

Linerboard Made from Soda-Anthraquinone (Soda-AQ) Treated Coconut Coir Fiber and Effect of Pulp Beating

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The performance of coir fiber in the production of linerboard made from soda-anthraquinone (soda-AQ) pulp was evaluated. Based on chemical analysis, the composition of coir fiber is suitable for the pulping process. Out of nine pulping conditions characterized, a pulping condition of 18% active alkali for 90 min cooking time was chosen. These conditions provided the highest screened yield (48.99%), a low rejection yield (0.27%), high viscosity (11.73 cP), and a kappa number (41) that is acceptable for unbleached linerboard production. Beating strengthened the coir pulp. Analyzing the beating revealed that coir pulp was optimized at 1000 to 2000 revolutions, based on a graph of freeness vs. burst index. For all beating conditions (1000 to 8000 revolutions), FESEM micrographs showed the presence of internal and external fibrillation of the fiber, which gradually increased fiber conformability and improved the inter-fiber bonding within the paper formation. Based on its burst strength of 4.57 kPa.m²/g and ring crush test of 1.76 Nm²/g, which complies with the minimum requirement of the industry standard, coir fiber can be considered an alternative fiber source for linerboard production.

Keywords: *Coir fiber; Soda-AQ pulping; Pulp and paper; Beating; Linerboard*

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INTRODUCTION

Coir is a lignocellulosic material derived from coconuts and is currently used extensively in many applications such as yarn, ropes, geo-textiles, brushes, and a variety of floor-furnishing materials. Coconuts are the fruit of *Cocos nucifera*, a tropical plant of the Arecaceae (Palmae) family, and are abundantly grown in the coastal areas of tropical countries. Coconut husk, which yields the coarse coir fiber, is fibrous and dry at maturity and is available in large quantities as residue from coconut oil production in Malaysia. In Malaysia, coconut is the fourth-most important industrial crop after oil palm, rubber, and paddy. There were about 108,828 hectares of coconut plantations in 2011, which produced about 577,647 metric tons worth about RM 264 million. The coconut industry is an important economic activity for approximately 80 thousand farmers and their families. Nowadays, over 98% of the land is the property of smallholders, while 2% is owned by large corporations. The Malaysian government plans to increase coconut production from 530 thousand metric tons (530 million seeds) in 2010 to 1.2 million metric tons (1.2 billion seeds) in 2020 (a growth of 8.7% per annum) in order to meet the

high local demand. This increase in production will be achieved through the increased productivity of 4.8 tons per hectare to 15.1 metric tons per hectare (MAO 2014).

Traditional coir products comprise only a small percentage of the potential total world production of coconut husk. According to Wang and Huang (2009), about 55 billion coconuts are harvested annually in the world, but only 15% of the husk fibers are currently recovered for consumption. Hence, research and development efforts have been undertaken to find new use for coir, *e.g.*, as a reinforcement in polymer composites (Monteiro *et al.* 2008; Satyanarayana *et al.* 2009; Asasutjarit *et al.* 2009; Ali 2010; Yao *et al.* 2012), cement composites, and particle board for building construction (Khedari *et al.* 2004; Agopyan *et al.* 2005; Asasutjarit *et al.* 2007).

There have been relatively few reports on the usage of coir fibers as an alternative raw material for pulp and paper products. For instance, Mohamad Jani and Rushdan (2014) have successfully produced bleached paper from coir fibers using a chemi-mechanical pulping process. Based on their findings, the bleached pulp-produced paper resulted in high tensile, burst and tear indices, and folding endurance, as well as high brightness properties. However, the paper had lower opacity compared with the unbleached pulp because of the removal of lignin. The fiber dimensions, derived values, and paper properties of coir fiber by the soda-AQ pulping process were recently reported by Nor Mazlana *et al.* (2014). They found that coir fibers are characterized as short fibers that have a felting power comparable to hardwood, high flexibility, and high runkel ratios. These characteristics are suitable for yielding pulps with acceptable tear, burst, and tensile indices. Based on the paper properties of coir fibers, the strength properties could not be further improved when the coir was cooked with 22% active alkali for 150 minutes because of carbohydrate degradation of the pulp fiber. These previous studies publicized by Mohamad Jani and Rushdan (2014) and Nor Mazlana *et al.* (2014) express that coir fiber's properties indicate its suitability as an alternative raw material for producing paper products, such as paper and board, for packaging applications.

Paper is an essential material that is used in packaging industry worldwide because of its remarkable properties such as being natural, renewable, inexpensive, and biodegradable. Packaging paper has been the largest category in paper industry production worldwide, accounting for 51.7% by mass in 2009. Printing and writing paper was ranked the second largest category (21.8% of the total), followed by newsprint paper (11.2%) (Jukka 2011). Similarly, in Malaysia, packaging paper contributes almost 50% of the total paper manufacturing production. Malaysia is a net importer of pulp (Singh *et al.* 2012), particularly virgin long-fiber pulp. Basically, the Malaysian paper and paperboard industries have been mixing imported virgin long-fiber pulp with secondary fibers, such as old corrugated container (OCC) and waste papers in order to produce paper that meets the requirements stated in the packaging specifications. However, the imported virgin pulp is expensive and can contribute to the additional cost in papermaking industry. Because of this, the Malaysian government has encouraged the utilization of non-wood sources gathered from either annual crops or agricultural residues as another alternative source in papermaking (FRIM 2009). From there, dependence on imported pulp, paper, and paperboard has diminished. In Malaysia, there are a wide variety of non-wood fibers that can be used for papermaking purposes such as bamboo, bagasse, kenaf, rice straw, oil palm empty fruit bunches (EFB) and oil palm fronds (OPF). Recently, the utilization of EFB as raw material for pulp and paper production has been developed by Eko Pulp and Paper Sdn. Bhd. with the collaboration between Forest Research Institute of Malaysia (FRIM) and Malaysian Palm Oil Board (MPOB). The manufacturing plant was located in

Kunak, Tawau, in the State of Sabah, Malaysia. The pulp and paper mill has capacity to produce up to 30,000 tons of pulp a year (www.ekopulpn.paper.com). Alkaline pulping is the most frequent pulping process for non-wood materials.

The two principle alkaline pulping processes used in chemical pulping are soda and kraft pulping. The addition of anthraquinone (AQ) in the soda pulping process generally increases the rates and selectivity of delignification, as well as reducing alkali charges and improving pulp properties and yields (Lowendahl and Samuelson 1977; Fleming *et al.* 1978; Khristova and Karar 1999; Shakhes *et al.* 2011) without environmental damage due to the absence of sulphur emissions (Holton 1977; Jiménez *et al.* 2009). Based on the previous work, numerous results have demonstrated that for soda with addition of AQ, the pulp offered was much higher in viscosity and its handsheets imparted better or comparable kappa number, brightness, and strength properties in comparison to the kraft pulp (Rodríguez *et al.* 2008; Ang *et al.* 2010). However, AQ cannot be employed in direct food contact paper and linerboard due to Proposition 65 (2011), German BfR (2013) and European Union (2014) requirements.

Beating is one of the most important processes performed on pulp fibers for improving certain physical properties of the final paper products. The main purpose of beating is to improve inter-fiber bonding and to develop the optimum strength of the pulp fiber. During this process, the outer fiber surfaces are removed, which causes external fibrillation, and increasing amounts of cellulosic fines are formed. The fines contribute to the bulk and opacity of the paper. At the same time, internal fibrillation occurs in the pulp fibers, which results in the expansion of fiber swelling and fiber flexibility (Ahmad Azizi *et al.* 2010). Both internal and external fibrillation provide better inter-fiber bonding in paper formation.

The main objective of this study was to evaluate the suitability of coir fiber utilization in producing linerboard using soda-AQ pulping. The effect of the beating process using the chosen pulp was then evaluated to determine the properties of linerboard from optimized pulp beating. Therefore, the outcomes from this study would be beneficial to the industry as a method for selecting the appropriate parameters to produce unbleached linerboard, according to the specific packaging products.

EXPERIMENTAL

Materials

For this study, coir fibers were used as the raw material and were supplied by Seng Kiat Coconuts Industries Sdn. Bhd., Perak, Malaysia. All raw material used was supplied at one time to ensure that changes in the raw materials were minimized. The raw material was then cut to the size of 2 to 5 cm using a fiber cutter and stored for later use. The various chemicals used for chemical analysis, pulping, and determination of Kappa number were purchased from local suppliers.

Methods

Chemical analysis

For chemical composition analysis, coir fibers were ground into fine fibers using a Wiley Mill. To obtain a homogenous sample, the ground fibers were then sieved through BS 40-mesh (425 µm) and BS 60-mesh (250 µm) sieve screens to remove fine and rough fibers, as described in Technical Association of the Pulp and Paper Industry (TAPPI)

Standards T 257 cm-02 - Sampling and Preparing Wood for Analysis. The determination of extractives content was carried out based on TAPPI T 204 cm-97, where ethanol-toluene (1:2) was used as the solvent. Holocellulose content of the extractive-free sample was determined according to Wise *et al.* (1946). The α -cellulose content was analysed according to the procedure described in the TAPPI T 203 os-74. Pentosan was determined using the method of Savard *et al.* (1954). The determination of lignin, alkali solubility, water solubility, ash, and silica content were performed as per TAPPI Standards Methods T 222 om-02, T 212 om-02, T 207 cm-99, and T 211 om-02, respectively. Each analysis was carried out in triplicate.

Chemical pulping and pulp characterization

The pulping experiment was conducted using a completely randomized design as full factorial with the two factors of active alkali (18%, 20%, 22%) and cooking time (90 min, 120 min, and 150 min). The soda-AQ pulping of 300 g of coir fibers (based on oven-dried fiber) was performed (Table 1) in a mini laboratory digester (MK systems, USA) with a 6-L capacity. The digester is equipped with a recirculation system with an external heat exchanger. The percentage of AQ concentration, cooking temperature, time to reach cooking temperature, and the ratio of liquor to raw materials were held constant during all experiments. The amount of AQ added into the liquor was the maximum value permitted by the Food and Drug Administration (FDA) of the United States (FDA 2014). Cooking temperature of 170 °C were selected based on the previous researches working with kenaf (Ibrahim *et al.* 2011) and EFB (Rushdan 2003a). The resultant pulp was completely cooked with desirable pulp and paper properties in these operating conditions. Since the coir fibers are very bulky, the high ratio of liquor to material (L: M) was 8:1 in order to have sufficient white liquor to completely immerse the material.

Table 1. Soda-AQ Pulping Condition for Coir Fibers

Pulping Condition	AA (%)	AQ (%)	L:M	Time to Temp. (min)	Time at Max. Temp. (min)	Cooking Temp. (°C)
L1	18	0.1	8:1	90	90	170
L2	18	0.1	8:1	90	120	170
L3	18	0.1	8:1	90	150	170
M1	20	0.1	8:1	90	90	170
M2	20	0.1	8:1	90	120	170
M3	20	0.1	8:1	90	150	170
H1	22	0.1	8:1	90	90	170
H2	22	0.1	8:1	90	120	170
H3	22	0.1	8:1	90	150	170

AA=active alkali (as Na₂O based on o.d fiber); AQ=anthraquinone; L:M=ratio of liquor to material; Time to Temp.=time to temperature; Time at Max. Temp.=time at maximum temperature; Cooking Temp.=cooking temperature; L=Low; M=Medium; H=High

At the end of the pulping process, pressure was reduced to atmospheric pressure. The resultant pulp was washed thoroughly with fresh water and disintegrated using a hydropulper for 10 min. Disintegrated pulps were screened in a vibratory flat screen with a slot width of 0.15 mm to determine screen rejects (pulp shives) and screen yield. Then, screen yield was spin-dried and disintegrated by a Hobart mixer. Yield and reject pulp were determined based on an oven-dried material basis. The reported total yield is the

sum of the reject and screen yields. Kappa number for all screened pulp samples was determined in accordance with TAPPI T 236 om-99. Meanwhile, the freeness and viscosity of the pulp were determined according to TAPPI T 227 om-04 and TAPPI T 230 om-99, respectively.

Mechanical treatment, paper, and linerboard characterization

The pulp that was prepared using 18% active alkali and cooked for 90 minutes was the selected parameter to be considered for the beating process. The pulp was beaten at 1000, 2000, 4000, and 8000 revolutions using a PFI mill. Laboratory handsheets with a basis weight of 60 g/m² and 120 g/m² were made from the beaten pulps according to the TAPPI T 205 sp-02 (Forming Handsheets for Physical Tests of Pulp). The samples were then evaluated according to Malaysian Standard Methods (MS ISO) for various physical strength properties, including bursting strength (MS ISO 2758: 2001, IDT), tensile strength (MS-ISO 1924-2: 2008, IDT) and tear strength (MS ISO 1974: 1990, IDT). A ring crush test (RCT) was performed on the coir linerboard according to TAPPI T809 om-93. The sheets were conditioned at 23 °C ± 1 °C and 50% ± 2.0% RH (T 402 sp-03) for at least 24 h before testing was carried out.

Morphology

The coir papers were cut into small pieces 8 mm long and 5 mm wide. The fiber surface and cross-section morphology in the coir papers were observed using a field emission scanning electron microscope (FESEM) Model Gemini Supra 40VP at various magnifications (500 X and 800 X). The specimen was attached to aluminum stubs with double-sided carbon adhesive tape and coated with gold before the examination using FESEM.

Statistical analysis of pulp characteristics

One-way analysis of variance (ANOVA) was employed to examine the significant effects of each factor (active alkali and time at maximum temperature) and level (three levels for each factor) on the response variables in this study (pulp characteristics). Treatment score means were compared using Tukey's Group Range Test ($P \leq 0.05$) using Minitab R. 16.2 software.

RESULTS AND DISCUSSION

Chemical Analysis of Coir Fiber

Chemical analyses of the coir fibers were carried out in order to assess their suitability for pulp and papermaking (Table 2). As can be seen in Table 2, the chemical composition found in this work was consistent with the published data (Van Dam *et al.* 2006; Mohamad Jani and Rushdan 2014), considering natural variations in the chemical characteristics of the raw materials. The maturity of the coconut harvest may influence the chemical composition of coir fibers. For example, the lignin and glucose associated with the formation of cellulose content were strongly increased when the maturity period (month) was increased but had the adverse effect of increasing the extractives content of coir fiber (Van Dam *et al.* 2004).

Table 2 Chemical Analysis of Coir Fiber

Composition (%)	Experimental Values	Mohamad Jani and Rushdan 2014	Van Dam <i>et al.</i> 2006
Holocellulose	69.1 ± 0.5	70.50	N/A
α-cellulose	37.2 ± 0.2	37.40	33.3 to 35.5*
Lignin	32.7 ± 0.1	32.10	33.6 to 36.6*
Solvent extractives ^a	2.9 ± 0.1	2.66	1.8 to 2.9*
Alkali Solubility	16.4 ± 0.1	17.30	N/A
Hot water Solubles	5.9 ± 0.2	2.55	N/A
Cold water Solubles	7.9 ± 0.1	N/A	N/A
Ash	2.4 ± 0.1	2.14	1.6 to 2.6*
Silica	1.0 ± 0.0	0.50	N/A
Pentosan	20.2 ± 0.3	22.00	N/A

All values presented as percent of oven-dry raw materials; ^aEthanol toluene; N/A=Not available;
*The values are the minimum and maximum obtained by different varieties and maturity degrees, respectively.

Carbohydrate composition is important in determining coir fiber's response to processing conditions and the development of handsheet physical properties. Coir fibers are rich in holocellulose (69.1%). However, alpha cellulose comprises only 37.2% of coir fiber. From the chemical composition point of view, plant fibers with an α-cellulose content of 34% and higher are still considered as promising material for pulp and paper production (Nieschlag *et al.* 1960).

Coir fibers contained the highest percentage of lignin (32.7%) compared with other non-wood fibers, but the lignin content of coir is still lower than that of wood fibers (14 to 37%) (Tsoumis 1991). The high content of lignin in coir fiber made the fiber tougher and stiffer, compared to other fibers (Abdul Khalil *et al.* 2006; Ali 2010). Lignin is often referred to as the plant cell wall adhesive and needs to be removed from the fibers during the pulping process. The ease of delignification of the material during the chemical pulping process can be predicted from the lignin content (Abdul Khalil *et al.* 2006). In practice, this means that coir fiber requires moderate to high cooking chemicals and a longer cooking cycle than other non-wood fibers in order to reach a satisfactory kappa number and thereby improve its strength properties and apparent density.

Compared to the pineapple leaves, coir fibers contain a low percentage of ethanol toluene extractives (2.9%), hot water soluble (5.9%), and cold water soluble (7.9%), whereas pineapple leaves have 7.0%, 21%, and 26% composition of extractives, hot water, and cold water soluble, respectively (Tran 2006). The high percentages of extractives in organic solvents are totally undesirable for pulping (pitch problems), bleaching, and papermaking and have a direct impact on pulp yield. However, coir fibers show moderate alkali solubility (16.4%), and are comparable with softwood of black spruce (14.1%) (Berzins 1966), hardwood such as *Acacia mangium* (16.4%) (Law and Wan Rosli 2000), and non-wood fibers such as EFB (14.5%) (Rushdan 2002). Coir fibers' high solubility in alkali indicates that the extent of carbohydrate degradation during the pulping process and thus the screen yield of the chemical pulps, for example, kraft and soda, would be low.

The ash and silica contents of the coir fibers were 2.4% and 1.0%, respectively. The ash content was lower than that of non-wood fibers, such as kenaf (4.2%) (Ang *et al.* 2010), rice straw (9.2%) (Rodríguez *et al.* 2008), and pineapple leaves (7%) (Tran 2006). Silica content also indicated a low reading. This indicates normal alkali consumption and fewer problems with waste liquor recovery. Basically, high ash contents are undesirable for pulping as they affect normal alkali consumption and cause problems at recovery of the cooking liquor and operational problems in material handling, pulp washing, and pulp beating (Dutt *et al.* 2009).

The pentosan content in coir fibers was found to be 20.2%, which is comparable with those normally found in common hardwood, *e.g.*, trembling aspen (20.2%) and white birch (24.1%) (Berzins 1966). Generally, pentosan indicates the retention or loss of hemicelluloses during the pulping and bleaching processes, and since hemicellulose contributes to the strength of paper pulps, high pentosan content is desirable (TAPPI T 223 cm-01).

Pulping and Pulp Characterization

The soda-AQ pulping of coir fibers with Tukey's Range Grouping are summarized in Table 3. Statistically, some of the results were found to be different between the parameters being assessed.

Based on the results of the screened yield, a significant reduction in yield was observed (48.99% to 38.26%) as the alkali charge (18% to 22%) and duration (90 to 150 minutes) of the pulping process were increased. The screen pulp yield of the optimum condition was L1 (49.26%). The screened yield is an extremely important parameter for the pulp manufacturer while considering the economic aspects related to material consumption because the raw material is accountable for most of the pulp production cost. Alén (2000) established that during alkaline pulping of lignocellulose, alkali-catalyzed reactions (primary peeling) are mainly responsible for the loss of yield. This involves a stepwise elimination of monosaccharide moieties from carbohydrates starting at their reducing ends and continuing along the polymeric chain until an alkali stable end group is formed by a competing reaction (the stopping reaction).

Table 3. Pulp Properties Results of Coir Fiber

Pulping Condition	Total Yield (%)	Screened Yield (%)	Reject (%)	Kappa No.	CSF (mL)	Viscosity (cP)
L1	49.26 ^a	48.99 ^a	0.27 ^a	41 ^a	646 ^a	11.73 ^a
L2	47.33 ^b	47.08 ^b	0.25 ^a	36 ^{ab}	636 ^a	11.56 ^a
L3	45.07 ^c	44.88 ^c	0.19 ^{cd}	35 ^b	610 ^{bc}	11.42 ^a
M1	43.83 ^{cd}	43.59 ^{cd}	0.25 ^{ab}	34 ^b	617 ^b	11.00 ^{ab}
M2	43.13 ^{de}	42.94 ^{de}	0.20 ^{bc}	27 ^{cd}	607 ^{bcd}	9.25 ^{cd}
M3	41.40 ^{ef}	41.26 ^{ef}	0.14 ^d	22 ^{de}	605 ^{bcde}	8.65 ^{de}
H1	39.89 ^{fg}	39.82 ^{fg}	0.07 ^e	28 ^c	601 ^{cde}	10.20 ^{bc}
H2	38.85 ^g	38.81 ^g	0.05 ^e	25 ^{cde}	598 ^{de}	8.40 ^{de}
H3	38.29 ^g	38.26 ^g	0.03 ^e	21 ^e	593 ^e	7.60 ^e

*Means with the same letters in a column are not significantly different at ($P \geq 0.05$).

The screened yield and kappa number are directly related to the process parameters. In alkaline pulping processes, the intensity of the delignification reaction is evaluated through the kappa number. Screened yield decreased as much as 21.9% for the condition L1 to H3, and kappa number also were decreased statistically from 41 to 21 (a reduction of 48.8%). The results show that with respect to selective delignification, the ability of AQ could be attributed to the preservation of polysaccharides against alkaline peeling, as well as improved delignification and the strength properties of the pulp (Khristova *et al.* 2006; Dutt *et al.* 2009). Low Kappa pulps are easier to bleach. High Kappa pulps usually require more energy in refining, but they often produce stronger paper or board (www.paperonweb.com).

As indicated in Table 3, reject yield contents were very low for all conditions; *e.g.*, 0.27% for condition L1 and 0.03% for condition H3. Results show that at high levels of AA charge (22%) and increased cooking time, some of the reject contents significantly differed from each other. Reject yield is the fraction of pulp retained on the screen, and it can be an indicator of the consistency of the raw material or the ineffectiveness of chemical treatment. A reject content of less than 1% is indicative of easy and uniform cooking (Wan Rosli *et al.* 2004).

Based on Table 3, CSF values varied and were statistically different between the lowest value of 593 (H3) to the highest value of 646 (L1). The freeness value has been shown to be related to the presence of more fine fibers with increasing AA and cooking time. The decrease of freeness increases the apparent density, thus leading to better fiber bonding in paper formation (Nor Mazlana *et al.* 2014).

The viscosity of pulp is a widely used parameter for controlling pulp quality in different phases of the production process and is associated with the average polymerization degree and corresponding molecular weight of the cellulose and hemicellulose polymers. This measure is used to indirectly estimate the carbohydrate degradation level during the phases of the pulping process. Generally, higher viscosity indicates greater preservation of carbohydrates and yields better physical resistance properties, mainly those that depend on inter-fiber bonding. Pulp viscosity showed a decrease from 11.72 cP to 7.60 cP (Table 3) with respect to the concentration of AA and time. The pulp viscosity results showed that no statistically significant reduction in the viscosity value of the pulp for conditions L1 to L3, which may be a transition region. However, the value started to decrease after condition M1. A possible explanation for this might be that, although there was a lower-molecular weight polymer removal for low AA levels (18%) compared with others (20% and 22%), the high-molecular-weight polysaccharides (cellulose) were preserved (at AA 18%), allowing maintenance of the average polymerization degree of the carbohydrates and viscosity of the pulp.

Mechanical treatment

At this stage, the pulp was chosen based on the properties portrayed in Table 3, where the sample L1 was judged to have the best parameters, such as the highest screened yield, low percentage of reject yield, high viscosity, and acceptable kappa number to produce a pulp and paper product that does not require any bleaching treatment. Besides that, the operating mode of 18% AA for 90 min cooking time provided acceptable pulp (Table 3) and paper properties (Nor Mazlana *et al.* 2014), while saving the percentage of chemical concentration and time by soda-AQ pulping compared with other conditions.

Generally, the original properties of pulp fibers and bonding ability of single fibers influenced the mechanical properties of the paper produced, such as burst, tensile, and tear strength. In this study, the mechanical strength of the coir paper was evaluated based on the effect on coir pulp fibers after the beating process.

Characterization of beaten pulp and paper

The graph illustrated in Fig. (1) shows the results of the freeness and burst index *vs.* beating revolution. The series of beating revolutions were 1000, 2000, 4000, and 8000 revolutions. The comparison was made with the unbeaten sample.

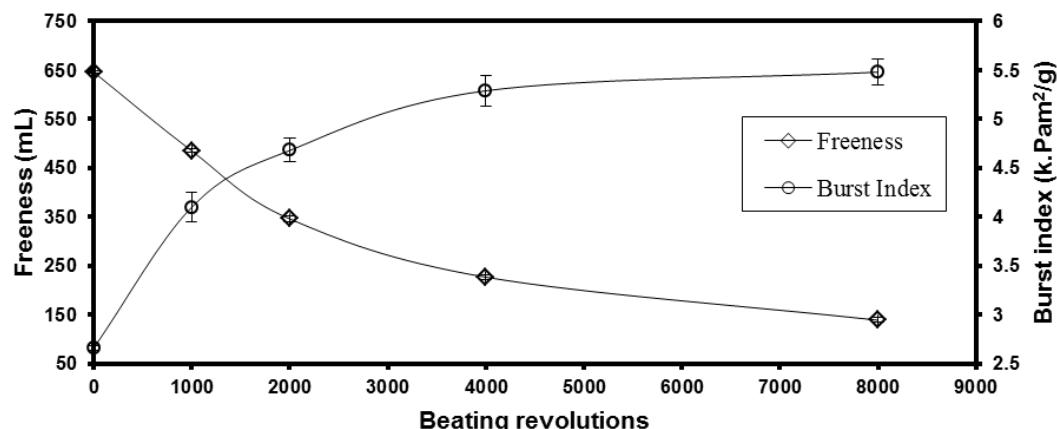


Fig. 1. Freeness and burst index at different beating revolutions

As can be seen in Fig. 1, the freeness readings were decreased as the beating revolutions were increased. These circumstances were caused by the effect of the beating process on the fiber. Beating effect can increase the coir fiber surface and density of the coir paper, as this characteristic would be able to increase the fiber compactness (Fig. 3f–j), and hence cause the freeness value to decrease. From Fig. 1, it can be seen that the reading of freeness for unbeaten coir pulp was 646 mL, then decreased to 485 mL at 1000 revolutions due to the beating effect. The value of freeness decreased until reaching 139 mL at 8000 revolutions.

The burst strength, as shown in Fig. 1, increased as the beating revolutions were increased. Similar results were shown by previous researchers working with oil palm EFB (Jiménez *et al.* 2009), various wood and non-wood pulps (Banavath *et al.* 2011), and semantan bamboo (Nurul Husna *et al.* 2013). The burst strength of the coir paper increased tremendously after the beating process at 1000 revolutions. The value of the burst index reached 4.10 k.Pam²/g after beating, as compared with the control sample, which started at 2.66 k.Pam²/g. The burst value was increased until the reading showed a value of 5.48 k.Pam²/g at 8000 revolutions, which was a more than 50% increment.

Figure 1 is plotted similarly to graphs plotted by the Malaysian paper and board industries in order to get the value of a revolution to be considered in making paper and board for packaging application. The analysis was made by obtaining the intersection value of the burst index *vs.* freeness. Therefore, the value of intersection as shown in Fig. 1 was between 1000 and 2000 revolutions. This value could be considered an optimization value of coir pulp for further processing.

Figure 2 shows the results of tensile and tearing indices *vs.* beating revolutions. Similar to the effect on burst strength, tensile strength increased as beating revolutions increased. Tensile strength increased by more than 50% when the beating process was applied until reaching 8000 revolutions with a value of $56.95 \text{ mN.m}^2/\text{g}$.

Increasing beating revolutions resulted in high fiber flexibility and fiber swelling due to fibrillation and the presence of more fine fiber content, then promoted better inter-fiber bonding within the paper formation and thus led to an increase in burst and tensile strength values.

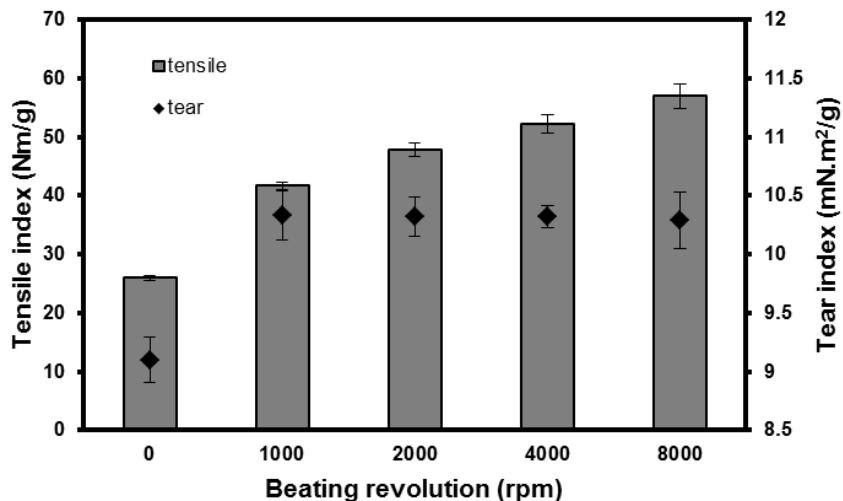


Fig. 2. Tensile and tearing indices at different beating revolutions

The tear strength of the coir fiber contradicted the tensile strength, whereby the tearing value increased by almost 12% at 1000 revolutions and started decreasing until 8000 revolutions (Fig. 2). The tear test is very sensitive to the physical properties of the fiber.

Fiber length and interfiber bonding are both important factors in tear strength. Increasing further beating after 1000 revolutions resulted in changes to the fiber dimension such as shorter fibers (Rushdan 2003b), hence contributing to the decrease in tear strength. In short fiber pulp, the existence of the critical bonding level was never attained by the unbeaten pulp, and only rarely in the beaten pulp, hence the tear factor increased with beating revolution (Watson and Dadswell 1964). Similar results were reported by Nurul Husna *et al.* (2013). However, it can be seen from the results that there were only slight decreases in tear strength. These circumstances might be due to the original properties of coir fiber, which are resiliency, strength, and high durability, resulting in the slow decrement. The percentage of decrement was only 0.4% at 2000 revolutions to 8000 revolutions.

Morphology

FESEM micrographs in Fig. 3 portray the surface morphology (Figs. 3a–e) and cross-sectional morphology (Figs. 3f–j) of the unbeaten and beaten coir papers at 1000, 2000, 4000, and 8000 revolutions.

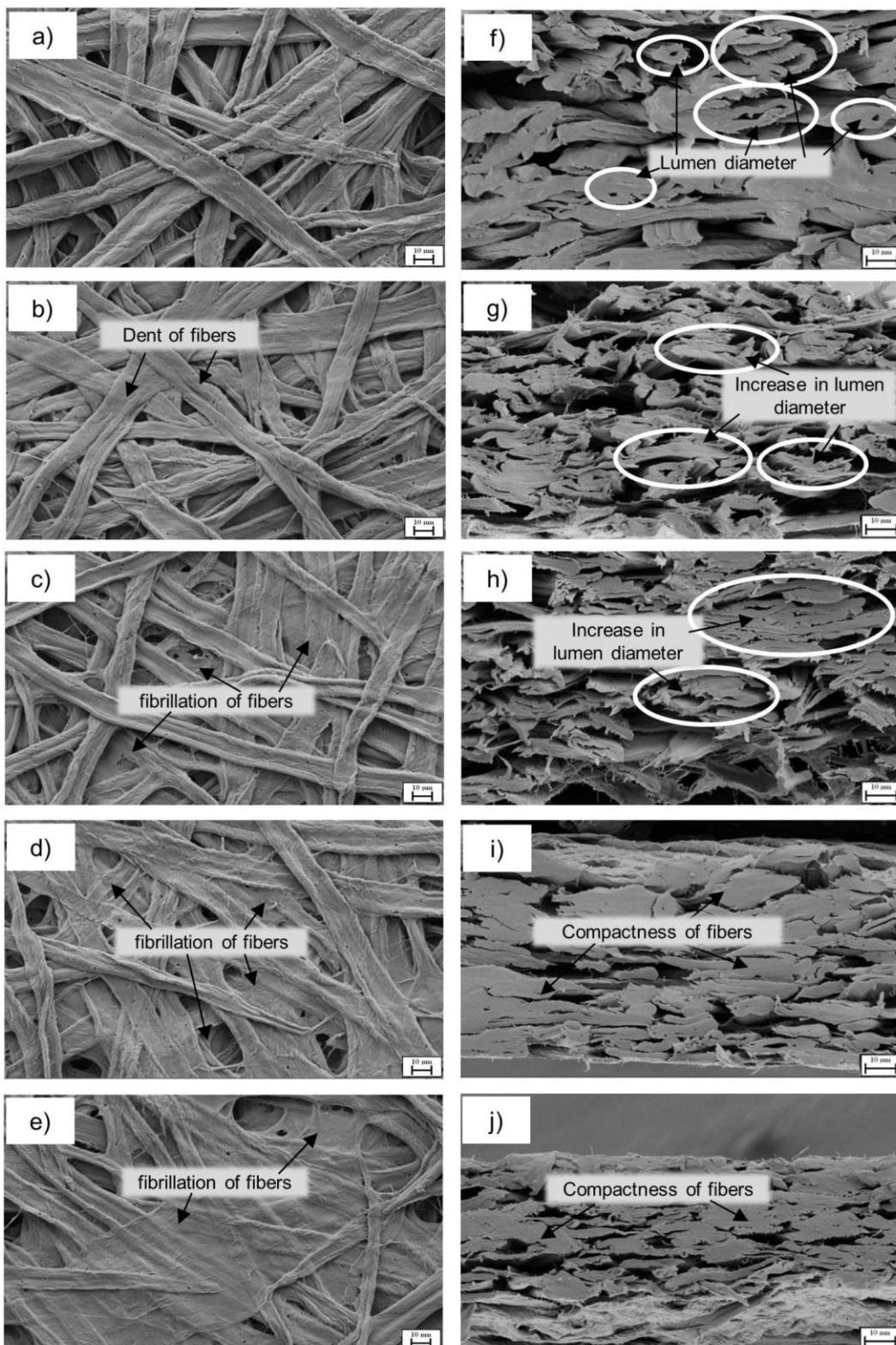


Fig. 3. FESEM micrographs of the coir paper 60 g/m² for surfaces viewed at 500 X: (a) unbeaten; (b) beaten at 1000 revolutions; (c) beaten at 2000 revolutions; (d) beaten at 4000 revolutions; (e) beaten at 8000 revolutions and for cross-sectional viewed at 800 X: (f) unbeaten; (g) beaten at 1000 revolutions; (h) beaten at 2000 revolutions; (i) beaten at 4000 revolutions; and (j) beaten at 8000 revolutions (scale bar: 10 µm)

The surface morphology of the beaten sample (Figs. 3a–e) showed changes in the coir fiber surface after the beating process. Theoretically, the beating process is capable of enlarging fiber surfaces with the effect of internal fibrillation of the fibers. Internal fibrillation may cause the intra-fiber bonds to be broken and the cell wall structures to become more porous, enhancing water absorption and thereby creating fiber swelling and fiber flexibility. The swelling of the fibers occurs towards and inwards of the lumen, with a corresponding reduction in the lumen volume, which can result in an increase in fiber surface area after beating (Ahmad Azizi *et al.* 2010; Banavath *et al.* 2011). At beating 1000 revolutions, as illustrated in Fig. 3b, fiber surfaces started to become indented. The cross-sectional view shown in Fig. 3g reveals the situation where the fiber lumen was larger than in the control sample (Fig. 3f). The sample became denser when the beating process applied to the coir fiber increased at 2000, 4000, and 8000 revolutions. This can be seen from the micrographs in Figs. 3c–e. The compactness of the coir fiber can be clearly seen in the cross-sectional views, as in Figs. 3h–j at beating processes with 2000, 4000, and 8000 revolutions, respectively. Besides that, the beating process narrowed the size of void that exists in fibers. This condition can be seen in all cross-sectional views in Figs. 3g–j.

External fibrillation started to occur in the sample beaten at 1000 revolutions. External fibrillation was increased when beating revolutions increased. The occurrence of external fibrillation caused by the outer layer of the fiber bonds was removed, exposing fibrils of the secondary wall. This condition created new surfaces that could participate in polyelectrolyte adsorption and inter-fiber bonding (Ahmad Azizi *et al.* 2010). External fibrillation is clearly seen in Figs. 3d and 3e. Other conditions, due to higher beating revolution, can cause the fibers to become easily collapsible into ribbon-like fibers, as illustrated in Fig. 3e, thus displaying high conformability and more areas for fiber-fiber contact. Hence, it improved inter-fiber bonding and yielded higher burst and tensile indices, as shown in Figs. 1 and 2, respectively.

Coir Linerboard

Structural and strength properties of coir linerboard

Table 4 presents the results of the structural and strength properties of coir linerboard from optimization of the beating pulp.

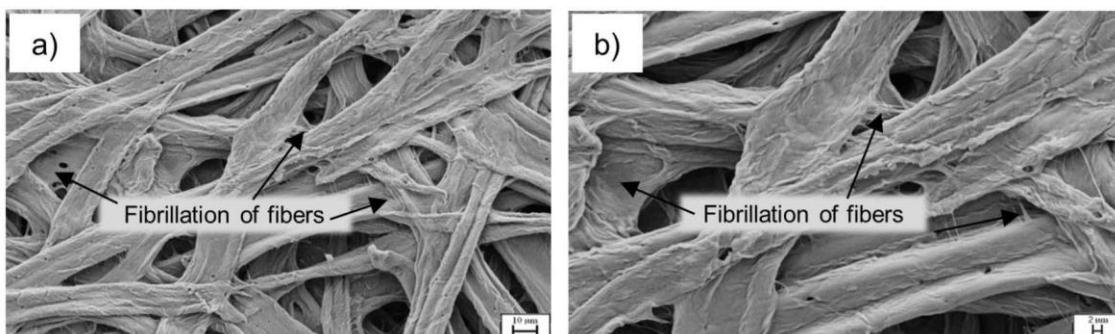
From the optimum range of 1000 to 2000 revolutions, beating coir pulp using 2000 revolutions was chosen to produce 120 g/m² linerboard. GS Paper and Packaging Sdn. Bhd. (GSPP) and Pascorp Paper Industries Bhd. are the main industrial contributors for paper and linerboard in Malaysia, which makes up the total production capacity over than 1 million metric tons per annum. Therefore, the results obtained from the study were compared in terms of their structural and strength properties with the commercial product specifications from these industry.

Apparent density is one of the structural properties used as an indicator of paper strength. A high level of fiber bonding can be expected to contribute to both strength and density. Coir linerboard has an apparent density value of 0.71 g/cm³ (Table 4), which shows that coir linerboard is comparable with industrial linerboard. Linerboard with a high apparent density is meant to have good bonding ability between fibers in paper formation. This is because the presence of fines resulting from the effects of fibrillation is capable of improving sheet consolidation (Ahmad Azizi *et al.* 2010), as is illustrated in Fig. 4.

Table 4. Properties of Commercial and Coir Linerboard

Sample	Basis Weight (g/m ²)	Apparent Density (g/cm ³)	Burst Strength (kPa.m ² /g)	Ring Crush Test (Nm ² /g)
Exp	120	0.71	4.57	1.76
GSPP Sdn. Bhd.				
IKL1*	150	0.68	≥3.12	≥1.39
IKL2*	175	0.73	≥3.12	≥1.47
IKL3*	275	0.79	≥2.85	≥1.71
IKL4*	165	0.72	≥2.70	≥1.58
IL1*	150	0.68	≥2.09	≥1.13
IL2*	180	0.72	≥2.09	≥1.27
IL3*	275	0.79	≥2.09	≥1.38
IL4*	140	0.79	≥1.80	≥1.04
IL5*	170	0.74	≥1.80	≥1.03
IL6*	250	0.81	≥1.80	≥1.03
Pascorp Paper Industries Bhd.				
IL1	135	0.71	≥2.00	≥1.11
IL2	140	0.70	≥2.09	≥1.14
IL3	150	0.71	≥2.09	≥1.13
IL4	165	0.72	≥2.00	≥1.21
IL5	170	0.71	≥2.00	≥1.26
IL6	175	0.70	≥2.00	≥1.30

Exp=experimental linerboard; IKL=Industrial kraft linerboard; IL=Industrial linerboard
 * <http://www.gspp.com.my/corp/doc/gspp.pdf>

**Fig. 4.** FESEM micrographs of coir linerboard 120 g/m² for surfaces viewed: a) 500 X magnification (scale bar: 10 μm); and b) 1000 X magnification (scale bar: 2 μm).

In industrial practices, burst strength indirectly measures the internal resistance of corrugated box container to any kind of force applied. Therefore, the burst strength of linerboard can be used to indicate the burst strength of the box (Twede and Selke 2005). Table 4 shows that the burst strength value of coir linerboard was 4.57 kPa.m²/g. The burst strength value of linerboard was higher than the minimum accepted value of commercial linerboard (3.12 kPa.m²/g for IKL1 and IKL2). Therefore, it can be concluded that coir linerboard achieved the industrial requirement for burst strength specification.

The ring crush test (RCT) is an indicator for determining corrugated box stacking performance (Dimitrov and Heydenrych 2009). Since corrugated box shipping containers are frequently subjected to the loads that are resisted by compression strength, the RCT property is an important measurement of corrugated board characteristic performance and

is useful in measuring the quality of the finished product. Similar to burst strength, the RCT value of coir linerboard also attained the minimum requirement of the industry at 1.76 Nm²/g, which is above the accepted value.

CONCLUSIONS

1. The lignin, holocellulose, pentosan, and ash contents of coir fibers were comparable to some hardwood and common non-wood fibers. However, coir fiber pulping requires moderate to high cooking of chemicals and a longer cooking cycles than other non-wood fibers. This is because of the high lignin content in coir fibers were needed to be removed during pulping process to reach a satisfactory kappa number, and thus improve paper strength properties, as well as their apparent density.
2. Pulp properties displayed a significant reduction in yield (49.26% to 38.26%), kappa number (41 to 21), and viscosity (11.72 to 7.70 cP) as the AA charge and duration of the pulping process increased. However, carbohydrate degradation started to decrease statistically under the condition of 20% AA concentration for 90 min. Reject yield contents were low for all conditions (below 1%).
3. The burst and tensile indices of coir paper increased as the beating revolutions were increased from 1000 to 8000. Meanwhile, the freeness values decreased (646 to 139 mL), and the tearing index increased at 1000 revolutions, and then slightly decreased after that.
4. Morphology analysis from FESEM indicated that coir fiber surfaces changed after the beating process was performed. Internal fibrillation increases fiber flexibility and fiber swelling by loosening the cell wall structure, and external fibrillation increases the outer surface of the fiber with higher beating revolutions. Both conditions provided high fiber conformability, hence improving inter-fiber bonding within the paper formation.
5. This study has demonstrated that coir fiber is acceptable for producing linerboard. It has an apparent density of 0.71 g/cm³ and is comparable with industrial linerboard. Meanwhile, its burst strength and RCT values substantiate that coir linerboard reached the minimum requirement values for Malaysian industrial linerboard.

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