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Residual Grade and Waste Abaca Fibers as Reinforcement for Packaging and Printing/Writing Papers from Recycled Fiber

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Fiber dimensions of residual grade abaca (tow grade) and waste abaca fibers (tuxy and stripping wastes) were measured. The fibers were found extremely long with thin cell walls. Fiber slenderness or felting point, flexibility, Runkel, and Muhlsteph ratios all indicate suitability for papermaking. Soda-pulping of the fibers, tow, and Tx80Sw20 (*i.e.*, tuxy and stripping waste fibers combined at 80:20) at NaOH charges of 8, 10, and 12%, yielded tow pulp twice greater than Tx80Sw20 pulp. Beating evaluation of tow-grade fiber pulped at 8% NaOH and the corresponding handsheet tests showed that acceptable beating time is 15–30 min. The Tx80Sw20 blend, on the other hand, already had a low freeness of only 227 mL and thus needed no further beating. The pulps were used as reinforcement for the production of papers from recycled or secondary fibers. The 80:20 blends of tow and Tx80Sw20 pulps were used to replace 3–10% levels of old corrugated cartons (OCC) to produce packaging paper, or mixed office wastes (MOW) to produce printing/writing paper. Results of tests on the handsheets produced therefrom indicate significant improvement in strength properties, even at low levels of 3–5% of reinforcement.

Keywords: good quality paper, recycled fiber, reinforcement, residual grade abaca, waste abaca

INTRODUCTION

The global paper industry is estimated at US$300–500 billion. Being domestically oriented and importing considerably, the participation of the Philippines in the paper global value chain is very limited – buoyed mainly by abaca pulp export that reached its peak in 2014 with US$127 million in revenue (Daly *et al.* 2016).

Abaca pulp is utilized by the importing countries in the manufacture of tea bags, currency paper, and other specialty paper products. Meanwhile, local paper products are mostly 95–100% based on recycled fiber. Recycling lessens fiber quantity and quality (Kleinau 1993, Mari *et al.* 2011) due to breakage, decreased flexibility, hornification, and other changes (Hubbe *et al.* 2007). Some wood pulp is imported for use as reinforcement. None of the locally produced abaca pulp goes to local production of paper despite its superior qualities (Torres *et al.* 1997, Estudillo *et al.* 1998, Mari *et al.* 2015). This is primarily because export of both fibers and pulp has been the primary goal of the abaca producers, while the local papermakers have not been aggressive in pursuing use of abaca pulp due to its high cost.

Meanwhile, there is increased pressure to implement regulations on the use of plastic-based materials for packaging due to its adverse effect on the environment. Local production of packaging grade papers reached 716,000 MT in 2016 from 314,000 MT in 2012. To

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augment this, between 2012 and 2016, importation of packaging grade papers hovered around 518,000–655,000 MT/y (PPMAI 2017). Considering this increasing demand for paper, the industry is eyeing the commercial utilization of abaca fiber in the absence of local wood pulp as reinforcement for paper to better compete with imported products (Geganto 2015). To address this concern, this report presents the results of experiments on the use of only the residual grade and waste abaca fibers for reinforcement of recycled fibers in the production of packaging paper and printing/writing paper. From the fiber harvesting data on a life cycle assessment of abaca (Cortez *et al.* 2015), tow- or residual-grade abaca fiber is about 5% of total fibers produced, while the stripping and tuxy wastes generated are estimated at 50–60% and more than five times of the total fibers, respectively. Thus – for an annual average abaca fiber production of about 60,000 MT – tow, stripping, and tuxy wastes are estimated at 3,000 MT, 30,000 MT, and 300,000 MT, respectively.

MATERIALS AND METHODS

Fiber Analyses of Tow-grade Abaca, Tuxy, and Stripping Wastes

The raw material in stripping of abaca fibers is the tuxy, which is the outer layer of the abaca leafsheath separated from the inner layer. Tuxy waste is the inner layer of the abaca leafsheath after stripping of the tuxy. Tuxy wastes are usually left in the field. Stripping waste is the final waste after stripping the fibers from tuxy layers (PhilFIDA/GIZ/Glatfelter 2016).

Tow grade abaca fiber is the lowest of residual grades of hand and spindle/machine stripped abaca fiber. Tow fiber is less than 60 cm in length and consists of abaca tip cuttings that are short, tangled, and broken – resulting from sorting during the process of classification (PhilFIDA 2016).

Figure 1 shows the usual processing of abaca from the fields indicating where the experimental fibers tow, tuxy waste, and stripping wastes are derived.

Samples of tow-grade fibers from an abaca pulp mill, tuxy, and stripping wastes from abaca farms in Catanduanes province, Philippines were cut to 2.54 cm long and submerged in test tubes with macerating liquid of equal volumes of hydrogen peroxide and glacial acetic acid. Following the Franklin (1945) method of maceration, the test tubes were placed in a hot water bath for 1–2 h or until the raw fibers turned whitish and soft. The macerated samples were washed thoroughly in running water until pH of water with the sample was almost neutral.

The fibers were dispersed by shaking the sample in distilled water. Using a medicine dropper, 1 mL portions were placed on slides, stained with Safranine for greater visibility – after which 50 random whole fibers were measured. The fibers were viewed under Primo Star Zeiss light microscope at a magnification of 10X for fiber length and 40X for fiber diameter, lumen width, and cell wall thickness. The dimensions were measured using a computer program, Zen Lite 2012. To ensure a uniform reference point for each fiber, cross-sectional measurement was taken at the widest portion. The mean of the fiber dimensions of each sample was computed and classified based on the FPRDI standards and procedures for descriptions of dicotyledonous woods/fibers (Tamolang *et al.* 1963) and microscopic features by IAWA Bulletin (Wheeler *et al.* 1989). Photographs of sample fibers were taken to accompany sample descriptions.

Derived values. Suitability of the fibers for pulp and papermaking were evaluated from the derived values calculated from the dimensions obtained. The derived values are:

slenderness ratio or felting point = L / D

flexibility ratio = lw / D

fiber density = 2 W / D

Runkel ratio = 2 W / lw

Muhlsteph ratio = $[1 – (lw / D)^2 \times 100]$

where L = fiber length, D = fiber diameter, W = cell wall thickness, and lw = lumen width.

Pulping, Beating, Handsheet Preparation, and Property Testing

The two sets of abaca fibers – tow, and Tx80Sw20 [80:20 mixture of tuxy, Tx, and stripping wastes (Sw)] – were pulped separately and the percentage yields and Kappa numbers were determined. Pulping was done in a laboratory rotary digester with a standard volume of 15 L. Maximum temperature was 170 °C with a working pressure range of up to 8 kg/cm^2. Temperature was digitally-controlled and with an automatic safety over-pressure release valve. About 1 kg samples (oven-dry weight basis) were cooked with sodium hydroxide (NaOH) at 8, 10, and 12% charges at liquor-to-fiber ratio of 5:1. The time required to raise the maximum temperature from the room temperature was 120 min. Cooking time was held for 120 min at 170 °C.

Tow pulp from the 8% NaOH level was subjected to beating in the laboratory valley beater for 0, 5, 10, 15, 30, and 35 min – with the drainability or pulp freeness determined each time. Handsheets were formed from

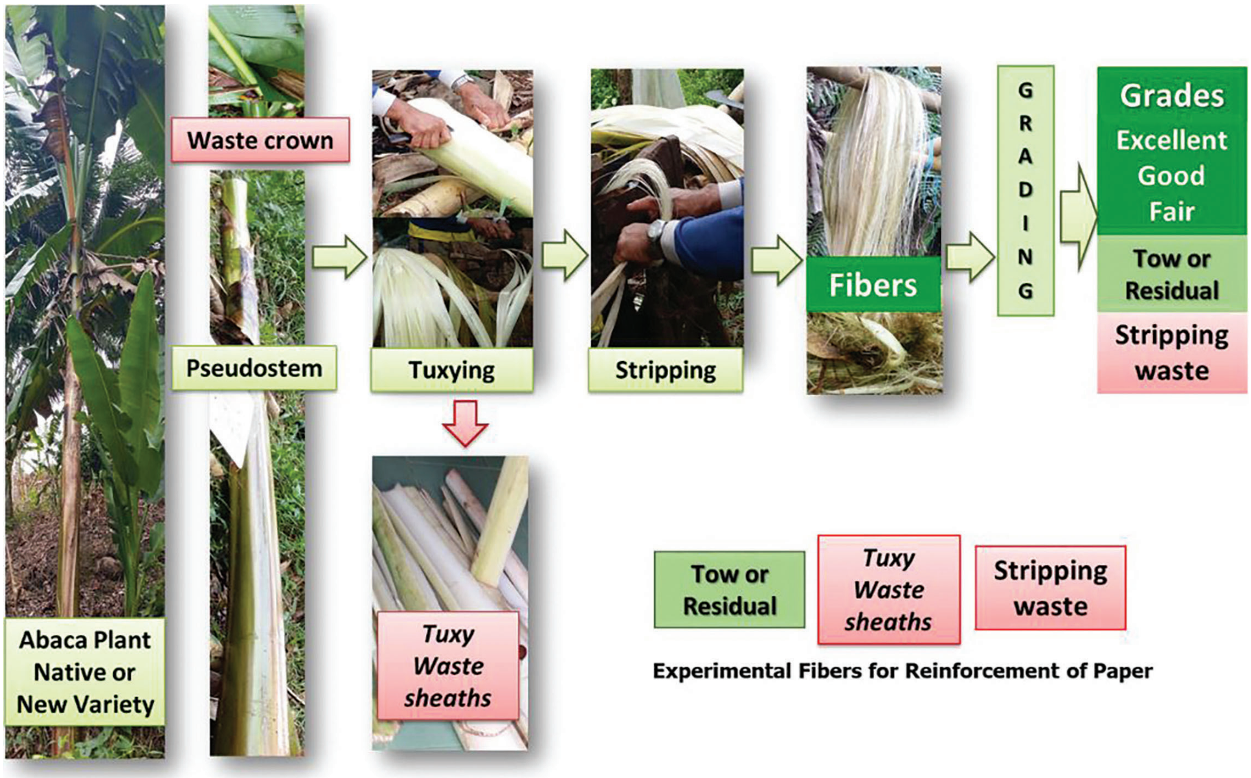

Figure 1. Traditional extraction of abaca fiber.

the pulp from each beating time and the properties (tear, tensile, burst, and folding properties) tested and compared with recycled fiber, OCC, and MOW. The OCC was obtained from a paper mill, while the MOW was gathered from used writing materials at the office. These were simply disintegrated and their pulp freeness measured before handsheet forming. Meanwhile, the pulp freeness of the tuxy/stripping waste pulp similarly cooked with 8% NaOH was also determined. No further beating was conducted.

Experimental Pulp Blends for Packaging Paper and Printing/Writing Paper

Table 1 shows the pulp combinations of the above beaten pulps with either OCC or MOW to produce handsheets for packaging paper and printing/writing paper, respectively. Maximum level of reinforcement was set at 10% in view of the high cost of even the residual grade commercial abaca pulp. All the pulp materials were separately beaten or disintegrated and appropriately mixed prior to handsheet forming. Target basis weight for all handsheets, including OCC and MOW, was 60 g/m^2. The handsheets were similarly tested for strength properties, tear, tensile, burst, and folding endurance.

The following standard methods and tests were followed in the above experiments:

Table 1. Recycled fiber and abaca pulp proportions to produce abaca-reinforced packaging and printing/writing paper.

Paper grade	Recycled fiber	Residual abaca	Waste abaca
	% in pulp furnish		
	OCC	Tow	Tx80Sw20
Packaging	100	–	–
	90	8	2
	93	5.6	1.4
	95	4	1
	97	2.4	0.6
	MOW	Tow	Tx80Sw20
Printing/ Writing	100	–	–
	90	8	2
	93	5.6	1.4
	95	4	1
	97	2.4	0.6

- ISO 5264-1:1979, Pulps – Laboratory beating, Part 1: Valley beater method
- ISO 5267-2:1999, Pulps – Determination of drainability, Part 2: "Canadian Standard" freeness method

- ISO 302:1981, Pulps – Determination of Kappa number
- TAPPI. 1988a. Test Methods T 205 om-88: Forming handsheets for physical tests of pulp.
- TAPPI. 1988b. Test Methods T 220 sp-01: Physical testing of pulp handsheets.

Evaluation of Data using SAS® Analytics Pro
One-way analysis of variance (ANOVA) in completely randomized design was used to analyze (1) variation due to the three fiber materials (tow, tuxy waste, and stripping waste) on the fiber properties (fiber length, fiber diameter, lumen width, cell wall thickness) of abaca; and (2) variation due to the pulp blends or abaca fiber reinforcement level on the strength properties of the papers (handsheets) produced. Means of tested properties were separated using Tukey's Honest Significance Difference (HSD) test ($\alpha = 0.05$).

RESULTS AND DISCUSSION

Fiber Dimensions
Table 2 summarizes the results of fiber measurements on the three abaca fiber samples shown in Figure 2 (with 0.1 mm scale shown). Tow fiber length ranged 3.31–6.92 mm while cell wall thickness, measuring 2.2–8.2 microns, was considered extremely long and thin. The average fiber length for commercial grade abaca was reported at 6.0 mm by Atchison (1993); 4.4 mm by Yamazaki *et al.* (1980); and 3.15–5.45 mm by Zerrudo and Escolano (1978). It is remarkable that the fiber length of the tuxy and stripping wastes ranged from medium to extremely long (0.92–7.73 mm) while the cell wall thickness was thin (2.0–8.0 microns). The fibers compare well with temperate zone coniferous wood with fiber length ranging 2.7–4.6 mm; and are much longer than hardwoods (0.7–1.6 mm), tropical hardwoods (0.7–3.0 mm), *Eucalyptus* (0.7–1.3 mm), and *Gmelina* species (0.8–1.3 mm) (Atchison 1993). Ververis *et al.* (2004) also reported on several non-wood fibers and wood fibers with fiber length ranging from 0.74 (Kenaf core) to 2.32 mm (Kenaf bark).

ANOVA indicated that the three fiber materials differed significantly in all four dimensions measured *i.e.*, fiber length, fiber diameter, lumen width, and cell wall thickness (Table 3). In terms of the first three dimensions, the stripping waste was significantly lowest in values, but the tuxy waste had the thinnest cell wall (Table 4). Long, fine, and thin-walled softwood fibers were reported to make strong sheets (Seth 1999).

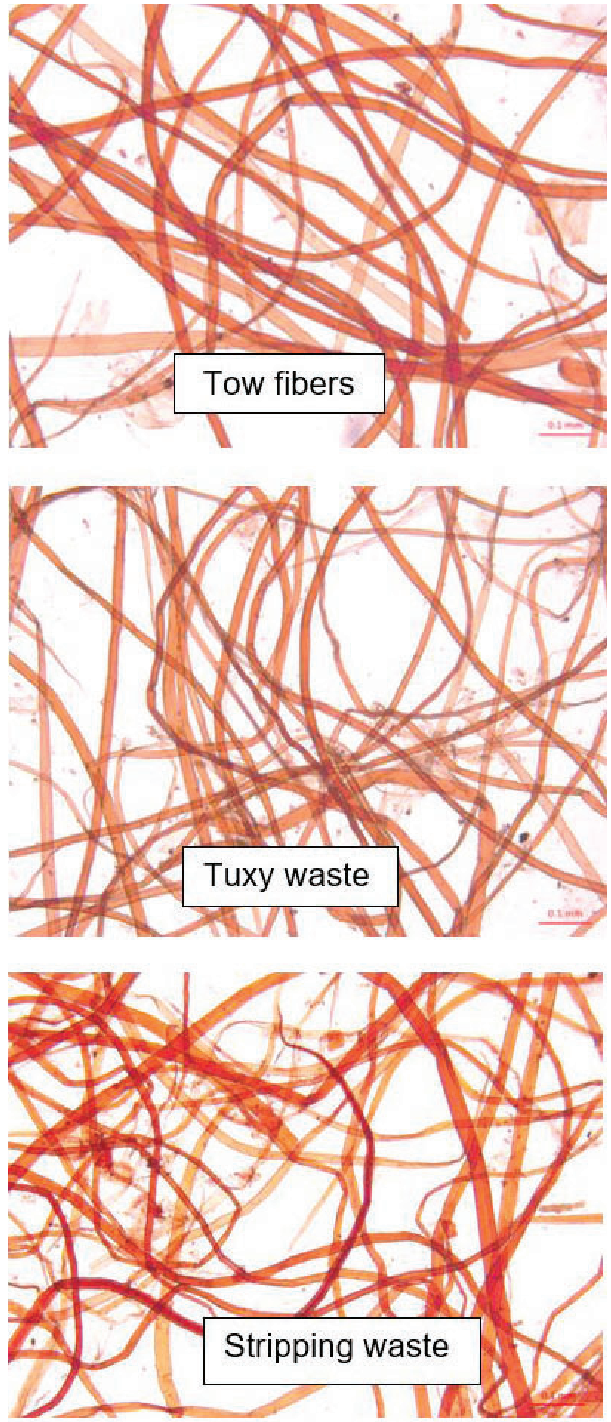

Figure 2. Photographs of the three abaca fibers.

Table 5 shows the derived values to evaluate the suitability of the fibers for pulp and papermaking compared with hardwood and softwood fibers. Both Runkel and Muhlsteph ratios of the abaca fibers compare with those of hardwood, but slenderness is much higher than that of softwood.

Table 2. Fiber dimensions of the fibers.

Abaca fiber		Fiber dimensions (range and average in mm)		
	Length	Diameter	Lumen width	Cell wall thickness
Tow	3.3100–6.9200	0.0167–0.0410	0.0096–0.0310	0.0022–0.0082
	Ave. **4.9428**	**0.0294**	**0.0202**	**0.0046**
Tuxy waste	2.1600–7.7300	0.0148–0.0450	0.0079–0.0400	0.0020–0.0060
	Ave. **4.6008**	**0.0289**	**0.0214**	**0.0038**
Stripping waste	0.9200–6.3600	0.0140–0.0423	0.0063–0.0310	0.0025–0.0080
	Ave. **3.6446**	**0.0260**	**0.0157**	**0.0052**

Note: Average of 50 measurements

Table 3. ANOVA on fiber dimensions of the three abaca fiber materials.

Source of variation	df	Fiber length, mm			Fiber diameter, mm			Lumen width, mm			Cell wall thickness, mm		
		Mean square	F value	Pr > F	Mean square	F value	Pr > F	Mean square	F value	Pr > F	Mean square	F value	Pr > F
Abaca fiber	2	22.6384	13.53	<.0001**	0.00017923	4.13	<.0180*	0.00045558	10.89	<.0001**	0.00002523	19.67	<.0001**
Error	147	1.6729			0.00004186			0.00004185			0.00000128		
Corrected total	149												
		R-square (%) = 15.6; CV = 29.4223			R-square (%) = 5.3; CV = 23.0152			R-square (%) = 12.9; CV = 33.930			R-square (%) = 21.1; CV = 24.9424		

**statistically significant at α = 0.05*
***statistically significant at α = 0.01*

Table 4. Tukey's HSD Test on the fiber dimension means.

Abaca fiber	Fiber length, mm		Fiber diameter, mm		Lumen width, mm		Cell wall thickness, mm	
Tow	4.9428	a	0.029429	a	0.020157	a	0.0046875	a
Tuxy waste	4.6008	a	0.028923	ab	0.021387	a	0.0037678	b
Stripping Waste	3.6446	b	0.025985	b	0.015654	b	0.0051656	a

Note: Column means followed by the same letter are not significantly different at $\alpha = 0.05$.

Table 5. Derived values for suitability for papermaking.

Fiber	Fiber length µm	Runkel ratio (RR) 2W / lw	Slenderness (felting point) L / D	Flexibility lw / D	Coefficient of rigidity W / D	Muhlsteph ratio (MR) [1 – (lw / D)^2 x 100]
Tow	4942	0.4605	167.9579	0.6849	0.1564	53.0873%
Tuxy waste	4601	0.3523	159.0701	0.7395	0.1315	45.3203%
Stripping wastes	3645	0.6600	140.2596	0.6024	0.2000	63.7095%
Hardwood		0.4–0.7	55–75			55–70
Softwood		0.35	95–120			75

Note: L – fiber length, W – cell wall thickness, D – fiber diameter, lw – lumen width

Pulping, Beating, Handsheet Preparation, and Property Testing

Pulp yields. Table 6 shows the % yield, % accept, % reject, and Kappa number values of the abaca tow and tuxy/stripping waste fibers after pulping under different charges of NaOH. The amount of pulping chemical did not show a marked effect on yield. The % yield and % accept values of tow grade fiber is about twice *vis-à-vis* the mixture of tuxy and stripping waste fibers. While the results on fiber mensuration of the three fibers indicated

Table 6. Yield and Kappa number of residual grades of abaca fibers at three levels of soda pulping charge.

Abaca fibers	Chemical concentration	% Accept	% Reject	% Total yield	Kappa number
Tow	8% NaOH	62.64	6.40	69.04	53.42
Tow	10% NaOH	62.42	7.02	69.44	46.55
Tow	12% NaOH	59.48	2.88	62.33	43.24
Tuxy: stripping (80:20)*	8% NaOH	36.82	6.64	43.46	49.00
Tuxy: stripping (80:20)*	10% NaOH	28.83	6.41	35.24	45.03
Tuxy: stripping (80:20)*	12% NaOH	29.39	7.10	36.49	43.63

*Henceforth referred to as Tx80Sw20

that they are all suitable for pulp and papermaking, the tow fibers are actually the end portions of graded fibers whereas both tuxy and stripping wastes are real wastes usually left in the field. These wastes contain more parenchymatous elements, which are known to dissolve during pulping and responsible for the fines (Horn 1978, Anupam *et al.* 2016). The high Kappa numbers indicate the need for bleaching; however, the pulps were no longer bleached as they were to be used for brown packaging grade paper and writing paper.

Effect of beating on pulp freeness. Figure 3 illustrates the result of beating for the two fiber materials both pulped with 8% NaOH. Unbeaten tow pulp had a freeness value of 665 mL to 230 mL after 35 min of beating. Freeness is a measure of drainability of pulp in which a higher value indicates ease of draining water during forming. Ibrahem *et al.* (1989) obtained a much faster decrease in drainability of wood pulp from 744 mL to 191 mL after beating for 35 min.

Pulp from the Tx80Sw20 had a freeness of 227 mL without undergoing beating. This may be attributed to the fines from parenchymatous elements (Horn 1978, Anupam *et al.* 2016). Beating for 3.5 min drastically reduced this freeness to 161 mL. Hence, unbeaten Tx80Sw20pulp was used in the succeeding experiment.

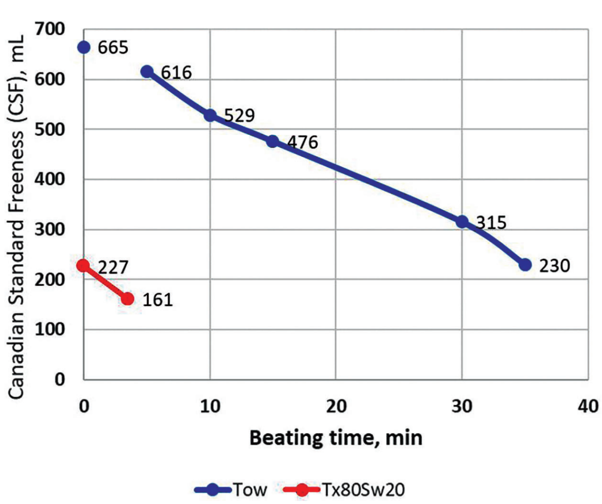

Figure 3. Effect of beating on pulp freeness. Note: Tx80Sw20 – tuxy: stripping (80:20)

Effect of beating on paper properties. As shown in Figure 4, the property indices – burst and tensile – of the tow pulp indicate increasing values with greater beating, reaching peaks at 12.2 kPA.m^2/g and 95.5 Nm/g, respectively at 315 mL CSF, while folding endurance decreased after 480 mL CSF. The tear index, however, decreased from 40.76 mN.m^2/g by more than half to about 16–20 mN.m^2/g.

For the Tx80Sw20 pulp – as the graphs illustrate – the tensile index (69.75 N.m/g) is still considerably high, but no further beating should be done as the pulp freeness (227

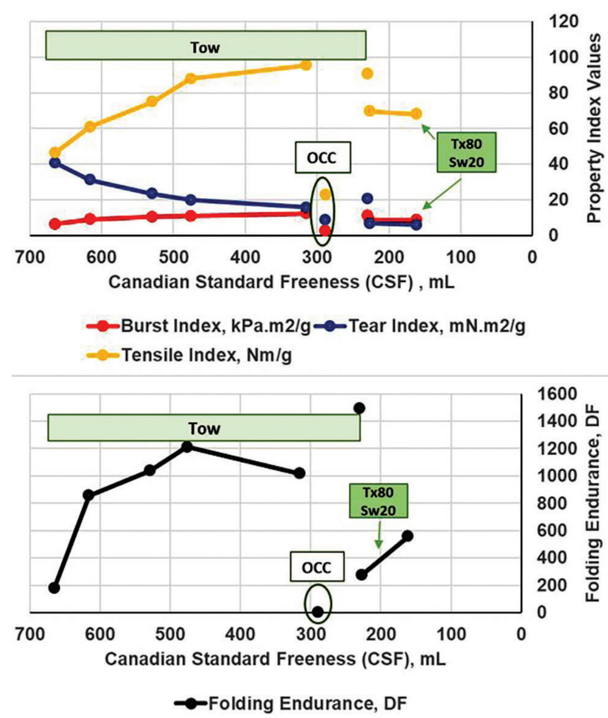

Figure 4. Effect of beating on the properties of handsheets from pulps from abaca tow fibers, tuxy-stripping waste, and OCC. Note: Tx80Sw20 – tuxy: stripping (80:20); OCC – old corrugated carton

mL) is already low and, consequently, the tear index (6.68 mN.m^2/g). Folding endurance is acceptable compared with the handsheets from OCC.

The handsheets from OCC are remarkably of very low tensile index (22.80 Nm/g), folding endurance, and burst index (2.62 kPA.m^2/g) – all of which are worse than in Tx80Sw20. Only tear index (8.56 mN.m^2/g) is higher than that of Tx80Sw20.

Results indicate the potential of both abaca Tow and Tx80Sw20 fibers to reinforce OCC.

Effect of pulp blends on packaging paper. Figure 5 shows the strength properties of the handsheets produced from the pure pulps of OCC, tow, and Tx80Sw20 – as well as their different blending proportions. Handsheets from tow pulp exhibited the highest strength values, followed by TX80Sw20 – particularly in tensile strength – while OCC registered the lowest values. The 80:20 combination of tow and Tx80Sw20 in small amounts (total of 10, 7, 5, and 3%) mixed with OCC remarkably increased all the strength properties compared with those from pure OCC. To wit, the 100% OCC (left end of the graphs) exhibited burst index, tear index, tensile index, and folding endurance values of 2.62 kPa.m^2/g, 8.56 mN.m^2/g, 22.80 Nm/g, and 0.56, respectively. Upon replacement of its 3% with Tow/Tx80Sw20 pulp (right end of the graphs), the values increased by 79%, 25%, 77%, and more than 85 times, respectively. This is a clear reinforcement for recycled fibers with just a small amount of residual grade and waste abaca fibers.

Table 7 shows highly significant effect of blending residual grade abaca pulp with OCC on the properties of the resulting handsheets, even at only 3% replacement of OCC as the results of Tukey's HSD test (Table 8) indicate.

Effect of pulp blends on printing/writing paper. Figure 6 illustrates the results of tests on handsheets prepared from blends of MOW with the same sets of residual grade/waste abaca pulps in previous experiment on packaging paper. The trends for all properties are similar with those obtained for experiments on packaging paper, but the increase in

Table 7. ANOVA on the effect of residual grade/waste abaca pulps on OCC.

Source of variation	df	Burst index			Folding endurance		
		MS	F value	Pr > F	MS	F value	Pr > F
Pulp blends	6	76.0270	112.83	<.0001**	949201.3380	53.61	<.0001**
Error	63	0.6738			17705.1100		
Corrected total	69						
		R-square (%) = 91.5	CV = 14.2374		R-square (%) = 92.0	CV = 54.1992	
Source of variation	**df**	**Tear index**			**Tensile index**		
		MS	F value	Pr > F	MS	F value	Pr > F
Pulp blends	6	87.0789	172.51	<.0001**	2349.9591	94.81	<.0001**
Error	28	0.5048			24.7870		
Corrected total	34						
		R-square (%) = 97.4	CV = 5.9182		R-square (%) = 95.3	CV = 9.993	

**Statistically significant at $\alpha = 0.01$

Table 8. Tukey's HSD test on the property means of the handsheets from different blends of OCC with residual grade/waste abaca pulps.

Pulp blends	Burst index, kPa · m^2 / g		Tear index, mN · m^2 / g		Tensile index, Nm / g		Folding endurance, DF	
Tow	10.71	a	19.79	a	87.88	a	1212.56	a
Tx80Sw20	8.27	b	6.68	e	69.75	b	276.28	b
OCC/Tow/Tx80Sw20 = 90/8/2	5.11	c	12.92	b	42.08	c	86.72	bc
OCC/Tow/Tx80Sw20 = 93/5.6/1.4	4.24	c	13.04	b	42.78	c	43.85	bc
OCC/Tow/Tx80Sw20 = 95/4/1	4.71	c	12.33	b	43.06	c	49.92	bc
OCC/Tow/Tx80Sw20 = 97/2.4/0.6	4.70	c	10.71	c	40.40	c	48.63	bc
OCC	2.62	d	8.56	d	22.80	d	0.56	c

Note: Column means followed by the same letter are not significantly different at $\alpha = 0.05$.

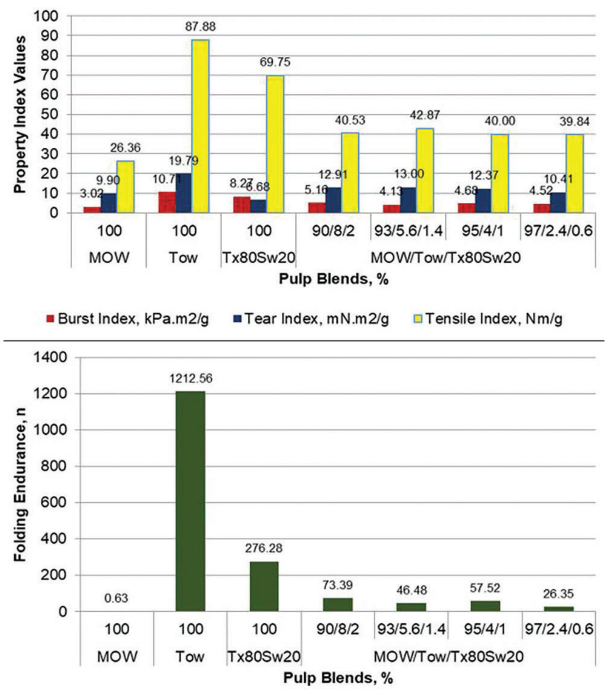

Figure 6. Effect of blending abaca tow and tuxy-stripping waste with MOW on the strength properties of paper for printing/writing. Note: Mean values outside each bar; Tx80Sw20 – tuxy: stripping (80:20); MOW – mixed office wastepaper

values due to replacement of MOW with the residual grade/waste abaca pulps is a bit lower. The MOW itself exhibited higher strength properties than the OCC. Thus, the increases in burst index, tear index, tensile index, and folding endurance with 3% replacement of MOW with residual grade/waste abaca pulps are 50%, 5%, 51%, and 40 times, respectively.

Results of statistical analyses among the 100% MOW and MOW/Tow/Tx80Sw20 pulp furnishes also indicate highly significant effect of the residual/waste grade pulps on the handsheets prepared (Table 9). Ranking of the treatment means by Tukey's HSD test (Table 10) shows that the burst, tensile, and folding properties of handsheets from pure wastepaper improved significantly even with only 3% replacement with residual abaca pulp (WP/Tow/Tx80Sw20=97/2.4/0.6). For tear index, 5% replacement is a safer level to make a significant difference.

CONCLUSION

The study proved that the tuxy waste sheaths (Tx) and stripping wastes (Sw) from the harvesting and processing of abaca are as suitable as the residual grade (Tow) abaca

Table 9. ANOVA on the effect of residual grade/waste abaca pulps on MOW.

Source of variation	df	Burst index			Folding endurance		
		MS	F value	Pr > F	MS	F value	Pr > F
Pulp blends	4	6.4693	34.67	<.0001**	3993.0511	21.29	<.0001**
Error	45	0.1866			187.5462		
Corrected total	49	6.4693					
		R-square (%) = 75.5	CV = 10.034		R-square (%) = 81.0	CV = 33.503	
Source of variation	**df**	**Tear index**			**Tensile index**		
		MS	F value	Pr > F	MS	F value	Pr > F
Pulp blends	4	10.6093	14.38	<.0001**	216.1541	11.66	<.0001**
Error	20	0.7377			18.5355		
Corrected total	24						
		R-square (%) = 74.2	CV = 7.3308		R-square (%) = 69.9	CV = 11.53	

**Statistically significant at $\alpha = 0.01$

Table 10. Tukey's HSD Test on the property means of the handsheets from different blends of MOW with residual grade/waste abaca pulps.

Pulp blends	Burst index, kPa · m²/ g	Tear index, mN · m²/ g	Tensile index, Nm / g	Folding endurance, df
Tow	10.71	19.79	87.88	1212.56
Tx80Sw20	8.27	6.68	69.75	276.28
MOW/Tow/Tx80Sw20 = 90/8/2	5.16 a	12.91 a	40.53 a	73.39 a
MOW/Tow/Tx80Sw20 = 93/5.6/1.4	4.13 a	13.00 a	42.87 a	46.48 bc
MOW/Tow/Tx80Sw20 = 95/4/1	4.68 ab	12.37 a	40.00 a	57.52 ab
MOW/Tow/Tx80Sw20 = 97/2.4/0.6	4.52 b	10.41 b	39.84 a	26.35 cd
MOW	3.02 c	9.90 b	26.36 b	0.63 d

Note: Column means followed by the same letter are not significantly different at $\alpha = 0.05$.

fibers for pulp and papermaking in terms of their fiber dimensions and their corresponding Runkel, Muhlsteph, and slenderness ratios. However, the pulp yield of the waste fibers (about 30%) is about half that of the tow fiber.

On the other hand, to arrive at desirable properties, the tow pulp needs to be refined or beaten for 15–30 min, whereas the waste fiber pulp no longer needs beating as its pulp freeness is already low. This implies possible savings from energy that may compensate for the cost disadvantage due to low pulp yield.

For use as reinforcement in paper, an 80:20 pulp mixture of tow and Tx80Sw20 when used to replace OCC/WP or MOW pulp at 3–10% levels for the production of packaging paper and printing/writing paper, respectively, can significantly improve paper properties.

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