Investigating the Possibility of Chemi-mechanical Pulping of Bagasse

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Chemi-mechanical pulping was evaluated as a potential way to prepare sugarcane bagasse fibers for papermaking. Cellulose, lignin, ash, and extractives soluble in alcohol-acetone were measured as 55.75%, 20.5%, 1.85%, and 3.25%, respectively. Fiber length, diameter, lumen cavity, and cell wall thickness were measured as 1.59 mm, 20.96, 9.72, and 5.64 µm. The chemi-mechanical pulping conditions were selected as follows: three charging levels of 10, 15, and 20% sodium sulphite, and three pulping times of 20, 30, and 40 minutes after reaching the pulping temperature. Pulping temperature was held constant at 165 °C. Different pulping conditions resulted in pulp yields between 65.38 and 84.28%. The highest yield (84.28%) was obtained using a treatment combination of 20 minutes pulping time and 10% sodium sulphite. The lowest yield (65.38%) was related to 40 minutes pulping time and 20% sodium sulphite. Pulps were refined to 300 ± 25 mL CSF, 60 gm^{-2} handsheets were made, and then strength indices and optical properties of the handsheets were measured. The results showed that 20% sodium sulphite, 40 minutes pulping time, at 165 ºC can be considered as the optimum pulping conditions for bagasse CMP pulping. Tensile, tear, and burst strength indices, as well as the opacity of this pulp were measured as 39.59 Nmg^{-1}, 6.66 mNm^2g^{-1}, 2.1 KPa m^2g^{-1}, and 95.35%, respectively.

Keywords: Bagasse; CMP; Yield; Tear index; Tensile index; Opacity; Fiber length

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INTRODUCTION

The rapid increase in the population of developing countries and the demand for different kinds of paper and paper products has led to greater and more diverse utilization of non-wood fiber resources, especially agricultural-based fibers. It has been estimated that more than 21 million tons of virgin pulp is produced from non-woody fiber resources (Jahan Latibari *et al*. 2011). The large increase in non-wood pulp production has motivated research activities worldwide, and various research groups have initiated research to improve non-wood pulping. Such research covers a wide range of materials, from conventional soda pulping of bagasse and cereal straws to reeds and bamboo or even date palm tree branches and rachises (Khristova *et al.* 2005). Alkaline sulphite/AQ pulping and totally chlorine-free bleaching have been applied to wheat straw, rice straw, and bagasse to develop an alternative pulping method for these raw materials (Hedjazi *et al.* 2008a, 2008b, 2009). Other pulping processes have been studied to increase the pulping yield. APMP pulping of bagasse and kenaf (Xu and Rao 2001) and chemi-mechanical pulping of kenaf (Law *et al.* 2003) are the most recent examples.

Sugarcane bagasse, a lignocellulosic byproduct of sugar production, is found in tropical countries, such as Brazil, India, Cuba, and parts of Iran. The sugarcane stalk consists of two parts: the inner pith, which is mostly filled up with a solution of sucrose (the "juice"), and the outer part which is rich in fibers. During sugar extraction, the sugarcane stalk is crushed to extract sucrose juice (Boopathy 2004). This procedure produces a large volume of residue, the bagasse, which contains both crushed fibers and pith particles. Bagasse, the sugarcane residue generated after sugar extraction, is one of the most readily available papermaking lignocellulosic fiber resources in some developing countries, *e.g.*, Iran. Approximately 4.3 million tons of bagasse is produced annually in Iran, mainly in the southwestern province of Khuzestan (Najafi *et al.* 2009), and about 54 million tons of bagasse is produced annually throughout the world. In general, sugar factories generate approximately 270 kg of bagasse (50% moisture content) per metric ton of sugarcane (Xu *et al.* 2006). Bagasse represents an abundant, inexpensive, and readily available source of renewable lignocellulosic biomass (Sun *et al.* 2004), and among the non-woody resources, bagasse makes up 6% of overall pulp production (Rowell *et al.* 1997).

Bagasse is currently used for the commercial production of paper products. However, although soda pulping of the bagasse has been practiced and it has reached a mature stage, the knowledge required for effective application of newer pulping technologies such as high yield pulping to produce pulps suitable for newsprint production is still lacking (Zanuttini 1997).

The soda process has many advantages, including chemical recovery and lower cooking time and temperature. However, it imposes disadvantages such as the difficulty in the recovery of chemicals due to the presence of silica compounds and the low yield (Hedjazi *et al*. 2009). Chemi-mechanical pulping has advantages including higher yield and lower consumption of chemicals, leading to environmental preservation. Studies in this field have led to the selection of suitable processes and also the design and development of new systems that lead to higher yield and increased pulp quality (Salehi 2001). Salehi (2001) investigated the high-yield chemi-mechanical pulping of bagasse with application of 10, 15, and 20% sodium hydroxide, 10, 15, and 20 minutes cooking times, and a temperature of 95 ºC. Resalati (2002) investigated the relative advantage of agricultural residues, including cereal straws and bagasse, from Mazandaran province to be used as raw material for newspaper and printing paper production. The bagasse NSSC pulp was prepared and was bleached using single stage bleaching with hydrogen peroxide to reach 55% brightness suitable for newspaper production. Results showed that NSSC pulp is stronger than the CMP pulp from Mazandaran Wood and Paper Mill (Resalati 2002).

The potential of bagasse for CMP pulp production has not been fully explored in the literature. Therefore, this study aimed to evaluate the potential of bagasse in chemi-mechanical pulping to produce pulp suitable for use as supplementary pulp in newspaper production. The fiber dimensions were measured, the biometrical coefficients were calculated, and the chemical composition and CMP pulp properties were determined.

EXPERIMENTAL

Materials

Wet, depithed bagasse collected from a local pulp and paper mill (Pars Paper Co. Haft Tapeh, Iran) was used in this experiment. The pulping liquor was obtained from the chemi-mechanical pulping line at Mazandaran Pulp and Paper Industries, Sari, Iran.

Methods

Measurement of fiber dimensions and chemical composition

The bagasse particles were macerated using the technique defined by Franklin (1954). Fiber length, fiber diameter, and lumen width of 120 randomly selected fibers were measured using a light microscope equipped with a Leica Image Analysis System (Quantimeta 100+). Fiber wall thickness was calculated as the difference of fiber diameter and lumen width divided by two. Average fiber dimensions were calculated and the biometrical ratios and coefficient were determined based on following equations:

Runkel ratio = 2 × (Wall thickness/Lumen width) × 100

Flexibility coefficient = (Lumen width of fiber/Diameter of fiber) × 100

Slenderness ratio = (Length of fiber/Diameter of fiber)

Lignin, ash and extractives soluble in alcohol-acetone were determined according to relevant TAPPI test methods. The cellulose content of bagasse was determined according to the nitric acid method (Rowell and Young 1997). All measurements were repeated three times.

Pulping

Three dosages of sodium sulphite (10%, 15%, and 20%, on the basis of oven dry mass of bagasse) and three pulping times of 20, 30, and 40 min were used. For each combination of variables, 3 replica pulp samples were made. A pulping temperature of 165 °C was kept constant. The cooking liqour to bagasse (L/W) was at a 10 to 1 ratio. The cooking trials were performed using an experimental rotating digester (HATTO), with 500 grams of depithed bagasse in each trial. Pulping time was measured after reaching 165 °C. The time to reach the cooking temperature was adjusted at 30 minutes. At the end of each cooking, the content of the cooking cylinder was discharged on a 200 mesh screen, and the cooked material was washed using hot water. The remaining liquor was separated by hand-pressing the cooked material. Digester yield was measured by weighing the washed material on top of the screen without defibration. The cooked material was defibrated using a 25 cm laboratory single-disc refiner, and then pulp was screened using a set of 2 screens, a 12 mesh screen on top of a 200 mesh screen. The material remaining on the 12 mesh screen was considered as reject (shives), and the fibers that passed the 12 mesh screen but remained on the 200 mesh screen were considered as accept. To estimate the required refining, initial freeness was determined according to TAPPI 227 om-92, and then the pulp was refined to 300 ± 25 mL CSF according to TAPPI 248 om-88, with a PFI Mill. Handsheets (with basis weight of 60 gm^{-2}) were made according to TAPPI 205 om-88. Handsheets were kept in a conditioning chamber at 23 °C and 50% RH for 24 hours. Then, basis weight, caliper, tensile strength index, tear strength index, burst strength index, and the opacity of the handsheets were determined according to TAPPI T410 om-88, T411 om-89, T494 om-88, SCAN P11:73, T403 om-91, and T 425 om-98 test methods, respectively.

Statistical Analysis

The data from the pulp evaluation were statistically analyzed using analysis of variance. In cases where a statistically significant difference was observed between the averages, Duncan Multiple Range Test was used for grouping the averages, as shown by lower-case letters on the bars in each figure.

RESULTS AND DISCUSSION

Fiber Dimensions and Chemical Composition

Fiber dimensions and biometrical coefficient of bagasse and the relevant data from the literature are summarized in Table 1. The percentage of cellulose, lignin, extractives soluble in alcohol-acetone, and ash are summarized in Table 2.

Table 1. Results of Fiber Dimension Measurements and the Relevant Data from the Literature

Material	Length (mm)	Diameter (µm)	Lumen width (µm)	Cell wall thickness (µm)	Runkel ratio	Slenderness ratio	Flexibility coefficient
Bagasse	1.59 ± 5.2	20.96 ± 3.1	9.72 ± 4.4	5.63 ± 3.2	1.16	76.05	46.37
Corn stalks*	0.88 ± 0.23	20.12± 3.63	10.92± 3.86	4.59 ± 0.98	0.84	44.08	54.27
Sunflower stalks*	0.96 ± 0.21	22.84± 3.96	11.12 ±3.32	5.85± 1.19	1.05	42.03	48.68
Rice straw*	0.83 ± 0.15	10.89± 1.30	4.57 ± 1.37	3.16 ± 0.53	1.38	76.58	41.96
Rapeseed straw*	0.95 ± 0.18	24.12 ± 6.02	15.5 ± 5.24	4.31 ± 1.88	0.55	39.59	64.26

* Data from Kiaei *et al.* (2011)

Fibers were classified into three groups. The first group was considered short fibers with lengths of less than 0.9 mm such as hardwood. The second group, like bagasse, had an average length between 0.9 to 1.9 mm. The results showed that the average fiber length of bagasse was 1.59 mm. The third group included fibers longer than 1.9 mm (Salehi 2001). Bagasse fibers are shorter than wheat straw (1.73 mm) (Mackean and Jacobs 1997). On the other hand, the cell walls of bagasse fibers are thicker than those of aspen (1.93 µm) (Law and Jiang 2001) and cotton stalks (3.40 µm) (Ververis *et al.* 2004). The calculated Runkel ratio for bagasse fibers (1.16) is higher than that of cotton stalks (0.84), aspen (0.23), and date palm rachis fibers (0.8). The slenderness ratio of bagasse fibers is 76.05 and is higher than that of cotton stalks (42.35) and aspen fibers (46.15), but the flexibility coefficient of bagasse fibers is less than both cotton stalks (65.31) and aspen (81.44). This indicates good sheet forming potential from these fibers. Data from the literature to compare with the fiber dimension of the bagasse with other agricultural residues are given in Table 1.

The cellulose content of bagasse was found to be 55.75%, which is in the satisfactory range for pulp production. The cellulose content of bagasse is more than rice straw (41.20%) (Rodriguez *et al.* 2008) and wheat straw (38.20%) (Deniz *et al.* 2004). The lignin content of bagasse was found to be lower than rice straw (21.90) and Egyptian cotton stalks (22.50) (Ali *et al.* 2001). The organic solvent extractive content of bagasse was found to be almost similar to rice straw but higher than aspen (2.50%), and lower than wheat straw (7.80%). The ash content of bagasse was also low.

Table 2. Chemical Composition of Bagasse and Relevant Data from the Literature

Material	Cellulose (%)	Lignin (%)	Extractives soluble in alcohol-acetone (%)	Ash (%)
Bagasse	55.75 ± 0.21	20.50 ± 0.35	3.25 ± 0.14	1.85± 0.07
Corn stalks*	47.33 ± 0.0.58	21.33 ± 0.57	2.40 ± 1	4.79
Sunflower stalks*	46 ± 1	21.33± 0..57	3.16± 0.15	7.60
Rice straw*	50.33 ± 0.57	21 ± 0.0.5	3.23± 0.25	15.73
Rapeseed straw*	44 ± 0.86	19.33± 0.57	6.10± 0.52	12.87

* Data from Kiaei *et al.* (2011)

Pulping and Pulp Evaluation

Cooking conditions, strength properties, opacity of CMP pulp, and digester yield are summarized in Table 2. The results show that a higher chemical charge and pulping time reduced digester yield.

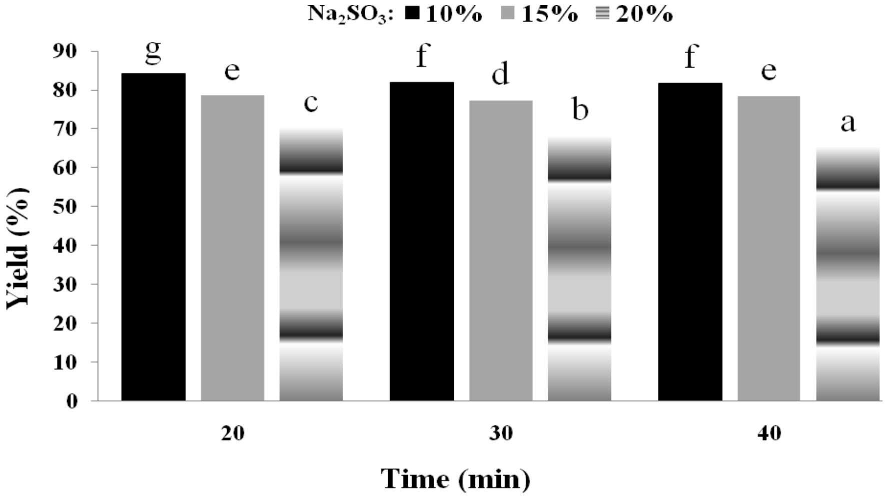

Fig. 1. Effect of pulping condition on bagasse CMP pulp yield

The yield of these pulps varied between the highest value of 84.28% to the lowest value of 65.38%, and the influence of pulping time was greater than chemical charge on yield. Statistical analysis indicated that the effect of chemical charge or cooking duration as well as the combined effect of the variables on digester yield was statistically significant at 95% (Table 3). Therefore, to compare the averages, the Duncan multiple range test was used, and the results are shown in each figure using lower case letters. An increase of cooking time and chemical charge resulted in a decrease of the pulping yield because of lignin and carbohydrate dissolution, especially hemicelluloses (under the influence of sodium sulphite). Generally, charging 10% chemical led to the greatest yield, and the lowest yield was related to 20% chemical charge as expected (Salehi 2001).

The impact of time and chemical charge on strength properties, including tensile strength index, burst strength index, and tear strength index, was statistically significant at 95% (Table 3). The results showed that a higher chemical charge and pulping time increased pulp strength properties. Even though the influence of chemical charge on strength indices revealed that higher chemical charges improved the strength values of the pulps, the duration of pulping had greater effect. As the pulping duration increased from 20 to 30 and 40 min, tensile index, tear index, burst index, and opacity increased to 39.59 Nmg^{-1}, 6.66 mNm^2g^{-1}, 2.1 $kPam^2g^{-1}$, and 95.35% ISO, respectively due to elimination of more lignin.

Table 3. Analysis of Variance (F-value and significance level) of the Results of Bagasse CMP Pulping

Properties Variable	Yield	Tensile strength index	Tear strength index	Burst strength index	Opacity
Pulping time	277.3*	348.6*	188.5*	676.6*	924.9*
Chemical	Properties Variables	3141*	644.7*	117.7*	296*
Pulping time x chemical	93.8*	1249*	1.23^{ns}	8.8*	21.77*

Significance level:**; 99%, *;95%, ns; no significance

Figures 2 through 4 show the effects on pulp strength properties under the influence of time and chemical.

The results of statistical analysis showed that chemical charge significantly influenced both strength properties. Longer cooking time and higher chemical caused softening of fibers and greater fiber flexibility, resulting in better fiber refining and fiber-to-fiber bonding. The contact area of fibers increased and strength indices (tensile index, tear index, and burst index) increased.

The effect of cooking time and chemical on the opacity of the pulps was statistically significant at 95% (Table 3). The results showed that higher chemical charge and pulping time increased opacity. Figure 5 shows the influence of time and chemical on pulp opacity.

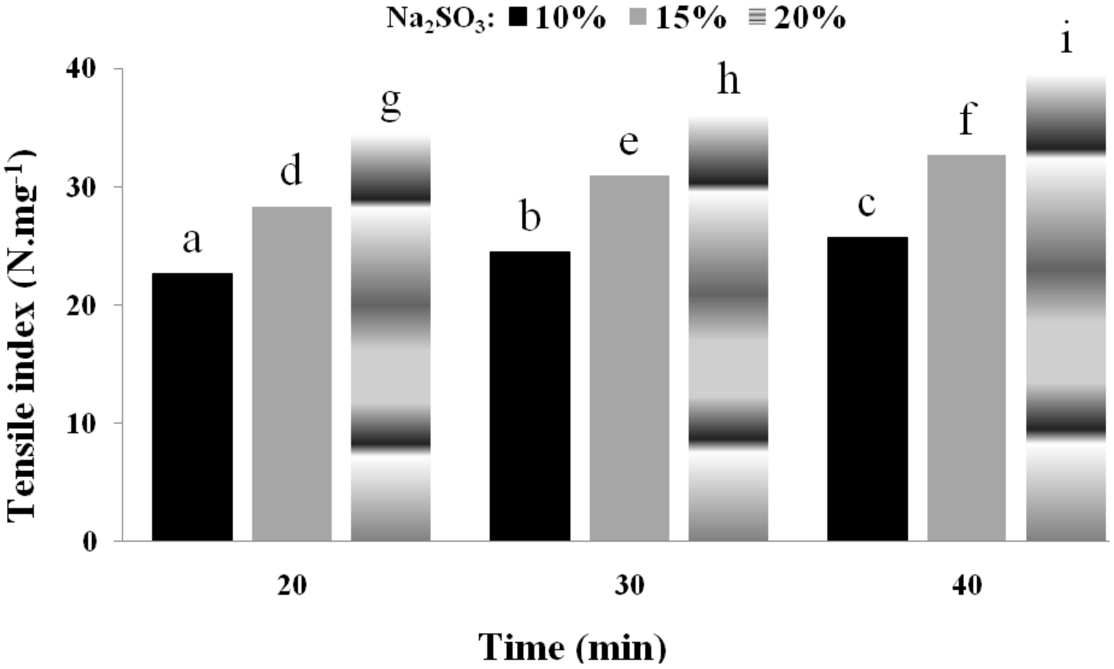

Fig. 2. Effect of pulping condition on tensile strength index of the bagasse CMP pulp

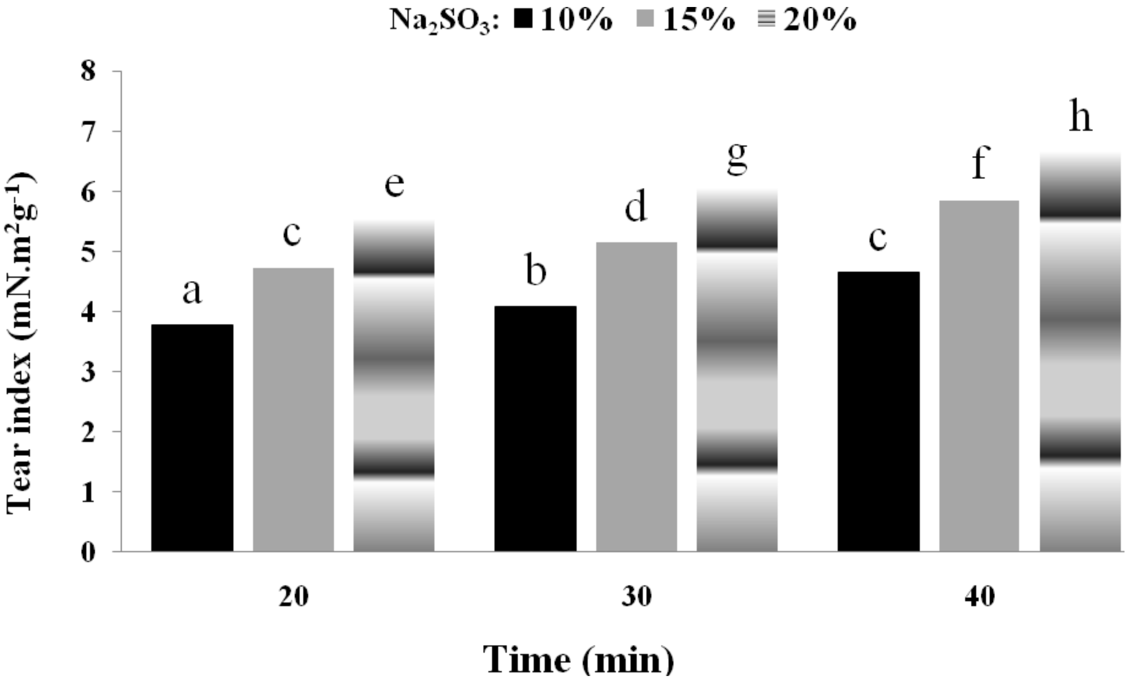

Fig. 3. Effect of pulping condition on tear strength index of the bagasse CMP pulp

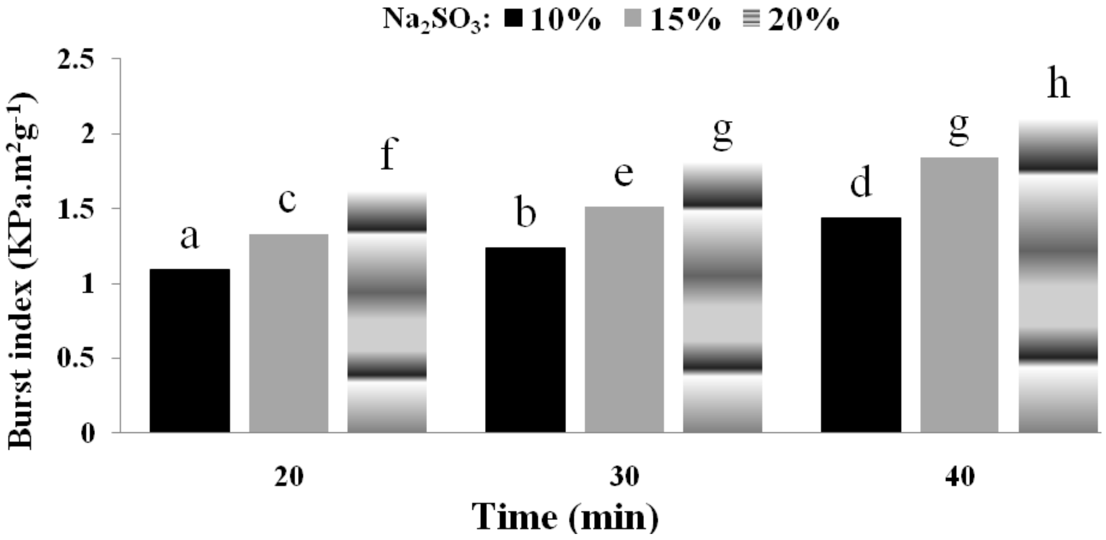

Fig. 4. Effect of pulping condition on burst strength index of the bagasse CMP pulp

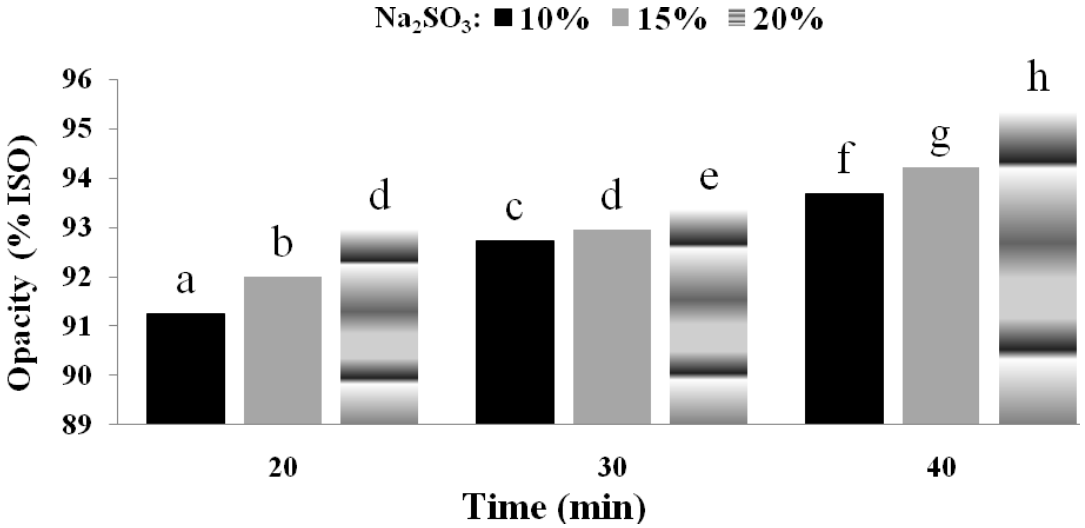

Fig. 5. Effect of pulping condition on opacity of the bagasse CMP pulp

CONCLUSIONS

1. World population, especially in developing regions, is growing, and this trend imposes steady growth of paper production and consumption. This phenomenon has led to inadequacy in the availability of wood raw material for the paper industry and has forced the utilization of unconventional fiber sources such as agro-based fibers. Among them, bagasse is unique. It is available in large quantities adjacent to sugar mills using sugarcane.
2. Soda pulping and traditional bleaching has been used for bagasse pulping, and this technology is in its mature stage. However, environmental concerns and

efficient use of raw material requires the development and application of more efficient technologies such as chemi-mechanical pulping for bagasse.

3. Results of chemi-mechanical pulping of bagasse indicated that applying mild chemical treatment (165 °C, 20% sodium suphite, and 40 minutes pulping time) compared to soda pulping produces pulp with the tensile, tear, and burst strength indices of 39.59 Nm/g, 6.66 mN.m^2/g and 2.1 kPa.m^2/g. The yield and opacity of this pulp were measured as 65.38% and 95.35% ISO, respectively. This pulp can be used as supplementary pulp for the production of newspaper in fiber-deficient regions with available supply of bagasse.

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