Properties of thermoplastic composites with cotton and guayule biomass residues as fiber fillers

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ABSTRACT

This study was conducted to evaluate the suitability of using residual plant fibers from agricultural waste streams as reinforcement in thermoplastic composites. Three groups of plant fibers evaluated included cotton burrs, sticks and linters from cotton gin waste (CGW), guayule whole plant, and guayule bagasse. The plant fibers were characterized for physical (bulk density and particle size distribution) and chemical properties (ash, lignin and cellulose contents). A laboratory experiment was designed with five fiber filler treatments, namely control (oak wood fiber as the filler - OWF), cotton burr and sticks (CBS), CBS with 2% (by weight) second cut linters (CBL), CBS with 30% (by weight) guayule whole plant (CGP), and CBS with 30% (by weight) guayule bagasse (CGB). The composite samples were manufactured with 50% of fiber filler, 40% of virgin high-density polyethylene (HDPE), and 10% other additives by weight. The samples were extruded to approximately 32 x 7 mm cross-sectional profiles, and tested for physico-mechanical properties. The CBS and CBL had considerably lower bulk density than the other fibers. Cotton linters had the highest cellulose (56.6%) and lowest hemicellulose (15.8%) and lignin (10.5%) of all fibers tested. Guayule whole plant had the lowest cellulose and highest ash content. Both CBS and guayule bagasse contained cellulose comparable to OWF, but slightly lower hemicellulose. Evaluation of composite samples made from the five fiber treatments indicated that fibers from cotton gin byproducts and guayule byproducts reduced the specific gravity of the composites significantly. However, the CBS and CBL samples exhibited high water absorption and thickness swelling, but the addition of guayule bagasse reduced both properties to similar levels as the wood fiber. The CGP exhibited significantly lower coefficient of thermal expansion. Composite samples with the five different fiber fillers showed similar hardness and nail holding capacity, yet oak fibers imparted superior strength and modulus under flexure and compression with the exception of the compressive modulus of CGB composites. In general, both cotton ginning and guayule processing byproducts hold great potential as fiber fillers in thermoplastic composites.

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1. Introduction

The vast agricultural industry produces many waste streams that are rich in ligno-cellulosic fibers. The ligno-cellulosic agricultural residues include cotton gin waste (CGW), fruit pulp, bagasse from various bioprocessing industries, plant stems and leaves, etc., to name a few. Alternative uses of such waste streams into value-added products can ensure significant environmental and economic benefits. One such value added application is as a fiber filler in reinforced thermoplastic composites (RTC). Wood fibers have been successfully utilized commercially as fiber fillers in wood plastic composites (WPC), a type of natural fiber reinforced thermoplastic composites (NFRTC). The steadily increasing price of wood fiber, stagnation of building industry in the US, and competition from bioenergy industry have caused business stagnation and declining profit margins in many WPC businesses. Therefore, use of relatively inexpensive and alternative sources of fiber filler is important for the long-term sustainability of the industry. Also, removal of the waste stream from the environment and embedding them into a recyclable product such as NFRTC can reduce
the environmental burden by reducing the waste going to landfills. Furthermore, they will potentially reduce the carbon footprint of agricultural operations by locking the plant material carbon in the matrix for a long time, and hence promote the sustainability of agriculture.

The NFRTCs are composites made of a thermoplastic substrate reinforced with a fiber filler. It may also include small amounts of mineral fibers, lacquers, coupling agents, and color. The WPC is an example of NFRTC that are commonly available in the market and used for non-structural building applications such as decking, fences, window and door jambs, landscaping products and automobile components. The WPC commonly use polyolefins as the resin substrate and wood fiber as the reinforcement. It is manufactured as a durable alternative for natural wood products because it combines the strength of wood fibers with the durability of plastic. The WPC are considered superior to wood in its weathering properties, and to plastic in its strength properties (Bajwa et al., 2009a). Therefore, they are commonly used for non-structural building applications where the product is exposed to weather extremes and moisture.

Although several of the commercial WPC products use recycled plant fibers from used pallets, furniture waste, rice hull, sawmill waste, pine scrap and other recycled products (Winandy et al., 2004). Agriculture waste is an untapped renewable resource that can provide an inexpensive alternative for ligno-cellulosic fiber fillers in NFRTC. For example, the CGW is plentiful in the cotton belt of the USA. This region generates approximately 2–3 million metric tons of CGW each year (Holt et al., 2000; Thomassen et al., 1998), most of which go to landfill. Fresh CGW as well as the cotton burr and stem (CBS) fraction of the CGW have shown great potential as ligno-cellulosic fiber fillers in NFRTC when used with a high density polyethylene (HDPE) substrate (Bajwa et al., 2009b). The CGW contains 50–70% CBS and 11% lint or linters, with the remaining comprised of leaves, seeds, soil particles and other plant materials (Schacht and Lepori, 1978; Baker et al., 1994).

Guayule bagasse is another waste stream from guayule processing that after the extraction of a hop pre-polymer. A resin contained in the guayule plant has both insect and fungal resistance, and has shown to be an effective wood preservative (Nakayama et al., 2001). The bagasse obtained after extracting the latex using the water-based extraction process still contains this resin with its desirable insect-repellant properties. Therefore, both the ground whole plant material and the bagasse could impart desirable insect and microbial resistance properties to NFRTC when used as a partial substitute for fiber filler (Chow et al., 2008). Both guayule plant and bagasse after latex extraction contain significant amounts of holocellulose, which is a desirable component in fiber fillers. Chow et al. (2008) reported that guayule wood contained 1.9–2.5% ash, 78.6–82.2% holocellulose, 44.8–46.9% α-cellulose, and 20–23% lignin, whereas the bark contained 5.8–6.3% ash, 60–70% holocellulose, 32–48% α-cellulose and 35–42% lignin. The bagasse contained 9.8% ash, 62.6% holocellulose, 41.3% α-cellulose and 25% lignin. Banigan et al. (1982) reported that various parts of guayule such as leaf, wood and seed contain 10.7–24.3% crude fiber, 4–17.2% lignin, and 4.1–19.9% ash. These differences could have been caused by the differences between cultivars and growing environment as well as the methods used for testing and reporting the fractions as a percentage of dry plant weight versus the immediate source material used for analysis (example, holocellulose and lignin as percentages of extractive free plant material, and α-cellulose as a percentage of holocellulose). The fibers of guayule stem has a specific gravity (SG) of 0.69–0.72 and fiber length of 0.39–0.48 mm. The high cellulose content along with low SG and fiber length comparable to that of wood are preferable properties for fiber fillers. Nakayama et al. (2001) demonstrated that composite boards made with 70% guayule fiber and 30% HDPE had good antitermite properties. Holt et al. (2009) also demonstrated the potential of cotton gin byproducts and guayule in bio-based composition boards.

This study was undertaken with the goal of testing the ligno-cellulosic fibers from CGW and guayule processing byproducts as alternative sources of fiber fillers in NFRTC. The specific objectives were to:

1. Characterize the physical properties and chemical composition of fibers from CBS, cotton linters, guayule whole plant and guayule bagasse to understand their suitability for application as fiber fillers in thermoplastic composites.
2. Evaluate thermoplastic composites made with blends of cotton ginning byproducts and guayule products as fiber fillers.

2. Materials and methods

2.1. Fiber filler characterization

Natural fibers explored in this study included white oak fiber, CBS and linters, guayule whole plant and guayule bagasse. The oak wood fiber (OWF) came from hardwood flooring mill waste, and the CBS and linters came from the USDA-ARS Cotton Ginning Laboratory at Lubbock, Texas and a nearby cottonseed oil mill, respectively. Both guayule whole plant and bagasse came from the USDA Arid land Agriculture Research Center at Maricopa, Arizona. The Guayule bagasse was extracted by first homogenizing the plant and then removing the latex in an aqueous solution. Therefore, the bagasse was already in a crushed form, and no further milling was required. All the other fibers were ground in a hammer mill to have a particle size distribution in the 20–60 mesh size. Because fiber size is an important factor affecting the bulk properties of composites (Stark and Berger, 1997), physical characteristics such as particle size distribution and bulk density of the milled fibers were quantified.

Both chemical and physical characteristics of the fiber filler play an important role in the final properties of the NFRTC. The chemical properties that are important for application in NFRTC include the amount of ash, lignin, α-cellulose and holocellulose. The α-cellulose is crystalline in nature and provides strength, and resistance to water absorption. Therefore, low amounts of ash, hemi-cellulose and lignin are preferred in fiber fillers. Because many reports were available for the chemical characteristics of white oak, which was used in this study, only CBS, linters, guayule whole plant and guayule bagasse were characterized for ash content, alcohol benzene extracts, lignin, holocellulose and α-cellulose.

2.2. Design of experiment

A laboratory experiment was formulated as a randomized complete block design to evaluate five combinations of fibers recovered from hardwood flooring, cotton ginning and guayule processing streams as potential fillers in NFRTC. The five different fiber filler treatments are listed below:

1. Oak wood fiber (OWF) as the control.
2. Cotton burr and sticks (CBS).
3. Cotton burr and sticks with 2% second cut linters (CBL).
4. CBS with 30% guayule whole plant (CGP).
5. CBS with 30% guayule bagasse (CGB).

All five treatments were replicated five times. The order in which samples were manufactured was randomized within each replication to avoid any potential biases in extruder conditions.
The ground fibers sized into 20–60 mesh size were dried in an oven at 2.4 C (306 F). The extruded samples had an average cross-sectional profile of 32.5 mm × 7.6 mm. These samples were water cooled to room temperature, and then conditioned at room temperature for approximately 3 months before testing. In order to avoid cross-contamination between successive samples, two color pellets were used between successive samples, and approximately 60 cm of material in the transition zone was discarded.

2.3. Composite sample preparation

The NFRTC samples were manufactured using an extrusion process. The composite samples were prepared using virgin high density polyethylene (HDPE) powder (Equistar Petrothene, LB-0100-00) with a melt flow index of 0.5 g per 10 min and specific gravity of 0.95 as the thermoplastic substrate. In addition to the thermoplastic substrate and fiber fillers, the matrix also contained zinc stearate as a lubricant and talc, a mineral filler. These are common additives used in these types of composites when they are manufactured by extrusion process. The basic formulation of the NFRTC was 50% fiber filler, 40% HDPE, 6% lubricant and 4% mineral filler, all percentages by weight. The composite samples used virgin high density polyethylene (HDPE) powder (Equistar Petrothene, LB-0100-00) with a melt flow index of 0.5 g per 10 min and specific gravity of 0.95 as the thermoplastic substrate. In addition to the thermoplastic substrate and fiber fillers, the matrix also contained zinc stearate as a lubricant and talc, a mineral filler. These are common additives used in these types of composites when they are manufactured by extrusion process. The basic formulation of the NFRTC was 50% fiber filler, 40% HDPE, 6% lubricant and 4% mineral filler, all percentages by weight. The ground fibers sized into 20–60 mesh size were dried in an oven at 2.4 C (306 F). The extruded samples had an average cross-sectional profile of 32.5 mm × 7.6 mm. These samples were water cooled to room temperature, and then conditioned at room temperature for approximately 3 months before testing. In order to avoid cross-contamination between successive samples, two color pellets were used between successive samples, and approximately 60 cm of material in the transition zone was discarded.

2.4. Sample testing

The extruded samples were tested for SG, both 24 h and equilibrium water absorption and swelling, coefficient of linear thermal expansion (CLTE), strength and modulus of elasticity (MOE) under flexure and compression, hardness and nail holding capacity (NHC). Details of the ASTM standards used for testing, along with the size of sample specimens used are shown in Table 1. The SG test was conducted as specified in the standard with the exception that measurements were made at 19 C, which was the average room temperature. The ASTM Standard D6341-98 (1999) for testing CLTE of plastic lumber and plastic lumber shapes calls for equilibrium temperatures at −34.4 C and 60 C (−30 F and 140 F). Due to the temperature setting in an available freezer, the actual low and high temperatures used for this test were −7.8 C to 60 C. Because the sample coupons extruded in this study had a thickness of approximately 7.6 mm, the individual samples were not appropriate for hardness and NHC tests. For testing hardness and NHC, the test specimens were prepared by gluing three 152 mm long pieces together, as suggested in ASTM D 1037-99 (2002). The molding surfaces of the individual samples were planed before applying a moisture-cured polyurethane glue. The glued and aligned samples were clamped under a light holding force for approximately 8 h for curing.

Physical and mechanical properties of the samples manufactured under the five different treatments were compared to each other by performing a student-t-test for mean comparison. The analysis was performed using JMP software (SAS Institute, Cary, NC).

3. Results and discussions

3.1. Physical properties of fiber fillers

A comparison of the physical properties of the five ground fiber combinations used for composite manufacturing showed that both the CBS and CBL fibers had significantly lower bulk density than oak. The bulk density of the fibers was 348.9 kg/m³ for OWF, 249.3 kg/m³ for CBS, 273.3 kg/m³ for CBL, 333.2 kg/m³ for CGP, and 340 kg/m³ for CGB. Both CGP and CGB had bulk densities comparable to that of OWF. Because the weight percentage of plant fiber in the composite material was maintained at a constant level in this study, the materials with lower bulk density (CBS and CBL) would have higher volume (more number of particles and larger total surface area) than the material with higher bulk densities, assuming similar particle size distributions for all materials.

A comparison of micrographs of the 5 fiber types showed some differences among the five fiber types (Fig. 1). The oak fibers were more uniformly distributed than all other fiber types, with long spindle shaped fibers. The CBS, CBL and CGB fibers had a range of sizes and shapes. The linters in CBL was much finer and longer than the CBS particles. Particle size analysis of the ground fiber samples showed that the OWF had significantly more particles in the size range of 0.42 mm or greater compared to all other fibers (Fig. 2). Although CBL showed more particles in the 0.59 mm and above size ranges, it was not reflective of the actual particle size distribution. The relatively longer linters and motes fibers in the mix entangled into balls that were collected in the top screens of the sieve shaker. Overall, CBS, CBL, CGP and CGB had similar size distributions. The OWF had relatively small amount of fine particles, with less than 5% of mass representing particles less than 0.25 mm. The smaller fibers offer more surface area for bonding with the substrate, hence requiring more plastic to encapsulate them. On the other hand, the longer fibers provide strength and dimensional stability to the composite material. Therefore, short fibers often act as fillers whereas longer fibers act as a reinforcement.
Fig. 1. Micrographs of the five fiber fillers used in the experiment, taken at a magnification of 27 x. Oak fibers appear to have a more uniform size distribution than all other fibers.

Fig. 2. Particle size distribution of the five fiber combinations used as fillers in the composite samples.

3.2. Chemical composition of fibers

The chemical composition of the fibers (Table 2) showed that cotton linters had the highest amount of holocellulose (86.9%), and relatively low amounts of ash and lignin. Cotton linters also had a very high concentration of α-cellulose (66.6%), which indicates that approximately 20% of the dry weight was hemicellulose. These results are comparable to the 85–90% holocellulose and 0.8–2% ash content reported for seed hull fiber by Han and Rowell (1997). The CBS and guayule fibers had approximately 21% lignin, and 45–63% holocellulose, of which more than one-half (52–59%) was α-cellulose. In most wood fibers, the α-cellulose is usually less than 50% of holocellulose, the remaining being hemicellulose (Han and Rowell, 1997).

The white oak (which was used in this study) fibers contains 0.4% ash, 3% alcohol benzene extract, 27% lignin, 35% hemicellu-
lose and 30% α-cellulose, all in percentage by weight of dry plant material (Pettersen, 1984). In comparison, the CBS contained higher ash (9.8%), lower lignin (21%), and lower hemicellulose (21%). The ash content of CBS was within the range of that reported for CGW whereas lignin was slightly higher than that reported for CGW (Holt et al., 2000). The white oak wood had more lignin and hemicellulose than all the other fibers used in this study, and the second highest amount of holocellulose. The amorphous hemicellulose and lignin are soluble in water, whereas the crystalline α-cellulose is not soluble (Botuk, 2005). Therefore, fibers with high amount of α-cellulose and low amount of lignin and hemicellulose are expected to have lower water absorption and thickness swelling, which is preferable for fillers in thermoplastic composites. Based on the chemical composition, white oak is expected to have more water absorption than cotton and guayule fibers. However, past studies have shown that the water absorption of white oak was significantly less than CBS and CBL (Bajwa et al., 2009b), mainly because of the high bulk density, and hence the lower volume and surface area available for water activity.

A comparison of the chemical characteristics of all fibers showed that the linters should be highly suitable as a fiber filler because it had very high amount of α-cellulose and low amount of lignin. Both guayule bagasse and CBS were similar to white oak in α-cellulose, but had relatively lower lignin content, indicating that both CBS and guayule bagasse should be equally good as fiber filler. Although high amount of α-cellulose is desirable for fiber fillers, the guayule whole plant had slightly lower amount of α-cellulose than those reported for other natural fibers. The holocellulose content of guayule whole plant we tested were lower than those reported by Chow et al. (2008). However, the lignin and ash content of guayule plant were comparable to those reported by Banigan et al. (1982). For guayule bagasse, the holocellulose was comparable to that reported by Chow et al. (2008) but the ash content was significantly lower. Combining the fibers such as CBS and guayule that contain low amount of cellulose, with those fibers such as wood and linters containing high amounts of cellulose has the potential to further strengthen the final composite product.

### 3.3. Performance of thermoplastic composite samples

The processing temperature setting for the samples changed slightly depending on the fiber filler type. Slightly lower die and extruder temperatures were used in case of CBL samples because the samples tended to char at die temperatures above 149°C (300°F). Once, the extruder and die temperatures were optimized, there were no surface defects apparent on the composite samples. The samples made from cotton gin byproducts (CBS and CBL) were dark brown in color compared to the lighter color of samples made from wood. When the samples were soaked in water for the water absorption test, the samples containing cotton gin byproducts released brown pigments (primarily tannins) and changed into a deeper shade of brown.

### 3.3.1. Specific gravity (SG)

A low SG (≤ 1) comparable to that of wood is preferred for composite materials intended as replacement of wood, especially in applications where light-weight components are favored. The NFRTC samples made from cotton and guayule byproducts exhibited low SG of less than unity, with treatment means varying from 0.97 to 0.98. In comparison, the composite samples made from oak fiber exhibited significantly higher specific gravities, with an average of 1.04 (Fig. 3).

![Fig. 3. Specific gravity of composite samples made with different fiber formulations (N=25). Different letters indicate a significant difference in treatment means at α = 0.05 according to student t-test.](image)

### 3.3.2. Water absorption

Natural fibers have a strong affinity to water specifically due to the hydrophilic nature of cellulose. In NFRTC materials, a low water absorption is preferred because the absorbed water causes fiber swelling leading to poor dimensional stability, decay and poor long-term performance. The 24-h water absorption test at 19°C indicated that the CGP samples exhibited an average water absorption of 4.1%, which was similar to the 3.2% exhibited by control treatment at 5% significance level (Fig. 4). The samples from the fiber treatments of CBS and CBL had significantly higher mean water absorption of 6.2 and 6.3% respectively, than the control and CGP. The CGB treatment exhibited a water absorption of 5.1%, which was higher than that of control but not different from the other treatments. The high water affinity of CBS and CBL fibers compared to the oak fibers can be attributed as the reason for the higher water absorption of these composite samples (Bajwa et al., 2009b).

The CGP treatment that had guayule whole plant at 30% of the fiber fraction had a 24-h water absorption comparable to that of the control. This is an interesting observation because lignin and hemicellulose contents of guayule plant were comparable to CBS, but slightly less than that reported for white oak. The high bulk densities of CGP and CGB fibers may have contributed to the decreased water absorption of those samples over a 24h period. This study indicates that guayule fibers can reduce the 24-h water absorption.
of NFRTC to levels similar to that of wood-based RTC when used in conjunction with CBS.

The 16-day water absorption test indicated that the water absorption increased somewhat linearly with square root of time (Fig. 4), although it was not a perfect Fickian trend (Glicksman, 2000). The Fickian diffusion behavior assumes that the moisture absorption through the thickness direction is constant for homogeneous plastics and reinforced polymer matrix composites under glass transition temperature. Wang and Morrell (2004) reported similar non-Fickian patterns of water absorption for commercially available WPC. The non-homogeneous distribution of fibers as well as the large sizes of samples may have influenced the water absorption properties to deviate from the Fickian trend. All five composite treatments in this study showed a slow rate of water absorption in the first 48 h, followed by a somewhat accelerated rate, and then reached equilibrium water content in approximately 15–18 days. Although the CGP samples showed lower 24-h water absorption, the water absorption trend of CGP over time was similar to that of CBS and CBL. The average equilibrium moisture content in water was the lowest for OWF (12.7%), followed by CGB (17.6%) and CGP (22.7%), with the highest values indicated by CBS (24.8%) and CBL (25.5%). From this study, the bulk density and the total surface area of plant fibers available for absorbing water seems to be a more critical factor than the ligno-cellulosic composition of fibers in determining water absorption characteristics.

3.3.3. Dimensional stability

Dimensional stability of composites refers to the ability of the composite to maintain stable dimensions under the extreme environmental conditions when exposed to various applications. Since composites used in outdoor applications such as decking, rails, fences, window and door components and landscaping products are exposed to both moisture and temperature fluctuations, it is important to evaluate these materials for dimensional stability under moisture and temperature variations. The dimensional stability under high moisture content is measured through swelling of the material when it is submerged in the water. The dimensional stability under temperature fluctuations can be estimated by measuring the CLTE. High values for thickness swelling and CLTE are undesirable because they can lead to potential issues such as swelling, bowing, cupping, misalignment and loosening of fasteners when used in various building applications.

Thickness swelling of all samples increased with time of soaking in a highly non-linear fashion (Fig. 5). The fluctuating thickness swelling with respect to time was unlike the smooth increasing trends reported for other NRTCS such as polypropylene-flax composites (Stamboulis et al., 2000). The CGB composite samples exhibited the lowest thickness swelling whereas CBL exhibited the highest thickness swelling after 24 h of soaking (Fig. 5). This trend changed after the second day of soaking with OWF samples indicating the lowest thickness swelling followed by CGB samples. Between days 5 and 13, the CGB samples exhibited the highest thickness swelling followed by CBL, CBS, CGB and OWF. However, from day 14, the trend changed again, resulting in the lowest thickness swelling by CGB samples followed by OWF. There was no significant difference among the CBS, CBL and CGP on thickness swelling after 13 days of soaking. Therefore, guayule bagasse may be a desirable co-filler with CBS to lower water absorption and thickness swelling of composites using CBS as the single filler.

The lower thickness swelling exhibited by CGB and OWF seem to be an interaction between bulk density and fiber chemistry. Both CGB and OWF had the highest bulk densities and a-cellulose content. Since thickness swelling is a measure of the swelling of cellulose fibers as a result of the water absorption, it is natural that the thickness swelling in NFRTC follows a trend similar to that of water absorption. However, all samples did not follow similar trends for thickness swelling to that of water absorption. For example, the CGB samples showed the highest thickness swelling even though its water absorption was lower than both CBS and CBL samples. Also, the decreased thickness swelling of CGB after 13 days compared to that of OWF was not apparent in the water absorption.

In an extrusion process, the majority of the fibers align in the direction of flow (or along the length). Most of the swelling due to water absorption in cellulose fiber occurs along its diameter. Therefore, swelling would be the highest across the direction of orientation of fibers, which is the direction of extrusion in this case. Because all fibers may not be aligned along the direction of extrusion, the relative swelling of the composite sample along the width and length can provide some insight into fiber orientation. The measured percentage swelling along the width and length of the composite samples showed similar non-linear fluctuating patterns with respect to time (Fig. 6). Theoretically, if all fibers were perfectly aligned along the direction of extrusion with similar fiber packing along thickness and width, the percentage swelling along thickness and width should be similar. The measured percentage swelling along the width ranged from 41% (for CGP and CGB) to 56% (for OWF) of thickness swelling. Similarly, the measured swelling along length varied from 12% (for OWF) to 21% (CGB) of thickness swelling. This result indicates that a majority of the fibers were oriented along the direction of extrusion. The difference between composite samples with various fiber treatment in 3-D swelling indicates that the relative fiber orientation of the various fibers may have differed slightly between treatments. The CLTE is an indicator of dimensional stability under temperature fluctuations. The CGB treatment showed significantly lower
Fig. 7. The coefficient of linear thermal expansion of composite samples with five different fiber fillers, showing a comparison of means (N=25). The treatments corresponding to the bars showing different letters are significantly different at α = 0.05.

Table 3

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Flexure</th>
<th>Compression</th>
<th>NHC (N)</th>
<th>Hardness (N)</th>
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<tr>
<td></td>
<td>MOE (MPa)</td>
<td>MOR (MPa)</td>
<td>Modulus (MPa)</td>
<td>Strength (MPa)</td>
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<td>OWF</td>
<td>1599.64 (356.73)</td>
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<td>15.57 (1.83)</td>
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<tr>
<td>CBS</td>
<td>1017.84 (91.20)</td>
<td>11.68 (0.87)</td>
<td>384.86 (42.64)</td>
<td>12.7 (0.67)</td>
</tr>
<tr>
<td>CBL</td>
<td>821.08 (144.54)</td>
<td>8.34 (1.66)</td>
<td>359.58 (36.32)</td>
<td>11.91 (1.50)</td>
</tr>
<tr>
<td>CGB</td>
<td>931.40 (73.27)</td>
<td>11.68 (1.29)</td>
<td>342.62 (24.27)</td>
<td>12.69 (2.21)</td>
</tr>
<tr>
<td>CGP</td>
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<td>12.40 (1.74)</td>
<td>442.59 (43.56)</td>
<td>12.70 (2.11)</td>
</tr>
</tbody>
</table>

Within a column, different letters indicate a significant difference between the treatments means.
Fig. 8. Scanning electron microscope (SEM) images showing the fiber–polymer interface and fiber distribution at the fractured surface of the composite samples made with different fiber fillers.
Composite samples made from the various fiber combinations exhibited similar surface hardness and NHC, indicating that all the four combinations of alternate fibers tested in this study are as good as wood fiber in maintaining the surface hardness and NHC of composites (Table 3). Surface hardness is an important property in flooring applications where surface denting is not desirable. It is preferable for the new composites to have surface hardness higher than or equal to that of the control that uses wood fiber. Similarly, NHC indicates the force required to loosen or pull out a nail that is commonly used for fastening composites boards to joists or other supporting structures. Again, NHC values higher than or similar to composites made of wood fiber are preferred.

4. Conclusions

A study was conducted to understand whether thermoplastic composite samples made with five different plant fibers recovered from agricultural and furniture waste streams as fillers will have similar physical and mechanical properties. This study indicated that plant fibers from cotton gin byproducts and guayule byproducts hold great potential as fillers in thermoplastic composites. The major benefit of the non-wood fiber fillers from waste stream was the lower specific gravity. The drawback of the non-wood fibers included higher water absorption and thickness swelling. Substitution of cotton burr and stem with 30% guayule bagasse in the fiber increases CLTE than the other four fiber treatments. Although modulus and toughness were significantly lower for the non-wood fibers, the surface hardness and NHC were similar. Both oak and CBS showed uniform fiber distribution in the polymer matrix and superior interfacial properties of wood-polymer composites. Therefore, it is concluded that plant fibers from waste stream have the potential to retain the desirable properties of both groups of fibers and should be explored in the future.

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References


