Comparative properties of sugarcane rind and wood strands for structural composite manufacturing

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Abstract

Anatomical, thermal, tensile strength, and moisture sorption properties of sugarcane rind (i.e., comrind) and wood strands from southern pine, yellow-poplar, red oak, and willow were investigated. Scanning electron microscopy observation showed that the comrind stem consists of an outer waxy layer, rind fibers, and an inner pith. Rind fiber cell walls are thicker than those of southern pine, which is especially true for the outer surface region. Compared to southern pine, rind has a less uniform cell structure. There are distinct regions where fibers with thick cell walls are surrounded with thin cell wall fibers. Differential scanning calorimetry (DSC) analysis revealed that the rind fibers and inner pith had the same DSC patterns. The outer waxy layer of rind showed inferior thermal stability. Rind nodes showed slightly less thermal stability than the stalk. Rind and wood had different DSC patterns in the temperature range from 150° to 200°C. Thermogravimetric analysis results showed that comrind was less thermally stable than southern pine wood. At a given level of relative humidity, comrind reached a slightly higher equilibrium moisture content (EMC) compared to wood strands for both adsorption and desorption. A sorption hysteresis was observed for all materials tested. Nelson’s sorption isotherm accurately reproduced the experimental data of these different materials. Comrind had the largest tensile strength among the various materials tested. Similar to wood, tensile strength of rind decreased with an increase of its moisture content except at a low EMC of 3.7 percent.

Sugarcane is an important agricultural crop in the southern United States with an annual yield of 15 million tons in Louisiana alone, accounting for more than 40 percent of the total U.S. production (Rowell 1995). Large quantities of outer layer rind (known as comrind) are produced after the inner pith that contains most of the sucrose is separated from sugarcane. Comrind with a high content of lignocellulosic fibers is a potential raw material for structural composite manufacturing (Atchison and Lengel 1985). Currently wood-based strand composites are widely used as sheathing, flooring, and I-joist material in construction. With the recent growth in manufacture and consumption of composites and the increasing wood cost, the development of new materials as a substitution for wood fibers is becoming increasingly important (Rowell 1998). The use of comrind can help reduce wood consumption, lower manufacturing costs, and improve panel performance.

Comrind contains lower amounts of lignin and a greater amount of hemi-cellulose compared to wood. The cellulose content of comrind is comparable to wood (Rowell 1996, Hurter 1997). Comrind has typical anatomical features. Rind stem with a thickness of 1.0 to 2.0 mm is divided into segments (10 to 25 cm in length) divided by nodes. On the cross section, the rind stem consists of an outer slippery waxy layer, rind fibers, and inner pith. Similar to other agricultural residues (Han et al. 1999), the...
waxy layer on the outer surface of comrind can have a significant impact on bondability when it is bonded with phenol- and urea-formaldehyde resins.

Temperature at the levels used for processing fiber-based composites significantly influences the physical, mechanical, and chemical properties of the material. Research has been conducted on the thermal properties of the material including wood and other agriculture fibers. Differential scanning calorimetry (DSC) and thermogravimetric analysis (TGA) are two common techniques for such analysis, and they have been widely used to characterize the thermal and chemical properties of lignocellulosic materials. By measuring the heat absorbed or evolved by a sample as it is heated or cooled under a controlled temperature and atmosphere, DSC and TGA are able to record changes in specific heat capacity and residual weight of tested samples. Early studies investigated the thermal properties of several wood species: spruce, balsam fir, Douglas-fir, hemlock, red cedar, maple, red alder, and white birch (Arseneau 1961, Sandermann and Augustin 1963, Chow and Pickles 1971). Recently, studies have been done on the conversion of bagasse into a thermoformable material through esterification of the fiber matrix (Hassan et al. 2000). In their study, DSC and TGA were used to characterize the chemical and thermal properties of the esterified fibers. The results showed that esterified-bagasse fibers were less thermally stable than the untreated bagasse fibers.

Among various properties, moisture sorption is a major concern for structural composite materials (Lee and Wu 2002). The relationships between equilibrium moisture content (EMC), relative humidity (RH), and temperature, known as sorption isotherms, are important properties that affect the strength and dimensional stability of composite products during service. Many studies have been done to establish sorption isotherm for wood-based materials (Wu and Suchsland 1996, Wu 1999). Nelson (1983) developed a model based on Gibbs free energy to describe the sorption behavior of cellulose materials. Wu (1999) applied this model to several types of composites and showed that it can be used to describe the sorption data from different composite materials. So far, little data has been reported on comrind’s sorption isotherm and the application of the model to the comrind material.

The mechanical properties of a raw material determine the ultimate strength of a composite product (Rowell and Banks 1987, Lee and Wu 2003). Several studies have established modulus and strength properties of wood strands. Among these studies, Price (1975) investigated the tensile properties of sweetgum in association with the effect of hot pressing. The results showed that tensile properties of pressed sweetgum strands increased at the face layer and reduced at the core layer due to vertical pressure variation. An extensive study was conducted at the USDA Forest Products Laboratory (Geimer et al. 1985). In their study, two levels of pressing temperature were used, and the higher temperature showed a greater effect on the strand properties of Douglas-fir.

Strand properties have been used to predict strength properties of structural wood composite materials (Barnes 2000, 2001; Lee and Wu 2003). However, very little information exists on actual strength properties of comrind. The objectives of the study were to develop comparative anatomical, thermal, moisture sorption, and strength properties of comrind and wood strands for structural composite manufacturing.

Materials and methods

Raw material selection

Sugarcane rind was prepared through the Tilby cane separation process (Atchison and Lengel 1985). During the process, the cane stalk was separated into rind, pith, sugar juice, and epidermis (wax) fractions. The rind was about 45 cm in length and had been air-dried. The bundles of rind were band-sawn into pieces 11 cm in length. For comparison purposes, wood strands of willow, red oak, southern pine, and yellow-poplar cut by an 882-mm disc flaker were also prepared for this study.

Scanning electron microscopy analysis

Samples of comrind were prepared both from the stalk (i.e., internodal section) and the node. The surface for observation was finished by a microtome. Wood samples of willow and southern pine strands were prepared in the same way. All samples were dried at 80°C for one day before undergoing scanning electron microscopy (SEM). The cross and tangential surfaces of the rind and wood were observed with an Edward S150 scanning electron microscope.

Thermal analysis

Comrind and wood samples of southern pine, willow, and oak were ground to pass through a 20-mesh screen and oven-dried at 80°C for 24 hours. For comrind, powder was made from the outer wax layer, middle tissue, pithy interior, and nodes. Thermal analysis was carried out using a TA Q-100 differential scanning calorimeter. The DSC was run on a 5-mg sample uniformly packed in an aluminum pan under a nitrogen atmosphere at a heating rate of 10°C/minute over a temperature range of 50°C to 400°C. TGA was carried out using an SDT-2960 DSC/TGA analyzer. An approximately 5-mg sample was used, and the test was carried out under a nitrogen atmosphere at a heating rate of 20°C/minute over a temperature range of 50°C to 500°C.

Tensile strength testing

Comrind strands without cracks were selected for the tensile strength test. They were hand-cut into samples varying in width from 6 to 12 mm. The samples were notched in the center part to ensure the breakage in the middle section of the samples. Wood samples of southern pine, yellow-poplar, and willow were also prepared in the same way. For comrind, tensile strength was examined after the test samples were conditioned to reach equilibrium at 20 percent, 60 percent, 87 percent, and 98 percent RH, and at water-soaking condition. All samples were tested according to the ASTM D 1037 (ASTM 1999) using an INSTRON machine at a loading speed of 4 mm/minute. Fifty specimens for each material type and RH condition were tested, and the results were averaged.

Sorption measurements

Samples for sorption test were prepared from comrind, southern pine, yellow-poplar, willow, and red oak by cutting samples into 50- to 70-mm lengths. Comrinds with the wax layer on the rind’s outer surface and those with the wax mechanically removed were used. Four specimens from each of the material types were randomly selected and numbered. They were combined to form one group, and a total of 10 groups were prepared. Five groups of samples were randomly selected and oven-dried at 70°C for two days to reach the dry state for the adsorption test. The remaining
five groups were conditioned over distilled water to reach the fiber saturation state for the desorption test. All groups of samples were conditioned to reach equilibrium at a RH of 32.5 percent, 66 percent, 76 percent, 81 percent, and 93 percent, respectively, over different saturated salt solutions in desiccators. The initial weight of all specimens was measured. After conditioning, the specimens were weighed before and after being oven-dried at 103°C for 24 hours. EMC of each specimen was calculated based on the oven-dry weight.

Experimental data of EMC at various RHs were fit to the sorption isotherm model proposed by Nelson (1983). The sorption isotherm is of the form:

\[
EMC = M_v \left( 10 - \frac{1}{A} \ln \left( -\frac{RT}{W_w} \ln(RH) \right) \right)
\]

where:
- \(\text{EXP} = \text{exponential function}\)
- \(W_w = \text{molecular weight of water (18.1/mole)}\)
- \(R = \text{universal gas constant (1.9858 cal/mole°K)}\)
- \(T = \text{absolute temperature (°K)}\)
- \(A = \text{natural logarithm of the Gibbs free energy per gram of sorbed water as RH approaches zero (\(\Delta G_r\) cal/g), i.e., } A = \ln(\Delta G_r)\)
- \(M_v = \text{material constant which approximates the fiber saturation point for desorption (°C)}\)

For a given temperature, the term \((-RT/W_w)\) becomes a constant and parameters \(A\) and \(M_v\) define the sorption isotherm. To determine the values of \(A\) and \(M_v\), a linear regression analysis was performed using Equation [1] with the measured EMC as the dependent variable and transformed RH, i.e. \(\ln((-RT/W_w) \ln(RH))\) as the independent variable (Wu 1999).

**Results and discussion**

**Basic anatomical feature**

Figure 1 shows SEM pictures of comrind and southern pine. It is observed from the transverse section that comrind stem consists of an outer layer, rind fibers, and an inner pith (Fig. 1a). The stem’s outermost layer is composed of epidermal cells that contain a waxy layer called cutin. This outer waxy layer is hydrophobic and gives the rind stem its glossy appearance. The wax makes the outside of the stalk’s tube smooth and slippery. It has been reported that this hydrophobic, slippery surface has significant implications for the bondability between particle elements and urea-based resin adhesives (Han et al. 1999). The innermost layer of the comrind is wrapped with pith cell, which was partly left after the inner pith that contains most of the sucrose was separated from the sugarcane. Similar to wood, the rind fibers contain parenchyma cells and vascular bundles. However, rind fiber cell walls are thicker than those of wood, which is especially true for the outer surface region. In addition, the comrind stem does not possess radial cell elements like wood (Fengel and Wegener 1984, Rowell 1996). Compared to southern pine (Fig. 1c), rind has a less uniform cell structure. There are distinct regions where fibers with thick cell wall are surrounded with thin cell wall fibers (Fig. 1b). The anatomical features of comrind affect its physical and mechanical properties, and the interaction with adhesives due to the waxy layer.

**Thermal properties**

DSC and TGA were used to analyze thermal properties of comrind and wood samples in the temperature range of 50° to 400°C and 50° to 500°C, respectively. Figure 2a shows DSC diagrams of comrind and southern pine. The comrind middle- and inner-layer samples had the same DSC patterns with different peak areas. The outer layer samples showed inferior thermal stability due to its higher wax content. Comrind node showed slightly less thermal stability than the stalk. This may be attributed to the higher lignin content in the node (Atchison and Lengel 1985). Generally, comrind has the same DSC patterns as wood except for peaks in the temperature range of 170° to 190°C (Shafizadeh et al. 1976, Back and Salmen 1982). This indicated that comrind and wood have the same major chemical compositions. The peaks at 170° to 190°C show glass transition temperatures of different comrind samples (Back and Salmen 1982). The peaks at 210° to 225°C could be related to the decomposision of glucose, sucrose, and other low molecular components in comrind (Shafizadeh et al. 1976). Those peak temperatures are lower than the peak at 240°C for wood.

This is due to the higher content of low molecular hemicellulosic components in comrind (Hurter 1997). All comrind samples recorded peaks at 330°C, which are lower than the peak temperature of 360°C for wood. This may be because of the higher content of short-chain compositions and lower degree of crystallization in comrind cellulose. Hassan (2000) reported that the DSC of bagasse fiber showed an endothermic peak at 360°C, which is close to the peak temperature of 330°C for comrind in this study. The peaks at 330°C are attributed to the cleavage of cellulose sugar units (Shafizadeh et al. 1976). In Figure 2b and Table 1, TGA results showed that temperatures for the initial weight loss and extrapolation onsets of all comrind samples were lower than those of south-

\[\text{Figure 1. — SEM images of (a and b) sugarcane rind and (c) southern pine strands.}\]
ern pine. The similar results with DSC indicated that comrind was less thermally stable than the wood samples from southern pine. Comrind middle layer (rind fibers) showed slightly higher thermal stability compared to other layer rind samples.

**Sorption isotherm**

Figure 3 shows the sorption properties of comrind and wood strands. At a given RH level, comrind reached a slightly higher EMC compared to wood strands for both adsorption and desorption. This may be due to the higher hemicellulose content in comrind and the loose inner pith layer, which makes a higher rate of moisture transmission through comrind’s inner surface (Hurter 1997). A sorption hysteresis was observed for all materials tested. The comrind with wax showed a smaller sorption hysteresis than the comrind without wax and other wood samples. EMC data as a function of RH were fitted to Nelson’s sorption model for cellulosic materials (Nelson 1983). Figure 4 shows typical graphs comparing measured and predicted EMCs for comrind and wood strands. It was found that Nelson’s sorption isotherm accurately reproduced the experimental data of these different materials. The results of the regression analysis on sorption isotherms for various materials are shown in Table 2. The parameters A and Mv are different for various materials. The magnitude of Mv was higher in desorption than in adsorption for all materials tested at a given RH level.
These parameters can be used in Equation [1] to predict the EMC of comrind and wood strands at a given RH level.

**Tensile strength**

Test data on sample density, moisture content (MC), and tensile strength of comrind and wood strands are summarized in Table 3, and the strength data are plotted in Figure 5a. It was found that comrind strands with the waxy layer had the largest tensile strength among the various materials tested. The tensile strength value of natural comrind (114 MPa) was more than two times higher than that of willow strands (31.5 MPa). Comrind with the waxy layer had a higher value of tensile strength than the rind with the waxy layer removed, possibly due to micro-cracks introduced during cane processing through the Tibly process. The significantly higher tensile strength of comrind is attributed to its typical anatomical features where rind fiber cell walls are thicker than those of wood especially in the outer surface region. The high tensile strength of comrind can be used to help improve bending properties of structural wood composites. Figure 5b shows the tensile strength of comrind as a function of MC. Similar to wood, the tensile strength of comrind attained a maximum value at 6.9 percent MC (about 5% for wood), and declined at low MC levels. It is believed that a decline in strength at a MC below 5 percent may be due to micro-failures in the cell which occur during drying (Bodig and Jayne 1993).

**Conclusions**

SEM observations showed that comrind stem consists of an outer wax layer, rind fibers, and an inner pith. The stem’s outermost layer is composed of epidermal cells that contain a waxy layer. The innermost layer of comrind is wrapped with pith cells. Similar to wood, the rind contains parenchyma cells and vascular bundles. Rind fiber cell walls are thicker than those of wood, which is especially true for the outer surface region. Compared to southern pine, rind has a

![Figure 4](image1.png)  
**Figure 4.** Typical graphs comparing measured and predicted EMC data for (a) sugarcane rind and (b) wood.

![Figure 5](image2.png)  
**Figure 5.** Comparison of (a) tensile strength of sugarcane rind and different types of wood strands, and (b) the effect of MC on strength properties of sugarcane rind with wax layer. The vertical lines through the bars represent the SD from the mean value. RDW – Rind with wax layer, RDNW-Rind no wax layer, SP-Southern pine, YP-Yellow poplar, and WL-Willow.

<table>
<thead>
<tr>
<th>Material Type</th>
<th>Density (g/cm³)</th>
<th>Moisture Content (%)</th>
<th>Sample Thickness (mm)</th>
<th>Tensile Strength (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Comrind-A</td>
<td>0.47</td>
<td>7.38</td>
<td>1.092 (0.127)</td>
<td>114.10 (31.33)</td>
</tr>
<tr>
<td>Comrind-B</td>
<td>0.47</td>
<td>7.38</td>
<td>0.940 (0.000)</td>
<td>77.77 (25.27)</td>
</tr>
<tr>
<td>Southern pine</td>
<td>0.51</td>
<td>10.34</td>
<td>1.905 (0.203)</td>
<td>58.05 (12.83)</td>
</tr>
<tr>
<td>Yellow-poplar</td>
<td>0.42</td>
<td>8.71</td>
<td>0.864 (0.000)</td>
<td>59.47 (13.26)</td>
</tr>
<tr>
<td>Willow</td>
<td>0.39</td>
<td>10.31</td>
<td>0.787 (0.076)</td>
<td>31.50 (7.54)</td>
</tr>
</tbody>
</table>

a The results are given as averages and standard deviations (in parentheses) from the mean values of 50 randomly chosen strand samples.
b Comrind-A: comrind with wax layer.
c Comrind-B: comrind with wax layer removed.
less uniform cell structure. These anatomical features of comrind can affect its physical and mechanical properties and influence the adhesive bonding process (due to the presence of the surface waxy layer).

DSC analysis revealed that the middle and inner layers had the same DSC patterns. The outer layer sample showed inferior thermal stability due to its higher wax content. Comrind node showed slightly less thermal stability than the stalk. Generally, comrind had the same DSC patterns as wood except for peaks in the temperature range of 170°C to 190°C. This indicated that comrind and wood have the same primary chemical compositions. TGA results showed that comrind was less thermally stable than southern pine.

At a given RH level, comrind reached a slightly higher EMC value compared to wood strands for both adsorption and desorption. A sorption hysteresis was observed for all materials tested. Nelson’s sorption isotherm accurately reproduced the experimental data of these different materials. Comrind had the largest tensile strength among the various materials tested. Similar to wood, the tensile strength of comrind attained a maximum value at 6.9 percent MC (about 5% for wood), and declined at low MC levels. The high tensile strength of comrind can be used to improve bonding properties of structural wood composites. Well-process comrind with comparable properties of wood strands has the potential to be successfully used as a substitute material in manufacturing structural composites. Future articles will discuss pure and mixed rind/wood strandboard bonded with phenol-formaldehyde resin.

**Literature cited**


