conf. on Processing and Utilization of Low-Grade Hardwoods and Inter. Trade of Forest-Related Prod., S.Y. Wang and R.E. Tang, eds. pp. 159-162.

*In:* Wood-fiber/polymer composites: Fundamental concepts, processes, and material options: Proceedings of 1st wood fiber-plastic composite conference; Madison, WI and 45th annual meeting of the Forest Products Society; New Orleans, LA. Madison, WI: Forest Products Society; 1993: 79-86.

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