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KRAFT AND MODIFIED KRAFT PULPING OF BAMBOO (*PHYLLOSTACHYS BAMBUSOIDES*)

Delignification of bamboo (Phyllostachys bambusoides) grown in the Eastern Black Sea region of Turkey was carried out by kraft, kraft-anthraquinone (AQ) and kraft-sodium borohydride ($NaBH_4$) pulping under a variety of conditions to determine the effect of AQ, $NaBH_4$ and cooking parameters on pulp and paper properties such as yield, kappa number, viscosity, and strength properties. The chemical composition and fibre dimensions of the cell wall of Phyllostachys bambusoides culm fibres were also investigated. The analysed data revealed the following optimum kraft pulping conditions: Active alkali, 16% (as Na_2O); $NaBH_4$, 0.3%; AQ, 0.1%; and cooking time, 90 min. The modified kraft method with 0.1% AQ was found to provide better pulp properties than those with 0.3% $NaBH_4$. Increasing the thickness of chip used in cooking from 2.0 mm to 4.0 mm increase the yield. The optimum cooking conditions of Phyllostachys bambusoides modified kraft pulps were found to be: screened yield, 48.1%; reject ratio, 0.53%; kappa number, 24.1; viscosity, 1210 ml/g; breaking length, 6.05 km; burst index, 5.08 kPa m^2/g; tearing index, 4.99 mNm^2/g; brightness 20.35%.

Keywords: bamboo (*Phyllostachys bambusoides*), cooking conditions, modified kraft cooking, strength and optical properties

Introduction

Despite a significant reduction in forest resources, global paper consumption and demand for paper, continuously increases. The pulp and paper industry is looking to use alternative fibrous resources such as non-wood plants. [Saijonkari-Pahkala 2001; Jahan et al. 2002]. Non-wood resources are important raw materials in Turkey, where wood is not available in sufficient quantities to meet the demand for pulping and papermaking [Salmela et al. 2008]. Also, large parts of cellulose are imported to Turkey. The national production of long fibre pulp is not sufficient to meet the internal market demand. The plantations of long

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fibrous and fast-growing bamboo species such as softwood species can take an important role in supplying raw-material to produce pulp and paper. In addition, bamboo is an attractive raw material for chemical pulp, due to its long fibre structure [Salmela et al. 2008].

When the fibre length (2.30-2.04 mm) of the bamboo species (i.e., *Phyllostachys bambusoides* and *Phyllostachys pubescens*) grown in Turkey is compared to that of softwood fibres, these bamboos can be used for more versatile paper products, compared to the majority of other non-wood pulps, due to the high strength of bamboo chemical pulps [Vu et al. 2004].

The most popular pulping process in the world is the kraft pulping process because of its excellent pulp strength and easy recovery of chemicals. Today the kraft process is not only a dominant alkaline pulping process for wood, but also it is the most used pulping process for nonwood such as bamboo [Kamthai and Puthson 2005]. In order to improve the properties of pulp, modification of kraft pulping is an important method [Rahmati et al. 2010]. The process modification, while having an effect on the pulp properties, can lead to an increase in the yield of kraft pulp, depending on the prevention of the peeling reaction, accelerating delignification, removing the barriers of efficient mass transfer, or a combination of these [Akgül et al. 2007]. Pulping additives are one of the most important modification methods. Anthraquinone (AQ) and borohydride are two common additives used for the pulp and paper industry. During the eighties, the addition of anthraquinone and related compounds to the alkaline pulping process opened up new possibilities for developing novel processes [Erişir et al. 2015]. AQ protects the reducing aldehyde groups of carbohydrates against alkaline peeling and improves lignin solubility and thus increases pulp yield through the greater retention of hemicelluloses [Rajan et al. 1992]. In the late fifties, several groups used sodium borohydride to increase the rate of delignification and the total pulp yield in the kraft pulping process [Erişir et al. 2015]. Borohydride is a powerful reducing agent that reduces the carbonyl group which is located on the end group of the cellulose, to the hydroxyl group during cooking [Courchene 1998].

The main aim of this study was to investigate the optimum kraft cooking conditions and the effect of sodium borohydride ($NaBH_4$) and anthraquinone (AQ) addition on pulp and paper properties for bamboo pulp.

Materials and methods

Materials

Phy. bambusoides from Rize/Pazar in Turkey was used as bamboo material in the study. The samples were approximately 3 to 4 years old, about 50 to 60 mm in diameter and 8 to 10 m in height. Bamboo samples were 5 cm in diameter. Nodes and rotten parts were removed from the body. It was cut into pieces with an average size of about 30 mm × 20 mm × 4 mm. For pulping, the bamboo chips were screened [SCAN-CM 40:94], air-dried, and stored at a dry solids content of 92%.

Analysis of raw materials

Analyses of the raw material and pulp of the bamboo were made according to TAPPI methods with the exception of the holocellulose content which was determined by Wise's sodium chlorite method [Wise and Murphy 1946] and cellulose content according to Kurscher and Hoffner's nitric acid method [Rowell 1984]. Using the respective TAPPI methods, alpha cellulose content was determined by TAPPI T203 cm-99:2009, lignin content was determined by TAPPI T222 om-11:2011 (acid insoluble lignin), silica content was determined by TAPPI T245 cm-98:2007, water solubility of the wood was determined by TAPPI T207 cm-08:2008, alcohol-toluene extraction was determined by TAPPI T204 cm-07:2007, and one percent sodium hydroxide solubility of wood was determined by TAPPI T212 om-12:2012. The determination of kappa numbers of pulp samples was carried out using the standard procedure described in TAPPI T236 om-06:2006. The pulp obtained was used to determine viscosity in accordance with SCAN-CM 15:88:1988.

Preparing of wood anatomy

For morphological wood samples, stems of about 3 × 3 × 14 mm in diameter in each case, were boiled in water and stored in 50% aqueous ethanol and sectioned using a sliding microtome at a thickness of about 20-25 µm and stained with a safranin and alcianblue combination [Ives 2001]. The permanent slides were examined and photographed by an Olympus BX 50 research microscope – Bs200Prop Image Processing and Analysis Systems.

Preparing of samples for fibre dimensions and derived values

The chloride delignification method was applied to measure fibre morphologic properties of the specimens (0.5 mm thickness and 2 cm long in parallel to fibre). In this method, specimens were immersed into chloride solution until they were defibred and later, morphologic properties were measured. A drop of the macerated sample was taken on a slide and fibre length, fibre width, lumen width and cell wall thickness were measured by using a vizopan microscope. For measuring fibre length, fibre width, lumen width hand cell wall thickness and diameter, 200 fibres were measured from the slides and average readings weretaken.

Three derived values were also calculated by using fibre dimensions: slenderness ratio as fibre length/fibre diameter, flexibility coefficient as (fibre lumen diameter/fibre diameter) × 100 and Runkel ratio as (2 × fibre cell wall thickness)/lumen diameter [Ogbonnaya et al. 1997].

Pulping method

Oven-dried 700-gram bamboo wood chips were used for each pulping trial. Pulping experiments were carried out in a 15 L electrically heated laboratory type rotary digester and governed by a digital temperature control system. The cooking conditions are given in table 1.

Table 1. Cooking conditions of active alkali (AA), cooking time and $NaBH_4$ and AQ

AA, on o.d. bamboo (as NaOH) (%)	12, 14, 16, 18
Cooking time (min.)	60, 90, 120, 150
AQ rate on o.d. bamboo (%)	0.1
$NaBH_4$ rate on o.d. bamboo (%)	0.3
Sulfidity (%)	25
Max. Temperature (ºC)	165
Liquor/chip	4/1

At the end of pulping process, degassed the reactor was opened. The pulp was washed, disintegrated in a laboratory type pulp mixer with a 2.0-L capacity and screened on a Noram type pulp screen with a 0.15 mm slotted plate. Pulp yield was determined as dry matter obtained on the basis of oven dried (o.d.) raw material.

Evaluation of pulp

The pulp was beaten to 50 ±3°SR (Schopper-Riegler) freeness with a Hollander according to TAPPI T200 sp-10:2010. Then, hand sheets were produced in a Rapid-Kothen Sheet Former. Hand sheets of 60 g/m^2 were formed and their properties were evaluated in accordance with the TAPPI methods. The hand sheets were conditioned in accordance with TAPPI T402 sp-08:2013, the burst index, tear index and tensile index of the hand sheets were determined by TAPPI T403 om-10:2010, TAPPI T414 om-12:2012 and TAPPI T494 om-01:2006, respectively. Brightness and opacity were calculated in accordance to the ISO standard.

Results and discussion

Chemical composition, fibre morphological and derived properties of *Phyllotachys bambusoides*

Paper strength depends on the chemical compositions of raw materials; pulp mechanical strength and especially tensile strength is directly proportional to cellulose content, whereas lignin is an undesirable polymer and its removal during pulping requires high amounts of energy and chemical [Ververis et al.

2004]. The chemical composition of *Phy. bambusoides* used in this study are given in table 2.

Table 2. Chemical composition of bamboo (*Phyllotachy bambusoides*)

Component	Determined	Vu et al. 2004	Yang et al. 2008	He et al. 2008	Jahan et al. 2017
Holocelullose	70.5%	68.6%	–	–	–
Celullose	50.1%	–	57-66%	51.09%	–
Alpha cellulose	43.3%	–	26-43%	–	45.2%
Lignin	24.5%	25.8%	20-30%	22.40%	25.5%
Ash	1.35%	2.2%	1-3%	1.53%	2.2%
Silica	1.03%	0.7%	–	–	–
Hot Water	6.47%	–	–	6.78%	–
1%NaOH	25.1%	–	–	22.26%	–
Alcohol-Benzene	3.94%	0.8%	–	1.64%	–

As seen in table 2, *Phy. bambusoides* contains holocellulose 70.5%, cellulose 50.1%, α-cellulose 43.3%, lignin 24.5%, ash 1.35% and silica 1.03%. The main components of bamboo (holocellulose and lignin) and solubility results were comparable with previous studies [Vu et al. 2004; He et al. 2008; Yang et al. 2008; Jahan et al. 2017]. But the holocellulose ratio is greater than that of *Phy. bambusoides* found in literature [Wai and Murakami 1982]. The differences between the chemical compositions of the bamboo wood samples could have originated from the age, species and ecological factors of the sample in their plantation area [Erişir et al. 2015]. The holocellulose fraction of stem is approximately equal to those of softwood. Also, the importance of fibre dimensions and their derived values (slenderness ratio, Runkel ratio and flexibility coefficient) on pulp and paper mechanical strength are well documented [Ververis et al. 2004]. As seen in table 3, average internodes, fibre length of *Phy. bambusoides* and *Phy. pubescens* are measured as 2.30 ±0.06 µm and 2.04 ±1.44 µm, respectively.

Bamboo samples are slightly shorter than pine fibres (2.7-4.6 mm); thus, they are long enough to be classified as long fibres. The fibre width of *Phy. bambusoides* is considerably narrower than softwood fibre (20-40 µm). The *Phy. bambusoides* fibre cell wall is twice as thick than that of *Phy. pubescens*; however, *Phy. pubescens* fibre lumen, is wider than that of *Phy. ambusoides* fibre lumen width. *Phy. bambusoides* fibre cell wall is also thicker than that of hardwood fibre and wheat straw fibre which could result in a higher fibre strength [Gomide et al. 1991; Tutuş and Eroğlu 2004]. The vascular bundle of *Phy. bambusoides* is shown in figure 1.

The Phyllostachys species is assigned to Type I in which vascular bundles consist of one part (central vascular strand) and sclerenchyma sheets as the supporting tissue. Wai and Murakami [1982] found that a large part of the fibres

Table 3. The fibre dimensions and derived values of *Phyllotachys bambusoides* and and *Phyllotachys pubescens*

Sample	Fibre length (mm)	Diameter (µm)	Lumen diameter (µm)	Cell wall thickness (µm)
Phy. bambusoides (Internode)	2.30 ±0.06	15.10 ±0.51	6.90 ±0.30	4.17 ±0.214
Phy. pubescens (Internode)	2.04 ±1.44	11.62 ±0.82	7.41 ±0.523	2.15 ±0.152
Phy. pubescens (Node)	1.48 ±0.104	14.34 ±1.01	8.83±0.624	2.69 ±0.19

Derived Values

	Slenderness ratio	Flexibility coefficient	Runkel Ratio
Phy. bambusoides (Internode)	152.31	45.69	1.21
Phy. pubescens (Internode)	175.55	63.76	0.58
Phy. pubescens (Node)	103.20	61.57	0.61

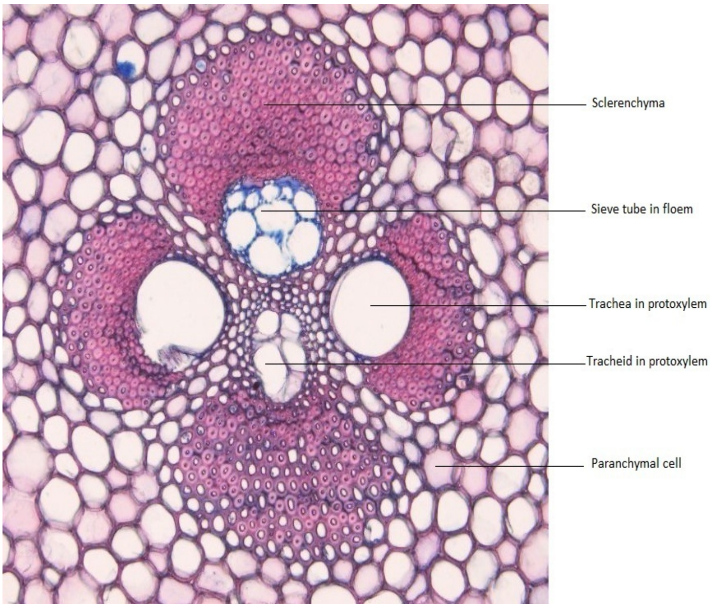

Fig. 1. The vascular bundle of bamboo (*Phyllostachys bambusoides*)

had a relatively larger lumen diameter. The rates of fibre and other cells, especially the parenchyma cells, in the cross-section of the *Phyllostachys* species are found to be 51.12% and 48.88%, respectively. In addition to fibres and vessel elements, bamboo pulp contains parenchyma cells as well. In order to separate these pulp elements, the holopulp was sorted using a Bauer-Mc Nett classifier equipment. The elements that passed through a 100-mesh screen consist of parenchyma cells and a few fibrous fines include 14.74% of the holocellulose pulp. It appears that the amount of the fraction on a 60-100 mesh screen is approximately equal to the amount of the fibre elements in the bamboo holocellulose pulp [Wai and Murakami 1982]. It has been found that the presence of thin-walled fibres in the pulp improves the sheet strength-properties, particularly the burst index and folding endurance [Wai and Murakami 1984; Bhargava 1987].

The strength properties of the papers were positively correlated with the slenderness ratio [Brindha et al. 2012]. If the slenderness ratio is lower than 70, it is invaluable for quality pulp and paper production [Bektas et al. 1999; Brindha et al. 2012]. As seen in table 3, the slenderness ratio of the *Phy. bambusoides* (internode), *Phy. pubescens* (internode) and *Phy. pubescens* (node) were found to be 152.31, 175.55 and 103.20 respectively. These values are higher than 70 and so it can be utilized in the paper industry. The Runkel ratio is a microscopic extension of the wood density in that ratio of fibre cell wall thickness to its lumen that determines the suitability of a fibrous material for pulp and paper production [Kiaei et al 2014]. Also, for any wood species to be good quality for pulp and paper production, its Runkel ratio must be 1 [Ververis et al. 2004; Xu et al. 2006; Enayati et al. 2009; Kiaei et al, 2014]. The Runkel ratio of *Phy. bambusoides* (internode), *Phy. pubescens* (internode), and *Phy. pubescens* (node) were determined to be 1.21, 0.58, and 0.61 respectively. Smook determined that the Runkel ratio was between 0.4-0.7 for hardwoods, and 0.35 for softwoods [Smook 1997]. Cao et al [2014] studied the Runkel ratio and slenderness ratio in green bamboo (*Dendrocalamopsis oldhami)* and moso bamboo (*Phyllostachys edulis*). They reported that the Runkel ratio of green bamboo was determined to be 2.96, while the Runkel ratio of moso bamboo was determined to be 4.53. The slenderness ratio of green bamboo and Moso bamboo was found to be 158.3 and 160.1, respectively [Cao et al. 2014]. The Runkel ratio of green bamboo and moso bamboo is higher than in our studies, but the slenderness ratio of green and moso bamboo are similar. Another important qualifying parameter is the flexibility coefficient for evaluating fibre quality. The flexibility coefficient of the *Phy. bambusoides* (internode), *Phy. Pubescens* (internode), and *Phy. pubescens* (node) were about 45.69, 63.76 and 61.57 respectively. The degree of fibre bonding depends largely on the flexibility of individual fibres [Kiaei et al. 2014]. There are four groups according to the flexibility ratio [Bektaş et al. 1999]. If the flexibility coefficient is greater than 75, this kind of fibre is called high elastic fibre. If the flexibility coefficient is between 50-75, this kind of fibre is call elastic fibre. If the flexibility coefficient is between 30-50, this kind of fibre is call rigid fibre. Finally, if the flexibility coefficient is less than 30, this kind of fibre is call high rigid fibre. As a result of this, bamboo fibres are called elastic fibre and they are suitable for paper production.

Effects of active alkali and cooking time on pulp properties

The effects of active alkali and cooking time on the kappa number, viscosity, yield of the pulp and physical properties are provided in table 4 and figures 2-3.

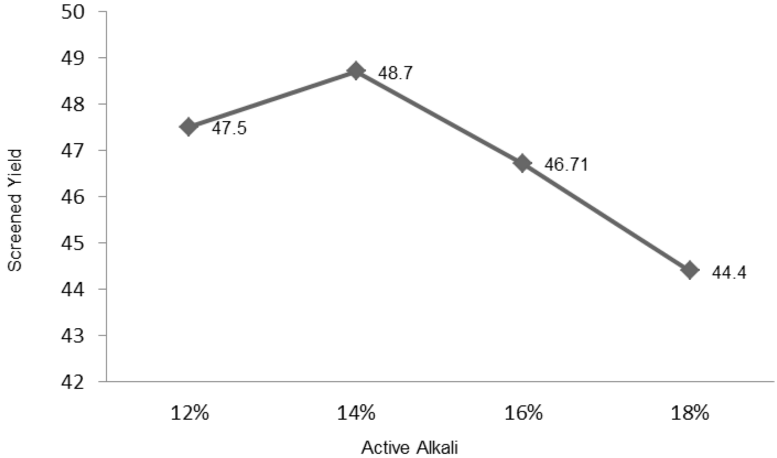

Fig. 2. Effect of active alkali charge ratio on the screened yield of bamboo kraft pulps (time 90 min.)

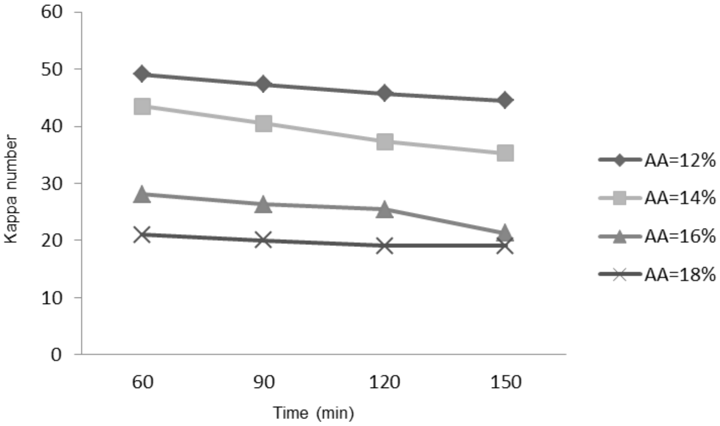

Fig. 3. Effect of cooking time at different AAcharge on the kappa number of bamboo kraft pulps

Table 4. The effect of AA charge, cooking time and pulping additives on strength and optical properties of bamboo kraft pulp

Cooking number	AA (%)	Cooking time (min)	Screened yield (%)	Reject (%)	Total yield (%)	Kappa No	Viscosity (ml/g)	Burst index (kPa·m^2/g)	Tensile index (Nm/g)/10	Tear index (mNm^2/g)	ISO brightness (%)	ISO opacity (%)
1	12	60	47.10	8.50	55.6	49.1	1370	4.42	5.826	4.94	11.76	99.06
2	12	90	47.50	6.10	53.6	47.3	1350	4.40	5.517	4.90	12.32	98.31
3	12	120	47.20	6.01	53.2	45.7	1275	4.15	5.425	4.63	13.70	99.35
4	12	150	46.30	5.75	52.1	44.5	1251	3.59	4.849	4.55	13.76	98.31
5	14	60	49.93	5.30	55.20	43.5	1315	5.62	6.726	5.96	14.12	97.89
6	14	90	48.70	4.40	53.10	40.5	1265	5.33	6.701	5.86	15.71	97.92
7	14	120	47.06	3.35	50.38	37.3	1210	5.13	6.404	5.27	15.77	98.20
8	14	150	45.70	2.00	47.70	35.3	1185	4.69	6.160	5.04	16.87	97.13
9	16	60	47.13	1.77	48.90	28.1	1290	5.56	6.785	5.46	17.74	96.76
10	16	90	46.71	1.50	48.21	26.3	1226	5.08	6.504	5.31	19.16	96.09
11	16	120	45.10	1.00	46.10	25.4	1204	5.15	6.207	5.21	20.42	96.05
12	16	150	44.71	0.75	45.46	21.3	1170	4.67	6.092	4.96	21.89	94.44
13	18	60	45.33	0.52	45.85	21.01	1250	4.66	5.899	5.28	22.23	94.60
14	18	90	44.40	0.31	44.07	20.03	1164	4.61	5.763	4.79	25.29	92.89
15	18	120	43.01	0.15	43.15	19.08	1153	4.09	5.506	4.51	26.44	94.72
16	18	150	42.30	0.10	42.40	19.05	1150	3.89	4.920	3.41	28.02	94.18
17 (0.3% $NaBH_4$)	16	90	48.1	0.87	48.1	25.07	1230	6.39	5.12	6.31	22.16	95.13
18 (0.1% AQ)	16	90	48.6	0.53	48.6	24.08	1210	6.05	5.08	4.99	20.35	95.18
19 (0.3% $NaBH_4$)	16	120	46.0	0.43	46.0	24.03	1230	6.04	5.05	5.07	21.52	93.81
20 (0.1% AQ)	16	120	47.50	0.15	47.50	24.10	1215	5.71	4.72	5.64	23.67	93.48
21 (0.3% $NaBH_4$)	18	90	45.40	0.30	45.40	19.71	1235	5.71	4.50	5.71	29.55	90.24

Modified cookings: maximum temperature: 165°C, sulphidity: 25%, liquor/wood: 4/1.

It can be seen that, using 14% AA charge and 90 min. pulping time (6th trial) provided a 48.70% screened yield, 4.40% reject, 53.10% total yield and a kappa number of 40.5. The 10th trial (16% AA, 90 min.) provided a 46.71% screened yield, 1.50% reject and 48.21% total yield, and a kappa number of 26.3. However, the kappa number of the pulp in the 10th trial (16% AA, 90 min.) is considerably lower than that of pulp found in the 6th trial (14% AA, 90 min.). The effect of the cooking time on the kappa number is given in figure 3.

Figure 3 shows that an increase in cooking time from 60 to 150 minutes resulted in a gradual decrease in screened yield, reject, kappa number and viscosity. Similarly, the screened yield was found to be gradually decreasing when the cooking period is prolonged. It can be concluded that, both AA and cooking time has a significant influence on screen yield and kappa number. Thus, an increase in AA at a constant cooking time or an increase in cooking time at a constant AA was found to reduce the kappa number. According to these results the most important factor for delignification is the alkali charge. Active alkali has a significant influence on the kappa number. The degree of delignification is relatively small with a short cooking time; thus, a considerable amount of lignin is still left in the pulp, resulting in lower bonding and reduced tear strength. In contrast, the degree of delignification is much higher with longer cooking times. As a result of longer cooking times, some degree of fibre damage is expected, which, in turn, improves the tear strength. These results agree very well with findings in literature [Shirkolaee et al. 2008; Jahan et al 2017]. It has been noticed that it is possible to delignify bamboo to a kappa number close to 20 [Vu et al. 2004]. Similar results were found by Shatalov and Pereira [2004]. In another study, an increase in active alkali at a constant sulfidity results in a clear reduction in the kappa number [Salmela et al. 2008; Rahmati et al. 2010]. It has been reported that in cases of 25% sulfidity, 120 min. time at max. temperature, 18% active alkali and with and without 0.05% AQ on o.d. bamboo, the screened yield and kappa number was found to be 42.1%; 19.8 and 42.1%, 18.6 respectively [Feng and Alen 1998]. Rahmati et al. [2010] observed that a lower alkali charge can increase rejects in bamboo kraft cooking, which could be also seen it this study. It can be concluded that, both AA and cooking time had a significant influence on screen yield and kappa number. Thus, an increase in AA at a constant cooking time or an increase in cooking time at a constant AA was found to reduce the kappa number. An interesting observation of this study is the relationship between viscosity and cooking time. A decrease in bamboo pulp viscosity as a factor of longer cooking times can be attributed to the dissolution of carbohydrates. In soda-AQ pulping of wheat straw and reed canary grass studies, the viscosity was found to be higher at lower kappa numbers than that at higher kappa numbers [Feng and Alen 2001]. The increase in viscosity below an H-factor value of 900 can be explained by the decrease in the hemicelluloses content of the pulp. It is believed that at the beginning of the cooking process, the dissolution of hemicelluloses has a more prominent effect than the alkaline cleavage of polysaccharides on viscosity.

Effect of pulping additives on pulp properties

AQ and $NaBH_4$ were used as pulping additives. The effect of pulping additives on the kappa number, viscosity, and yield of the pulps is shown in table 4 (17th, 18th, 19th, 20th, 21th trials). The comparison of modified cooking and alkali pulping reveals that AQ and $NaBH_4$ had a moderate effect on the kappa number, viscosity, and yield. Data obtained from the 10th (without AQ and $NaBH_4$), 17th (with and 0.3% $NaBH_4$) and 18th (with 0.1% AQ) pulping trials reveal the following data for the screened yield, kappa number, and viscosity: 46.71%, 1226 ml/g, and 26.3 for 10th trial; 48.1%, 1230 ml/g, and 25.07 for 17th trial and 48.6%, 1210 ml/g and 24.08 for 18th trial, respectively. It can be concluded that, cook number 18 may be preferred as the most appropriate pulping conditions for screened yield and kappa number of pulp produced.

The addition of AQ and $NaBH_4$ to the kraft pulping solution improves screened yield and the kappa number. The kappa number and viscosity of the pulp samples were more affected by the addition of AQ than the addition of $NaBH_4$ for modified kraft pulping. Furthermore, the screened yield provided higher results with the addition of AQ than with $NaBH_4$. Increasing pulping time and active alkaline generally provided lower pulp viscosity, kappa number, and screened yield for kraft pulping both with and without AQ and $NaBH_4$. The addition of AQ to the cooking medium ensured a higher screened yield, lower screen residue and higher total yield as compared to the addition of $NaBH_4$; however, no significant change was observed in the kappa and viscosity value.

Effect of pulping additives, active alkali and cooking time on strength and optical properties

Alkali pulping and modified alkali pulping parameters and some pulp properties of bamboo are given in table 4. The data provided in table 4 indicates that the effect of alkali charge on paper properties is more pronounced than that of pulping time. As shown in figure 4, the effects of 14% AA and 16% AA at 90°C (cooks 6, 10) on the strength properties of pulp are similar. An increase in alkali charge from 12 to 14% was found to increase all strength properties.

An increase in the alkali charge from 14 to 16 and 18%, however, show the strength properties diminished for 60, 90, 120 and 150 minutes. These findings are in agreement with most literature values of both wood and some non-wood products [Jahan et al. 2002]. Also, when the alkali charge was increased, ISO brightness was higher. A regular increase of the brightness value with an increase of the alkali charge from 12 to 18% was observed (fig. 5). These results were found to be similar to other literature [Ateş et al. 2008].

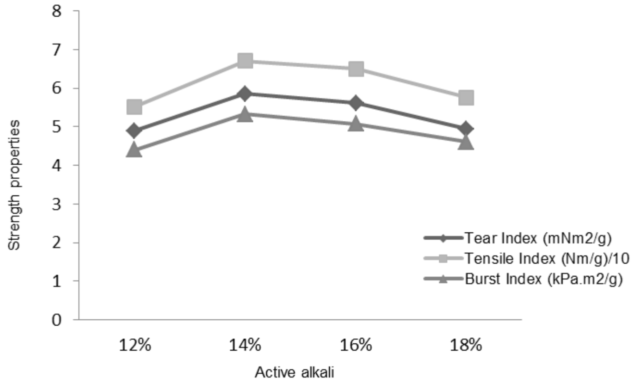

Fig. 4. Effect of active alkali charge ratio on the strength properties of bamboo kraft pulps (time 90 min.)

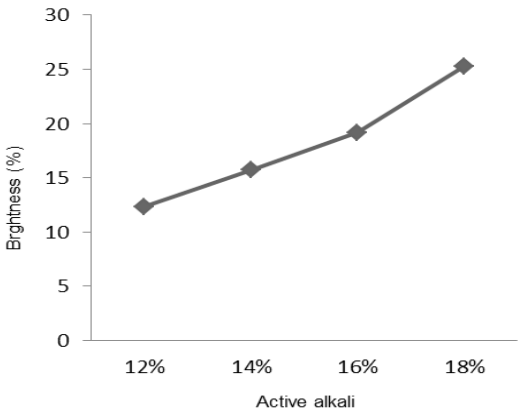

Fig. 5. Effect of active alkali ratio on the brightness of bamboo kraft pulps (time 90 min.)

The modified cooking data listed in table 4 shows that there are small differences among the control kraft pulps (10th trial) and the kraft-$NaBH_4$ (17th trial) and kraft-AQ (18th trial) pulps regarding strength properties. The added $NaBH_4$ and AQ in the kraft pulp slightly decreased the level of strength properties in Bamboo. A decrease in strength values with the addition of AQ was also observed in similar studies that are reported in literature. For instance, the kraft pulp was cooked by adding 0.1% AQ and methyl-AQ (MAQ) at three different alkali dosages and the yield was found to increase in the presence of 0.1% AQ or MAQ when compared with control pulps, where no addition was made; however, the resistance features were found to decrease [Biswas et al. 2011; Okan et al. 2013]. Also, comparisons between control kraft pulps and modified pulps reveals that the latter are decreased slightly in breaking length, burst index, tensile index and tear index. The addition of $NaBH_4$ and AQ is believed to weaken the bonding between the individual fibres due to the preserved hemicelluloses by these methods [Akgül et al. 2007]. When the modified kraft method of bamboo pulp that we applied in this study was compared with similar studies reported in literature, it is obvious that modifying the kraft method with $NaBH_4$ and AQ results in a decrease in physical properties such as breaking length, burst index, stretch index and tear index [Macleod et al. 1979; Istek and Gonteki 2009]. As expected, the ISO brightness of $NaBH_4$ and AQ modified pulps was higher compared to the kraft pulp produced under the same conditions. The modified kraft method of adding 0.3% $NaBH_4$ and 0.1% AQ resulted in (experiments 17 and 18) respective increases of 22.16% and 20.35% in pulp brightness. In contrast, a small decrease in opacity was observed for $NaBH_4$ and AQ modified pulp. Also, when other variables were kept constant, a constant decrease of the physical values was observed with the increase of time from 60 min. to 150 min. (fig. 6).

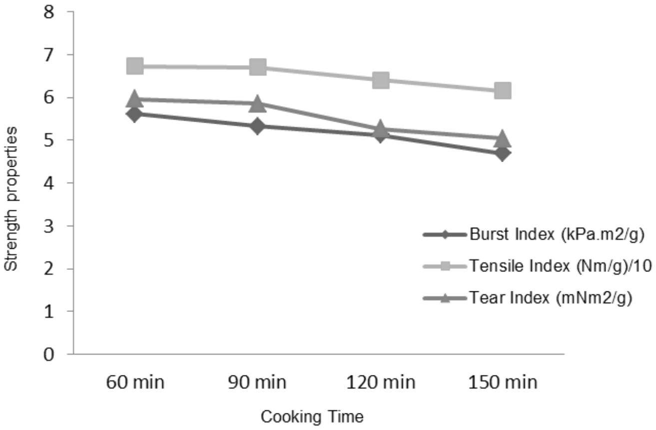

Fig. 6. Effect of cooking time on strength of bamboo kraft pulps (AA 14%)

Most of the pulp mills began cooking to a lower kappa number to reduce the rising cost in the bleach plant, often using digester additives such as AQ and polysulfide. Thus, cooking to a lower kappa number did reduce bleaching cost and obtain bleachable pulp [Patrick 2005]. Bleachable pulp has generally been described as a 16 or less kappa number for the pulp samples [Danielewicz and Ślusarska 2006]. When the cooking time of 90 min. was applied, physical properties were moderately affected and bleachable pulp was obtained. Based on the results, the optimum cooking time was found to be 90 minutes.

Conclusions

The optimum alkali charge must be kept at around 16% for the production of bleachable pulp (kappa number varies from 24.8 to 26.3 in presence of 0.1%

AQ). Increasing the active alkali charge and cooking time generally results in a slight decrease in the screened yield, kappa number, viscosity and mechanical properties, but results in an increase in optical properties. Screened yield values of 46.71 and 48.21 (in the presence of 0.1% AQ) were achieved under the following conditions: 16% AA, 90 min. cooking time at 165°C (cooks 10 and 17).

Modification of the kraft methods with 0.1% AQ provided better results than with 0.3 % $NaBH_4$. The presence of AQ and $NaBH_4$ results in a moderate decrease in strength properties, but an increase in screen yield, kappa number and viscosity of the pulp samples, as compared to the kraft pulp. For a bleachable pulp, 16% active alkali charge and 90 min. cooking time are found to be optimum for *Phyllotachys bambusoides.*

References

Akgül M., Copur Y., Temiz A.S. [2007]: Comparison of kraft and kraft-sodium borohydrate brutia pine pulps. Journal of Build and Environmental 7: 2586-2590

Ateş S., Kırcı H., Tutus A. [2008]: Influence of cooking variables of Crimean Pine (*Pinus nigra* Arnold SBSP. Pallassiana) kraft pulp on the resulting paper sheets. Wood Research 53 [1]: 81-90

Bektaş İ., Tutuş A., Eroğlu H. [1999]: A study of the suitability of Calabrian pine (*Pinus brutia* Ten.) for pulp and paper manufacture. Turkish Journal of Agriculture and Forestry 23: 589-598

Bhargava R.L. [1987]: Bamboo pulp and paper manufacture. In: Kocurek M.J., Hamilton F., Leopold B. (eds.), Secondary Fibers and Non Wood Pulping Vol. 3. TAPPI CPPA: 71-81

Biswas D., Misbahuddin M., Roy U., Franci R.C., Bose S.K. [2011]: Effect of additives on fiber yield improvement for kraft pulping of kadam (*Anthocephalus chinensis*). Bioresource Technology 102: 1284-1288

Brindha D., Vinodhini S., Alarmelumangai K. [2012]: Fiber dimension and chemical contents of fiber from *Passiflora foetida* L. and their suitability in paper production. Science Research Report 2: 210-219

Cao S., Ma X., Lin L., Huang F., Huang L, Chen L. [2014]: Morphological and chemical characterization of green bamboo (*Dendrocalamopsis oldhami* (Munro) Keng f.) for dissolving pulp production. BioResources 9 [3]: 4528-4539

Courchene C.E. [1998]: The tired, the true and the new-getting more pulp from chips--modifications to the kraft process for increased yield. Proceeding of: Breaking the Pulp Yield Barrier Symposium, Tappi Press, Atlanta: 11-20

Danielewicz D., Ślusarska B.S. [2006]: Oxygen delignification of high-kappa number Pine Kraft Pulp. Fibres & Textiles in Eastern Europe 2 [56]: 89-93

Enayati A., Hamzeh Y., Mirshokraie S.A., Molaii M. [2009]: Papermaking potential of canola stalks. BioResources 4: 245-256

Erişir E., Gümüşkaya E., Kırcı H., Misir N. [2015]: Alkaline sulphite anthraquinone pulping of Caucasian spruce (*Picea orientalis* L.) chips with added sodium borohydride and ethanol. Drewno 58 [194]: 89-102

Feng Z., Alen R.J. [1999]: Soda-AQ, Kraft and Kraft – AQ pulping of muli bamboo, University of Jyvaskyla, Laboratory of Applied Chemistry [Conference Note]

Feng Z., Alen R.J. [2001]: Soda-AQ pulping of wheat straw. Appita Journal 54 [2]: 217-220

Gomide J.L., Colodette J.L., Campos A.S. [1991]: Kraft pulping and oxygen delignification of bamboo. In: Atchinson J. (ed.), Nonwood Plant Fiber Pulping Progress Reports No. 20. Tappi Press: 419-425

He J., Cui S., Wang S. [2008]: Preparation and crystalline analysis of high-grade bamboo dissolving pulp for cellulose acetate. Journal of Applied Polymer Science 107: 1029-1038

Istek A., Gonteki E. [2009]: Utilization of sodium borohydride ($NaBH_4$) in kraft pulping process. Journal of Environmental Biology 30 [6]: 5-6

Ives E. [2001]: A Guide to Wood Microtomy: Making Quality Microslides of Wood Sections. Sproughton, England

Jahan S.M., Harun M., Monilur S. [2002]: Utilization of saw mill wastes as a pulping raw materials kraft pulping of sapwood. Journal of African Pulp and Paper Week 12-18

Jahan S.M., Sarkar M., Rahman M.M. [2017]: Mixed cooking of bamboo with hardwood. Cellulose Chemistry and Technology 51 [3-4]: 307-312

Kamthai S., Puthson P. [2005]: Effect of beating revolution on sweet bamboo (*Dendrocalamus asper* Backer) kraft pulp properties. Chiang Mai University Journal 4 [2]: 137-147

Kiaei M., Milad T., Ramin V. [2014]: Chemical and biometrical properties of plum wood and its application in pulp and paper production. Maderas 16 [3]: 313-322

Macleod J.M., Fleming B.I., Kubes J.G., Bolker H.I. [1979]: The strengths of Kraft-AQ and Soda-AQ Pulps. In: Gopal C.G. (ed.), Anthraquinone Pulping. Tappi Press, Atlanta: 158-161

Okan O.T., Deniz İ., Yıldırım İ. [2013]: Bleaching of bamboo (*Phyllostachys bamusoides*) kraft-aq pulp with sodium perborate tetrahydrate (SPBTH) after oxygen delignification. BioResources 8 [1]: 1332-1344

Ogbonnaya C.I., Macauley H.R., Nwalozie M.C., Annerose D.J.M. [1997]: Physical and histochemical properties of kenaf (*Hibiscus cannabinus* L.) grown under water deficit on a sandy soil. Industrial Crops and Products 7 [1]: 9-18

Patrick K. [2005]: Mills boost production, cut fiber cost by cooking to Optimum Kappa Levels. PaperAge March/April: 34-37

Rahmati H., Ebrahimi P., Sedghi M. [2010]: Effect of cooking and oxygen-delignification on Bambusatulda kraft pulping. Indian Journal of Chemical Technology 17: 74-77

Rajan P.S., Griffin W.C., Jameel H., Gratzl J.S. [1992]: Extending the digester delignification with anthraquinone. In: Gopal C.G. (ed.), Anthroquinone Pulping. Tappi Press, Atlanta: 10-29

Rowell R. [1984]: The chemistry of solid wood. Proceedings of: 185th Meeting of the American Chemical Society, 20-25 March 1983. Seattle: 70-72

Saijonkari-Pahkala K. [2001]: Non-wood plants as raw material for pulp and paper. Agricultural Food Science 10: 1-101

Salmela M., Alen R., Vu H.T.M. [2008]: Description of kraft cooking and oxygen-alkali delignification of bamboo by pulp and dissolving material analysis. Journal of Industrial Crops and Products 28: 47-55

Shatalov A.A., Pereira H., [2004]: Arundo donax L. reed: new perspectives for pulping and bleaching Part 3. Ethanol-reinforced alkaline pulping. Tappi Journal 2: 27-31

Shirkolaee Y.Z., Rovshandeh M.J., Charani C.R., Khajeheian M.B. [2008]: Influence of dimethylformamide pulping of wheat straw on cellulose degradation and comparison with kraft process. Bioresources Technology 99: 3568-3578

Smook G.A [1997]: Handbook for pulp and paper technologists. Tappi Press USA: 358-391

Tutuş A., Eroğlu H. [2004]: An alternative solution to the silica problem in wheat straw pulping. APPITA Journal 57 [3]: 214-217

Ververis C., Georghiou K., Christodoulakis N., Santas P., Santas R. [2004]: Fiber dimensions, lignin and cellulose content of various plant materials and their suitability for paper production. Industrial Crops and Products 19: 245-254

Vu M.H.T., Pakkanen H., Alen R. [2004]: Delignification of bamboo (*Bambusa proceraacher*) kraft pulping and the subsequent oxygen delignification to pulp with a low kappa number. Part 1. Journal of Industrial Crops and Products 19: 49-57

Yang Z., Xu S., Ma X., Wang S. [2008]: Characterization and acetylation behavior of bamboo pulp. Wood Science Technology 42: 621-632

Wai N.N., Murakami K. [1982]: Holopulp elements of Burmese bamboos in relation to their papermaking properties. Bulletin of the Kyoto University Forests, November 54: 236--242

Wai N.N., Murakami K. [1984]: Relationships between fiber morphology and sheet properties of Burmese bamboos. Mokuzai Gakkaishi 30 [29]: 156-165

Wise L.E., Murphy M. [1946]. A chlorite holocellulose, its fractionation and bearing on summative wood analysis and studies on hemicelluloses. Paper Trade Journal 122: 35-43

Xu F., Zhong X.C., Sun R.C., Lu Q. [2006]: Anatomy, ultra structure, and lignin distribution in cell wall of Caragana korshinskii. Industrial Crops and Products 24: 186--193

List of standards

ISO 2470-1:2009 Paper, board and pulps – Measurement of diffuse blue reflectance factor – Part 1: Indoor daylight conditions (ISO brightness)

ISO/CD 5631:2009 Paper and board – Determination of colour by diffuse reflectance – Part 1: Indoor daylight conditions (C/2 degrees)

ISO/DIS 11476 Paper and board – Determination of CIE whiteness, C/2° (indoor illumination conditions)

SCAN-CM 15:88:1988 Viscosity of cellulose in cupperethylenediamine solution (CED)

SCAN-CM 40:94 Wood chips for pulp production

TAPPI T200 sp-10:2010 Laboratory beating of pulp (Valley beater method)

TAPPI T203 cm-09:2009 Alpha, beta and gamma-cellulose in pulp

TAPPI T204 cm-07:2007 Solvent extractives of wood and pulp

TAPPI T207 cm-08:2008 Water solubility of wood and pulp

TAPPI T212 om-12:2012 One percent sodium hydroxide solubility

TAPPI T222 om-11:2011 Acid-insoluble lignin in wood and pulp

TAPPI T236 om-06:2006 The kappa number of pulp

TAPPI T245 cm-98:2007 Silica content

TAPPI T402 sp-08:2013 Standard conditioning and testing atmospheres for paper handsheet

TAPPI T403 om-10:2010 Bursting strength of paper

TAPPI T414 om-12:2012 Internal tearing resistance of paper (Elmandorf-type method)

TAPPI T494 om-01:2006 Tensile properties of paper and paperboard

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