EFFECT OF BAMBOO AGE ON THE PULPING PROPERTIES OF *BAMBUSA STENOSTACHYA* HACKEL

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Received December 4, 2011

This study investigated the effects of stem age of thorny bamboo (*Bambusa stenostachya*) on the results of different cooking methods, conditions, bleaching conditions, and handsheet properties. The stems of 0.2-, 1.2- and 3-year-old thorny bamboo were separately cooked by kraft and soda processes. The resulting pulps were then subjected to a single-stage hypochlorite bleaching. The unbleached and bleached pulps were beaten with PFI mill to 400 mL CSF, formed into handsheets and then compared as to their properties. Chemical analyses indicated that lignin content increased with increasing bamboo age, while holocellulose and pentosans showed a contrary trend. The results of kraft and soda cooking indicated that mature (3-year-old) bamboo was difficult to digest. Although pulp yields were fairly high (55%), a substantial portion (22.4%) consisted in shives and coarse materials. At identical chemical charges, the mature stems produced pulp with higher kappa number (28.2) than that of the youngest stems (22.9). The bleaching results indicated that young, tender stems produced pulps with better brightness gains, and also the bleached pulps had lower kappa numbers. At a hypochlorite charge of 10%, pulps from the young bamboo stems reached a brightness of 74% ISO. The pulps from mature stems, however, barely reached a brightness of 55% ISO. As to pulp handsheet strength properties, the pulps made from young stems retained the best properties. Pups from mature bamboo stems were more difficult to bleach and if more severe bleaching conditions were applied, the pulp strength properties suffered a higher extent of degradation. Therefore, to garner benefits of both brightness and strengths, only younger than 1-year-old bamboo stems should be used for pulping and papermaking, as they have both adequate strengths and brightness needed for fine paper.

Keywords: *Bambusa stenostachya* Hackel, bamboo age, kraft pulping, soda pulping, hypochlorite bleaching, physical properties

INTRODUCTION

Bamboos mainly grow in the tropical and subtropical regions of the world. India has the greatest volume production of bamboo pulp, accounting for 44.7% of the total; China is next in production. Fibers of bamboo have lengths between 1.5 and 4.4 mm and high slenderness ratio. Papers made from bamboo often have smooth surface, high tearing strength, good water absorbency, good ink holdout and well-suited to render brush strokes. Therefore, it is widely used in high-end Suan paper for Chinese painting and calligraphy. In recent years, bamboo pulps have seen rapid growth in China and Thailand, while Burma has the most unexploited bamboo stands.[1-5]

Bamboo stems grow rapidly, attaining full height within the first year of growth and nearly full maturity by the 3rd year. During the growing process, there are structural and chemical modifications taking places, causing the strength of the stems to increase with age, usually reaching the maximum by ca. the third year. The modification of mechanical properties is related to the alteration of its fiber cell structure. The cell wall thickness tends to increase with age, and younger stems often have more parenchymatous cells, which may contribute to paper strength.[6,7]

Processes of bamboo pulping are well established. The production scale of a typical commercial bamboo pulp mill increased from 150 ADMT/d in 1966 to 410 ADMT/d in 1980, and to 850 ADMT/d by 2007. Bamboo pulping is mainly done using continuous kraft pulping to a kappa number of 16-18. The commonly used active alkali charges are of about 19 to 20%, and the maximum cooking temperature around 142-144 °C, providing a pulp yield of about 50~54%. Depending on the brightness requirements, bamboo pulps are often bleached with ECF processes, such as D0-(EOP)D, D0-(EOP)-D-(PO), (DQ)(PO), and TCF sequences of Q-(EOP)-Q-(PO), and Q-(PO) etc.[8-12]

Rahmati *et al*.[13] investigated the effects of alkali charge and sulfidity on the kappa number, yield and viscosity in the case of *Bambusa tulda* kraft pulping process before and after O_2-delignification. The results indicated that higher alkali charge can lead to higher residual alkali and lower yield, kappa number and viscosity. Higher sulfidity can determine higher viscosity and lower yield, residual alkali and kappa number. Li[14] studied the kraft pulping delignification of bamboo (*Neosinocalamus*), the results indicated that in order to obtain relatively low kappa numbers (17~27), high sulfidity (20~40%) at lower EA (14~16%) increased pulp yield, compared to the case of low sulfidity (0~10%) at higher EA (16~18%). Pulp with lower kappa numbers (13~15) and acceptable yield can be obtained at a sulfidity level of 20~30% with 18% EA or at a sulfidity level of 10~30% with 20% EA. Kamthai[15] compared the AS-AQ pulping of sweet bamboo (*Dendrocalamus asper* Beacker) and pulping by conventional kraft process. Parthasamty[16] investigated the feasibility of using NaOH at the alkaline extraction stage to replace Na_2CO_3. Mittal and Maheshwari[17] described the mill experience of using extended oxygen delignification on bamboo pulp. Mahashwari and Gopichand[18] studied the effect of adding hydrogen peroxide to the bamboo pulp optical properties. Vu *et al*.[19] investigated the feasibility of decreasing the chlorine dioxide charge in the ECF bleaching of bamboo kraft pulp. Anapanurak *et al*.[20] explored steam explosion pre-treatment on alkali-oxygen pulping of bamboo. Zhao *et al*.[21] explored the replacement of softwood kraft pulp with ECF bleached bamboo kraft pulp in fine paper. The literature survey indicates that, practically, no study has been reported investigating the effects of bamboo stem age on the cooking, bleaching and handsheet properties. This study will be one of the first taking this factor into consideration.

This study focuses on thorny bamboo (*Bambusa stenostqachya* Hackel), a dense sympodial (clumped) bamboo capable of reaching a height of 16 m and diameter of 8 to 15 cm. It is distributed in the SE part of China and Taiwan. Materials of different stem ages were harvested and pulped by kraft and soda processes. The pulps were then bleached with a single stage of sodium hypochlorite. Before and after bleaching, the obtained pulps were beaten with PFI mill to 400 mL CSF and transformed into handsheets and the effects of bamboo age on the handsheet properties were examined. Different active alkali charges were used in the pulping process to study the effect on kappa number, yield and reject ratio. In the bleaching process, chemical charges were varied to examine the effects on the kappa number of the bleached pulp and on the handsheet physical properties. Handsheets were tested for grammage, caliper, bulk, tensile index, tearing index, burst index, folding endurance, brightness and water absorbency.

EXPERIMENTAL

Materials

Stems of (*Bambusa stenostachya* Hack.) 2-month, 14-month and 3-year-old thorny bamboo were harvested from a secondary stand at Fangyuan, Changhua County, in central Taiwan. The stems were cut at 0.5 m from the ground level and the branches were trimmed. The stems were sawn into short pieces and split to produce chips of 0.5 cm x 2.5 cm size for pulping.

Methods

Chemical analysis

Bamboo materials of different ages were ground in a Wiley mill to produce powders between 40-60 mesh of suitable sizes, which were then analyzed for their chemical compositions, including content of ash (TAPPI T211 om-07), hot-water extractives (TAPPI T428 om-08), 1% NaOH extractives and alcohol-benzene extractives (TAPPI T204 cm-07), holocellulose (TAPPI T203 cm-09), Klason lignin (TAPPI T222 om-02) and pentosans (TAPPI T223 cm-01) etc. All chemical analyses were replicated twice, so as to allow the calculation of means and standard deviations.

Kraft and soda pulping

The bamboo materials of 3 different ages were subjected separately to 2 pulping processes using a digester (AU/E-20, Bycobel, Belgium).

The kraft pulping involved the following conditions: 150 g o.d. bamboo chips with 16%, 18% and 20% active alkali charges (as Na_2O), sulfidity – 25%, liquor to chips ratio – 4:1, maximum temperature – 160 °C, time to temperature – 90 min, time at temperature – 90 min.

The soda process was performed under the following conditions: 150 g o.d. bamboo chips with active alkali charges (as Na_2O) of 16%, 18% and 20%; liquor to chips ratio – 4:1; maximum temperature – 160 °C, time to temperature – 90 min, time at temperature – 150 min.

At the end of each cooking, a 200-mesh screen was used to calculate pulp yield and reject rate. The accepted pulps (both before and after bleaching) were then measured for their kappa numbers (TAPPI T236 om-06).

Pulp bleaching

The conditions of hypochlorite bleaching included: bleaching agent dosages of 5% and 10% (as Cl_2), temperature – 40 °C, bleaching time – 3 h, pH adjusted to 10, bamboo pulp consistency – 6%. Bleaching was carried out by placing a known quantity of pulp in a PE plastic bag, different hypochlorite bleaching liquor was added; the bag was sealed and placed in a 40 °C water bath. The bags were kneaded periodically during bleaching to ensure even distribution of the liquor.

Handsheet preparation and testing

Both before and after bleaching bamboo pulps were separately beaten in a laboratory PFI mill (KRK, Japan) to a 400 mL Canadian Standard Freeness (tested according to TAPPI T227 om-99, Lesson, Taiwan). Then the pulps were formed into standard handsheets of 60 g/m^2 with a sheet mould (Lesson, Taiwan) in accordance with TAPPI T205. The handsheets were conditioned at an atmosphere of 20 °C and 65 %RH for 24 h before testing.

The handsheets were tested for grammage (TAPPI T410 om-98), caliper (TAPPI T411 om-95) with a Lesson instrument (Taiwan), bulk, tensile strength (TAPPI T494 om-96) with a Toyoseiki tester (Japan), tearing strength (TAPPI T414 om-98), with an Elmendorf type instrument HD-D, VE5D by Toyoseiki, Japan, burst strength (TAPPI T403 om-97) with a Toyoseki instrument (Japan), folding endurance (TAPPI T511 om-96) with a MIT type instrument, Model S, Toyoseiki (Japan), and brightness (TAPPI T452 om-98) with an Optron type instrument, Toyoseiki (Japan).

All experimental sets, from pulping, bleaching, handsheet preparation and testing were replicated twice and the results were then used to calculate the means and standard deviations of the experiments.

RESULTS AND DISCUSSION

Chemical composition of bamboo of different ages

Table 1 shows the chemical composition of thorny bamboo of different ages (0.2-, 1.2- and 3-year-old). The items examined included the contents of ash, hot-water extractives, 1% NaOH extractives, alcohol-benzene extractives, holocellulose, lignin and pentosans. There appeared to be insignificant influence of stem age on ash content, which ranged from 2.0% to 2.7%. The 1.2-year-old bamboo had the highest hot-water and alcohol-benzene extractives content. The 0.2-year-old bamboo tended to have all extractives contents higher than those of the 3-year-old bamboo. Klason lignin content showed an increasing trend, rising with increasing stem age. Mature bamboo stems tended to have a greater degree of lignification and fiber cell walls tended to increase in thickness with increasing stem age. Consequently, the proportions of holocellulose and pentosans decreased with increasing stem age.

Morphology of vascular bundles in bamboo of different ages

Figure 1 shows the SEM micrographs of vascular bundles in the mid-section of each bamboo stem of 0.2, 1.2 and 3 years old, respectively. The photos show that cell walls of the isolated fiber sheathes are thickened with increasing stem age. However, the fiber sheathes associated with vessels were thickened even in juvenile bamboo. Thickening of these fiber cells starts from the tips of the fiber cells and propagates toward the base tissues, whereas fiber cells in isolated fiber sheathes thicken from outside inward.[7]

Pulping

Table 2 shows kappa number, yield and reject ratio of thorny bamboo kraft pulps of differently aged materials cooked with different active alkali charges. Table 3 provides data for the soda process.

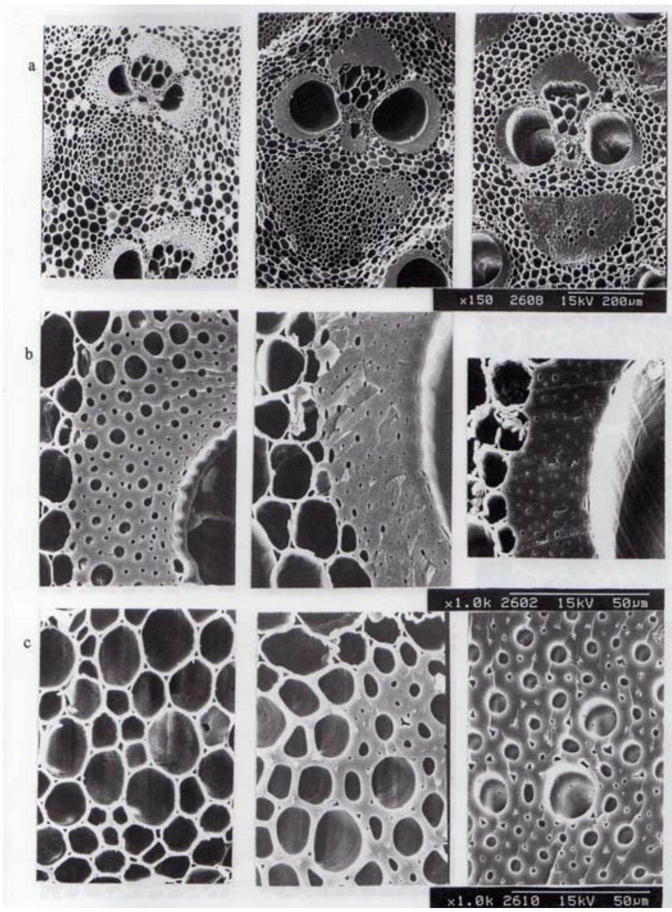

Figure 1: Typical mid-zone fibers of 3 different ages of thorny bamboo (a: vascular bundle, b: free fiber strand, c: vascular fiber-caps)

Table 1
Chemical composition of *Bambusa stenostachya* Hack. of different ages

Age (year)	Ash (%)	Hot water extractives (%)	1%NaoH extractives (%)	Alcohol -benzene extractives (%)	Lignin (%)	Holo-cellulose (%)	Pentosans (%)
0.2	2.68±0.071	8.75±0.170	29.62±0.40	5.61±0.085	20.68±0.071	76.17±0.10	18.99±0.19
1.2	2.08±0.028	9.43±0.042	28.08±0.11	7.55±0.042	23.17±0.042	69.84±0.11	17.58±0.10
3.0	2.66±0.028	7.52±0.057	25.62±0.10	4.75±0.141	25.21±0.057	68.53±0.11	17.55±0.10

Table 2
Effects of bamboo age and active alkali charge on kraft pulping results

Age (year)	Active alkali (%)	Yield (%) Screened	Shives	Total	Kappa No.
0.2	16	46.73±0.26	1.50±0.071	48.33	22.86±0.45
	18	45.56±0.18	0.83±0.042	46.39	15.37±0.18
	20	41.96±0.23	0.22±0.028	42.18	15.02±0.68
1.2	16	41.26±0.15	1.83±0.028	43.09	26.91±0.72
	18	42.52±0.34	0.81±0.042	43.33	19.58±0.45
	20	40.19±0.16	0.05±0.003	40.24	18.93±1.00
3.0	16	32.78±0.11	22.36±0.085	55.14	28.22±0.16
	18	35.69±0.26	18.32±0.028	54.01	24.53±0.30
	20	40.37±0.17	5.20±0.071	45.57	23.62±0.68

Table 3
Effects of bamboo age and active alkali charge on soda pulping results

Age (year)	Active alkali (%)	Yield (%) Screened	Shives	Total	Kappa No.
0.2	16	47.72±0.31	0.99±0.057	48.71	27.25±0.20
	18	47.08±0.18	0.99±0.049	48.07	22.92±0.30
	20	42.88±0.77	0.36±0.028	43.24	18.60±0.42
1.2	16	40.56±0.51	4.46±0.057	45.02	42.50±0.57
	18	42.39±0.39	1.18±0.035	43.57	32.72±0.86
	20	36.96±0.79	1.24±0.028	38.20	25.16±0.18
3.0	16	38.70±0.71	9.90±0.113	48.60	50.98±0.65
	18	38.43±0.33	6.82±0.092	45.25	46.77±0.67
	20	38.69±0.30	3.09±0.057	41.78	34.55±0.64

The results of kraft cooking indicated that mature (3-year-old) bamboo was difficult to digest. Although pulp yields were fairly high (55%), a substantial portion (22.4%) consisted in shives and coarse materials. A possible explanation was that mature bamboo stems had a higher lignin content (25.2%). To achieve complete defibrillation, it was necessary to increase the amount of liquor. In addition, at identical chemical charges, the mature stems produced pulp with a higher kappa number (28.2) than that of the youngest stems (22.9). This bode ill for the subsequent bleaching operation as well. The youngest stems with their lower lignin content (20.7%) and higher holocellulose content (76.2%) required a lower chemical charge, while produced a higher yield and lower kappa number. The trend of bamboo soda pulping largely paralleled that of kraft pulping. Despite a longer digestion time, soda pulping mostly produced pulps with higher kappa numbers, particularly, from older culms.

Kappa numbers of the pulps tended to decrease with increasing active alkali charge. On the other hand, kappa numbers of the pulps increased with increasing stem age. In general, the results of kraft pulping were superior to those of soda pulping with yields mostly ranging from 40% to 47%. The sodium sulfide in kraft cooking liquor appeared to exert stronger delignification efficacy, which is in agreement with certain commercial bamboo pulping results.[8,11]

Handsheet properties of unbleached bamboo pulps

Unbleached bamboo pulps were beaten in a PFI mill to 400 mL CSF. The kraft pulp of 0.2-year-old bamboo required only 3000 revolutions to decrease freeness to 400 mL, the pulp of 1.2-year-old bamboo required 5000 revolutions to reach the same freeness, and for the 3-year-old bamboo pulp it took 6000 revolutions.

Thus, the young bamboo pulp was easier to beat, as there were more parenchymatous cells. The older bamboo pulp fibers, on the other hand, had thickened cell walls, which hindered the beating action, hence younger, tender bamboo culms appeared to have advantages in pulp beating and refining.

The beaten pulps were formed into standard handsheets for pulp evaluation. Tables 4 and 5 show the handsheet properties of kraft and soda pulps, respectively, of thorny bamboo culms of different ages.

The results indicated that younger, tender stems produced pulps with better physical characteristics, particularly having folding endurance >1000 double folds. Also, it had the best brightness. At the highest active alkali charge (20%) studied, however, the properties of the pulps derived from the younger stems showed marked decreases, in particular, in folding endurance. We deem that the holocellulosic portion of the young stems might suffer substantial degradation and dissolution at the higher alkali charge, causing the observed decreases. Thus, in pulping young bamboo stems high active alkali charges should be avoided.

Comparing the pulps made by different processes, the mechanical properties and brightness of the handsheets from kraft pulps were superior to those of the soda pulps. At high active alkali charge (20%), however, both processes produced pulps with decreased strength properties. Therefore, the recommended active alkali charges were of 16% ~ 18%. For kraft pulping, an active alkali charge of 18% produced the best handsheet strength properties; whereas for soda pulping, 16% active alkali appeared to produce handsheets of the best strength properties.

Bleaching and handsheet properties of bleached pulps

The unbleached bamboo pulps were bleached with hypochlorite in a single-stage bleaching, using charges of 5% and 10% Cl_2 equivalent. The bleached pulps were similarly beaten in a PFI mill to a target freeness of 400 mL CSF. The resulting handsheet properties are shown in Tables 6 and 7 for kraft and soda pulps, respectively.

The results indicated that young, tender stems produced pulps with better brightness gains, and also the bleached pulps had lower kappa numbers. Less residual lignin probably means that the pulp will have less color reversion in service. At a hypochlorite charge of 10%, pulps from the young bamboo stems reached a brightness of 74% ISO. Pulps from mature stems, however, barely reached a brightness of 55% ISO. In order to attain the same brightness level of the young culms, more severe cooking and bleaching conditions are required, which consequently will produce pulps of poorer strength properties.

Table 4
Effects of bamboo age and active alkali charge on handsheet properties of unbleached sulfate pulp

Age (year)	Active alkali (%)	Freeness (mL, CSF)	Brightness (%ISO)	Bulk (cm^3/g)	Breaking length (km)	Tear index ($mN \cdot m^2/g$)	Burst index ($kPa \cdot m^2/g$)	Folding endurance (double folds)
0.2	16	416±8.5	31.1±1.27	1.92±0.028	9.54±0.10	262±5.7	8.58±0.085	1517±24
	18	406±5.7	34.9±0.71	1.96±0.014	10.27±0.41	245±7.1	7.94±0.057	1097±64
	20	418±4.2	35.4±0.85	2.04±0.014	6.29±0.14	140±4.2	4.93±0.042	452±10
1.2	16	428±11.3	28.0±0.99	2.22±0.042	7.02±0.17	219±2.8	6.12±0.028	559±27
	18	411±7.1	30.9±0.57	2.17±0.028	7.26±0.28	232±1.4	6.22±0.057	412±11
	20	422±9.9	33.2±0.57	2.08±0.042	6.85±0.35	197±5.7	5.17±0.099	241±10
3.0	16	410±15.6	24.0±0.99	2.38±0.028	5.49±0.13	180±5.7	4.81±0.028	315±14
	18	412±5.7	26.2±0.57	2.32±0.014	6.44±0.62	201±2.8	5.58±0.113	245±35
	20	419±9.9	27.2±0.28	2.38±0.014	5.28±0.37	170±4.2	4.65±0.071	235±7

Table 5
Effects of bamboo age and active alkali charge on handsheet properties of unbleached soda pulp

Age (year)	Active alkali (%)	Freeness (mL, CSF)	Brightness (% ISO)	Bulk (cm^3/g)	Breaking length (km)	Tear index ($mN\cdot m^2/g$)	Burst index ($kPa\cdot m^2/g$)	Folding endurance (double folds)
0.2	16	425±7.1	30.1±0.28	1.85±0.042	6.19±0.057	246±8.5	5.39±0.085	796±23
	18	425±5.7	32.1±0.85	1.89±0.028	6.08±0.014	227±9.9	5.66±0.057	594±13
	20	423±4.2	34.5±0.71	1.85±0.042	4.06±0.071	200±14.1	3.95±0.141	268±18
1.2	16	422±8.5	25.0±0.57	2.13±0.028	6.13±0.042	227±9.9	5.60±0.071	362±17
	18	405±7.1	27.9±0.85	2.17±0.042	5.70±0.057	225±5.7	4.79±0.085	203±10
	20	429±14.1	30.3±0.42	2.13±0.028	4.21±0.028	223±4.2	3.78±0.042	129±17
3.0	16	402±8.5	21.0±0.71	2.56±0.057	4.87±0.071	209±12.7	4.25±0.071	118±14
	18	422±4.2	21.9±0.57	2.50±0.071	4.80±0.028	219±7.1	4.10±0.283	112±17
	20	432±5.7	23.6±0.71	2.63±0.042	5.14±0.057	206±4.2	4.30±0.141	89±13

Table 6
Effects of bamboo age, active alkali charge and NaOCl dosage on handsheet properties of bleached sulfate pulp

Age (year)	Active alkali (%)	NaOCl charge (%)	Kappa no.	Freeness (mL, CSF)	Brightness (% ISO)	Bulk (cm^3/g)	Breaking length (km)	Tear index ($mN\cdot m^2/g$)	Burst index ($kPa\cdot m^2/g$)	Folding endurance (double folds)	Water absorbency (cm/10 min)
0.2	16	5	8.8 ±0.42	403 ±9.2	53.0 ±0.71	2.04 ±0.028	7.09 ±0.042	251 ±8.5	6.41 ±0.141	917 ±24	9.4 ±0.42
		10	5.1 ±0.57	423 ±11.3	67.7 ±0.57	2.08 ±0.014	6.21 ±0.014	245 ±7.1	5.45 ±0.071	763 ±10	9.7 ±0.99
	18	5	5.7 ±0.28	423 ±4.2	66.1 ±0.14	2.00 ±0.014	6.48 ±0.028	221 ±15.6	5.86 ±0.028	755 ±7	9.2 ±0.28
		10	3.7 ±0.14	420 ±5.7	74.3 ±0.42	2.08 ±0.007	6.38 ±0.042	211 ±2.8	5.05 ±0.071	727 ±23	9.5 ±0.71
1.2	16	5	9.8 ±0.28	416 ±4.2	49.8 ±0.28	2.08 ±0.014	5.26 ±0.014	201 ±4.2	5.04 ±0.042	360 ±8	10.7 ±0.28
		10	8.4 ±0.42	427 ±8.5	59.9 ±0.42	2.17 ±0.028	5.61 ±0.071	190 ±7.1	5.08 ±0.028	313 ±18	10.7 ±0.14
	18	5	7.3 ±0.57	413 ±4.2	51.2 ±0.28	2.04 ±0.057	4.81 ±0.028	207 ±2.8	4.59 ±0.057	348 ±18	10.1 ±0.85
		10	5.3 ±0.35	390 ±7.1	62.9 ±1.27	2.08 ±0.014	4.77 ±0.099	197 ±5.7	4.65 ±0.071	334 ±16	8.4 ±0.28
3.0	16	5	13.9 ±0.57	413 ±5.7	37.2 ±0.28	2.22 ±0.014	5.96 ±0.085	178 ±4.2	4.95 ±0.057	239 ±13	11.6 ±0.42
		10	11.5 ±0.42	401 ±8.5	48.0 ±0.71	2.13 ±0.042	5.75 ±0.141	169 ±9.9	4.78 ±0.113	208 ±11	10.9 ±0.85
	18	5	11.4 ±0.35	423 ±2.8	41.7 ±0.28	2.13 ±0.028	4.99 ±0.085	167 ±5.7	4.37 ±0.099	206 ±8	11.3 ±0.42
		10	9.6 ±0.57	407 ±9.9	55.3 ±0.42	2.13 ±0.014	4.86 ±0.028	159 ±4.2	3.80 ±0.057	198 ±11	10.5 ±0.57

Table 7
Effects of bamboo age, active alkali charge and NaOCl dosage on handsheet properties of bleached soda pulp

Age (year)	Active alkali (%)	NaOCl charge (%)	Kappa no.	Freeness (mL, CSF)	Brightness (%ISO)	Bulk (cm^3/g)	Breaking length (km)	Tear index ($mN·m^2/g$)	Burst index ($kPa·m^2/g$)	Folding endurance (double folds)	Water absorbency (cm/10 min)
0.2	16	5	22.2 ±0.57	413 ±4.2	44.7 ±0.99	2.17 ±0.028	5.52 ±0.099	214 ±5.7	4.92 ±0.028	463 ±18	10.9 ±0.57
		10	5.0 ±0.99	393 ±11.3	67.8 ±0.42	2.08 ±0.014	5.46 ±0.042	206 ±8.5	4.86 ±0.085	388 ±11	10.2 ±0.28
	18	5	13.6 ±0.85	413 ±4.2	50.9 ±0.85	2.08 ±0.014	5.37 ±0.028	201 ±5.7	4.61 ±0.042	268 ±14	10.7 ±0.99
		10	3.7 ±0.14	410 ±7.1	72.5 ±0.71	2.04 ±0.007	4.89 ±0.071	199 ±7.1	4.60 ±0.071	245 ±7	9.9 ±0.57
1.2	16	5	27.7 ±0.28	423 ±4.2	29.1 ±0.14	2.33 ±0.014	4.86 ±0.028	210 ±8.5	4.23 ±0.042	218 ±11	11.5 ±0.71
		10	13.4 ±0.57	413 ±5.7	45.6 ±0.42	2.22 ±0.028	4.55 ±0.071	196 ±8.5	4.27 ±0.099	140 ±10	11.1 ±0.14
	18	5	19.0 ±0.57	413 ±4.2	34.1 ±0.57	2.27 ±0.057	4.50 ±0.057	201 ±1.4	4.04 ±0.057	167 ±8	10.4 ±0.42
		10	8.8 ±0.85	393 ±9.9	59.6 ±0.85	2.08 ±0.014	4.31 ±0.042	190 ±7.1	4.02 ±0.028	120 ±10	10.2 ±0.28
3.0	16	5	34.5 ±0.71	420 ±7.1	23.0 ±0.57	3.13 ±0.014	4.25 ±0.071	188 ±11.3	4.19 ±0.057	102 ±8	12.9 ±0.57
		10	19.6 ±0.57	393 ±4.2	34.7 ±0.28	2.38 ±0.042	4.10 ±0.099	179 ±4.2	3.66 ±0.085	88 ±7	12.1 ±0.14
	18	5	30.8 ±0.57	413 ±2.8	25.0 ±0.57	2.63 ±0.028	3.88 ±0.113	189 ±7.1	3.72 ±0.028	98 ±11	12.5 ±0.71
		10	15.6 ±0.85	409 ±9.9	38.2 ±0.28	2.33 ±0.014	3.67 ±0.085	182 ±4.2	3.64 ±0.057	66 ±8	11.7 ±0.99

Bleached pulp handsheet strength properties, regardless of the pulping process, active alkali charge and bamboo age, all showed the impacts of the bleaching chemical and became lower than those of their unbleached counterparts. Nevertheless, the pulps made from young stems still retained their better properties. As noted above, mature bamboo stems are more difficult to bleach, if more severe bleaching conditions are applied, then the pulp strength properties will suffer degradation to a higher extent. Therefore, to garner benefits of both brightness and strengths, only younger than 1-year-old bamboo stems should be used for pulping.

The bleached bamboo pulps also illustrated that young stems retained more thin-walled, flexible fiber cells, which produced handsheets with a tighter and more compact texture. The higher conformity of the fibers also contributed to better interfiber bonding and superior strength properties.

CONCLUSION

The stems of 0.2-, 1.2- and 3-year-old thorny bamboo were separately cooked by kraft and soda processes. The resulting pulps were then subjected to a single-stage hypochlorite bleaching. The unbleached and bleached pulps were formed into handsheets and compared as to their properties. Chemical analyses indicated that lignin content increased with increasing bamboo age, while holocellulose and pentosans showed a contrary trend. Pulp beating results indicated that the pulp made from young culms was easier to beat. Handsheets made from young bamboo also possessed better brightness and strength properties, notably attaining a folding endurance >1000 double folds. Kraft pulps, in general, had better strength and brightness performance than the corresponding soda pulps. The recommended active alkali charge for pulping should be 16% to 18%. The bleaching experiment also indicated that pulps made from young bamboo culms showed better brightness gain and lower kappa number. Compared to the unbleached pulps, all bleached pulps showed decreases in strength properties. Nevertheless, pulps made from young stems still retain their strength advantages. In conclusion, only young stems of thorny bamboo are suitable for pulping and papermaking, as they have both adequate strengths and brightness needed for fine paper.

REFERENCES

1. A. Y. Kulkarni and P. M. Parkhe, *Procs*. *TAPPI Pulping Conference*, Atlanta, TAPPI Press, 1990, pp. 313-320.
2. J. E. Atchison, *Tappi J*., **79**, 87 (1996).
3. D. G. Meadows, *Tappi J*., **80**, 99 (1997).
4. J. E. Atchison, *Procs*. *North America Nonwood Fiber Symposium*, Atlanta, 1998, pp. 13-42.
5. R. Mormanee, Sustainable utilization of bamboo for pulp and paper manufacturing in Thailand, *Procs*. *VIII World Bamboo Congress*, September 18, 2009, vol. 8 (powerpoint file).
6. J. Y. Quan, J. S. Huang, X. Zhang, and P. Q. Wang, *Procs*. *Second International Nonwood Fiber Pulping and Papermaking Conference*, Atlanta, TAPPI Press, 1994, pp. 639-649.
7. R. J. Murphy and K. I. Alvin, *IAWA J*., **18**, 147 (1997).
8. S. Andtbacka, A Fiberline Designed for Bamboo Pulping, APPW, 2004.
9. A. R. K. Rao and A. G. Kulkarni, *Procs*. *North America Nonwood Fiber Symposium*, Atlanta, TAPPI Press, 1998, pp. 189-196.
10. J. T. Jeyasingam, *Procs*. *Pulping/Process and Product Quality Conference*, Atlanta, TAPPI Press, 2000, pp. 139-147.
11. J. T. Jeyasingam, *Procs*. *TAPPI Pulping Conference*, Atlanta, TAPPI Press, 1998, pp. 767-774.
12. K. H. Lee and J. M. Won, US Patent 20080295982, 2008.
13. H. Rahmati, P. Ebrahimi and M. Sedghi, *Indian J*. *Chem*. *Eng*., **17**, 74 (2010).
14. P. Y. Li, M. Y. Zhang, X. X. Xia and C. T. Lin, *Advanced Materials Research*, **418-420**, 2241 (2011).
15. S. Kamthai, *Chiang Mai J*. *Sci*., **34**, 97 (2007).
16. V. R. Parthasamthy, *Tappi J*., **74**, 183 (1991).
17. S. K. Mittal, and S. Maheshwari, *Procs*. *TAPPI Pulping Conference*, Atlanta, TAPPI Press, 1994, pp. 243-249
18. S. Mahashwari and K. Gopichand, *Procs*. *TAPPI Pulping Conference*, Atlanta, TAPPI Press, 1990, pp. 481-485.
19. M. T. V. Vu, R. Alen and H. Pakkanen, *Procs*. *Engineering, Pulping, and PCE&I Conference*, Atlanta, TAPPI Press, 2004, pp. 77-91.
20. W. Anapanurak, N. Laemsak, T. Veenin and R. Boonpradit, *Procs*. *Engineering, Pulping and Environmental Conference*, Atlanta, TAPPI Press, 2007, pp. 69-78.
21. G. L. Zhao, R. Lai, B. H. He, T. Greschik and X. F. Li, *BioResources*, **5**, 1733 (2010).