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ORIGINAL PAPER

Ceibapentandra (L.) *Gaertn* (Kapok) Seed Fibre as a Recycled Paper Reinforcement Pulp

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Abstract

The kapok (*Ceibapentandra* (L.) *Gaertn*) seed fibre is unicellular with length up to 35 mm, however, it is covered by a hydrophobic waxy layer that limits its application in paper production. In this study, the effect of various pulping methods namely mechanical, chemi-mechanical, semichemical and chemical pulping on kapok fibre properties was investigated. Each kapok pulp was then blended with the secondary fibre recovered from kraftliner board for handsheet making to examine their reinforcing ability on strength properties. The results showed that kapok mechanical pulps (with and without dewaxing (5% (v/v) diluted detergent) and chemimechanical pulp were unable to improve the strength properties of the handsheet. Kapok pulps chemically treated with 18–25% of sodium hydroxide gave a better effect on handsheet strength properties whilst fibre treated with 20% sodium hydroxide showing the highest increment. Although the reinforcing effect of the 4% native cooked starch was slightly higher than that of the 10% kapok pulp blended in recycled paper, the recycling potential of the latter was better as all strength properties retained unchanged after recycling. The findings indicated that kapok chemical pulp is a promising reinforcing fibre source with superior recycling potential.

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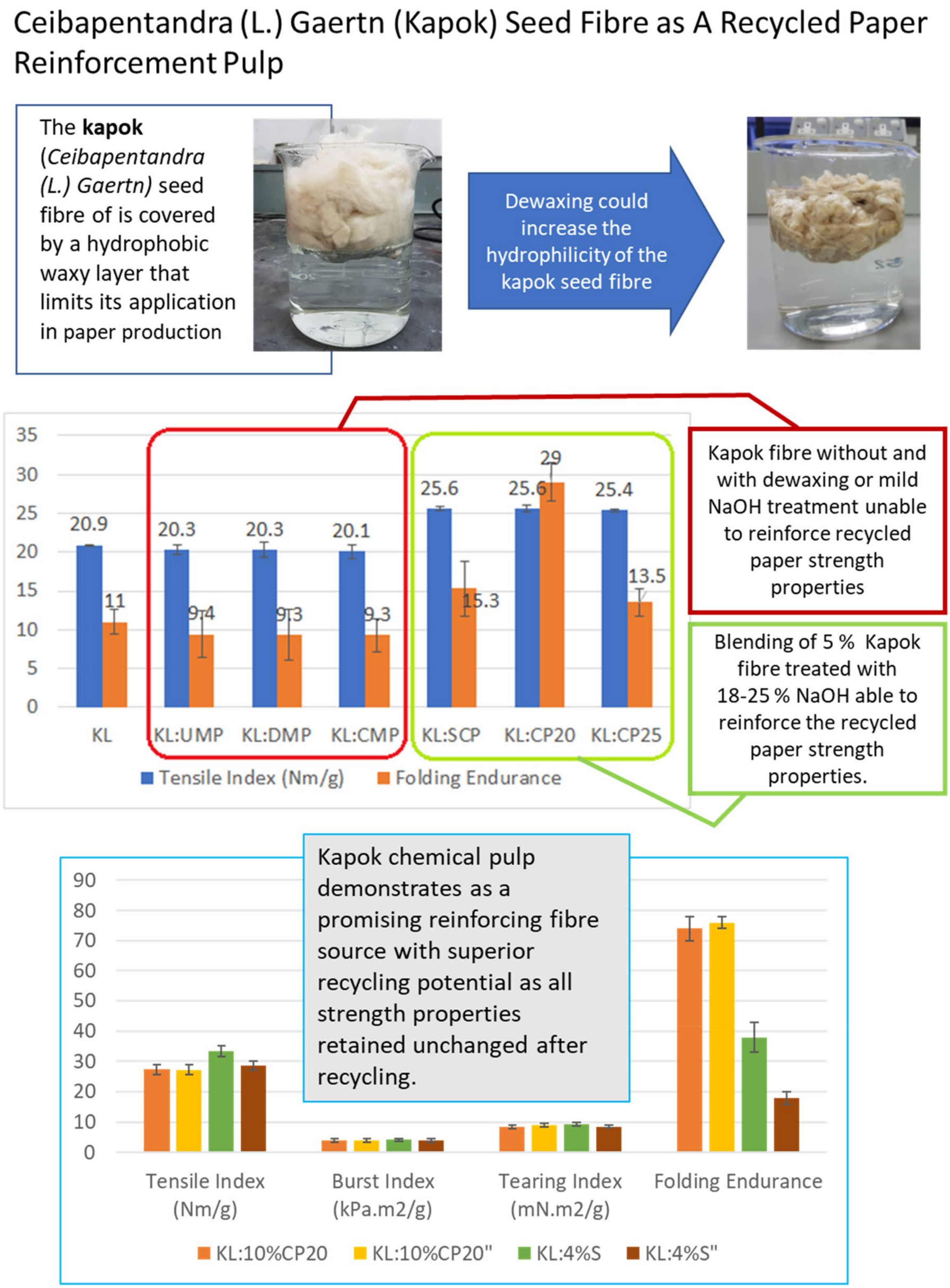
Graphic Abstract



Keywords Secondary fibres · Kapok fibre · Mechanical strength · Pulping · Reinforcing fibre

Statement of Novelty

This research presents a comparative study on the effect of different agents used to dewax the waxy kapok seed fibre. As compared to methods required reflux condition proposed previously, the dewaxing methods applied in this study were much simpler. However, although the proposed simple dewaxing step could increase the water absorption of kapok fibre, the blending of its mechanical refined pulps with recycled pulp was still unable to reinforce the resultant paper strength. It was verified that kapok fibre required 18–25% NaOH and cooked under 160 ℃ to improve the paper strength significantly. The most essential and novel finding was the strength of the kapok pulp reinforced recycled paper retained unchanged after recycling.

Introduction

The activities of paper recycling help saving landfill space [22] and reduces the amount of water, chemicals [7], and energy [29] used in the pulp and paper industry. It is well accepted that without cutting down the trees and going through pulping and bleaching processes, the production cost for paper recycling is lower in comparison to that for processing virgin pulps. Hence the production of recycled pulp and paper is relatively cost-efficient [12]. Based on Pulp and Paper Capacity report (2018), there are around 57% of total paper production worldwide are based on the recycled fibre from recovered paper. However, some paper grades such as corrugated medium and test liner are produced exclusively from recycled fibres, which has resulted in a deterioration of the paper strength properties [3]. The strength properties of paper are very important for some paper products especially for packaging purposes regardless the raw material used is from virgin or recycled pulps [2], 37. Thus, efforts to retain the strength of recycled paper products are very essential, and many attempts have been done to achieve this purpose.

In most common practices, the strength of recycled paper is intensified by either beating the fibres, adding the paper strength additives, or blending with strengthening virgin pulp [17]. The beating action improves fibre bonding potential by restoring the fibre wall swelling ability, which has partially lost once experiencing the drying process in papermaking. The loss of fibre swelling ability is known as hornification, which is due to the closure of pores that allow water to pass back and forth between fibres during fibre drying. As a result, the fibre flexibility reduces as well as their bonding ability among fibres, leaving a stiffer recycled pulp that produces weaker paper [30]. However, the beating action will cause fibre shortening and fines generation which may reduce the effective bonded area per fibre and pulp freeness, respectively, resulted in lower paper strength and production efficiency. Moreover, beating is also a very costly process in terms of energy consumption.

Starch is currently the most widely used dry-strength agent because of its relatively low price and high performance. Starch has an abundance of hydroxyl groups, which could form hydrogen bonds with recycled fibre furnish to compensate for the loss in original strength [36, 24]. In practical applications, starches are often modified with a cationic charge or with amphoteric starches to increase starch retention. However, starch modification usually increases the cost of starch by at least $500/ton [21].

The blending of recovered pulp with reinforcing fibres is another way to restore the recycled paper strength in. The addition of reinforcement fibres will not only increase the strength of both the wet web and its dry sheet, and it will also strengthen the rewetted sheet and improve the runnability of the paper machine. Lehto et al. [18] reported that a significant improvement of the run ability of paper machine is observed as well. Using of reinforcing fibre is encouraging as it could overcome those drawbacks triggered by using starch additives such as the pulp slurry will provide a very good medium for microorganism, impairing of dewatering in web formation, and the fungal attack can result in spots and holes in the paper product [11].

Currently, the most used reinforcing fibre is softwood kraft pulp as it fulfils the requirements of long and flexible fibre as well as high fibre strength [6]. Due to the increased price of softwood pulp, new reinforcing fibres from non-wood source should be considered. Kapok (*Ceibapentandra* (L.) *Gaertn*) fibre is a kind of seed-hair fibre conventionally used as stuffing material, there are only few research studies reported on utilizing of kapok fibres for papermaking. Malab et al. in 2001 [23], as cited in Chaiarrekij et al. [8], had blended 75:25 (w/w) of kapok fibres to bamboo pulps, which had been treated with detergent and sodium hydroxide, respectively, to produce paper. The finding ascertained that blending of detergent treated kapok fibre significantly reduced the amount of the bamboo pulp applied, and which indirectly decreased the consumption of chemical reagents and energy during the pulp preparation process while retaining the paper strength properties.

Chaiarrekij et al. [8] stated that their previous study [10] had proven the feasibility of producing papermaking pulp from kapok fibre and the resultant paper shown a substantial sizing effect. Besides, Chaiarrekij et al. [8] found that the soda pulp produced by using 20% (w/w) of sodium hydroxide has a rather low brightness (18.6%), thus the kapok soda pulp was bleached by hydrogen peroxide before blended with the commercial softwood pulp and/or hardwood pulps. The results showed that the hydrogen peroxide bleached kapok soda pulp could enhance the tensile and burst strengths of the blended sheets produced due to increase of interfibre bonding ability, whilst the paper produced remained its water repellency property. A further study by Chaiarrekij et al. [9] towards the blending effect of sodium hydroxide (5% and 20%) dual-treated kapok pulp on improving the recycled commercial A4 paper properties demonstrated that the detrimental effect on paper strength properties by recycling was not been seen even after three cycles of recycling.

Since the length of kapok fibre is long, it is believed that this fibre can be used as one of the reinforcement fibres for papermaking with a targeted amount no more than 10%. In another word, kapok pulp with appropriate properties is recommended to be used in a minimum amount as a function of dry-strength additives like the native or cation starch used in paper production. However, kapok fibre contains waxy cutin on the surface, which makes it hydrophobic and causes some difficulty during processing this fibre [34]. Although Wang et al. [35] found that the wax on the kapok fibre can be removed by pretreating it with a solvent such as water, chloroform or sodium chlorite under a reflux condition, the proposed method was rather time and energy consuming. In this study, the effectiveness of simpler dewaxing methods using four different solvents are investigated through fibre floating property and FTIR analysis.

On the other hand, the pulping methods applied in previous studies were dual-treatment—20% (w/w) sodium hydroxide pulping for 120 min at 120 °C followed by 3% (w/w) aqueous hydrogen peroxide bleaching for 120 min at 80 °C [8] and 5% (w/v) sodium hydroxide solution soaking for 2 weeks and followed by pulping with 20% (w/w) for 120 min at 120 °C and blended with commercial virgin wood pulps and secondary pulps from recycled commercial A4 paper, respectively. Thus, this study aimed to identify a simpler and most suitable pulping method for kapok fibre to produce pulp which is suitable to be used as reinforcement pulp with an amount of no more than 10% for recycled packaging paper product. To achieve the objectives, various kapok pulps were prepared by using mechanical (with and without dewaxing), chemimechanical, semichemical and chemical pulping methods. The resultant pulps would then blend with secondary pulp which was reslushed from kraftliner made from 100% recycled paper. A comparative study on the paper strengthening effect and recycling potential between the kapok pulp and starch was also conducted.

Table 1 Solvent for dewaxing of kapok fibre

Solvent	Concentration	Temperature
Ethanol (industry grade)	95%	60 °C
Diluted detergent	5% (v/v)	Ambient
Sodium hydroxide	0.5 M	60 °C
Distilled water	–	60 °C

Experimental

Determination of the Best Dewaxing Solvent

Fifteen millimetres of solvents as shown in Table1 were prepared and added into respective 100 ml conical flask. Kapok fibres (1.5 g o.d.) were weighed and put into each conical flask containing solvent. Then the kapok fibres and solvents in each conical flask were stirred with glass rods for 10 min. For treatment with distilled water, ethanol (95%) and 0.5 M NaOH solution, the flasks were covered with a 50 ml beaker and placed into a 60 °C water bath for 15 min while the treatment with diluted detergent, the flask was kept on the bench at ambient temperature for 15 min. After the completion of treatment, the treated kapok fibres were washed thoroughly with distilled water until the solvent was removed completely. Without any delay, the treated kapok fibres were placed into respective 100 ml beakers filled with 100 ml of distilled water. After 10 min, the fettle of all the treated fibres was observed and recorded by taking photos. The best solvent would be identified and used for dewaxing the kapok fibre before pulping process.

Dewaxing Pretreatment with 5% (v/v) Detergent

One hundred gram of oven-dried kapok fibre were soaked with 1000 mL of 5% commercial detergent (Kao Malaysia Attack Liquid Detergent), which is declared to have low risks to the environment, especially the aquatic organisms [15] with the ratio of liquor-to-biomass of 10:1 for 15 min. Then, the fibre was agitate-washed in a 30 L hydrapulper with half-filled tap water for 10 min. After that, the fibre was thoroughly rinsed with running tap water in a stainless-steel mesh until no bubbles were observed. The washed kapok fibre was considered dewaxed and it was spin-dried, weighed and determined the moisture content. The dewaxed fibres were then kept in a polyethylene (PE) bag and placed in a refrigerator before use. The undewaxed and dewaxed kapok fibres were denoted as UK and DK.

Preparation of Secondary Fibre from Kraft Liner

Kraft liner (testliner) provided by Muda Paper Mill Sdn. Bhd, Simpang Ampat, Pulau Pinang was used. 40 g (oven-dried basis) of kraft liner was weighted and then torn by bare hands into small pieces and soaked in a pail filled with 2000 mL of filtered tap water for above 4 h. The wetted kraft liner was then disintegrated at 50,000 revolutions. After completion, the disintegrated pulp was spin-dried before keeping in a refrigerator. The kraft liner pulp was denoted as KL.

Preparation of Various Pulps from Kapok Fibre

Chemical Treatment/Pulping

For Chemimechanical Pulp Thirty gram (o.d.) of DK was treated with 6% NaOH (based on o.d. weight biomass) in a ratio of liquor-to-biomass of 7:1 in a PE plastic bag and conditioned at 60 °C for 1 h. At the completion, the biomass was wash thoroughly under running tap water until all the liquor was removed.

For Semichemical and Chemical Pulp Soda-AQ pulping process was carried out in a 4 l stationary stainless steel digester (NAC Autoclave Co. Ltd., Japan), fitted with a microcomputer-controlled thermocouple. Thirty gram (o.d.) of DK was cooked with three conditions as shown in Table 2. Upon completion of pulping, the fibre pulps were further disintegrated with a hydrapulper for 10 min and then washed thoroughly in a stainless-steel mesh using pipe water to remove all the remaining black liquor.

Mechanical Refining

Mechanical Pulp Thirty grams (o.d.) of kapok fibres (UK and DK) were soaked in hot water for at least 1 h. To avoid the long kapok fibre stuck in the refiner, it was cut into a shorter length of about 0.5–1.0 cm using a scissor before refining with Antritz Sprout Bauer refiner with 1/65-inch disc gap for two times. Refined kapok pulps were screened using a Sommerville screener with 0.15 mm slot size. The screened yield (%) was determined based on the oven-dry weight. The undewaxed and dewaxed kapok mechanical pulp were denoted as UMP and DMP.

Table 2 Chemical treatment/pulping conditions for kapok fibre

Conditions	Types of pulping			
	Chemi-mechanical (CMP)	Semi-chemical (SCP)	Chemical (CP20)	Chemical (CP25)
Weight, g (OD)	30	30	30	30
Alkaline charge, (NaOH) %	6	18	20	25
AQ charge, %	–	0.1	0.1	0.1
Liquor-to-biomass ratio	–	15:1	15:1	15:1
Pulping temperature, °C	60	120	160	160
Time-to-temperature, min	–	30	60	60
Time-at-Temperature, min	60	60	120	120

Chemimechanical, Semichemical and Chemical Pulps Kapok seed fibre is a kind of single long fibre with the length of 10–35 mm and chemical treatment although causes degradation of cellulose chain in the fibre cell wall, the treatment gives negligible shortening effect on fibre length. Thus, all the chemical treated kapok fibres would be refined twice through Andritz Sprout Bauer refiner with 1/65-inch disc gap to obtain suitable fibre length for paper making.

Pulp Screening

All the refined kapok pulps were screened using a Sommerville screener with 0.15 mm slot size. The screened yield (%) was determined based on the oven-dry weight.

Pulp Fibre Analysis

ATR-FTIR Analysis

Untreated and treated kapoks were analysed using an ATR-FTIR machine which is Thermo Scientific NICOLET iS10 where the transmission mode ranging from 400 to 4000 cm^{-1} with a 4 cm^{-1} resolution. The ATR clamp and platform were cleaned with a cotton swab dampened with isopropyl alcohol and allowed to dry between analysis of each kapok sample.

Micro Kappa Number Analysis

Kappa number test is an indirect method to determine the lignin content based on the consumption of permanganate ion by lignin retained in unbleached semichemical pulp, chemical pulp and semi-bleached pulps. It indicates the number of millilitres of 0.1 N (0.02 M) potassium permanganate ($KMnO_4$) consumed by 1.0 g of pulp. The procedure of kappa number was carried out by using modified TAPPI standard T236, the Useful Method 246 – Micro kappa number (UM-246).

Fibre Length Determination

Fibre lengths of pulps were determined using a FAS-3000 fibre analyzer according to TAPPI standard (T 271 pm-91) for wet pulp sample. 0.5 g of pulp based on the oven-dry basis was dispersed by a magnetic stirrer in 200 ml of warm (50 °C) distilled water before the test.

Preparation of Handsheet

The handsheets of 60 g/m^2 was prepared according to T 205 om-88 based on the actual stock consistency. Then the formed handsheet was dried in a conditioning room under standard conditions at 50 ± 2% RH and 23 ± 1 °C (TAPPI 402) prior testing. Five per cent of each pulp—mechanical kapok pulp (UMP and DMP), chemimechanical kapok pulp (CMP), semichemical kapok pulp (SCP) and chemical kapok pulps (CP20 & CP25), were added, respectively, with the recycled pulp prepared from kraftliner (KL) on an oven-dried weight basis. To further investigate the effect of percentage of CP on the physical and mechanical properties of handsheet, the percentage of CP25 was increased to 10% as well.

Handsheet with Starch Addition

4% of cooked native starch was prepared by measure the weight of starch and added into 100 mL distilled water. The starch suspension was then heated with continuously stirring until the starch is fully dissolved. The cooled starch solution (room temperature) was then mixed with recycled pulp stock at disintegration stage.

Handsheet Testing

The handsheet preparation for testing was conducted according to the TAPPI 402 sp-03—Standard Conditioning and Testing Atmospheres for Paper, Board, Pulp Handsheets, and Related Product. All handsheets must be exposed in the conditioning environment (50 ± 2% RH and 23 ± 1 °C) at least 3 h before the testing of physical (TAPPI T410 om-02, TAPPI T411 om-97) and mechanical (TAPPI T494 om-01, TAPPI 414 om-98, TAPPI T403 om-02, and TAPPI T511 om-02) carried out.

Result and Discussions

Kapok Fibre Floating Property

Without any treatments, kapok fibre is a hydrophobic and buoyant material due to its waxy surface [38]. Several pretreatments were carried out aiming to remove the wax from the fibre surface to increase the hydrophilicity of the fibre. Figure 1 shows the qualitative observations of various pretreatments on buoyant ability and hydrophilicity of kapok fibre. Obviously, the effect of distilled water on kapok fibre (Fig. 1b) was negligible as the fibre still floated on the surface of the water and remains fluffy and hydrophobic like the untreated kapok fibre (Fig. 1a).

On the other hand, although NaOH-treated kapok fibre (Fig. 1c) became more compact or less fluffy as it was moistened easily, it still showed very weak water absorption ability, thus the fibre could not immerse fully in water or retained its buoyant property. Since kapok fibre is a single hollow cell, it is reported that the NaOH treated fibres floated on the water was due to water could not be absorbed into the lumen (hollow part) of the fibre and thus the air in the fibres remained the buoyant property of the kapok fibre [19]. This indicated that the NaOH treatment could only remove part of the wax from the fibre surface where most of the fibre parts remained hydrophobic. Whilst, the detergent (Fig. 1d) and ethanol-treated (Fig. 1e) kapok fibre exhibited a better water absorption ability, particularly the ethanol-treated kapok because it had sunk to the bottom of the beaker which indicated that the hollow part of fibre was being filled with water.

The water absorption ability of detergent treated kapok fibre was moderate wherein the fibre was fully immersed but still floated in the water. As the density of lignocellulosic

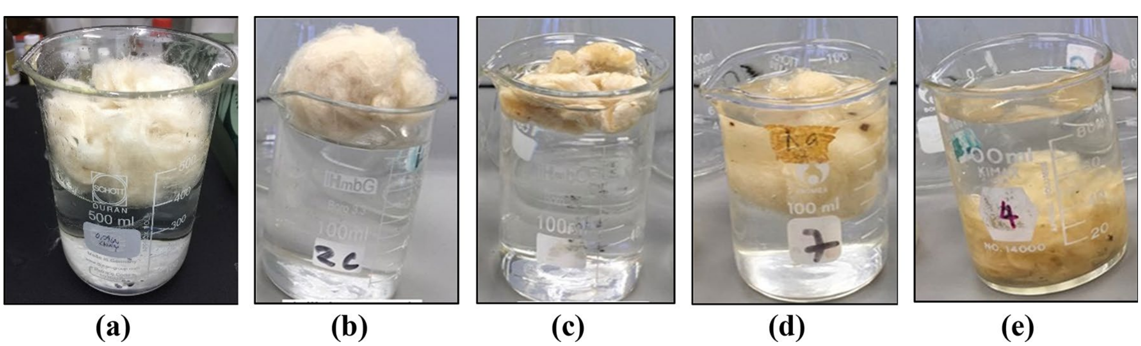


Fig. 1 The visual image of water absorbability test for various type of kapok fibres; **a** untreated, **b** distilled water-treated, **c** 0.5 M NaOH-treated, **d** 5% detergent-treated and **e** ethanol-treated

biomass is around 1.5 g/cm^3, thus it normally sinks to the bottom of the beaker. The floating detergent treated kapok fibre revealed that the hollow part of the fibre was not fully filled with water and there was air still kept inside.

FTIR Analysis

The results of the FTIR spectra of untreated and solvent-treated kapok were shown in Fig. 2. All type of treated kapok fibres displayed the same pattern in spectra. The strong and broad peak around 3340 cm^{-1} was assigned to non-free O–H stretching vibration and the strong peak around 2916 cm^{-1} was assigned to asymmetric and symmetric stretching vibration in CH_2 and CH_3, a peak associated with the presence of plant wax which is comprised long-chain alkane, ketones, alcohols, aldehydes and ester [20]. The peak at 1732 cm^{-1} was attributed to C–O stretching vibration of ketones, carboxylic groups and esters in lignin and acetyl ester groups in xylan [25]. The absorption bands at 1504 and 1595 cm^{-1} were attributed to aromatic ring carbon skeletal stretching of lignin [5] and the bands around 1371 and 1240 cm^{-1} were within the range of C–H and C–O bending vibration [28, 33].

By comparing the spectra of untreated and solvent-treated kapok fibres, there was no noticeable reduction of band intensity at 2916 cm^{-1} which indicated that the dewaxing by soaking the fibre was not efficient, even with 98% ethanol. However, minor changes in peak intensity at bands 1732 cm^{-1} and 1240 cm^{-1} was observed for NaOH, ethanol and detergent-treated samples. The band intensity at 1732 cm^{-1} showed a slight increase from 81.55% (untreated) to 83% (solvent-treated) while at 1240 cm^{-1} slightly increased from 70.38% for the untreated sample to 72.50%, 72.75% and 73.15% for NaOH, ethanol and detergent treated samples, respectively. This suggests that these three solvents could cause de-esterification of kapok fibre and some of the esters linked with the aromatic ring of lignin were slightly removed [26]. These observations indirectly suggested that there was a possibility of wax removal from the kapok fibre surface as reported previously by Abdullah et al. [1].

The changes of treated kapok fibre were not clearly shown by FTIR spectra as reported by previous studies [20, 35], this might be due to the treatments applied were relatively much milder. Nevertheless, based on the qualitative observation from the buoyancy property of the treated fibre and the FTIR spectra analysis, it was concluded that ethanol and diluted detergent could decrease the hydrophobicity of the kapok fibre. However, for economic consideration, between the two solvents used, the diluted detergent with only 5% (v/v) was more cost and energy saving as it could be only carried out at ambient temperature while the 95% industrial grade of ethanol was carried out at a temperature of 60 °C. Therefore, the diluted detergent was selected as the most suitable dewaxing agent for the subsequent works in this study.

Fibre Properties of Various Pulping Methods

The diluted detergent dewaxed kapok fibre (DK) was further undergone various pulping process as tabulated in Table 3. The mechanical kapok pulp screened yield after dewaxing (DMP) was 86.83%, which was more than 10% higher as compared to the undewaxed kapok Mechanical pulp (UMP) screened yield (77.56%). Some losses of UMP were observed in the refiner disc clumped, entangled and stuck in the refiner disc. This was most possibly due to the waxy smooth surface of the fibres that make it hydrophobic and remained unwetted after soaking in water. The dry kapok fibre will be assembled thus possessed better

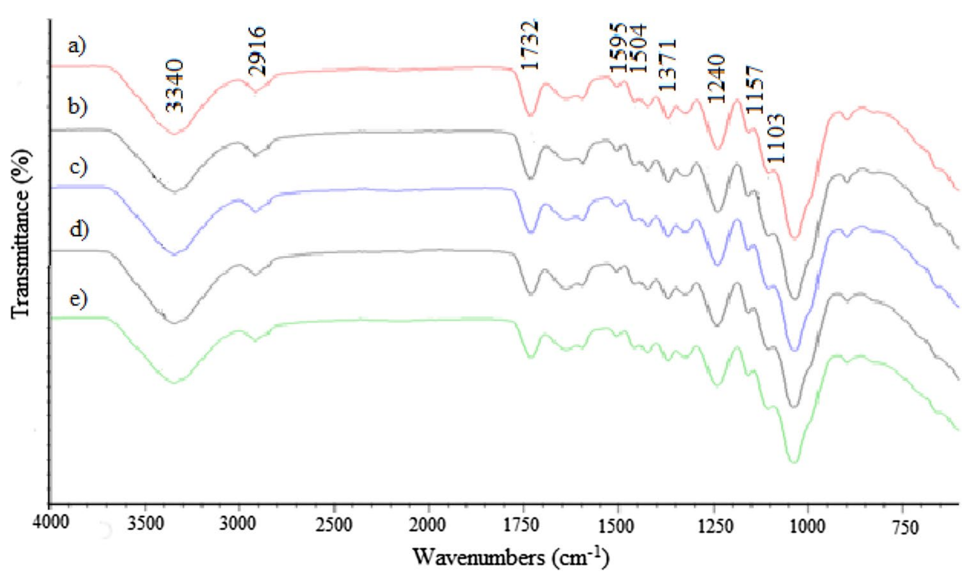


Fig. 2 FTIR spectra of various type of kapok fibres; (a) untreated, (b) distilled water-treated, (c) 0.5 M NaOH-treated, (d) ethanol-treated and, (e) 5% detergent-treated

Table 3 Fibre properties of all types of kapok fibre

Fibre properties	Types of kapok pulps					
	UMP	DMP	CMP	SCP	CP20	CP25
Screen yield# (%)	77.6	86.8	83.7	59.1	55.7	45.2
Average fibre length (mm)	0.61	0.56	0.64	0.62	0.81	0.64
Kappa number	–	–	–	84.2 (2.4)	67.7 (1.4)	49.1 (1.6)

Types of pulp: *UMP* undewaxed mechanical pulp, *DMP* dewaxed mechanical pulp, *CMP* chemimechanical pulp, *SCP* semichemical pulp, *CP20* chemical pulp cooked with 20% NaOH, *CP25* chemical pulp with 25% NaOH

*The values in parentheses are standard deviations

#The screened yield was calculated based on the original weight of undewaxed kapok fibre (UK)

compression resilience and higher strains than the wetted kapok fibre [36]. Therefore, the shear force imparted by rotating of refining disc becomes less effective to the dry fibre made the UK more difficult to be refined into short fibre and thus resulted in high reject yield during screening.

It was observed that the screened yield of pulping decreased with the increase of chemical treatment severity (alkali charge and temperature), where the screened yields of CMP, SCP, CP20 and CP25 were 83.7, 59.1, 55.7 and 45.2%, respectively. CP25 retained the lowest yield was due to the intensive treatment applied (25% NaOH and 165 °C) was capable of removing the lignin and some extent of hemicellulose as well as cellulose. This is because, the higher the temperature and/or alkali charge applied is the large the amount of chemical composition in biomass degraded and resulting in a decrease of pulp yield [16]. During an alkaline pulping, the increased alkali charge improved the delignification rate as the active species—hydroxyl ion (OH–) from NaOH, will attack lignin as well as carbohydrates. Consequently, the screened yield progressively decreases [13].

It was interesting to see that all types of pulp prepared from kapok fibre which had undergone the same refining intensity showed an average fibre length in the range of 0.56–0.64 mm, except for CP20, which presented the longest fibre length of 0.81 mm. Without or with only mild chemical treatment, fibres remain hard and stiff, thus the compression and shearing forces applied on fibre causes fibre breakage more easily. On the other hand, a strong chemical treatment (CP25) decreased the individual fibre strength due to cellulose degradation, as a result, the weak fibres are easily shortened by the frictional action exerted during refining [38]. For CP20, the fibre was softer and flexible but yet remained sufficient individual fibre strength. Thus, the refining action did not cause serious fibre shortening. However, the range of average fibre length obtained indicated that the fibres were over shortened by the double refining.

Effect of Various Kapok Pulps as Reinforcing Fibre on Kraftliner Recycled Paper

Physical Properties

Density is the most fundamental parameter in paper properties, and it is closely related to quality and quantity of interfibre bonding, which is mainly affected by processes undertaken such as pulping process, beating process and calendaring process [14]. Obviously, the pulping method was the only factor related to interfibre bonding in this study. As can be seen in Table 4, the highest density of 0.473 g/cm^3 is the handsheets made from recycled krafliner blended with kapok chemical pulp (KL:CP20) and the lowest density of 0.440 g/cm^3 went to the recycled kraftliner blended with undewaxed mechanical pulp (K:UMP). Apparently, kapok fibre was hydrophobic and therefore when UMP was blended with KL, it not only couldn't reinforce the interfibre bonding but adversely decreased the interfibre bonding ability and resulted in bulkier handsheets formed.

The density of handsheets made from kraftliner blended with dewaxed mechanical pulp (KL:DMP) and chemimechanical pulp (KL:CMP) exhibited the similar value with that of 100% recycled kraftliner (KL). This phenomenon indicated that although the hydrophilicity of chemically mild treated kapok pulps (DMP and CMP) was improved (Fig. 1), there was air remained being kept in the hollow part (lumen) of the kapok fibres and made it remained stiff and less collapsibility. Hence the pulps presented the same conformability with the hornified recycled pulp.

The interfibre bonding reinforcement effect was observed when the KL was blended with semichemical (SMP) and chemical kapok pulps (CP20 and CP25), respectively, in which the density of handsheets increase significantly (Table 4). The results suggested that although kapok fibres were in form of single fibre rather than vascular bundle like others non-wood biomass, sufficient chemical treatment (pulping) is still necessary on producing pulps which were capable of enhancing the interfibre bonding of KL handsheet. This indicated that degradation and dissolution of

Table 4 Comparison of mechanical properties of handsheets made from blending of recycled kraft liner with 5% (w/w) of kapok fibers

Types of handsheet	Physical and mechanical properties						
	Grammage (g/m^2)	Thickness (mm)	Density (g/cm^3)	Tensile index (Nm/g)	Burst index ($kPa\ m^2/g$)	Tearing indsex ($mN\ m^2/g$)	Folding endurance
KL	61.7 (1.1)	0.136 (0.003)	0.450 (0.004)	20.9 (0.1)	3.93 (0.24)	7.39 (0.15)	11 (1.6)
KL:UMP	65.3 (0.6)	0.149 (0.002)	0.439 (0.004)	20.3 (0.7)	3.65 (0.17)	7.60 (0.06)	9.4 (3.0)
KL:DMP	63.9 (0.2)	0.143 (0.002)	0.450 (0.009)	20.3 (0.9)	3.68 (0.14)	7.54 (0.32)	9.3 (3.3)
KL:CMP	64.7 (0.2)	0.143 (0.003)	0.451 (0.009)	20.1 (0.9)	4.10 (0.14)	8.02 (0.21)	9.3 (2.1)
KL:SCP	59.0 (0.2)	0.127 (0.003)	0.464 (0.009)	25.6 (0.2)	4.29 (0.21)	8.51 (0.27)	15.3 (3.5)
KL:CP20	65.2 (0.2)	0.138 (0.002)	0.473 (0.008)	25.6 (0.5)	4.32 (0.07)	8.50 (0.22)	29 (2.5)
KL:CP25	65.3 (0.3)	0.141 (0.003)	0.463 (0.007)	25.4 (0.2)	4.76 (0.16)	8.63 (0.13)	13.5 (1.7)

KL kraftliner recovered pulp, *UMP* undewaxed mechanical pulp, *DMP* dewaxed mechanical pulp, *CMP* chemimechanical pulp, *SCP* semichemical pulp, *CP20* chemical pulp cooked with 20% NaOH, *CP25* chemical pulp with 25% NaOH

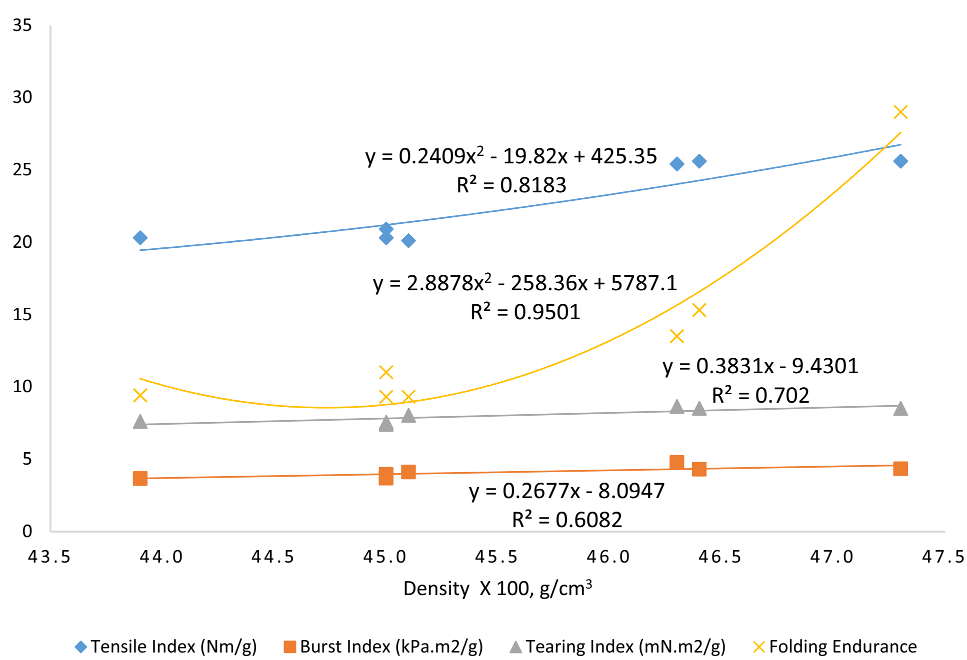
*The values in parentheses are standard deviations

lignin from the fibre cell wall is necessary to obtain good interfibre bonding. The removal of the hydrophobic lignin increases the fibre hydrophilicity and hence enhances fibre swelling ability and flexibility as well as fibre conformability. This would result in a more compacted sheet as the kapok fibres have a very thin cell wall, being easily collapsed after an appropriate chemical pulping.

Mechanical Properties

The mechanical properties of handsheet made with 100% KL and 95% KL blended with 5% of various kapok pulps were shown in Table 4. For the tensile index, although there was a slight decrease in the mean values shown on KL:UPM, KL:DMP and KL:CMP handsheets in comparison to 100% KL, statistically the blending of those kapok pulps with KL did not exert any significant effect, which corresponded to their results in density too. A significant increment of c.a. 22% was observed on KL pulp blended with SCP, CP20 and CP25. Figure 3 shows the correlationships between the density of handsheet and various mechanical properties. The strongest relationship with the highest R-squared value was presented by folding endurance ($R^2 = 0.95$) and followed by tensile index ($R^2 = 0.82$) in polynomial regressions. Although the changes in tear and burst indices were albeit small, linear regression with R-squared values of 0.70 and 0.61 was also observed, respectively.

Fig. 3 The correlationship between density and mechanical properties of handsheets



These results indicated that the increment of handsheet density because of the improvement in interfibre bonding is very essential for enhancing the handsheet mechanical properties. Besides, to achieve the targeted objective as a reinforcement pulp, a substantial chemical treatment was necessary to increase the hydrophilicity of kapok fibre for better hydrogen bond formation among fibres. However, it was obvious that the pulping with a too high dosage of sodium hydroxide (CP25) led to detrimental in the tensile and burst strengths, which was owing to cellulose degradation through random cleavage in a strong alkali medium [27]. From the observation, semichemical (SCP) and chemical (CP20) pulping could produce reinforcement pulp for recycled fibre, while the CK20 kapok pulp exhibited the greatest reinforcing ability wherein the tensile index, bursting index, tearing index and folding endurance increased 22.5, 9.9, 16.8 and 163.6%, respectively.

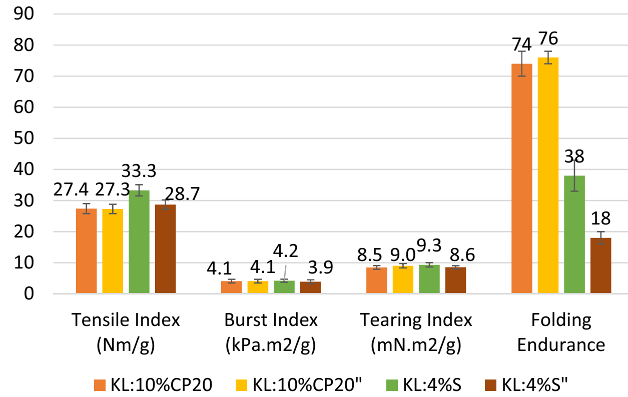


Fig. 4 Mechanical strength properties of handsheet made by blending of kraftliner (KL) with 10% kapok chemical pulp treated with 20% NaOH (KL:10%CP20) and with 4% cooked starch (KL:4%S) as well as their recycled handsheets (KL:10%CP20" and KL:4%S")

Comparing the Effect of Kapok Pulp and Starch Addition on Recycled Paper Properties and Their Recyclability

Adding of starch for internal and surface sizing as well as for improving paper strength is the common practice in recycled paper mills. To produce liner board, especially the testliner from secondary pulp, the addition of starch (native or modified cationic starch) is ranged from 1.5 to 10.0%, which depends on several factors such as the quality of raw material, ratio of long and short fibre, process undergone and etc. In general, average starch consumption in testliner production is about 4% [4]. Thus, a comparative study between the addition of 4% of native cooked starch (KL:4%S) and 10% of CP20 (KL:10%CP20) into KL was carried out. The percentage of CP20 added was increased to 10% instead of 5% because the former showed better comparable properties to those of KL:4%S. Besides examine their effect of paper mechanical properties, the recyclability of these two papers was also observed.

Effects on Mechanical Properties

Figure 4 shows that, as compared to KL:4%S, the handsheet of KL:10%CP20 exhibited a slightly lower tensile index, comparable bursting and tearing indices, while superior folding endurance. In comparison to KL, the improvement of the tensile strength by the cooked starch and CP20 was 59.3% and 31.1%, the burst index was 7.1% and 3.8%, the fold endurance was 245% and 573% and the tear index was 26.1% and 14.7%, respectively. The dry-strength additive strengthening mechanism involves the hydroxyl group between additive and fibre. This improvement of mechanical strengths was contributed by the high amount of hydroxyl groups of starch which increased the bonding quality and quantity between fibres after adhering on fibre surfaces [32].

Effect on Recyclability

From Fig. 4, it is noticed that after one cycle of recycling, most the mechanical properties of recycled KL:10%CP20 (KL:10%CP20")—tensile index, bursting index and folding endurance were retained while the tearing index showed slight increment as compared to the KL:10%CP20. Generally, in papermaking, the chemical pulp will experience hornification due to the strong hydrogen bonds formed intrafibre during the drying process and diminished the fibres' water absorption ability, swelling ability and fibre flexibility when rehydrating. This occurrence causes recycled paper has weaker mechanical strength properties. Since the recycling did not impose a detrimental impact on the mechanical strength properties of KL:10%CP20", this revealed that hornification might not occur in CP20 and its reinforcement ability was retained after recycling.

On the other hand, all the mechanical properties of the recycled KL:4%S (KL:4%S") showed a significant drop, in which the tensile index, bursting index, folding endurance and tearing index reduced 37.8%, 7.1%, 52.6%, and 9.0%, respectively as compared to the KL:4%S. The results show that the capacity of starch as a dry-strength additive declined after recycling. Especially for burst strength and folding endurance. This might be due to the strong bonding between starch and fibre was not fully reopened during the recycling process. Consequently, the strength boosting effect of starch was lessened after the recycling process. These findings indicated that the KL:10%CP20 showed better recycling potential than KL:4%S, wherein no reduction of handsheet strength properties was not observed on KL:10%CP20".

Conclusion

Dewaxing of kapok fibre could be achieved by using 0.5 M NaOH, 95% ethanol, and 5% (v/v) detergent. Kapok fibre treated with ethanol and detergent showed greater water absorbability and hydrophilicity while the latter is more cost-efficient. In the case of performing as reinforcing fibre additive for recycled paper made from kraftliner, sufficient chemical treatment was required to increase the hydrogen bonding ability of kapok pulps, thus only the semichemical kapok pulp (SCP) treated with 18% NaOH at 120 ℃, chemical kapok pulps treated with 20% (CP20) and 25% (CP25) NaOH at 160 ℃ successfully functioned as the reinforcing fibre by producing denser sheets and showed a significant improvement in all mechanical strength properties. Among these three chemical pulps, the 20% NaOH treated pulp (CP20) has a greater reinforcing ability. Moreover, the kraftliner recycled paper added with 10% CP20 (KL:10%CP20) although showed a lower tensile index in comparison to that added with 4% cooked starch (KL:4%S), it exhibited a higher recycling potential as all the mechanical strength properties were retained unchanged after the first cycle of recycling.

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