bioresources.com

THE EFFECTS OF PROCESSING VARIABLES ON THE SODA AND SODA-AQ PULPING OF KENAF BAST FIBER

Jalal Shakhes,[a,]* Farhad Zeinaly,[a] Morteza a.b. Marandi,[a] and Tayebe Saghafi [b]

Iran is facing a severe lack of fibrous raw materials for paper production. Kenaf *(Hibiscus cannubinus* L.) is a superior complement to wood as a source of fiber. Kenaf bast fibers are excellent for making pulp and paper of various grades due to the presence of high alpha cellulose (56.43), holocellulose (77.71), and ultimate fiber length (2.77 mm). Fiber length is an important factor in the development of tear and tensile properties. The aim of this work is to study the effect of charge alkali (20 and 25% oven dried, as NaOH) and cooking time (30, 60, 90, 120, 150, and 180 min) of kenaf bast fiber on soda and soda-anthraquinone (AQ) pulp yield, kappa number, rejects, and strength properties of their handsheets. Results indicated that alkali charge and cooking time had significant influence on kappa number, yield, and rejects of pulps, whereas PFI revolution had only a minimal effect, especially at higher cooking times. The soda method was modified by adding 0.2% anthraquinone, and the resultant pulps displayed an increase in pulp yield and reduction in both kappa number (by 6 to 9 units) and screening rejects. The strength properties obtained with the two cooking processes used were compared, and those provided by soda-AQ process were found to be best. Regarding handsheet properties, a significant improvement in tensile index could be obtained by the soda-AQ process, compared to the soda process.

Contact information: a: Department of Wood & Paper Science, Faculty of Forestry and Wood Technology, Gorgan University of Agricultural Sciences and Natural Resources, Gorgan, Iran (Postal code15339-95911); b: Department of Forestry Science, Faculty of Agricultural Sciences and Natural Resources, Tehran University, Karaj, Iran (Postal code31585-3314).
*Corresponding author: jalalshakhes@yahoo.com

INTRODUCTION

The utilization of nonwood raw material for production of paper pulp has risen more rapidly than pulp from wood in the last two decades, especially in countries such as Iran, which do not have adequate forest resources. There are a wide variety of nonwood plant fibers that can be used for pulping and papermaking. Kenaf (*Hibiscus cannabinus* L) is a fast-growing, warm-season, annual plant in the malvacea family, which is grown in many parts of the tropics and in some subtropical and warm temperate areas. Kenaf has attracted attention as a potential nonwood raw material for pulp and paper making over the last decade. The plant grows to a height of 3 to 5 m with a diameter of 25 to 51 mm and yields 4 to 8 metric tons of dry fiber per hectare, depending on silvicultural conditions (Webber et al. 2002). The kenaf stem consists of two fiber components, which are different morphologically and chemically; however, both are suitable for producing paper and paperboards (Touzinski et al. 1973).

The bast fibers are about 2.5 to 4.0 mm in length and slender, and they constitute 35 to 40% by weight of the kenaf stem. The shorter core fibers, about 0.5 to 0.7 mm in length, constitute 60 to 65% of the stem by weight. The bast fiber has high quality papermaking properties that are similar to softwood fibers, while the core fiber has strength properties similar to hardwood fiber (Kaldor et al. 1990). However, both components of kenaf are different from those of wood fiber with respect to chemical, morphological, physical, and anatomical characteristics (Touzinski et al. 1973; Saikia et al. 1997). The separation of the two fiber fractions will provide more flexibility in using bast as a long-fiber source for the countries where softwood or any other long fiber is not available (Dinesh 2001).

Kenaf yields in northern Iran are about 12 ton per hectare, which makes it a suitable fiber for papermaking. Otherwise, the main fibrous raw material resources available for papermaking in Iran are short-fibered hardwoods and recycled papers (Shakhes et al. 2009).

The kenaf bast and core fibers have a different nature and structure, and they show different behaviors during pulping processes. Several investigations have been focused on the application of farming and pulping techniques (Villar et al. 2001; Khristova et al. 1998). The results of previous studies strongly implied that pulp delignification, yield and cellulose protection were increased by addition of AQ (Dutt et al. 2010; Azizi et al. 2009; Khristova et al. 1998; Chai et al. 2007; Yoshito et al. 2001).

Alkali cooking is traditionally divided into three distinct delignification phases: the initial, bulk, and the residual delignification phases. The rapid solubilization of bulk of lignin (bulk delignification) corresponds to the removal of easily assessable lignin present in the middle lamella, whereas the slow solubilization of the residual lignin (residual delignification) corresponds to the removal of lignin present in the primary wall, secondary wall layers, and the central interconnection cavities (Lalet al 2010). The delignification in alkaline pulping is also associated with the solubilization of significant amounts of hemicelluloses (Kleinert 1965). Moreover, at higher temperature or higher alkaline pH, the degradation of carbohydrates also increases, thereby reducing the pulp yield (Kleinert 1965). Beyond optimum cooking temperature, in addition to the peeling reaction, alkaline hydrolysis (depolymerization) of the polysaccharide chains occurs and is subjected to further degradation reactions (secondary peeling) (Hinrichs 1967; McGinnis and Shafizadeh 1980). Various technologies to reduce kappa factor before pulp bleaching for mitigating emissions of absorbable organic halogens (AOX) in bleaching plant effluents are available. Use of cooking aids like anthraquinone or other additives (Blain 1992; Azizi et al. 2010) will further help to reduce kappa number.

It is known that AQ behaves as a redox catalyst during alkaline pulping, unlike hydroxide ions (OH⁻) in the conventional soda process. AQ reacts with reducing aldehyde end groups of the carbohydrates, oxidizing them to create carboxylic acids (Azizi et al. 2010). This oxidation of aldehyde to carboxylic acid inhibits the alkaline depolymerization reaction that occurs with the reducing sugar end groups, which results in an increased yield. The interaction of these conditions allowed for the attainment of pulps with similar cooking times at much different yields and kappa numbers. The environmentally friendly soda-AQ trials gave good results in terms of strength and yield, especially for the bast fiber (Khristova et al. 1998; Azizi et al. 2010; Kaldor 1990).

In this work, the pulping and papermaking characteristics of soda and soda-AQ processes using kenaf bast fibers under various cooking conditions were investigated. The morphological properties, chemical composition, soda, and soda-anthraquinone pulping of kenaf bast were investigated to evaluate the potential utilization of kenaf bast fibers in pulp and paper production in Iran instead of importing long fibers.

EXPERIMENTAL

Raw Materials and Preparation

In this study, kenaf (variety Nejer) was planted on 19 May and harvested 135 days after planting, on 29 September. The stalks were predominantly 145.96 cm in height and 8.61 mm in diameter at the base. The stem yield was in the range of 10 to 12 t/Ha yr. The stem consisted of 61.96% core and 38.04% bast on an oven-dry weight basis. Kenaf stalks were cleaned from leaves, roots, and soil. The bast fiber was separated by hand and, after air-drying, was cut into chips with a length of 3 to 3.5 cm then stored in polyethylene bags.

Fiber Dimensions

Stem samples for the fiber studies were obtained from approximately the fifth internodes, counting from the base. For measurements of fiber length, fiber width, lumen width, and cell wall thickness, the material was macerated using Franklin's method in acetic acid and hydrogen peroxide (1:1) at 60ºC for 48 h. The macerated fiber suspension was finally placed on a slide (standard, 7.5 cm×2.5 cm) by means of a medicine dropper (Han et al. 1999). All fiber samples were viewed under a projection microscope. For measuring fiber length and diameter, 200 fibers were measured from 10 slides and an average reading was taken.

Derived Values

Three derived values were also evaluated using fiber dimensions: slenderness ratio as fiber length/diameter of fiber, flexibility ratio as (lumen width of fiber/diameter of fiber) × 100, and Runkel ratio as (2 × wall thickness)/lumen width (Saikia et al. 1997). The derived values were then compared to nonwoods and hardwood to assess the acceptability of the plant raw materials for pulp and paper production (Ververis et al. 2004).

Chemical Composition of Raw Material

The kenaf bast and core were respectively pulverized by a Wiley mill. For the chemical composition analysis, 100-mesh fractions were selected. The chemical analysis included Klason lignin content, holocellulose, alpha cellulose, extractives, and ash content. The procedures were performed according to TAPPI Method T264 om-88. The hot and cold water solubility of the kenaf constituent stalk (T 207 om-93), one percent caustic soda solubility (T 212 om-98), and alcohol-benzene solubility (T 204cm-97) were determined in accordance with TAPPI Test Methods. Alpha-cellulose, which is insoluble in 17.5% NaOH, was analyzed according to the procedure described in the TAPPI

method. The determination of lignin, α, β, and γ cellulose, and ash content were performed as per TAPPI Standard Methods T 222 cm-99, T203 cm-99, and T 211 om-02, respectively. Holocellulose content of the extractive-free sample was determined according to Wise's method (Wise et al. 1946). Three replicates were done for each experiment.

Pulping Procedure

Bast fibers were cut into pieces of 3 to 5 cm length. The soda and soda-AQ methods were employed as conventional pulping processes. Pulping experiments with air-dried chips of kenaf bast fiber were conducted on a 2.5-L laboratory-scale batch cylindrical mini digester (stainless steel 321). This mini digester includes an electrical heater, a motor actuator, and required instruments for measurement and control of temperature and pressure. The normal charge was 100 g air-dried chips of kenaf bast fiber (moisture content 15%). Pulping conditions for soda and soda-anthraquinone are presented in Table1.

Table 1. Soda-AQ Pulping Conditions for Kenaf Bast Fiber

Pulping condition	Values
Active alkali (as NaOH based on oven-dry fiber)	20%, 25%
AQ charge (based on oven-dry fiber)	0.2%
Liquor to raw material ratio	10:1
Time at maximum temperature, min	30, 60, 90, 120, 150, 180
Cooking temperature, ºC	165
Raw material weight (oven-dried), g	100

At the end of each cook, the contents of each cylinder were discharged on 200 mesh screens, and the cooked material was washed using hot water. The remaining liquor was separated by hand, pressing the cooked material and disintegrated pulp, disintegrated with a mechanical standard disintegrator (T205 sp-02). The cooked pulp was screened (Somerville-type equipment) with screen plate of slit width 0.15 mm, washed, pressed and crumbled. The pulp was then evaluated for kappa number (T 236 cm-85), screened pulp yield, and screening rejects. The unbleached pulp was beaten in a PFI mill (T 248 sp-00) at a freeness level of 400±20 CSF (T 227 om-04). Laboratory handsheets of 60 g/m^2 was prepared (T 205 sp-02), air dried, conditioned at 23 ºC, and relatively humidity of 50%, and tested for basis weight (T 410 om-02), caliper (T 411 om-05), tensile strength (T 404 wd-03), burst strength (TAPPI T 403 om-97), and tear strength (SCANp11:73).

Experimental Design for the Pulping Conditions

The data were subjected to analysis of variance, and the sample means were tested for significant differences using the multiple intervals test (Duncan). This was carried out using the statistical package SPSS 13.0.

RESULTS AND DISCUSSION

Fiber Dimensions and Derived Values

The fiber morphology and the values derived from kenaf stalks, bast, and core fibers are presented in Table 2. Bast fibers have very good derived values (especially slenderness ratio) compared to those of some softwoods and certainly to most hardwoods (Saikia et al. 1997; Neto et al. 1996). Therefore, papers made from kenaf bast fibers are expected to have increased mechanical strength and thus be suitable for writing, printing, wrapping, and packaging purposes (Ververise et al. 2004). The length of bast fibers was found to be double the length of the core fibers. Fiber length and strength have been shown to be particularly important for tearing resistance (Wangaard and Williams 1970).

Table 2. Fiber Dimensions and Derived Values of Kenaf

Ratios	Fiber Length (mm)	Fiber Diameter (µm)	Fiber Lumen Diameter (µm)	Fiber Wall thickness (µm)	Runkel ratio, 2e/l	Slenderness ratio, L/d	Flexibility ratio, l/d
Bast	2.77	17.99	5.37	6.31	2.35	154.21	0.29
Core	0.721	29.89	23.03	3.43	0.297	24.12	0.770
Whole stalk	1.31	24.12	16.40	4.25	0.518	54.32	0.67
Note: e- cell wall thickness, l- lumen diameter, L- fiber length, d- fiber diameter.							

Core fibers had shorter and thinner cell walls and were much wider in lumen and diameter than the bast fibers. Core fibers also showed a poor slenderness ratio, which in turn reduced tearing resistance dramatically. Thus, core is expected to collapse easily, allowing good surface contact and interfibre bonding during papermaking (Ververise et al. 2004). The length of the fibers (1.31 mm) from whole stalk was found to be within the same range as hardwoods and other agricultural residues, such as rapeseed residue (1.19 mm) (Enayati et al. 2009) and date palm tree rachis fibers (1.3 mm) (Khristov et al. 2005), but shorter than wheat straw (1.73 mm) (Mackean and Jacobs 1997).

The thickness of the fiber wall has an important bearing on most paper properties, with thick-walled fibers forming bulky sheets of low tensile, burst, and folding endurance but with a high tearing strength (Haygreen and Bowyer 1996). The strength properties of papers were found to positively correlate with the slenderness ratio (fiber length/fiber diameter). Although bast fibers have a very good slenderness ratio, core fibers are shorter and have a poor slenderness ratio. Generally, it is stated that if the slenderness ratio of a fibrous material is lower than 70, it is not valuable for quality pulp and paper production

(Ververis et al. 2004). Result for the Runkel ratio for bast fiber conflicted with the findings of Udohitinah and Oluwadre (2011), who reported a low Runkel ratio below 1.0. The Runkel ratio for bast fiber is higher than core and stalk fibers (Table 2).

Higher Runkel ratio fibers are stiffer, less flexible, and form bulkier paper of lower bonded areas than lower Runkel ratio fiber (Ververis et al. 2004). The average fiber length and Runkel Ratio are important parameters for papermaking purpose. High average fiber length and low Runkel Ratio result in good pulp strength properties. The core fibers are still highly flexible with a low Runkel ratio but the average fiber length of Core fiber is 0.72 mm lower than that of bast fiber (Ververis et al. 2004; Khristova et al. 1998).

Chemical Composition of Raw Material

The chemical compositions of bast, core, and whole kenaf stalks are given in Table 3. Although the kenaf bast fiber contained high holocellulose, alpha cellulose, and cellulose, core fibers contained less ash content. Additionally, the bast fiber contained significantly less lignin content than other parts of the kenaf plant. The holocellulose and α-cellulose ratio of bast fiber were 77.71% and 56.43%, respectively. These values for whole kenaf were 74.31% and 44.48%, respectively. Cellulose and lignin content for bast, core, and whole stalk kenaf fiber were found to be 77.71%, 71.92%, 74.31%, 10.14%, 17.84%, and 15.74%, respectively.

Table 3. Chemical Composition of Kenaf

Component	Holocellulose (%)	Alpha-cellulose (%)	Lignin (%)	Ash content (%)	Alcohol benzene (%)	1% NaOH (%)	Hot water (%)
Bast	77.71	56.43	10.14	5.92	3.36	27.56	5.38
Core	71.92	38.25	17.84	4.66	4.83	24.32	4.53
Whole stalk	74.31	44.48	15.74	5.13	3.94	---	---

The plant materials with 34% and over α-cellulose content were characterized as promising for pulp and paper manufacture from a chemical composition point of view. For chemical pulping, the pulp yield has generally been found to be positively correlated with holocellulose and α-cellulose contents. Paper strength properties are dependent on the cellulose content of raw materials. For this reason, paper produced from kenaf pulp has good quality and strength and is ideal for high-speed presses (Robinson 1988; Dutt et al. 2004).

The mineral component of lignocellulosic material is generally indicated as ash content. The ash content of bast fiber was 5.92%. Like most of the nonwood fiber's ash content, the content of bast fiber was markedly higher than that of the wood species, but still lower than rice straw 16.6% (Tutus et al. 2010). A high ash content is undesirable during refining and recovery of cooking liquor (Rodra-Gueza et al. 2008).

Kenaf had low extractives, as shown by the amount of alcohol-benzene solubility. The average alcohol-benzene solubility, 1% NaOH solubility, and hot water solubility of bast fiber were 3.36%, 27.56%, and 5.38%, respectively. Generally the presence of

extractives in woody materials increases the pulping effluent load and consumption of pulp reagents, but reduces yield (Azizi et al. 2010).

Pulp Properties

Soda and soda-AQ pulping of bast fiber with a chemical charge of 20 to 25% and cooking time from 30 to 180 min at maximum temperatures of 165 °C, gave kappa numbers in the range of 39.8 to 10.0 with a screened pulp yield range between 45.06 and 49.37 (Table 4). The increase in cooking time from 30 to 180 min at 20% and 25% charge alkali resulted in a decreased screened pulp yield and reject. Also, the investigation into the effect of adding AQ to soda pulping, on pulp yield, kappa number, and reject at 20 to 25% chemical charge, has shown that the pulping process was modified by 0.2% AQ, and the chemical charge was increased by about 5%. The pulping chemical mainly affected screen yield and kappa number of soda-AQ pulping.

Table 4. Cooking Conditions (Independent Variables) and Experimental Results of Pulping Process

Cooking no.	NaOH charge (%)	Cook ing time Temp. (min)	AQ (%)	Kappa number	Screen pulp yield (%)	Rejects (%)	CSF (ml)	PFI revolution
E1-1	20	30	-	39.8	47.51	3.41	632	1400
E1-2	20	60	-	35.1	47.32	2.86	623	1500
E1-3	20	90	-	32.3	47.09	2.48	629	1500
E1-4	20	120	-	31.2	46.82	2.07	621	1500
E1-5	20	150	-	30.6	46.55	1.64	625	1500
E1-6	20	180	-	29.4	46.27	0.84	620	1500
E2-1	20	30	0.2	31	49.18	2.17	586	1600
E2-2	20	60	0.2	28	49.34	1.56	578	1600
E2-3	20	90	0.2	24	49.37	0.97	566	1700
E2-4	20	120	0.2	21.5	49.31	0.56	558	1700
E2-5	20	150	0.2	19.5	49.14	0.14	553	1800
E2-6	20	180	0.2	18.6	48.76	0	549	1800
E3-1	25	30	-	26.9	47.94	0.81	620	1500
E3-2	25	60	-	21.6	47.15	0.49	615	1600
E3-3	25	90	-	20.1	46.88	0.25	605	1600
E3-4	25	120	-	18.6	46.63	0.19	610	1700
E3-5	25	150	-	16.8	46.01	0.11	595	1700
E3-6	25	180	-	15.5	45.06	0.03	593	1800
E4-1	25	30	0.2	18.1	49.58	0.07	565	1800
E4-2	25	60	0.2	14	48.67	0.04	542	1900
E4-3	25	90	0.2	13.1	48.02	0.02	540	1900
E4-4	25	120	0.2	12.2	47.54	0	531	2000
E4-5	25	150	0.2	10.9	46.97	0	528	2100
E4-6	25	180	0.2	10	46.29	0	520	2100

A higher pulp yield with soda-AQ pulps, compared to the soda method, was attributed to higher hemicellulose retention (Atik 2002; Lowendahl and Samuelson 1978). Pervious studies have shown that the modified pulping process by AQ addition in laboratory and industrial scales resulted in more uniform pulps with lower rejects, higher pulp yield at constant kappa number, and lower consumption of alkali (Akgül and Tozluo 2009; Kuang 1986). Similar results by Kamthai (2007) and Miller and Gounder (1986),

reported that the addition of AQ to soda pulping can raise the delignification rate and protect cellulose degradation, which was demonstrated by the quantity of screened pulp yield.

Experiments conducted to determine and compare the effect of anthraquinone on pulp properties showed that adding anthraquinone to cooking liquor resulted in pulps with a lower kappa number by 6 to 9 units; the drops being greater at lower alkali levels (Table 4). The higher charge of NaOH reduces the kappa number further, but this reduction is to a lesser extent. These results reveal that the addition of AQ in soda pulp can be used to reach a certain kappa number in a shorter cooking time and higher yield, resulting in advantageously shorter process and reduced energy consumption.
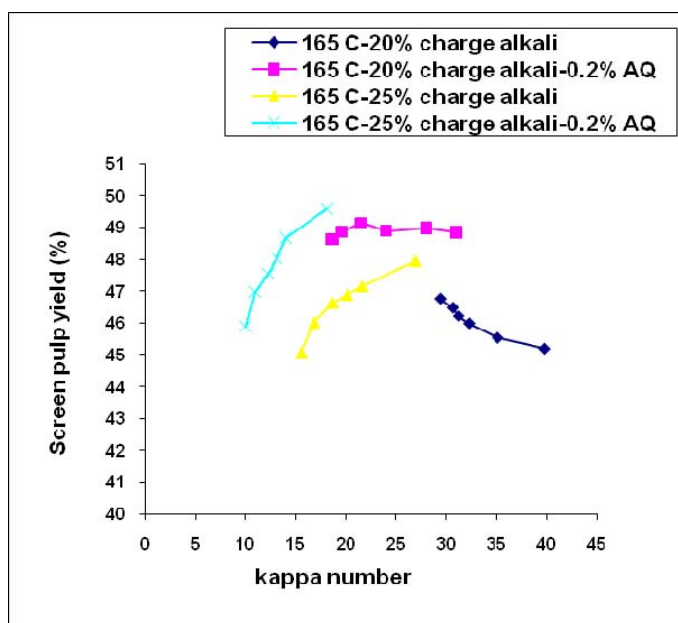
Fig. 1. Relationship between kappa number and screen yield in soda and soda-AQ of kenaf bast fiber at different conditions of cooking

According to the present experiment, the effects of AQ application provide an improved cooking process with two key advantages: increased pulp yield by stabilization of carbohydrates and increased rate of reaction for the delignification process. The delignification results obtained from the pulping experiments using the bast fiber for the different conditions investigated (Table 4) show that the rejects yield and CSF clearly decreased with an increase of active alkali. Results indicate that the maximum screened yield value (about 49.58% with 18.1 kappa number) was obtained by soda-AQ pulping at 165°C and 25% alkali charge in 30 min of cooking time (Table 4).

Table 4 also shows that pulp yield in bast fiber was higher and kappa numbers were lower than other non-wood pulps (Clark et al. 1970). This finding could be explained by the low amount of water and alkali solubility of bast fiber (Tutus et al. 2010). The relationship between screened pulp yield and kappa number for the bast pulps is shown in Fig. 1. It is apparent from these results that the 25% alkali charge decreased pulp yield dramatically.

Pulp Strength Properties

The characteristics of the handsheets obtained in 4 treatments are shown in Fig. 2 to 4. The strength properties of handsheets were affected by the delignification rate of each pulp fiber in the handsheet. Results showed that the increment of chemical charge and cooking time in soda and soda-AQ pulping led to changes in the initial CSF. Furthermore, an increase in cooking time and charge alkali made pulp beating easier, also affecting paper strength and PFI revolutions. These results are given in Table 4. The reason that the soda-AQ process shows a faster rate of PFI revolution could be attributed to differences in the relative amounts of holocellulose and lignin contents and a higher hemicellulose content, enhancing swelling and flexibility. The flexibility and collapsibility increases fiber bonding in a sheet of paper. Fiber bonding increases the burst and tensile index of the paper but it decreases the tear index (Rushdan 2005; Villar et al. 2009). Cooking time, alkali charge, and anthraquinone had a positive effect on delignification rate for all pulps.

The highest tensile index was 83.90 Nm/g at E4 treatment in cooking time 180 min, PFI revolution 2100 revs, and 10 kappa number (Table 4). The relationship between tensile index and cooking time is shown in Fig. 4; it demonstrates the trend of tensile strength development after delignification rate.
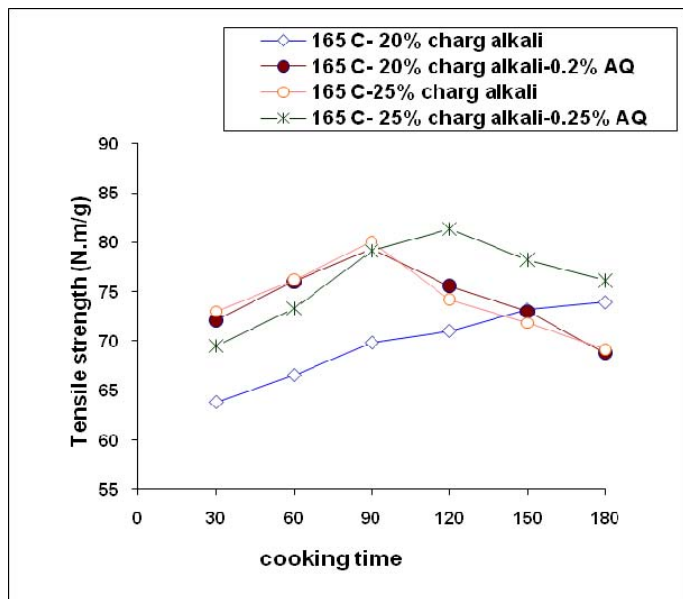
Fig 2. Tensile strength (N.m/g) versus cooking time for bast fiber soda and soda-AQ

The strength of a sheet of paper depends not only on the inherent strength of the original fibers, but also on the degree of bonding between the fibers (Clark 1944; Smook 1997). Clark and Smook are of the view that the degree of bonding between fibers could be affected by the ratio between beaten fibers and delignification rate. Figures 4 and 5 show that higher tensile and burst indices were produced when a high alkali charge was used for soda and soda-AQ pulping. Higher tensile and burst indices brought about by the use of a PFI mill could be explained by the PFI effects of external and internal fibrillations. Anthraquinone could also be the reason for the pulps with lowest lignin and

highest hemicellulose contents. When the soda and soda-AQ pulps were compared after equal cooking times, the obtained data indicated that the mechanical properties of the paper samples were affected by the delignification rate. Refining had a positive effect on tensile and burst strength for all pulps, and the PFI revolutions were affected by the delignification rate when pulps have a large decrease in kappa number. When the high kappa pulps are beaten, the increasing in PFI revolution leads to cutting fiber instead of collapsing them, consequently these pulps become destroyed, as the fiber becomes progressively broken down into fines. Thus, CSF decreases and pulp quality is often too low to enable them to effectively resist the applied tensile and burst index. Furthermore, the handsheet density and the cohesiveness of the fiber is decreased. Higher PFI revolutions could be the explanation for the results corresponding to pulps with lowest kappa numbers (lignin) and highest hemicellulose contents, which means that the paper strength is developed. The beating not only increases the handsheet density, but also reduces the length of the fibers. Tear strength is a function of both fiber length and fiber coarseness (Shakes et al. 2010; Azizi et al. 2010; Akgül and Tozluo 2009; Wan Rosli et al. 2004; Biermann 1993).
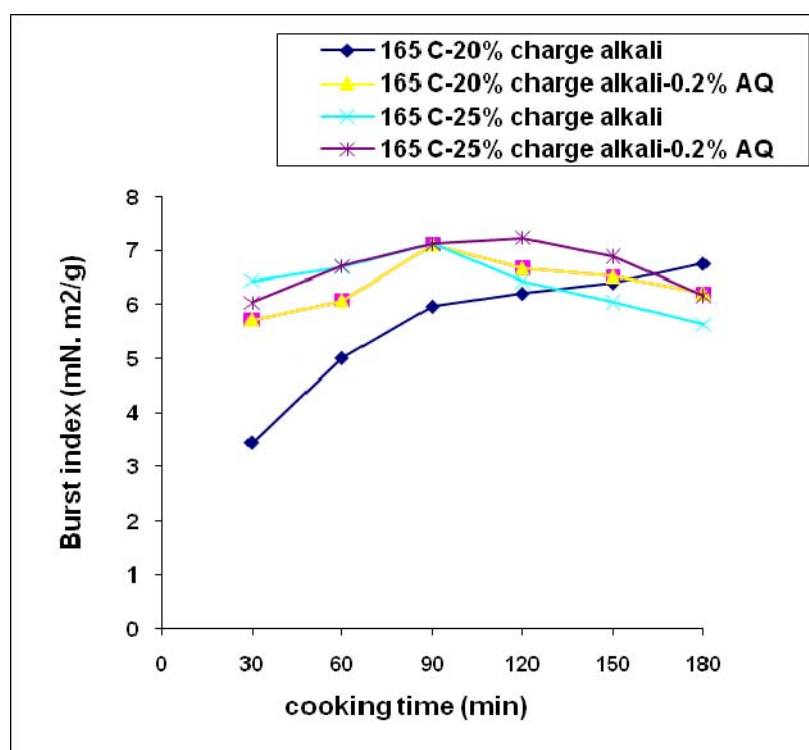
Fig 3. Burst strength (kPa.m^2/g) versus cooking time for bast fiber soda and soda-AQ

The curve shown in Fig. 6 illustrates the trend of tear strength development against cooking time in most of bast fiber pulps. The range of tear index of all bast fiber pulp was 23.98 to 18.23 mN.m2/g. The highest tear strength was 23.98 mN.m2/g at 1600 beating rev, and a kappa number of 31.
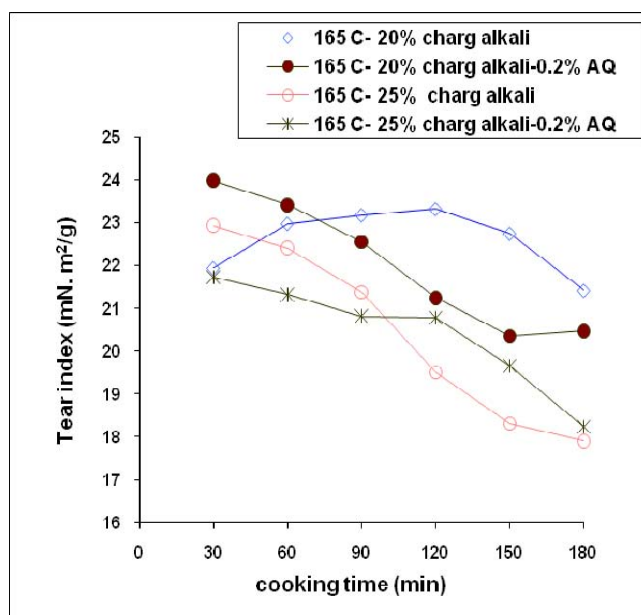
Fig 4. Tearing strength (mN.m2/g) versus reaction time for bast fiber soda and soda-AQ

CONCLUSIONS

It was shown that Iranian cultivated kenaf can produce pulp of good quality under different conditions by an environmentally friendly process (soda-AQ). The effects of alkali charge and cooking time on screen pulp yield, rejects, and kappa number during soda and soda-AQ pulping of bast fiber showed that both alkali charge and cooking time had a significant influence on kappa number. Thus, either an increase in alkali charge at a constant cooking time or an increase in cooking time at a constant alkali charge resulted in a clear reduction in kappa number. It can also be seen that total yield and rejects increased significantly as alkali charge decreased. A significant reduction in pulp rejects was observed with addition of AQ in the soda method. Adding AQ into the soda pulp led to an increase in screen pulp yield and a reduction in kappa number and rejects. Thus, the preliminary trials of modified soda pulping process by AQ addition reveals that the soda-AQ pulping process can produce high pulped yield and low kappa number. Also, the addition of AQ resulted in easier refining of the pulps and the refined soda-AQ pulps displayed the highest strength properties. For the bast fibers, it can be concluded that the morphological factors are similar to those of softwoods and are important for the development of tear and tensile properties. Finally, pulp produced from kenaf bast fibers could be an alternative raw material for commercial long fiber pulp production.

ACKNOWLEDGMENTS

REFERENCES CITED

Akgül, M., and Tozluo, A. (2009). "A comparison of soda and soda-AQ pulps from cotton stalks," *African Journal of Biotechnology* 8(22), 6127-6133.

Anonymous (2007). "TAPPI Standard Test Methods," TAPPI PRESS, Atlanta,GA, USA.

Atick, C. (2002). "Soda-AQ pulping of okra," *Cellulose Chemistry and Technology* (34), 353-356.

Azizi Mossello, A., Ainun, Z. M. A., and Rushdan, I. (2010). "Chemical, morphological, and technological properties of Malaysian cultivated kenaf (*Hibiscus cannabinus*) fibers," *BioResources* (bioresources.com), 5(4), 2112-2122.

Biermann, C. J. (1993). *Essentials of Pulping and Papermaking*, Academic Press, Inc., California.

Blain, T. J. (1992). TAPPI Pulping Conf., TAPPI Press, Atlanta, GA.

Chai, X. S., Samp, J., Hou, Q. X., Yoon, S. H., and Zhu, J. Y. (2007). "Possible mechanism for anthraquinone species diffusion in alkaline pulping," *Industrial & Engineering Chemistry Research* (46), 5245-5249.

Clark, J. d'A. (1970). *Handbook of Pulp and Paper Technology*, Van Nostrand Reinhold, New York, 671.

Clark, T. F., Cunningham, R. L., Lindelfelser, L. A., Wolff, I. A., and Cummins, D. G. (1970). "A search for new fiber crops, Part XVI, kenaf storage," TAPPI Non-wood Plant Fiber Conference, New Orleans, La., published as CA Report No. 34, Tappi Non-wood Fiber Pulping Progress Report, 107-132.

Dutt, D., Upadhyaya, J. S., and Tyagi, C. H. (2010). "Studies on *Hibiscus cannabinus*, *Hibiscus sabdariffa* and *Cannabis sativa* pulp to be a substitute for softwood pulp-Par-I: AS-AQ delignification process," *BioResources* 5(4), 2123-2136.

Dutt, D., Upadhyaya, J. S., Malik, R. S., and Tyagi, C. H. (2004). "Studies on pulp and paper-making characteristics of some Indian non-woody fibrous raw materials, Part II," *Journal of Scientific and Industrial Research* 63(2), 58-67.

Enayati, A. A., Hamzeh, Y., Mirshokraie, S. M., and Molaii, M. (2009). "Paper making potential of canola stalk," *BioResources* 4(1), 245-256.

Han, J. S., Mianowski, T., and Lin Y. (1999). "Validity of plant fiber length measurement—A review of fiber length measurement based on kenaf as a model," *Kenaf Properties, Processing and Products*, Sellers, T., Reichert, N.A. (eds.), Mississippi State University, 149-167.

Haygreen, J. G., Bowyer, J., (1996). *Forest Products and Wood Science: An Introduction*, Third Edition, Iowa University Press.

Hinrichs, D.D. (1967). "The effect of kraft pulping variables on delignification," *Tappi J*. 50(4), 173-175.

Kaldor, A. F., Karlgren, C., and Verwest, H. (1990). "Kenaf, a fast growing fiber source for papermaking," *TAPPI Journal* 73 (11), 205-209.

Khristova, P., Kordsachia, O., and Khider, T. (2005). "Alkaline pulping with additives of date palm rachis and leaves from Sudan," *Bioresources Technology* (96) 79-85.

Khristova, P., Bentcheva, S., and Karar, I. (1998). "Soda-AQ pulp blends from kenaf and sunflower stalks," *Bioresource Technology* (66) 99-103.

Kleinert, T. N. (1966). "Mechanism of alkaline delignification part-I, "the overall reaction pattern, *TAPPI Journal* (49), 43-57.

Kleinert, T. N. (1965). "Discussion of results and the principles of rapid delignification. Part-VI of a series of alkaline pulping studies," *Tappi J.* 48(8), 447-451.

Kuang, S. (1986). "Some aspects of soda and soda-AQ pulping of reed," *Cellulose Chemistry and Technology* 20(1), 93-105.

Lal, M., Dutt, D., Tyagi, C. H., and Upadhyay, J. S. (2010). "Characterization of *Anthocephalus cadamba* and its delignification by kraft pulping," *TAPPI J.* 9(3), 30-37.

Lowendahl, L., and Samuelson, O. (1978). "Carbohydrate stabilization during soda pulping with addition of anthraquinone," *TAPPI Journal* 61(2), 19-21.

Mackean, W. T., and Jacobs, R. S. (1997). "Wheat straw as a paper fiber source," Unpublished report, The Washington Clean Center. Seattle, WA. USA, 1-47.

McGinnis, G. D., and Shafizadeh, F. (1980). "Cellulose and Hemicellulose," In: *Pulp and Paper Chemistry and Chemical Technology*, J. P. Casey (ed.), Vol. 1, 3rd Edn.,Wiley-Interscience, New York, Chap. 1.

Miller, M. L. and Gounder, R. (1986). "Comparison of AS-AQ pulping of mixed hardwood and pulping by conventional Kraft process," *Tappi Journal* 69(11), 118-125.

Neto, P., Fradinho, D., Coimbra, M. A., Domingues, F., Evtuguin, D., Silvestre, A., and Cavaleiro, J. A. S. (1996). "Chemical composition and structural features of the macromolecular components of *Hibiscus cannabinus L.* grown in Portugal," *Industrial Crops and Products* 5, 189-196.

Ogunsile, B. O., Omotoso, M. A., and Onilude, M. A. (2006). "Comparative soda pulps from the mid-rib, pseudostem and stalk of *Musa paradisiacal*," *International Journal of Biological Sciences* 6(6), 1047-1052.

Robinson, F. E. (1988). "Kenaf; A new fiber crop for paper production," *California Agriculture* 42, 31-32.

Rodra-Gueza, A., Morala, A., Serranoa, L., Labidib, J., and Jimanez, L. (2008). "Rice straw pulp obtained by using various methods," *Bioresource Technology* (99) 2887-2886.

Rushdan, I. (2005). "Tearing strength of paper made of *Acacia mangium* kraft pulp," International Science Congress 2005. Kuala Lumpur, 3-6 August 2005.

Saikia, S. N., Goswami, T., and Ali, F. (1997). "Evaluation of pulp and paper making characteristics of certain fast growing plants," *Wood Science and Technol.* 31, 467-475.

Shakhes, J., Rezayati-Charani, P., and Zeinaly, F. (2010). "Evaluation of harvesting time effects and cultivars of kenaf on papermaking," *BioResources* 5(2), 1268-1280.

Shakhes. J., Pahlavani, M. H., and Zeinali, E. (2009). "Effect of genotype and harvest time on relative parameter to yield in kenaf," *Electronic Journal of Crop Production* 2(1), 135-144.

Kamthai, S. (2007). "Preliminary study of anthraquinone in sweet bamboo alkaline sulfite pulping," *Chiang Mai Journal of Science* 34(2), 235-247.

Smook, G. A. (1997). *Handbook for Pulp and Paper Technology, 2nd Ed.* Angus Wide Publication Inc., Vancouver.

Touzinski, G. F., Clark, T. F., Tallant, W. H., and Knolek, W. F. (1973). "Soda pulps from kenaf bark and from core," CA report no. 52, TAPPI non-wood plant fibre pulping progress report, Atlanta, Georgia.

Tutus, A., Comlekcioglu, N., Karaman, S., and Alma, M. H. (2010). "Chemical composition and fiber properties of *Crambe orientalis* and *Crambe tataria*," *International Journal of Agriculture and Biology* (12), 286-290.

Udohitinah, J. S., and Oluwadare, A. O. (2011). "Pulping properties of kraft pulp of Nigerian-grown kenaf (*Hibiscus cannabinus* L.)," *BioResources* 6(1), 751-761.

Ververis, C., Georghiou, K., Christodoulakis, N., Santas, P., and 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.

Villar, J. C., Revilla, E., Gómez, N., Carbajo, J. M., and Simón, J. L. (2009). "Improving the use of kenaf for kraft pulping by using mixtures of bast and core fibers," *Industrial Crops & Products* 29(2-3), 301-307.

Villar, J. C., Poveda, P., and Tagle, J. L. (2001). "Comparative study of kenaf varieties and growing conditions and their effect on kraft pulp quality," *Wood Science and Technology* 34(6), 543-552.

Wangaard, F. F., and Williams, D. L. (1970). "Fiber length and fiber strength in relation to tearing resistance of hardwood pulp," *TAPPI Journal* 53(11), 2153.

Wan Rosli, W. D., Law, K. N., Zainuddin, Z., and Asro, R. (2004). "Effect of pulping variables on the characteristics of oil-palm frond-fiber," *Bioresource Technology* 93, 233-240.

Webber, C. L., Bhardwaj, H. L., and Bledsoe, V. K. (2002). "Kenaf production: Fiber, feed, and seed," *Trends in New Crops and New Uses* Janick, J. and Whipkey, A. (eds.), ASHS Press. Alexandria, VA, 327-339.

Wise, L., Murphy, M., and Daddieco, A. (1946). "Chlorite holocennulose, its fractionation and bearing on summative wood analysis and on studies on the hemicelluloses," *Paper Trade Journal* 122(2), 11-19.

Yoshito, O., Bibhuti Bushan, M., and Kazuhiko, S. (2001). "Influence of the chemical composition of kenaf bast and core on the alkalin pulping response," *J. Wood Sci.* 47(1), 30-35.