

Optimal Substitution of Cotton Burr and Linters in Thermoplastic Composites

Sreekala G. Bajwa
Dilpreet S. Bajwa*
Greg Holt

Abstract

A study was conducted to evaluate various substitutions of cotton burr and linters from cotton gin waste (CGW) as natural fiber reinforcements in ligno-cellulosic polymer composites (LCPC). Samples were fabricated with approximately 50 percent natural fiber, 40 percent high-density polyethylene, 4 percent mineral filler, and 6 percent lubricant, by weight. The experiment included substituting wood fiber in LCPC with 25, 50, 75, and 100 percent (by weight) cotton burr (CB) and cotton burr mixed with 2 percent (by weight) second-cut linters (CBL), respectively, with the remaining fraction as wood fiber and comparing it against the control (100% wood). Samples were extruded into rectangular profiles and tested for physical and mechanical properties such as specific gravity (SG), water absorption, thickness swelling, coefficients of linear thermal expansion (CLTE), flexural strength and modulus, compressive strength, hardness, and nail withdrawal force (NWF). The CB and CBL treatments exhibited SG, CLTE, hardness, and NWF comparable to the control. However, the water absorption and thickness swelling, flexural strength and modulus, and compressive strength all deteriorated at high substitution rates of CB and CBL. The favorable properties of cotton burr included its tendency to decrease CLTE and increase hardness of LCPC.

Wood plastic composites (WPC) are manufactured as durable alternatives for wood. They combine the strength of wood fibers with the durability of plastic. Therefore, WPC products are superior to both wood and plastic for nonstructural and outdoor applications such as deck board, fencing, window and door jambs, railings, park benches, and landscaping products. The majority of the commercially available WPCs use a thermoplastic substrate reinforced with wood fiber. The role of the fiber filler is to reinforce the polymer matrix by imparting desirable mechanical (primarily strength) properties without deteriorating the physical properties of the WPC. Therefore, ligno-cellulosic waste streams from agriculture could become potentially effective fiber reinforcement in WPCs.

Natural fibers were used as fiber fillers in 13 percent of the polymer composites produced in 2002 (Morton et al. 2003). Most of the WPC products are made from recycled ligno-cellulosic fibers, primarily from furniture waste. Some WPC manufacturers also have used sawmill waste, pine scrap, recycled paper fiber, used pallets, rice hull, and natural fibers (Winandy et al. 2004). Agriculture waste is a largely untapped renewable resource that can become an inexpensive source of fiber filler in WPCs. The vast

agricultural industry in the world produces millions of tons of ligno-cellulosic wastes. Cotton gin waste (CGW), an agricultural waste stream from cotton gins, is rich in ligno-cellulosic fibers that could potentially become a viable and inexpensive source of fiber fillers.

Approximately 2 to 3 million metric tons of CGW are generated each year across the cotton belt of the United States (Thomasson 1990, Holt et al. 2000). The CGW contains mostly carpels or burrs (40% to 70% by weight) depending on the type of equipment used for harvesting. The remaining portions of CGW are composed of sticks, leaves, soil particles, motes/liners, and other plant materials (Baker et al. 1994). There are limited applications for CGW.

The authors are, respectively, Associate Professor, Dept. of Biological and Agric. Engineering, Univ. of Arkansas, Fayetteville (sgbajwa@uark.edu); Research and Development Manager, Greenland Composites, Greenland, Arkansas (dbajwa@email.com); and Agric. Engineer, USDA-ARS, Cotton Production and Processing Research Unit, Lubbock, Texas (greg.holt@ars.usda.gov). This paper was received for publication in September 2008. Article no. 10537.
*Forest Products Society member.

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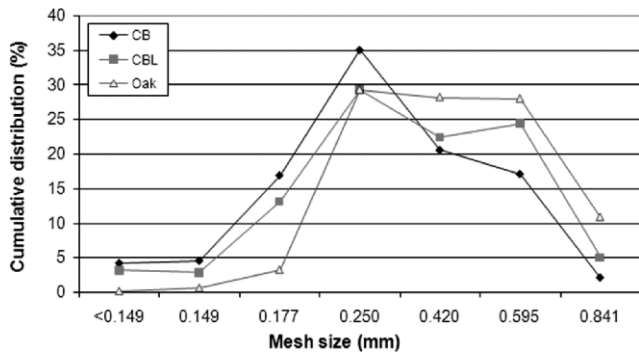


Figure 1.—Actual particle size distribution of the three fiber materials ground to 20 to 60 mesh size.

Those that have shown some potential include composting, livestock feed, energy source, fire logs, fuel pellets, and soil amendment (Thomasson 1990, Poore and Rogers 1995, Holt et al. 2004). None of these applications have ever reached widespread commercial acceptance, mainly due to the presence of impurities such as soils particles (Holt et al. 2000). Currently, the disposal of CGW is more of a financial liability than a revenue generator.

A preliminary evaluation of the CGW as a fiber filler in ligno-cellulosic polymer composites (LCPC) showed that it holds great potential (Bourne et al. 2007). The major disadvantage of using the entire stream of CGW is the presence of impurities such as soil particles (that are abrasive to equipment) and the difficulty in handling high proportions of lint waste (linters). The cotton lint waste, the small cotton lint fibers in the waste stream, form fiber balls that are difficult to separate and mix uniformly in a polymer matrix. Therefore, this study was undertaken with the objective of evaluating the waste stream collected from the lint extractor during cotton ginning, which contains primarily cotton burr, sticks, and small amounts of linters, as an alternative source of fiber reinforcement in LCPC.

Materials and Methods

Raw material preparation

This study used two new raw materials as substitutes for wood fiber in LCPC. They were cotton burr (CB) and cotton burr with 2 percent second-cut linters (CBL). The cotton burr and linters used in this study came from the USDA-ARS Cotton Ginning Laboratory at Lubbock, Texas, and a nearby cottonseed oil mill, respectively. The CB fiber contained the CGW collected at the extractor during ginning, and consisted primarily of carpels and stems (CS) along with a small amount of approximately 0.5 to 1 percent by weight (Holt et al. 2006) lint waste. The fiber source CBL was obtained by mixing second-cut linters with the waste stream from the extractors at a mixing ratio of 1:49 (2% by weight). The term “cotton linters” refers to motes or lint waste, the short fibers that escape to the waste stream, as well as the short fibers obtained from the delinting phase of a cottonseed oil mill. The linters obtained from cottonseed oil mills are generally classified into first-cut and second-cut linters with the second-cut being the shortest fibers. High amounts of linters in the order of 10 to 11 percent causes mixing problems, which tend to negatively affect the strength properties of composites (Bourne et al. 2007). Since the CB contains 0.5 to 1 percent short lint fibers, we decided to include an

additional 2 percent (twice as much as the maximum lint content of CB) second linters in CBL. This is still a relatively small amount, but would allow us to verify if it is possible to distribute the linters well enough in the polymeric matrix to take advantage of the high strength properties of the lint fibers. The wood fiber used in the study was commercially available oak flour. All three fibers (CB, CBL, and oak) were ground to a 20- to 60-mesh size distribution by hammer milling. An analysis of the actual particle distribution of the three fiber materials showed that wood had a greater percentage of coarser particles in the 0.42- to 0.84-mm size (20 to 40 mesh) than CB and CBL (Fig. 1). The differences in particle size distribution observed between CB and CBL were primarily due to the balls formed by linters. All fiber fillers were dried in a convective oven at 105°C for 15 to 20 hours to reduce the moisture content to less than 1 percent by weight prior to sample manufacturing.

Water absorption and bulk density of the three fiber sources were measured because they were critical factors that influenced LCPC properties. Water absorption was measured by securing 25 g of material at room temperature in a muslin sachet, and soaking it in water at room temperature for 24 hours. After 24 hours, the material was removed and hung for 1 hour for draining and then spread on tissue paper to remove extra water. The material was weighed 30 minutes and 1 hour after spreading it on the tissue paper. The water absorption was calculated as the percent weight gain due to water soaking.

Experimental design

An experiment was designed to identify the acceptable substitution level of the two fiber fillers (CB and CBL) for wood in LCPC. The experiment was a completely randomized block design with nine treatments and three replications, resulting in 27 sample runs. The nine fiber filler treatments included a control (100% wood) and eight different substitutions for wood. The eight different substitutions for wood included 25 percent CB, 50 percent CB, 75 percent CB, 100 percent CB, 25 percent CBL, 50 percent CBL, 75 percent CBL, and 100 percent CBL, all expressed as percentages of the total fiber filler weight.

Sample preparation

The basic formulation of LCPC used in this study was 50 percent fiber filler, 40 percent virgin high-density polyethylene (HDPE; Equistar Petrothene, LB-0100 to 00), 6 percent zinc stearate as a lubricant, and 4 percent talc as a mineral filler. The experimental samples used a relative proportion of HDPE close to most commercial samples. Commercial samples were shown to contain approximately 35 to 39 percent thermoplastic polymer and 50 percent or more cellulosic fibers (Bajwa et al. 2009). Powdered virgin HDPE was used in this study due to its good mixing and flow capabilities that are important for extrusion operation. The HDPE powder had a melt flow index of 0.5 g/10 minutes and an SG of 0.95.

Each sample set of LCPC was manufactured with 800 g of raw material. The exact amount of each ingredient was weighed and hand mixed to obtain a total weight of 800 g. A set of nine samples corresponding to the nine treatments was prepared before starting the extrusion process. The order in which samples were extruded was randomized within each block to avoid any potential biases. The nine samples within

a block were extruded continuously one after another with color introduced between samples to identify the transition region. Initial trials showed that an approximately 40-cm length of sample during the transition from one formulation to another contained materials from both samples. Therefore, approximately 50 cm of material in the transition region was discarded from any testing.

Samples were extruded with a counter rotating twin screw extruder into rectangular profiles with a 31.7 by 6.3-mm die. The extruder had four barrel zones with individual temperature controls. The temperature profile used was 160°C (320°F), 149°C (300°F), 149°C, and 135°C (275°F) for barrel zones 1 through 4, respectively. The die temperature was set at 149°C at the beginning of a batch to account for the drop in temperature that occurs when the first batch of material begins to flow through the die, and then lowered to 146°C since the surface appearance was good at this temperature. The die temperature usually fluctuated between 141°C (286°F) and 152°C (306°F). The extruder screw was run at 30 rpm. The extruded samples were water cooled and then conditioned at room temperature for 8 to 12 weeks before testing.

Sample testing

The LCPC samples were tested for important physical properties, such as SG, water absorption, thickness swelling, and coefficient of linear thermal expansion (CLTE), and mechanical properties, such as flexural strength and modulus, compressive strength, hardness, and nail withdrawal force (NWF). A minimum of one specimen per treatment × replication combination was subjected to each of the tests. SG, water absorption, and thickness swelling of the samples were tested according to the American Society for Testing and Materials (ASTM) D1037-99 (ASTM International 2002) standard test method for evaluating properties of wood-based fiber and particle materials. All three tests were conducted at a room temperature of 19°C. SG was measured as the ratio of sample density (ratio of sample weight to water volume displacement when immersed) to tap water density. Water absorption was measured as the percent increase in weight after 24 hours of immersion in water at room temperature, followed by pat drying with paper towels. For measuring thickness swelling, four sections were marked on the sample, where the thickness of the sample was measured with a vernier caliper before and after the 24-hour water absorption test. The average size of samples used for both tests was 32.5 by 7.65 by 152 mm.

The CLTE was determined using the guidelines for determination of the CLTE of plastic lumber (ASTM D6341-98, 1999). The CLTE was measured in the axial or extruded direction. Due to laboratory limitations, the actual low and high temperatures used for this test were -7.8°C and 55°C, respectively, such that a difference of 62.8°C between the two exposed temperatures was maintained. The samples were maintained at each temperature extreme for 24 hours to ensure that they reached atmospheric equilibrium. The average length of specimens used for this test was 292 mm at room temperature. The length of the specimens was measured with a vernier caliper after reaching equilibrium at room temperature, freeze temperature, and oven temperature.

Flexural properties of the composite samples were determined using an Instron universal testing machine with a three-point bending configuration based on ASTM Standard D1037-99 (2002) test method. The average

cross-sectional size of specimen used for this test was 32.4 by 7.6 mm at the center. The modulus of rupture (MOR) was calculated as the ultimate strength of the specimen under flexure. Modulus of elasticity (MOE) was calculated as the slope of the stress-strain curve at 40 percent of the MOR. The compressive strength was tested based on ASTM D1037-99 test method on sample coupons prepared into short columns of 25.4-mm height and width.

Since the sample coupons extruded in this study had a thickness of approximately 7.6 mm, the individual samples were not appropriate for hardness and nail withdrawal tests. For testing hardness and NWF, the test specimens were prepared by gluing three 152-mm-long LCPC pieces together, as suggested in ASTM D1037-99 (2002). The mating 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 hours for curing. Hardness of the LCPC samples was measured following the modified Janka ball test (Method D1037-99). Two sets of readings were made on each sample specimen and averaged as the sample hardness. For measuring NWF, two nails were inserted into each of the specimens prepared as described for hardness testing. The NWF was measured using the Instron following the ASTM D1037-99 method. Two readings from each NWF test were averaged to obtain a representative value for each specimen.

Data analysis

To identify the fiber filler compositions that were either comparable or superior to the control, the physical and mechanical properties of the LCPC treatments with CB and CBL fiber substitutions were compared with that of the control using the Dunnett test. In addition to the Dunnett test, the effect of the percentage of cotton CS and linters on the physical and mechanical properties of the LCPC was analyzed with a stepwise regression procedure. For this analysis, the CB fiber was assigned to have an average of 0.75 percent linters and 99.25 percent CS since it contained approximately 0.5 to 1 percent linters, and the CBL fiber was assigned to have 2.75 percent linters and 97.25 percent CS. All tests were considered significant at an α value of 0.05. The data were analyzed with JMP 7.0 software (SAS Institute Inc., Cary, North Carolina).

Results and Discussion

The two fiber fillers CB and CBL exhibited significantly higher water absorption and lower bulk density than wood (Table 1). The water absorption of CB and CBL at room temperature was 55 and 76 percent higher than the oak fiber used in the study. The reason for higher water absorption by a fiber sample could be due to higher levels of cellulose content or high surface area. Our preliminary laboratory analysis

Table 1.—Water absorption and bulk density of wood, CB, and CBL fibers ground to 20 to 60 mesh size.^a

Fiber type	Water absorption (% by wt)		Bulk density (g/cm ³)
	After 90 min	After 120 min	
Wood	144.1 A	124.8 A	0.321 A
CB	232.6 B	220.1 B	0.239 B
CBL	224.0 B	213.1 B	0.243 B

^a Each number is an average of four samples. Values in a column followed by a different letter are significantly different at $P < 0.05$.

Table 2.—Physical and mechanical properties of the LCPC samples under the nine different fiber filler treatments.^a

Treatment (% linters)	SG (ratio)	Water absorption (%)	Thickness swelling (%)	CLTE ($\mu\text{m}/\text{m}/^\circ\text{C}$)	MOE (MPa)	MOR (MPa)	Compression strength (MPa)	Hardness (N)	Nail withdrawal force (N)
1: 100% W (0% L)	1.01 (0.02)	3.51 (0.41)	0.92 (0.18)	12.55 (2.38)	1,644.29 (182.71)	15.34 (1.78)	13.06 (2.41)	5,004.00 (24.77)	992.65 (91.87)
2: 25% CB (0.19% L)	0.97 ^c (0.01)	4.51 (0.49)	1.11 (0.63)	16.00 (3.32)	1,424.70 (325.93)	14.68 (2.25)	10.63 (0.87)	5,159.68 (109.32)	865.88 (95.12)
3: 50% CB (0.37% L)	1.00 (0.01)	5.97 ^b (0.31)	1.94 (0.00)	13.46 (9.95)	1,289.50 (291.22)	13.53 (2.00)	12.57 (2.37)	5,241.23 (292.84)	913.32 (60.55)
4: 75% CB (0.56% L)	1.00 (0.03)	7.69 ^b (0.16)	2.18 ^b (0.25)	15.46 (9.15)	1,100.40 ^b (184.74)	11.77 (2.61)	12.19 (1.82)	5,187.85 (674.23)	947.42 (58.17)
5: 100% CB (0.75% L)	0.99 (0.02)	5.53 (1.87)	1.63 (0.36)	12.72 (11.56)	1,062.41 ^b (35.57)	11.65 (0.70)	12.18 (2.67)	5,829.85 (608.46)	1,021.56 (92.49)
6: 100% CBL (2.75% L)	0.99 (0.01)	6.04 ^b (1.05)	2.74 ^b (0.87)	7.09 (2.73)	870.81 ^b (52.96)	7.62 ^b (0.57)	11.86 (0.90)	5,697.89 (521.69)	851.05 (73.94)
7: 75% CBL (2.06% L)	0.98 (0.02)	8.16 ^b (1.06)	2.55 ^b (0.50)	3.45 (2.27)	894.45 ^b (190.50)	10.59 ^b (1.57)	10.69 (1.05)	5,101.86 (75.88)	888.12 (103.39)
8: 50% CBL (1.38% L)	0.98 (0.04)	6.16 ^b (0.39)	1.68 (0.09)	3.27 (3.78)	1,046.14 ^b (128.49)	11.56 (1.46)	8.0 ^b (2.81)	5,417.66 (27.78)	916.29 (53.38)
9: 25% CBL (0.69% L)	0.98 (0.01)	4.29 (0.39)	1.97 (0.52)	9.10 (1.57)	1,123.80 ^b (209.39)	11.94 (1.98)	12.21 (1.65)	5,396.91 (117.88)	1,048.25 (73.40)

^a Each treatment represents an average of three samples. The standard deviation is shown in parentheses.

^b Treatment is significantly ($P < 0.05$) different from control based on Dunnett test. Undesirable difference.

^c Treatment is significantly ($P < 0.05$) different from control based on Dunnett test. Desirable difference.

indicated that the holocellulose content of CS was 55 percent and linters was 69 percent, as opposed to 68 to 70 percent reported for American white oak by Pattersen (1984). Therefore, cellulose content may not be the reason for the increased water absorption. The ground CB and CBL were bulkier than oak, with bulk densities approximately 34 and 32 percent less than that of the oak fiber, which had a bulk density of $0.32 \text{ g}/\text{cm}^3$. The higher bulk density of the CB and CBL would mean that for particles with similar size distribution, there would be more particles and more surface area for CB and CBL compared with oak flour. Since CB and CBL also showed relatively higher amounts of finer particles compared with oak flour (Fig. 1), both these materials had significantly more surface area than the same amount of wood flour. We anticipate that the higher surface area available for contact with water resulted in higher water absorption in both CB and CBL. There was no significant difference between CB and CBL in water absorption or bulk density.

Composite samples

The extruded sample coupons had a very smooth and normal appearance, comparable to most commercial WPC. There were no surface defects apparent on the samples. The 800 g of sample containing CB or CBL was extruded in approximately 7 minutes resulting in a throughput rate of 6.85 kg/hour, compared with 7.75 kg/hour for wood. The samples with high amounts (75% to 100% of fiber filler) of CB and CBL were dark brown compared with the light yellowish color of the control samples that had oak as the only fiber filler. Also, exposure to water (during water absorption test) allowed the samples with high amounts of CB and CBL to release more brown pigment, resulting in significant darkening of the samples after water soaking for 24 hours.

Physical properties

A low SG (≤ 1) is preferred for composite materials intended as replacement of wood, especially in applications

where lightweight components are preferred. The LCPC samples made from CBL exhibited SGs slightly below unity, with a range of 0.93 to 1. A majority of the CB treatments exhibited SGs around 1, with a range of 0.95 to 1.02. In comparison, the control samples made with oak wood flour had an average SG of 1.01, with a range of 0.99 to 1.03. Comparison of treatment means with the Dunnett test showed that SG of all the treatments, except 25 percent CB, was similar to that of the control (Table 2). The 25 percent CB sample exhibited a slightly lower SG than the control. Although the plot of the SG with respect to the amount of linters (expressed as percentage of the total weight of composites) showed a slight parabolic trend (Fig. 2), it was not significant. A stepwise regression analysis confirmed this fact since SG was not correlated to the amount of linters or CS (Table 3).

Water absorption is an important property of LCPC. A lower water absorption rate is preferred because it can reduce susceptibility to decay and shortened life of cellulosic materials in the composite matrix. Water absorption of the control was 3.5 percent, with a range of

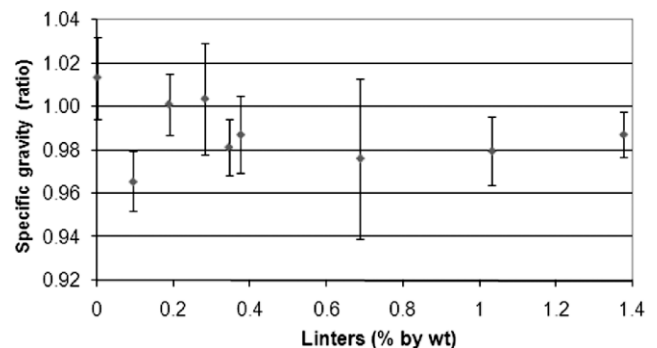


Figure 2.—Variation of SG of composite samples with respect to the amount of linters in the mix.

3.1 to 3.9 percent. All the LCPC samples with 75 percent CB or CBL had consistently higher water absorption above 7 percent (Table 2). The high water affinity of CB and CBL in comparison to oak is the reason for the higher water absorption of the LCPC samples with high amounts of CB or CBL (Table 1). The LCPC samples with 25 percent CB or CBL, as well as 100 percent CB showed water absorption comparable to the control. A plot of water absorption against percentage of linters showed two distinct parabolas corresponding to CB and CBL (Fig. 3). The CB material showed the peak water absorption at 0.28 percent linters whereas the CBL showed peak water absorption at 1.03 percent linters. It is not clear why two material showed such distinctly different trends since the two material differed only in the amount of linters. A potential reason could be the mixing dynamics and interaction between wood and CB fibers within the plastic matrix. The stepwise regression analysis confirmed the polynomial relationship between the percentage of linters and water absorption (Table 3). The amount of linters explained 59 percent of the variability in water absorption.

A comparison of the samples from this study with those made with the whole CGW fraction as reported by Bourne et al. (2007) showed that both SG and water absorption of the CB and CBL samples were slightly higher. The samples manufactured in this study were slightly different from that of Bourne et al. (2007) in manufacturing conditions (pressure and temperature), composite formulation (48% fiber, 48% HDPE, and 4% lubricant in Bourne et al. [2007] as opposed to 50% fiber, 40% HDPE, and 4% talc in this study). The high SG may have resulted from the addition of talc, better mixing, or the higher pressure used during the extrusion process. However, SG of the CB and CBL samples was toward the low end of the values reported for most commercial WPC (Kumari et al. 2007, Bajwa et al. 2009).

Dimensional stability

Thickness swelling and CLTE are two important indicators of dimensional stability of the LCPC. High values for thickness swelling and CLTE are undesirable since they can lead to potential issues such as bowing, cupping, misalignment of deck or floor boards in building applications, and potential loosening of fasteners. The samples with 75 percent CB or CBL, and 100 percent CBL had significantly higher thickness swelling than the control (Table 2). All other treatments showed statistically similar thickness swelling as control. A CB or CBL substitution of up to 50 percent can be recommended to maintain thickness swelling comparable to control. The

cellulosic fibers swell when they absorb water. Therefore, the thickness swelling is related to the water absorption characteristics of the fiber. Since CB and CBL have high affinity for water relative to oak, treatments with high amounts of CB and CBL will have higher thickness swelling than the control. The plot of thickness swelling against percentage of linters followed the same trend as water absorption, with less diminished peaks (Fig. 3), showing distinctly different parabolic distributions for CB and CBL, with the thickness swelling being the lowest at 0 percent and approximately 0.4 percent linters. However, the overall tendency of the thickness swelling data with respect to percentage of linters was linear. Regression analysis confirmed this trend and showed that 44 percent of the variations in thickness swelling could be explained by the amount of linters in samples (Table 3). The regression equation showed that every percent increase in the amount of linters, increased the thickness swelling by 1.07 percent. A comparison with commercial samples (Bourne et al. 2007, Bajwa et al. 2009) indicated that all treatments except the 75 and 100 percent CBL had thickness swelling comparable to commercial samples.

The CLTE of all CB and CBL treatments were similar to that of the control (Table 1). Although the treatment means were different, they were not significant due to the large amount of deviation in the CLTE data (Fig. 4) The regression analysis showed that CLTE exhibited a low but significant ($P < 0.05$) negative correlation with the amount of CS, and it explained 22 percent of variability in CLTE (Table 3). Since a low CLTE is preferred and CS showed a negative correlation with CLTE, it is possible to use CS as a substitute for wood in applications that require low CLTE. All treatments exhibited CLTE comparable to commercial products (Bajwa et al. 2009)

Mechanical properties

WPCs are used primarily in nonstructural applications in which strength properties are not critical. High levels of fiber substitution with CB and CBL decreased the MOE. When 100 percent of the wood was substituted by CB, the average MOE dropped from 1,644 to 1,062 MPa, and the average MOR dropped from 15.34 to 11.65 MPa (Table 2). The MOE of LCPC treatments containing up to 50 percent CB was similar to control. All CBL as well as 75 and 100 percent CB treatments had significantly lower stiffness than control. However, MOR was not as seriously affected by the fiber substitution. Except for the 75 and 100 percent CBL, all the other treatments showed MOR similar to that of the control. A plot of MOE against the percentage of linters

Table 3.—Stepwise regression of measured physical and mechanical properties of the LCPC with respect to the amount of cotton carpels and stems (CS) and linters (L) in the LCPC samples.^a

Composite property	Multiple regression equation	Adjusted R^2 value	RMSE
Water absorption (%)	$Y = 2.77 + 0.23L - 0.003L^2$	0.59	1.06
Thickness swelling (%)	$Y = 1.32 + 1.07L$	0.44	0.5
CLTE ($\mu\text{m}/\text{m}^\circ\text{C}$)	$Y = 14.2 + 7.98CS$	0.22	6.2
MOE (MPa)	$Y = 1,609.06 + 939.9CS - 10.1L + 15.9CSaL$	0.60	184.3
MOR (MPa)	$Y = 14.32 + 4.63L$	0.57	1.7
Compression strength (MPa)	$Y = 14.30 + 8.94CS - 0.03L + 0.19CSaL$	0.40	1.32
Hardness (N)	$Y = 5,043.8 + 10.87CS$	0.20	369.9

^a Only the significant models ($P < 0.05$) are listed here.

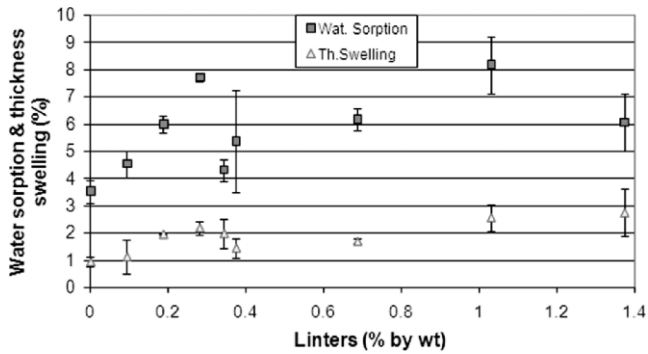


Figure 3.—Effect of the amount of linters in the composite on its water absorption and thickness swelling characteristics.

indicated a bilinear trend with a faster rate of decrease in MOR when percentage of linters increased from 0 to approximately 0.4 percent, followed by a gradual decrease in MOR at higher amount of percentage of linters (Fig. 5). The MOR also showed a similar bilinear trend, but the decrease was much more gradual than observed in the case of MOE (Fig. 5). Linear regression analysis indicated that MOE was influenced by the amount of linters, CS, and their interaction (Table 3), with these factors accounting for 60 percent of the variability in MOE. The high negative coefficients for CS along with the higher range of values for CS indicates a net decrease in MOE as the percentage of CS is increased. The slightly higher positive coefficient for the interaction term, compared with the negative coefficient for percentage of linters in the regression equation for MOE, indicates that the net effect of the interaction term is to decrease the rate at which MOE reduced as percentages of linters and CS increased. The amount of linters was the only factor that affected MOR, explaining 57 percent of its variability. The MOR decreased by 4.63 MPa for every percentage point increase in linters.

The compressive strength of LCPC samples with various proportions of CB and CBL was similar to those of the control except for the 50 percent CBL treatment (Table 2). The plot of compressive strength against percentage of linters showed relatively constant values except for the dip corresponding to the T8 treatment, which resulted in a parabolic trend (Fig. 5). Regression analysis showed that both the amount of linters and CS negatively influenced the

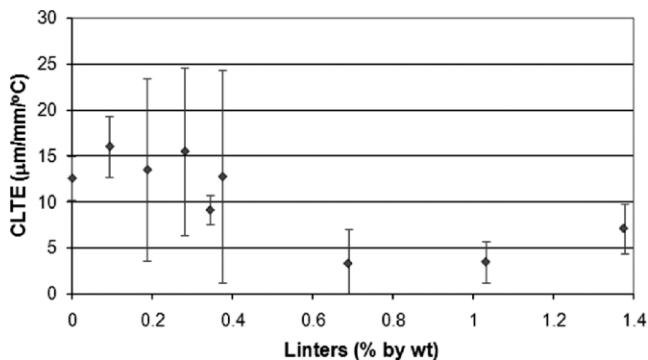


Figure 4.—Effect of the amount of linters on the coefficient of linear thermal expansion of thermoplastic composites.

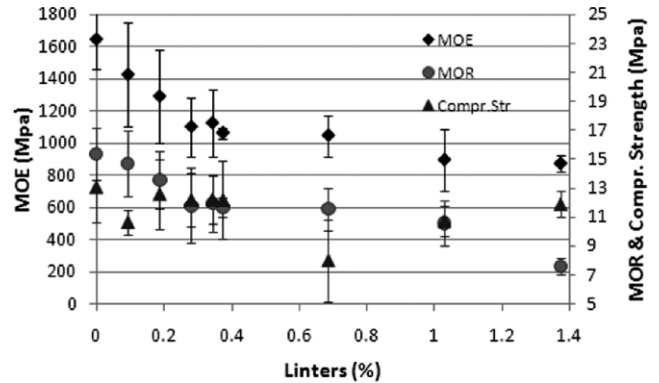


Figure 5.—Effect of the amount of linters on the flexure properties (MOE and MOR) and compressive strength of thermoplastic composites.

compressive strength (Table 3). However, there was a positive interaction between CS and linters as indicated by the positive coefficient for the interaction term in the regression equation. The significantly higher regression coefficient for percentage of CS indicates an overall decrease in compressive strength with respect to increase in percentage of CS. The positive interaction indicates that within the range of data, the overall effect of increasing the amount of percentage of linters and percentage of CS has reduced the rate at which compressive strength is diminished.

The Janka Ball hardness test showed that the LCPC samples exhibited excellent surface hardness properties comparable to the control. High surface hardness is highly desirable for applications such as flooring and decking. The average Janka Ball hardness of all treatments exceeded 5,000 N (Table 2). A comparison of treatment means showed that all treatments had Janka Ball hardness comparable to the control. However, a plot of hardness against percentage of linters showed a parabolic trend with a peak hardness at approximately 0.4 percent linters (Fig. 6). Some of the treatments showed high deviations to result in significant differences between treatments. The stepwise regression analysis showed that the Janka Ball hardness had a low but significant correlation ($R^2 = 0.2$) to the amount of CS in the samples (Table 3).

The mean NWF for the treatments varied from 851 N for 100 percent CBL to 1,048 N for 25 percent CBL (Table 2).

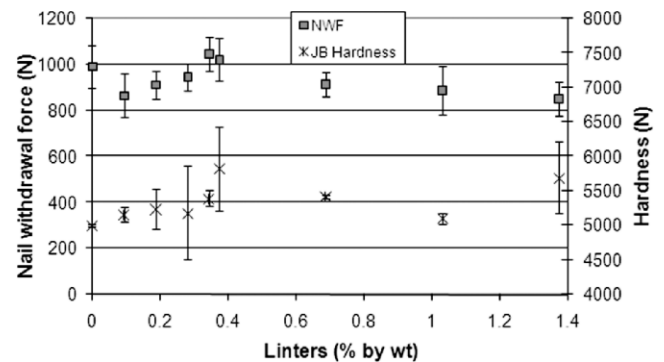


Figure 6.—Effect of the amount of linters on the nail withdrawal force (NWF) and Janka Ball hardness of thermoplastic composite materials.

Although the eight treatments exhibited NWF similar to that of the control, the CBL treatments showed considerable variability within the treatment. Although the NWF showed a parabolic trend with respect to percentage of linters, it was not correlated to the amount of CS or linters (Fig. 6). The low NWF values corresponding to the high CBL samples may be an indication of the mixing and dispersion issues with fiber containing a high amount of linters.

Cotton linters typically have higher aspect ratio than commercial wood flour fiber, and high aspect ratio leads to higher strength properties in WPC (Stark and Rowlands 2003). The high amount of linters in this study was shown to deteriorate the mechanical properties except surface hardness and NWF. A major reason for the negative impact of linters on the strength properties of LCPC is the short linters forming balls that were not easy to separate and distribute uniformly. The short linters may have been nonuniformly dispersed in the polymer substrate, causing polymer encapsulation problems and potentially weak spots within the LCPC matrix. This observation is also supported by Kumari et al. (2007) who claimed that longer fibers (high aspect ratio) can affect fiber dispersion, mixing, and melt fluidity of the product during extrusion. If the handling and mixing issues associated with linters can be addressed, the CBL may prove to be a good fiber filler in LCPC. In general, both CB and CBL can be used as partial substitutes for wood fiber in LCPC, and the CS fibers can be selectively used to improve hardness of composites.

Conclusions

A study was conducted to understand whether cotton burr and linters recovered from CGW could be used as an alternate source of natural fiber filler in LCPC. This study indicated that CB holds great potential for partial substitution in LCPC. In general, CB can substitute up to 25 percent of wood in LCPC without significant changes in physical and mechanical properties, and up to 50 percent with slight deterioration in MOE and water absorption. The desirable properties observed with the new material include a decrease in CLTE and an increase in hardness proportional to the CS content. The undesirable properties of the new fiber fillers include increased water absorption and thickness swelling, and decreased MOR, MOE, and compressive strength. The results of this study can be useful in selecting an ideal substitution rate for wood by CB or CBL fibers for specific applications. In general, CB can replace wood by 100 percent for applications where strength properties are not critical and the material is not exposed to water. The future direction in this research would be to verify the

observed characteristics of LCPC made with CB at a commercial scale.

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