



UNIVERSITI PUTRA MALAYSIA

***PRODUCTION OF HIGH QUALITY PACKAGING PAPER FROM
BAMBOO ASAM PULP WITH CELLULOSE NANOCRYSTALS***

AMIN MORADBAK

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By

AMIN MORADBAK

**Thesis Submitted to the School of Graduate Studies, Universiti Putra Malaysia,
in Fulfillment of the Requirements for the Degree of Doctor of Philosophy**

December 2016

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DEDICATION

This Thesis Is Dedicated To:

My Lovely Family

Mother, Father, and My Brother



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Abstract of thesis presented to the Senate of Universiti Putra Malaysia in fulfillment of the requirement for the Degree of Doctor of Philosophy

PRODUCTION OF HIGH QUALITY PACKAGING PAPER FROM BAMBOO ASAM PULP WITH CELLULOSE NANOCRYSTALS

By

AMIN MORADBAK

December 2016

Chairman : Professor Paridah Md Tahir, PhD
Institute : Tropical Forestry and Forest Products

Bamboo is a non-wood fiber that has been proven to be a viable alternative source for pulp and paper industry. However, due to the large variation in species, anatomical structure and chemical composition, significant variations in the performance of paper made from bamboo have been reported. Like softwood, paper made from bamboo can have excellent properties particularly in stiffness, bending quality, tear strength, and crush resistance, which are found suitable for paperboard. Kraft pulping is the most common method used for bamboo because it generates relatively high pulp yield and kappa number with value approximately 46.4% and 24.6, respectively. Kraft paper however tends to be lower in initial brightness and has limited chemical penetration. Having strong bundle sheathes, impenetrable epidermis, a complete absence of ray cells, and limited area of conducting tissues, bamboo requires a more rigorous pulping regime as compared to wood.

This study employed alkaline sulfite anthraquinone with methanol (ASAM) method of pulping for bamboo (*Gigantochloa scortechinii*) with a main aim to develop high performance paper for packaging application. ASAM pulping process has combined advantages of suitable paper properties obtained from kraft pulping, and higher initial pulp brightness, obtained from sulfite pulping. Low kappa number, high pulp yield, and high paper strength are the main advantages of ASAM pulping in comparison with kraft. In addition, ASAM pulping reduces the bad odor from methyl mercaptan that is generated in kraft pulping. The objectives of the study were: (I) to characterize the basic properties of *Gigantochloa scortechinii* bamboo fiber (II) to determine optimum pulping condition with maximum pulp yield and under less severe pulping conditions (III) to develop high strength bleached bamboo papers by applying minimum beating revolution (IV) to evaluate the effects of cellulose nanocrystals (CNC) on the properties of bamboo paper.

The study was divided into: (1) evaluation of biometric characteristics and chemical composition *Gigantochloa scortechinii* bamboo; (2) determination of the effect of pulping conditions on the pulp and paper properties, (3) evaluation of beating and

bleaching effects on the pulp and paper properties, and (4) improvement of paper properties by adding cellulose nanocrystals (CNC). Compared to cellulose fiber, CNC has many advantages such as unique optical properties, high specific strength, and high surface area. Therefore, in this study, CNC was prepared from bleached bamboo ASAM pulps and applied as an additive to improve paper properties such as the permeability, tensile, burst, and tear indices.

Franklin (1954) and TAPPI standard methods were used to determine the biometric characteristics and chemical compositions of bamboo culms, respectively. The results show that bamboo has fiber length similar to that of softwood (1980 - 4000 μm), a runkel ratio of 0.86 and flexibility ratio of 50.19. Bamboo contains 47.67% cellulose, 68.33% holocellulose, 26% lignin and 3.69% solvent extractive, which are also within the range of wood from softwoods species.

The pulping was conducted using ASAM process at 170°C and alkali ratio ($\text{Na}_2\text{SO}_3/\text{NaOH}$: anthraquinone: methanol) of (80/20: 0.1%: 15%). It was found that the highest yield (52.36%) was achieved by applying 14% sodium hydroxide and 90 min cooking time whilst the lowest kappa number (10.38) was observed using 18% and 120 min. Further increase of both alkali and cooking time resulted in marked decrease in both kappa number and pulp yield. The optimum pulping condition was obtained at 16% alkali and 90 min cooking time with resulting kappa number of 14.17 and pulp yield of 49.06%.

The tear, tensile, and burst indices of unbleached bamboo ASAM paper were within the range of 26.33-18.64 $\text{mN}\cdot\text{m}^2/\text{g}$, 24.8-17.87 Nm/g , and 10.83-9.27 $\text{kPa}\cdot\text{m}^2/\text{g}$, respectively, which is suitable for packaging paper. The study revealed that the optimum ASAM pulping parameters was at 16% NaOH and 90 min cooking time, resulting in paper having tensile index of 20.86 Nm/g , tear index of 22.64 $\text{mN}\cdot\text{m}^2/\text{g}$ and brightness of 39.32%.

Bleaching study was conducted on bamboo pulps that have been digested using the optimized pulping conditions, 170°C, 16% NaOH and 90 min. The final brightness of bamboo ASAM pulp was 84% ISO suggesting an almost pure cellulose have been obtained. To improve the paper properties of bleached-beaten bamboo paper, cellulose nanocrystals (CNC) was added. The same ASAM bleached bamboo pulp was used to produce the CNC. For this purpose, the bleached pulp was reacted with sulfuric acid (64%) at 45°C for 45 min with dynamic stirring. The CNC was analysed under UTHSCSA image Tool and the final diameter of the CNC was found to be between 10 to 20 nm.

Based on the paper properties, bamboo appears to require high level of beating (as high as 9,500 revolutions) in order to achieve acceptable properties for packaging application. Bamboo pulp fibers have very small lumen diameter therefore, the swelling of the cell wall is very difficult. On the other hand, bamboo culms have two major types of vascular bundles, type III (sclerenchyma sheaths, and one fiber strands) and type IV (sclerenchyma sheaths and two fiber strands). Type IV was located in the middle part of culm wall, whilst type III in the inner and outer parts of the culm wall. The distributions of vascular bundle type III is higher than type IV by 71.05%. Fiber strands was found to have a much larger cross-section area than the sclerenchyma

sheaths. Thus, the swelling of bamboo pulp fibers is more difficult consequently require higher number of beating.

Since beating significantly affects the paper strength, as well as require high energy, CNC was added to help reinforce the paper with minimum beating. For this purpose, three different types of bamboo pulp were prepared: Type 1 – fully beaten pulp, Type 2 - slightly beaten pulp without reinforcement by CNC, and Type 3 - slightly beaten pulp with reinforced by CNC. The results show that the mechanical properties of paper reinforced with CNC (Type 3) were similar to those of paper made from beaten pulp (Type 1). The tensile, tear, burst indices, and folding endurance of the former were 20 - 48.3 Nm/g, 19 - 24.6 mN.m²/g, 1.96 - 4.40 kPa.m²/g, and 20 - 353 double folds, respectively as compared to 50.70 Nm/g, 17.10 mN.m²/g, 4.48 kPa.m²/g, and 446 double folds, in the latter.

In summary, ASAM was found to be a suitable pulping process for bamboo compared to kraft as it produced pulps at higher yield and lower kappa number. The bleaching of ASAM pulp is relatively easy when compared to kraft. In ASAM pulping process, the initial delignification phase proceeds very fast and more than 50% of the lignin was removed in bulk delignification phase. This method also produced pulp with high hemicellulose content and low residual lignin content which can easily be bleached to a brightness of 80% ISO. The paper produced from ASAM pulping process has properties suitable for packaging paper, however the pulps require a substantial amount of beating. The addition of CNC was able to improve the final paper properties at low levels of beating (<7,000 revolutions) by creating better fiber-to-fiber bonding among the pulp fibers.

Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia
sebagai memenuhi keperluan untuk Ijazah Doktor Falsafah

PENGHASILAN KERTAS PEMBUNGKUSAN BERKUALITI TINGGI DARIPADA PULPA ASAM BULUH DENGAN NANOKRISTAL SELULOSA

Oleh

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Buluh ialah gentian bukan kayu yang telah terbukti sesuai sebagai bahan alternatif untuk industri pulpa dan kertas. Walau bagaimanapun, beberapa perbezaan yang ketara dari segi prestasi kertas yang diperbuat daripada buluh telah dilaporkan disebabkan terdapatnya variasi yang besar dalam kepelbagaian spesies, struktur anatomi dan komposisi kimia. Seperti kayu lembut, kertas yang diperbuat daripada buluh berupaya mempunyai sifat-sifat yang sangat baik terutamanya sifat kekakuan, kualiti lenturan, kekuatan koyakan, dan rintangan tekanan, yang mana didapati sesuai sebagai kertas bod. Pemulpaan kraft adalah kaedah yang sering digunakan untuk buluh kerana ia menghasilkan hasil pulpa yang tinggi dan nombor kappa sebanyak 46.4% dan 24.6 masing-masing. Walaupun begitu, kertas kraft cenderung untuk mempunyai kecerahan yang rendah dan mempunyai had penyerapan bahan kimia yang terhad. Berbanding kayu, buluh memerlukan sistem pulpa yang lebih teliti kerana buluh mempunyai berkas selaput yang kuat, epidermis yang tidak dapat ditembusi, ketiadaan lengkap sel ray, serta tisu pembawa yang terhad.

Kajian ini menjalankan kaedah pemulpaan terhadap buluh Semantan (*Gigantochloa scortechinii*) menggunakan alkali sulfit anthraquinone dengan metanol (ASAM) yang bermatlamat utama untuk membangunkan pembuatan kertas berprestasi tinggi bagi kegunaan pembungkusan. Proses pemulpaan ASAM telah menggabungkan kelebihan sifat-sifat kertas yang bersesuaian, yang mana telah diperolehi dari kaedah pemulpaan kraft, dan juga kecerahan awal pulpa yang lebih tinggi, yang mana diperolehi daripada kaedah pemulpaan sulfit. Berbeza dengan pemulpaan kraft, kaedah pemulpaan ASAM memberi kelebihan dengan menghasilkan nombor kappa yang rendah, hasil pulpa yang tinggi, dan kekuatan kertas yang lebih tinggi. Di samping itu, kaedah pemulpaan ASAM dapat mengurangkan bau busuk dari mercaptan metil yang dihasilkan dalam pemulpaan kraft. Objektif kajian ini ialah: (I) untuk mencirikan sifat-sifat asas gentian buluh Semantan (II) untuk mengkaji kondisi pemulpaan yang paling optima dengan menghasilkan hasil pulpa buluh yang maksimum di bawah keadaan pulpa yang kurang teruk (III) untuk membangunkan kertas buluh terluntur berkekuatan tinggi dengan

menggunakan revolusi pemukulan yang minimum (IV) untuk menilai kesan nanokristal selulosa (CNC) terhadap sifat-sifat kertas buluh.

Kajian ini telah dibahagikan kepada: (1) penilaian ciri-ciri biometrik dan komposisi kimia buluh Semantan; (2) penentuan kesan keadaan pemulpaan terhadap sifat-sifat pulpa dan kertas; (3) penilaian kesan pukulan dan pelunturan ke atas sifat-sifat pulpa dan kertas, dan; (4) penambahbaikan sifat kertas dengan menambah nanokristal selulosa, iaitu CNC. Berbanding dengan serat selulosa, CNC mempunyai banyak kelebihan seperti ciri-ciri unik optik, kekuatan spesifik yang tinggi dan luas permukaan yang tinggi. Oleh itu, dalam kajian ini, CNC telah disediakan daripada pulpa buluh terluntur ASAM dan digunakan sebagai bahan tambahan untuk meningkatkan sifat kertas seperti kebolehtelapan, indeks tensil, pecahan, dan koyakan.

Kaedah Franklin (1954) dan kaedah piawai TAPPI digunakan masing-masing untuk menentukan ciri-ciri biometrik dan juga komposisi kimia batang buluh. Keputusan menunjukkan bahawa buluh mempunyai panjang gentian yang sama dengan kayu lembut (1980 - 4000 mikron), nisbah Runkel 0.86 dan nisbah fleksibiliti 50.19. Buluh mengandungi 47.67% selulosa, 68.33% holoselulosa, 26% lignin dan 3.69% ekstrakatif pelarut, yang juga berada dalam lingkungan kayu dari spesies kayu lembut.

Pemulpaan ini dijalankan menggunakan proses ASAM pada 170°C dan nisbah alkali (Na_2SO_3 / NaOH: anthraquinone: metanol) dari (80/20: 0.1%: 15%). Daripada kajian, didapati bahawa hasil yang paling tinggi (52.36%) telah dicapai dengan menggunakan 14% natrium hidroksida dengan masa memasak 90 minit manakala bilangan kappa paling rendah (10.38) dapat diperhatikan apabila menggunakan 18% natrium hidroksida dan 120 minit masa memasak. Pertambahan seterusnya peratusan alkali dan masa memasak menyebabkan penurunan yang ketara dalam kedua-dua bilangan kappa dan hasil pulpa. Keadaan pemulpaan yang optimum telah diperolehi dengan 16% alkali pada masa memasak 90 minit dengan menghasilkan bilangan kappa 14.17 dan hasil pulpa 49.06%.

Indeks koyakan, tegangan, dan pecahan kertas buluh tidak terluntur ASAM adalah dalam julat 26.33-18.64 $\text{mN.m}^2/\text{g}$, 24.8-17.87 Nm/g , dan 10.83-9.27 $\text{kPa.m}^2/\text{g}$, masing-masing, iaitu sesuai untuk digunakan sebagai kertas pembungkusan. Kajian ini mendedahkan bahawa parameter pemulpaan ASAM yang optimum adalah sebanyak 16% NaOH dan 90 minit masa memasak, menghasilkan kertas dengan indeks tensil 20.86 Nm/g , indeks koyakan 22.64 $\text{mN.m}^2/\text{g}$ dan kecerahan 39.32%.

Kajian pelunturan telah dijalankan ke atas pulpa buluh yang telah dicerna menggunakan keadaan pemulpaan optimum, iaitu 170 °C, 16% NaOH, dan 90 minit. Kecerahan akhir pulpa buluh ASAM adalah 84% ISO, dimana ianya menunjukkan selulosa yang hampir tulen telah diperolehi. Untuk meningkatkan sifat-sifat kertas kertas buluh terluntur-dipukul, nanokristal selulosa iaitu CNC telah ditambahkan. Pulpa buluh terluntur ASAM yang sama telah digunakan untuk menghasilkan CNC. Bagi tujuan ini, pulpa terluntur telah bertindak balas dengan asid sulfurik (64%) pada 45°C untuk 45 min dengan pengacauan secara dinamik. CNC dianalisa menggunakan alat imej UTHSCSA dan diameter akhir CNC didapati antara 10 hingga 20 nm.

Berdasarkan sifat-sifat kertas, buluh dilihat memerlukan tahap pukulan yang tinggi (setinggi 9,500 revolusi) untuk mencapai sifat-sifat yang boleh diterima untuk kegunaan pembungkusan. Gentian pulpa buluh mempunyai diameter lumen yang sangat kecil oleh itu, pembengkakan dinding sel adalah sangat sukar. Sebaliknya, batang buluh mempunyai dua jenis berkas vaskular utama, jenis III (sarung sel sklerenkima, dan satu helai serat) dan jenis IV (sarung sel sklerenkima dan dua helai serat). Jenis IV terletak di bahagian tengah dinding batang buluh, manakala jenis III di bahagian dalaman dan luaran dinding batang buluh itu. Taburan berkas vaskular jenis III adalah lebih tinggi daripada jenis IV dengan 71.05%. Helaian gentian didapati mempunyai luas keratan rentas yang lebih besar daripada sarung sel sklerenkima. Oleh itu, pembengkakan gentian pulpa buluh adalah lebih sukar seterusnya memerlukan pemukulan yang lebih tinggi.

Oleh kerana pemukulan memberi kesan ketara kepada kekuatan kertas, serta memerlukan tenaga yang tinggi, CNC telah ditambah untuk membantu mengukuhkan kertas dengan pukulan minimum. Bagi tujuan ini, tiga jenis pulpa buluh telah disediakan: Jenis 1 - pulpa dipukul sepenuhnya, Jenis 2 - pulpa sedikit dipukul tanpa penambahan CNC, dan Jenis 3 - pulpa sedikit dipukul dengan diperkukuh oleh penambahan CNC. Keputusan menunjukkan bahawa sifat-sifat mekanik kertas diperkukuh dengan CNC (Jenis 3) adalah setara dengan kertas dibuat daripada pulpa dipukul (Jenis 1). Indeks tensil, koyakan, pecahan, dan lipatan adalah 20-48.3 Nm/g, 19-24.6 mN.m²/g, 1.96-4.40 kPa.m²/g, dan 20-353 lipatan dua, masing-masing berbanding kepada 50.70 Nm/g, 17.10 mN.m²/g, 4.48 kPa.m²/g, dan 446 kali ganda berganda, dalam kedua.

Kesimpulannya, ASAM didapati merupakan proses pemulpaan yang sesuai untuk buluh berbanding kraft kerana ia menghasilkan pulpa pada kadar hasil yang lebih tinggi dan bilangan kappa yang lebih rendah. Pelunturan pulpa ASAM juga adalah lebih mudah jika dibandingkan dengan kraft. Dalam proses pemulpaan ASAM, fasa awal delignifikasi sangat cepat dan lebih daripada 50% lignin telah dibuang dalam fasa delignifikasi pukal. Kaedah ini juga menghasilkan pulpa dengan kandungan hemiselulosa tinggi dan rendah kandungan sisa lignin yang dengan mudah boleh terluntur kepada kecerahan 80% ISO. Kertas yang dihasilkan daripada proses pemulpaan ASAM mempunyai ciri-ciri yang sesuai untuk pembungkusan kertas, namun pulpa memerlukan sejumlah pukulan tambahan. Penambahan CNC dapat meningkatkan sifat-sifat akhir kertas pada tahap yang rendah pukulan (<7000 revolusi) dengan mewujudkan ikatan gentian ke gentian yang lebih baik di antara gentian pulpa.

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I certify that a Thesis Examination Committee has met on 28 December 2016 to conduct the final examination of Amin Moradbak on his thesis entitled "Production of High Quality Packaging Paper from Bamboo Asam Pulp with Cellulose Nanocrystals" in accordance with the Universities and University Colleges Act 1971 and the Constitution of the Universiti Putra Malaysia [P.U.(A) 106] 15 March 1998. The Committee recommends that the student be awarded the Doctor of Philosophy.

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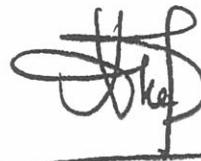
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LIST OF ABBREVIATIONS

a.d	Air-Dried
AHQ	Anthrahydroquinone
AQ	Anthraquinone
ASAM	Alkaline Sulfite Anthraquinone with Methanol
CNC	Cellulose Nanocrystals
CSF	Canadian Standard Method
CWS	Cold Water Solubility
CWT	Cell Wall Thickness
ECF	Elemental Chlorine Free
EDTA	Ethylene Diamine Tetraacetic Acid
FD	Fiber Diameter
FESEM	Field Emission Scanning Electronic Microscopy
FL	Fiber Length
FTIR	Fourier Transform Infrared Spectroscopy
h	Hours
HWS	Hot Water Solubility
ISO	International Organization for Standardization
kWh	Kilowatt Hour
LD	Lumen Diameter
L/W	Liquor to Wood Ratio
MC	Moisture Content
o.d	Oven-Dried
QM	Quinine Methides

SE	Solvent Extractive
SEM	Scanning Electron Microscopy
TCF	Totally Chlorine Free
TEMP	Temperature
XRD	X-ray Diffraction



CHAPTER 1

INTRODUCTION

1.1 General Background

In the world, more than one billion tons of non-wood materials are available. However, only 20% out of this amount is or 240 million tons can be used in pulp and paper mills, which provide far more than the potential of forest. Inevitably, the pulp and paper industry has to accept this new source of raw material as an important for development and be able to make huge changes in pulp and paper manufacturing line to suit these non-wood fibers. Among the various sources used in the pulp and paper production, non-wood such as bamboo and bagasse has a special place. In the last decade, 24 to 36% of total productions of paper in developing countries were from non-wood sources and the amount in some Asian countries were reported between 16 to 33% (FAO, 2010). Hence, it is very crucial to carry out studies on the characteristics of non-woods as they are processing sequence, physical and chemical properties that are very different than natural woods.

One of the most potential non-wood fibers is bamboo, which is due to its fast growth. Bamboo plant has only one culm. Every year new culms spring up from the rhizome, forming a clump. Bamboo grows rapidly and reaches a height of 35 to 45 m with a basal diameter of 15 to 20 cm in 6 to 8 year (Chaowana, 2013; Choudhury et al., 2010; Singhal et al., 2013). The yield from natural forest ranges from 2 to 4 ton/ha/year. However, with proper plantation and silvicultural practices, the yield can be considerably improved up to 15 ton/ha/year on a sustained basis (Chandra, 1998; Chapman, 1997). The investigation on utilizing bamboo plant as a raw material for pulp and paper industry has started in the early 1980s (Dhamodaran et al., 2003). Papers from bamboo have many advantages such as: good water absorbency, high mechanical strength, smooth surface, and good ink holdout (Chang et al., 2013). On the other hand, the mechanical and optical properties of ECF-bleached bamboo kraft paper was similar to bleached softwood kraft pulp (Zhao et al., 2010).

In any packaging application, the package must contain and protect the product or contents. Depending on the product, these two major functions can take on a wide range of meaning. Paper and paperboard can be of greater value in their ability to contribute strength and stiffness or rigidity to the container. Plastics, glass and metals may also offer strength and stiffness, but paper is more resilient than glass and can be more resilient than plastic over a wider temperature range (Adamopoulos et al., 2007; Chen et al., 2013; Kirwan, 2005). The most basic paper properties as important for packaging paper are: basic weight, caliper, moisture content, and directionality (machine to cross-machine differences). Optical tests of importance depend on the type of paper and the application. Printable grades need whiteness, brightness, and opacity, while optical properties are not too critical in the unbleached grades. The tensile, tear indices, and folding endurance are the most important strength tests for packaging paper (Kirwan, 2005; Liu et al., 2010).

Most of packaging papers are made from kraft pulps due to good paper properties. The kraft or sulfate process is an offspring of soda process, having been discovered by Dahl, a German chemist, in 1879. Dahl found that when the alkaline lost in the soda process is replaced by sodium sulfate instead of sodium carbonate, the term sulfate process is therefore misleading since it implies that sulfate is the active cooking agent, whereas the active agents are actually sodium hydroxide and sodium sulfide. The name kraft (from the German and Swedish words for strong) has been applied to this process because the pulp produced is very strong, particularly when the cook is terminated while the lignin content is still at a relatively high level (Clark, 1985; Smook, 1992).

There are a number of drawbacks to kraft process, however, not the least of which is the obnoxious odor associated with even the most advanced mills. Even more serious is the problem associated with mill size. New kraft mills must have a production capacity of 1,000 tons per day or more to be economic, and this, of course, requires a tremendous capital investment.

Alkali sulfite pulping on the other hand, had been known to give good strength properties and significantly higher yields than kraft process. The addition of anthraquinone helped to reduce unbleached kappa number, but the attainment of the low kappa number needed for TCF bleaching. Patt and Kordsachia (1986) found the addition of methanol or ethanol extended delignification to levels below kraft or sulfite pulps. They named their process as ASAM, alkali-sulfite-anthraquinone-methanol.

In comparison with kraft pulping process, the ASAM pulping process have a higher digester pressure and the cooking temperature by 1.3-1.4 MPa and 5-10°C, respectively (Jahan et al., 2003). Several studies have considered the application of ASAM in the cooking process of both hard and soft wood. Kordsachia, et al., (1992) reported that *Eucalyptus globulus* had been cooking by ASAM pulping process, which resulted in 56.9% and 53.6% pulp yield, and 14 and 10 kappa number, respectively. Pulp yield and kappa number of *Pinus sylvestris* were found to be from 52.9% to 52.5% and 31 to 27, respectively (Patt and Kordsachia, 1988).

1.2 Problem Statement and Justification

In Malaysia, packaging paper mills consume recycled fibers as a main source of raw materials. The main problem with recycled fiber is the limitation in recycling time. Normally, fibers can be recycled between 5 to 7 times. The number of recycled uses is limited because the fibers get shorter, difficult to collapse, and stiff (Rushdan, 2003).

Increasing and maintaining the mechanical properties of paper products may affect the cost of production, as virgin long fiber needs to be added. Imported softwood virgin long fiber is expensive and may increase the final cost of products. Therefore, the costs that can be reduced by utilizing other long fibers, such as bamboo.

Kraft pulping is the most common method used for bamboo because it generates relatively higher pulp yield and kappa number with value approximately 46.4% and 24.6, respectively (Chang et al., 2013; Kamthai and Puthson, 2005; Kamthai, 2007). Like softwood, paper made from bamboo has excellent properties particularly in stiffness, bending quality, tear strength, and crush resistance, which are found suitable for paperboard. Kraft paper however tends to be lower in initial brightness and has limited chemical penetration.

Kraft pulping process has some advantages and disadvantages such as: suitable for all range fiber sources, high possible strength, high efficiency of the recovery of cooking chemical, low pulp yield, high consumption of bleaching chemicals, and formation of odorous gases. For these reasons and others, there has been renewed interest in recent years in trying to find alternatives to the kraft system that will yield with kraft like strength properties but without the environmental drawbacks. To counter the short coming in kraft pulping Patt and Kordsachia invented an alkaline sulfite anthraquinone and methanol pulping (ASAM) process. ASAM pulping, when compare with other process has some advantages for instance: better pulp strength properties, totally chlorine-free bleaching in a sequence with low chemical demand, high pulp yield, and no odor problem (Gominho et al., 2014; Mertoglu-Elmas et al., 2012; Miranda and Pereira, 2002; Shukry et al., 1999).

Studied by Dhamodaran et al., (2003), have revealed that bamboo is not relatively easy to pulp. Having strong bundle sheathes, impenetrable epidermis, a complete absence of ray cells, and limited area of conducting tissues, bamboo requires a more rigorous pulping regime as compared to wood. The cross section of bamboo culms is shown in Figure 1.1.

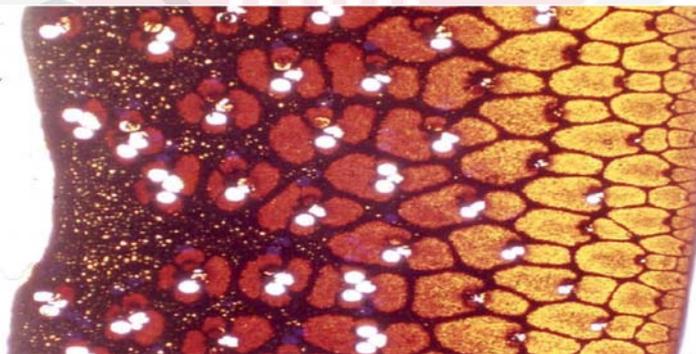


Figure 1.1 : Cross section of bamboo culms
(Source: Schott, 2016)

Due to the use of methanol and anthraquinone in the cooking liquor of ASAM process, it is anticipated that the penetration of chemicals into chips would be much deeper, thus greater improvements such as pulp with high yield, low kappa number, and suitable paper properties will be achieved. Several studies (Chang et al., 2013; Kamthai, 2007; Rahmati et al., 2010) have reported that by using kraft pulping alone the pulp yield is low but the kappa number is high. Therefore, by using ASAM pulping

process, bamboo can be pulped more efficiently and the resulting bamboo pulp would generate suitable paper properties.

1.3 Objectives

The main objective of this study was to evaluate the pulp properties of bamboo culms (*Gigantochloa scortechinii*) under alkaline sulfite anthraquinone and methanol (ASAM) pulping process and enhancing the paper properties by addition of cellulose nanocrystals (CNC). This study was divided into four main parts: evaluation of biometric characteristics and chemical composition of *G. scortechinii* bamboo, optimization of ASAM pulping process and properties evaluation, evaluation of ASAM bleached pulp, and improvement of paper properties by addition of CNC.

The specific objectives were:

1. To characterize the basic properties of bamboo fibers.
2. To evaluate the effect of ASAM pulping under reduced chemical condition on the properties of bamboo pulp and paper.
3. To determine the effect of beating revolutions on the strength of bleached bamboo papers.
4. To improve the properties of bleached bamboo paper by addition of CNC.

1.4 Organization of the Thesis

The general outline of this study is as follows. In the first chapter, the general background of bamboo culms and pulping process, problem statement and justification, and objectives of the thesis are presented.

The properties of bamboo culms on the anatomical and chemical level, bamboo for pulp and papermaking, effects of beating process on pulp properties, and addition of additives into pulp are discussed based on literature in chapter two.

Chapter three presents the basic properties of bamboo culms, which include the biometric characteristics and chemical compositions. The effects of biometric characteristics and chemical compositions on pulp and paper properties were also evaluated.

Chapter four reports and discusses the pulp and paper properties of unbleached alkaline sulfite anthraquinone and methanol (ASAM) pulping process, such as pulp yield, kappa number, brightness, and the tensile index.

Chapter five discusses the effect of beating process on bleached bamboo ASAM paper properties. The ECF bleaching sequence was used in this study. The effect of beating revolutions on bleached pulp and paper was observed using Scanning Electron Microscopy (SEM) method, mechanical and optical tests.

Chapter six investigated the improvement of paper properties by cellulose nanocrystals (CNC) addition. The effects of the addition of CNC on the paper properties, crystalline structure analysis of CNC, and properties of CNC-reinforced paper are addressed. Finally, the summary of findings, conclusions, and recommendations from this study are given in chapter seven.



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