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Comparison of Two Bar Edge Lengths of Refining Plates on the Properties of American Old Corrugated Container Pulp during Low Consistency Refining

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Commercial American old corrugated container pulp (AOCC) boards were used as the starting material for repulping and low consistency (LC) refining to investigate the effects of LC refining plate geometry on the fibre and strength properties of the generated pulp. Specific refining energy that ranged from 0 to 120 kWh/air-dried ton (ADT) of pulp was explored for the two bar edge lengths (BEL) of refining plate patterns, wide 0.99 km/rev BEL and interim 2.01 km/rev BEL. The results showed that fibre length, curl index, kink index, and pulp freeness decreased while fines content increased with increasing refining energy input for both of the two refining plates during LC refining. LC refining with 2.01 BEL plate at low intensity of 0.24 J/m showed less fibre length reduction and more tensile strength development than that obtained with 0.99 BEL plate at high intensity of 0.48 J/m when compared at the same specific energy. Moreover, to achieve the desired tensile strength of the AOCC pulp, lower energy was needed for the interim 2.01 BEL plate than the wide 0.99 BEL plate. Thus, the interim 2.01 km/rev BEL refining plate provided potential for saving refining energy to reach a desired tensile strength of AOCC pulp.

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INTRODUCTION

The increasing demand for packaging papers has motivated the utilization of recycled old corrugated container (OCC) as the raw material for the production of paper boards and corrugating mediums for various packaging purposes (Kang *et al.* 2017). Different from the virgin fibres from wood or other lignocellulosic materials, recycled OCC has relatively lower strength due to hornification of fibres (Fernandes Diniz *et al.* 2004; Hubbe *et al.* 2007). To overcome the strength reduction of the recycled fibres, considerable efforts and technological approaches have been conducted (Gurnagul 1995; Viesturs *et al.* 1996; Oliveux *et al.* 2015). However, most previous studies have focused on the improvement of paper strength, water resistance value, and paper machine speed by adding different types of papermaking additives (Bajpai 2015). In addition, although refining is recognized to be an important stage and has been widely investigated during papermaking, the studies on understanding the fundamental properties of OCC pulp such as the evolution of fibre morphology and pulp freeness during refining are limited.

Compared to Chinese OCC pulp, American OCC (AOCC) pulp generally has longer fibre and higher pulp strength due to the lower number of recycled times (Cai *et al.* 2017). Thus, AOCC could be an appropriate raw material for the replacement of a portion of original pulp for the production of high-grade products such as high-strength packaging paper (Hunt and Vick 2004). To prepare OCC pulp, refining is a mechanical strategy to improve the bonding properties of the fibres in the pulp, in turn, improving the paper properties such as tensile strength (Nugroho 2012). Additionally, the appropriate refining technology, such as low consistency (LC) refining, could also alleviate the problems caused by the variability in the collection of used corrugated containers and improve the drainage of the obtained pulp, thereby providing a potential to increase the output capacity of the papermaking machine (Gorski *et al.* 2012).

During the refining process, fibres undergo various structural changes including increased fibre swelling, fibre shortening, fines formation, fibre straightening, as well as internal and external fibrillation (Ingmanson and Thode 1959; Gharehkhani *et al.* 2015; Rubiano Berna *et al.* 2018). The refining process is also recognized as a process of energy conversion, in which electrical energy is converted into mechanical energy to make changes on the fibres. To describe the refining process, the term refining theory, aiming at predicting changes in pulp properties from known refining conditions, has been proposed since the early 1920s (Gominho and Pereira 1995; Sain *et al.* 2002). The theory reported by Smith (1922) was completely based on visual observation of the refining process and lacked experimental support. With the improvement of experimental devices and research methods, some new refining theories have been put forward due to the deeper understanding of the refining mechanism. This understanding includes specific edge load (SEL) theory (Wultsch and Flucher 1958; Prairie *et al.* 2008), specific surface load (SSL) theory (Lumiainen 1990), and C-factor theory (Kerekes 1990). To the best of the authors' knowledge, the most widely used refining theory is the SEL theory, which comprises only simple calculations (equations), such as specific refining energy (SRE), SEL, and bar edge length (BEL), in which all parameters are readily available. The SEL is determined by the net power divided by the BEL multiplied by the rotational speed (Wultsch and Flucher 1958). The SEL theory helps experienced papermakers know approximately what kind of fillings and specific edge load should be used when refining certain pulp at a given consistency.

LC refining, which is typically conducted at a fibre consistency of approximately 4% (w/v), has been reported to be a more effective strategy for saving refining energy compared to that of high consistency (HC) refining with a refining consistency of approximately 40% (w/v) (Muenster *et al.* 2005). For LC refining, the refining plate is normally grooved so that the bars treat the fibres and the grooves between bars allow fibre transportation through the machine (Sixta 2008). Once refining starts, fibre flocs are first collected on the leading edge of the stator bar and then compressed when the leading edge of the rotor bar approaches the leading edge of the stator bar. Simultaneously, short fibres with low flocculation ability are peeled off and flow into the grooves between the bars, resulting in most of the long fibres remaining in the bar zone to receive refining.

Although substantial work has been conducted on developing different patterns of refining plates to increase the overall efficiency on the utilization of electrical energy to improve fibre morphology (Olson *et al.* 2003; Gorski *et al.* 2010), limited work has been conducted with recycled OCC pulp. Due to the different characteristics, such as fibre length, fines content, and curl index between virgin fibres and recycled OCC fibres, it is of great importance to investigate the effects of the refining process on the change of fibre

properties of OCC pulp. This not only provides marginal insights into the mechanism of refining of OCC pulp, but also improves the papermaking process with using OCC pulp as the raw material. Additionally, the investigation of refining OCC pulp might be able to provide potential in seeking an effective strategy for energy saving during processing recycled corrugated containers. This work preliminary investigated the effect of refining AOCC pulp with two kinds of refining plates, wide 0.99 km/rev bar edge length (BEL) plate and interim 2.01 BEL km/rev plate, on the properties of fibre, such as freeness, fibre length, and tensile strength, of the produced paper sheets. The main objective of this study is to expand the application of AOCC pulp in various grades of paper products such as linerboard, corrugating medium, and folding boxboard.

EXPERIMENTAL

Materials

The AOCC was provided by Norampac Co., Ltd. (Richmond, Canada). The obtained commercial AOCC were torn into pieces (10 to 15 mm in width and 12 to 17 mm in length). The obtained pieces of AOCC were stored at room temperature for further utilization.

Low Consistency Refining

The LC refining experiment was conducted at the Pulp and Paper Centre of University of British Columbia (BC, Canada). Before LC refining, the AOCC pieces were soaked in deionized water at a solids consistency of 4.0% for 24 h and then repulped (AFT; Sherbrooke, Quebec, Canada) for 24 min at 3.2% pulp consistency to produce AOCC pulp. During the pilot-scale repulping process, the refining plate (0.99 km/rev BEL and 2.01 km/rev BEL) was installed into the repulping system. Thus, the fibres might have become slightly refined before engagement of the refiner plate as the pulp was passing through the system. Pulps with same freeness were selected when studying the repulping process (as SRE = 0) to investigate the effects of the refining plates on the properties of the refined pulps. For the refining process, the pulp at 3.2% consistency was passed through a 16-inch single disk refiner by pumping the pulp through the refiner at a specific energy of 20 kWh/t. The pulp suspension was refined at a target of SEL of 0.48 and 0.24 J/m for 0.99 BEL plate and 2.01 BEL plate, respectively. The pulp was then sampled before passing through the refiner again at the same specific energy. The process was repeated six times to a total specific energy of 120 kWh/t. While running the refiner, other refining process parameters were always kept constant for every different plate. The schematic of the LC refining system is illustrated in Fig 1. All the LC refining trials were completed with targets of 1200 rpm refiner speed, pulp volumetric flow rate of approximately 250 L/min, and 3.2% pulp consistency. The refined pulps were collected and stored at 4 °C until further experimentation. Table 1 shows the refiner plate geometries used in this study. The refiner disks had a common outer diameter of 406 mm and inner diameter of 229 mm. Both refiner plates had a groove depth of 4.8 mm and bar angle of 15°. For each trial, the temperature of pulp after repulping was also measured. All experiments were performed at least in triplicate.

Table 1. Summary of LC Refining Plate Geometries Used

Trial	Bar Type	BEL (km/rev)	Bar Width (mm)	Groove Width (mm)	Temperature (ºC)
1	Wide	0.99	3.2	4.8	45.4
2	Interim	2.01	2.0	3.6	42.7
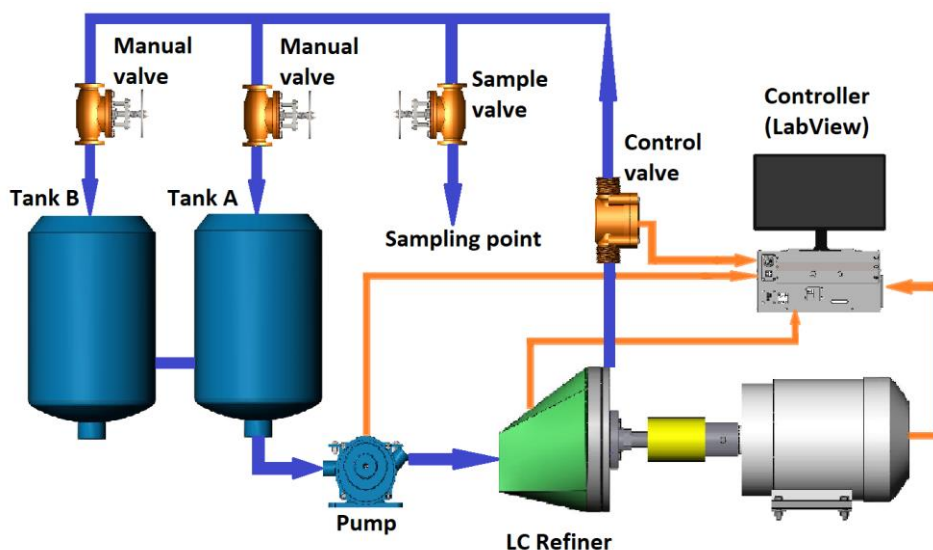
Fig. 1. The schematic of LC refining system

Analytical Methods

The moisture content of solid samples was measured by drying at 105 ± 2 °C to constant weight. The freeness of pulps was tested according to TAPPI method T227 om-99 (1999). Pulp properties of length-weighted fibre length, curl index, kink index, and fines content were determined with a fibre quality analyzer (FQA; OpTest Equipment Inc., Hawkesbury, Canada) following the ISO 16065 (2014) standard. Briefly, a total of 2 to 4 mg oven-dried (o.d.) pulp samples were diluted with 600 mL deionized water and mixed for 5 min for the measurement with the FQA. The fibre morphology was observed with a light microscope (Microflex HFX-II; Nikon, Tokyo, Japan) at 400× magnification. The procedure for using this equipment was based on the manual for the Nikon microscope PPCT 1020. A pulp handsheet with a grammage of 60 g/m^2 was prepared according to TAPPI T205 sp-02 (2002) standard. The prepared handsheets were air-dried in a constant temperature and humidity room (23.0 °C, 48.5% relative humidity) for 24 h prior to measuring the strength and optical properties. Tensile strength was determined according to the TAPPI T494 (2006) method using an L&W tensile strength tester.

Statistical Analysis

Data collected from triplicate measurements were analyzed by a one-way analysis of variance (ANOVA) using the Origin software (OriginLab Corporation, Origin85, Northampton, MA, USA). Multiple comparisons among treatments were performed using the Tukey *post hoc* test. Significant differences between treatments were evaluated at p ⩽ 0.05. Error bars in all graphs are 95% confidence intervals.

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RESULTS AND DISCUSSION

Mechanical Fibrillation

To evaluate the effects of refining on the properties of the AOCC pulp, LC refining was conducted on the pulp. Figure 2 shows the effect of the refining process on the properties of the obtained pulp. It needs to be noted that due to the different patterns of the refining plate installed during the repulping process, the fibre length and fines percentage of the fibre suspension at SRE = 0 might be different even at the same pulp freeness. Figure 2a shows that, as anticipated, the average weighted fibre length decreased with increasing refining energy for both the 0.99 BEL and 2.01 BEL plates. This could be attributed to the fibre shortening created by refining/beating (Sjoberg and Hoglund 2007). Figure 2a also reveals that the refining with 2.01 BEL plates generally resulted in higher fibre length than that of the 0.99 BEL plate under the same refining energy. One likely reason might be that plate 2.01 BEL is a low-intensity interim plate that produced less fibre cutting than plate 0.99 BEL (Olson *et al.* 2003).
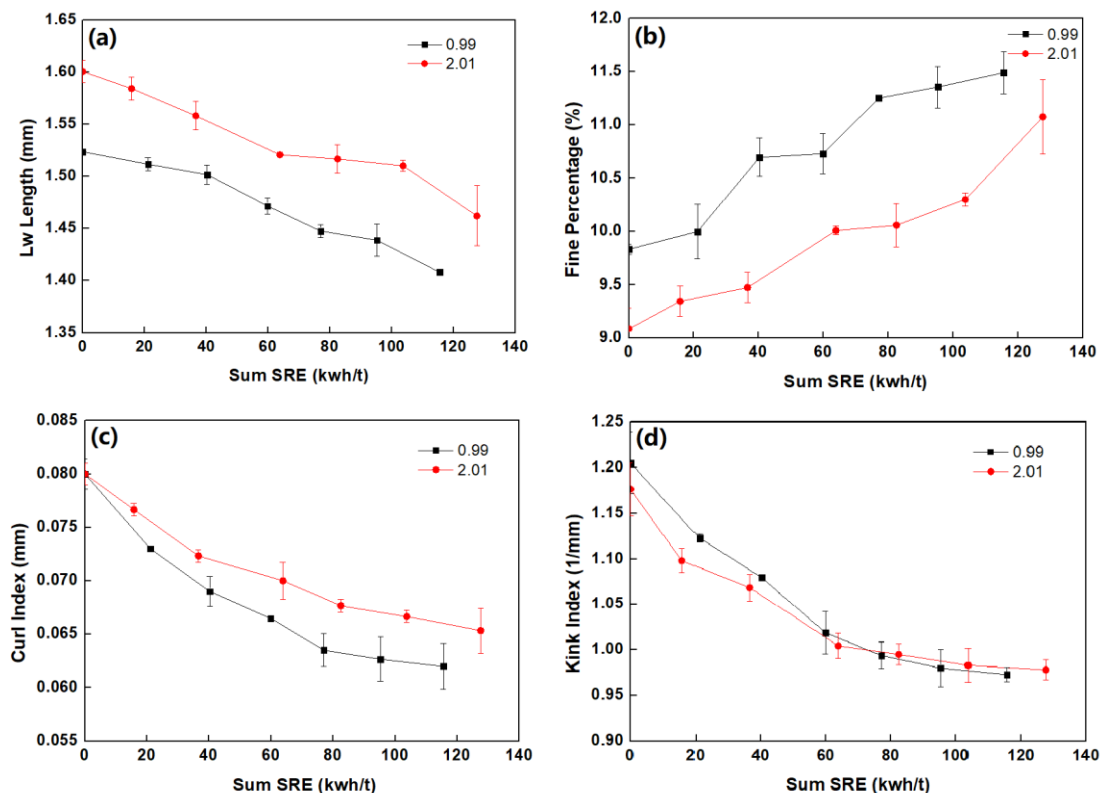

Fig. 2. The pulp properties development during LC refining: (a) the development of length-weighted fibre length *versus* sum SRE; (b) the development of fine percentage *versus* sum SRE; (c) the development of curl index *versus* sum SRE; and (d) the development of kink index *versus* sum SRE

The content of fines in the refined pulp was determined (Fig. 2b). To further assess the fibre cutting during the refining process, the fibre length distribution of the AOCC pulp during the LC refining was investigated and is given in Fig. 3. As shown in both Fig. 2b and Fig. 3, the content of fines gradually increased with increasing SRE used for refining. Moreover, the fines content in the pulps obtained from the refining with the 2.01 BEL plate

was much lower than that of the 0.99 BEL plate. This was in accordance with the results of Fig. 2a. These results demonstrated that the refining with the 2.01 BEL plate had the potential to preserve fibre length, in turn reducing the amount of short fibre fragments in the pulp suspension after refining.
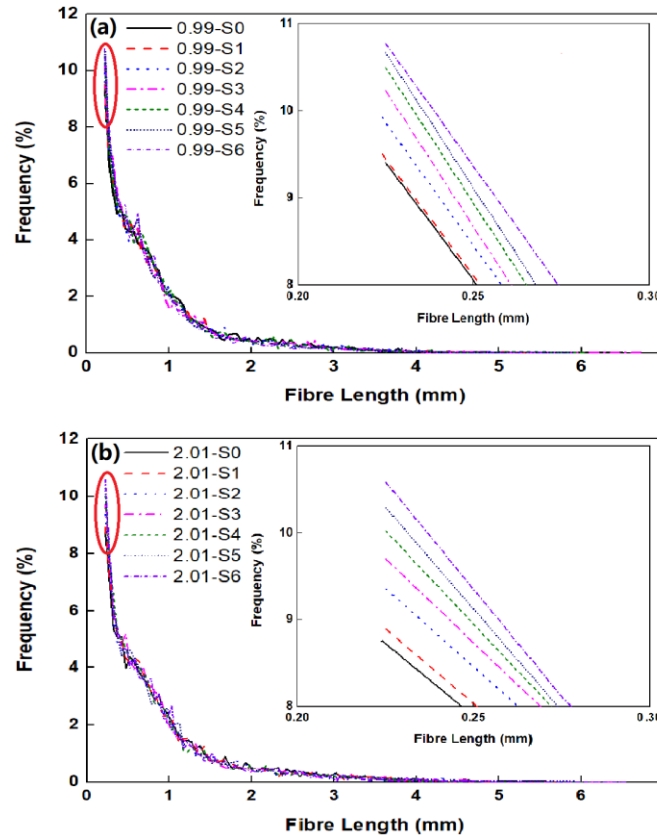

Fig. 3. The fibre length distribution of the AOCC pulp used in this research (SO, S1, S2, S3, S4, S5, and S6 at 0, 20, 40, 60, 80, 100, and 120 total specific energy, respectively): (a) fibre length distribution of the AOCC pulp using 0.99 BEL refining plate; (b) fibre length distribution of the AOCC pulp using 2.01 BEL refining plate

The fibre curl index, which is the ratio of the fibre contour length to the projected length ends minus one, is an assessment of the straightness of the fibre (Page and Seth 1980; Gion *et al.* 2011). The decrease of fibre curl has also been found to improve the tensile strength of the produced paper (Seth 2006). Figure 2c shows that the curl index of the refined AOCC pulp decreased for both interim 2.01 BEL and wide 0.99 BEL plates through increasing the refining energy. This is in agreement with a previous study on LC refining of chemical fibres (Mohlin and Alfredsson 1990). Additionally, compared to refining with 0.99 BEL plate, the 2.01 BEL plate resulted in a much greater decrease of curl index under the same refining energy. One possible explanation might be that the fibres had more chance to pass through greater filling grooves (0.99 BEL) rather than being trapped by the bars (Gharehkhani *et al.* 2015). In addition, the kink index of AOCC fibres decreased by increasing the refining energy (Fig. 2d), which further indicates that fibres were straightened by the refining treatment.

Figure 4 shows microscopic images of AOCC pulp fibres obtained from the refining at different energies with two different refining plates.
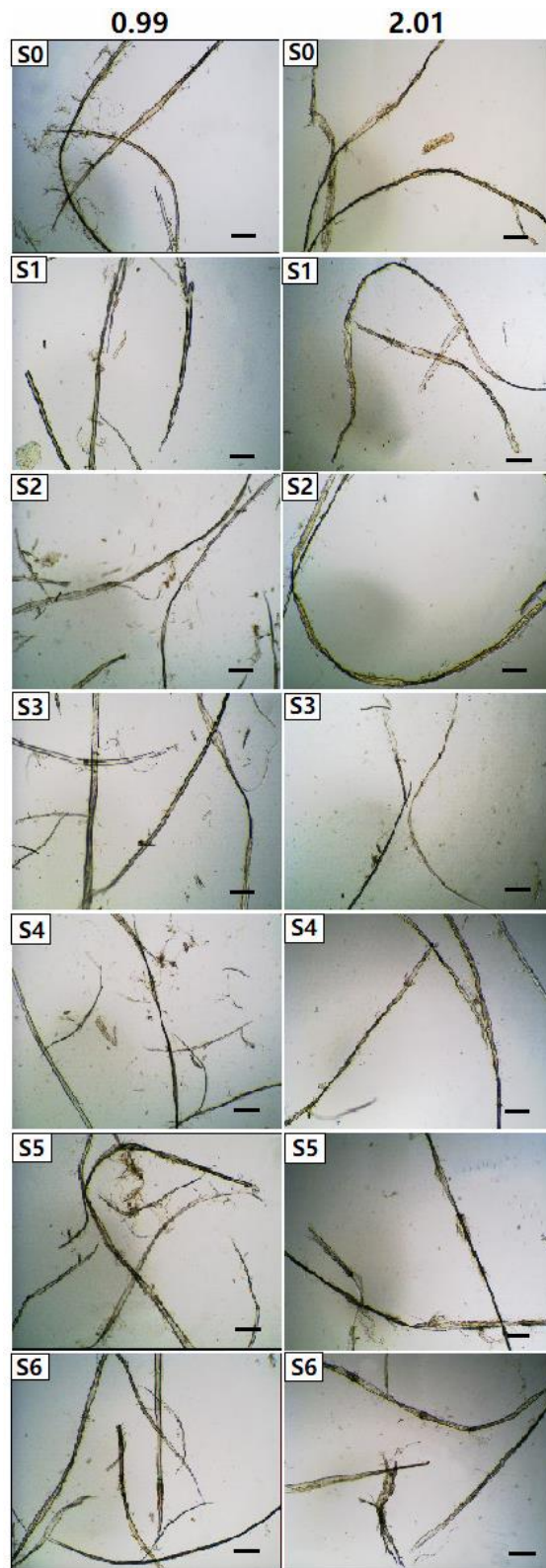
Fig. 4. Effects of mechanical refining on AOCC pulp fibres through 2.01 BEL and 0.99 BEL plates; SO, S1, S2, S3, S4, S5, and S6 at 0, 20, 40, 60, 80, 100, and 120 total specific energy, respectively; Scale bar = 50 μm

As shown in Fig. 4, the fibres became more fibrillated and flexible with increasing total SRE. The fibrillation made fine fibres loose, which yielded an amount of fine fibres and microfibrils. This resulted in a fast increased fines content. In addition, the length of fibres from both 2.01 BEL and 0.99 BEL plates gradually decreased with increasing SRE under the same magnitude ratio. Furthermore, the 2.01 BEL plate was not fibrillated to the same extent as the 0.99 BEL plate during refining. This was the same for results obtained from the FQA experiments, the length of AOCC refined with the 2.01 BEL plate was longer than that of AOCC refined with the 0.99 BEL plate.

Freeness

Freeness, which represents the amount of water flowing through a bed of fibre network, is the most widely used control test in the stock preparation area of the paper mill. The freeness of AOCC pulp decreased with increasing refining energy input (Fig. 5), indicating that the refining process increased the fibrillation of fibres and created more short fibres. Moreover, the initial freeness was the same for both 2.01 BEL and 0.99 BEL plates; thereafter it changed slightly. Refining with the interim 2.01 BEL plate had slightly higher pulp freeness than the 0.99 plate at the same SRE (Fig. 5). The higher pulp freeness was related to longer fibre length and lower fines generated during LC refining (Fischer *et al.* 2017). Once more energy was transferred to the pulp suspension, a lower drop in freeness was observed.
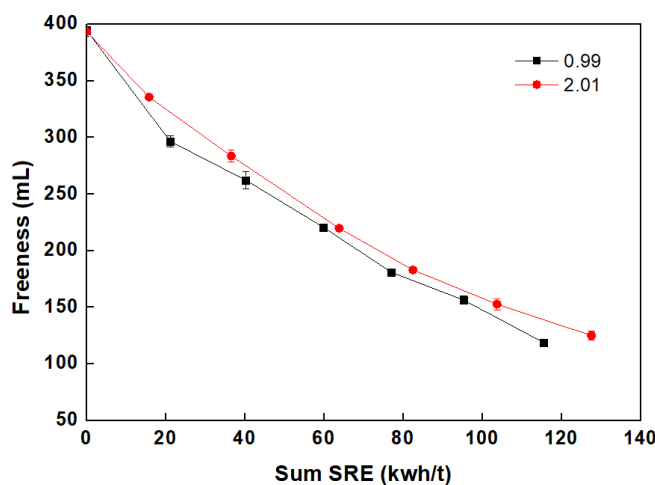

Fig. 5. The development of freeness *versus* sum SRE during LCR

Tensile Strength Development

To further evaluate the effect of LC refining with the two plates, the tensile strength of the obtained pulp was determined. As shown in Fig. 6, the tensile index of the obtained pulp initially increased with the increase of SRE used for LC refining, and thereafter the increase rate started to level off for both two plates. Although the refining could increase the fibrillation of fibres and the hydrogen bonding among fibres, the extensive refining caused a decrease in fibre length and generated more fines in the pulp suspension, which decreased the tensile strength of the pulp. Moreover, compared to the pulp made from the refining with the 2.01 BLE plate, the pulp obtained from the 0.99 BEL refining plate showed lower tensile strength (Fig. 6). For example, at a refining energy of 60 kWh/t, the tensile indexes were 53.0 and 50.5 Nm/g ($p \leq 0.05$) for 2.01 and 0.99, respectively (Fig.

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6). The experimental results showed that with using the interim 2.01 km/rev BEL plate, the tensile strength of the produced AOCC pulp increased from 39.5 to 57.0 Nm/g by increasing the refining energy from 0 to 127 kWh/t, while for wide 0.99 km/rev BEL plate, with increasing refining energy from 0 to 116 kWh/t, the tensile strength of the obtained AOCC pulps increased from 38.0 to 46.9 Nm/g.

Figure 6 also shows that at a given refining energy input, the interim plate 2.01 accomplished the higher tensile strength. Although at lower SRE, the difference of tensile strength between two plates was slight, but at higher SRE the effect of plate geometries on tensile strength became more obvious. This suggested that at the same refining energy, the treated AOCC fibres with the interim plate 2.01 BEL built up a stronger fibre network that resulted in higher tensile strength. This was different from the results obtained by Salim and Olson (2017), who investigated the tensile development of northern bleached softwood kraft pulp (NBSK) in a low consistency refiner. They concluded that there was no appreciable difference in the tensile development when refined by different bar geometries (wide, narrow). This distinction might be explained by the differences of the fibre structure between the two kinds of pulps and the difference of plate geometries involved.
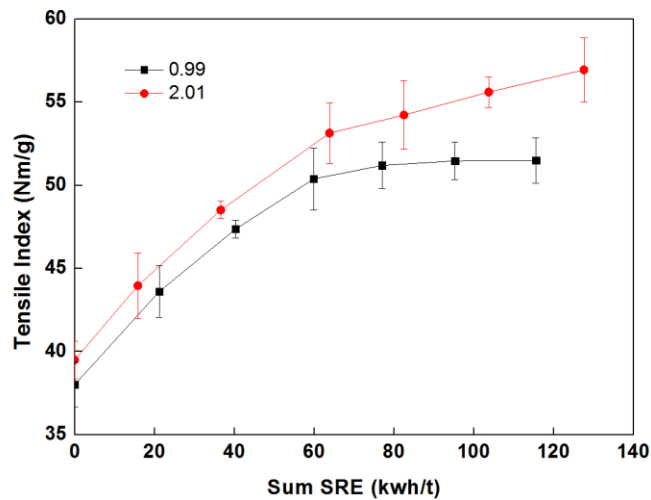
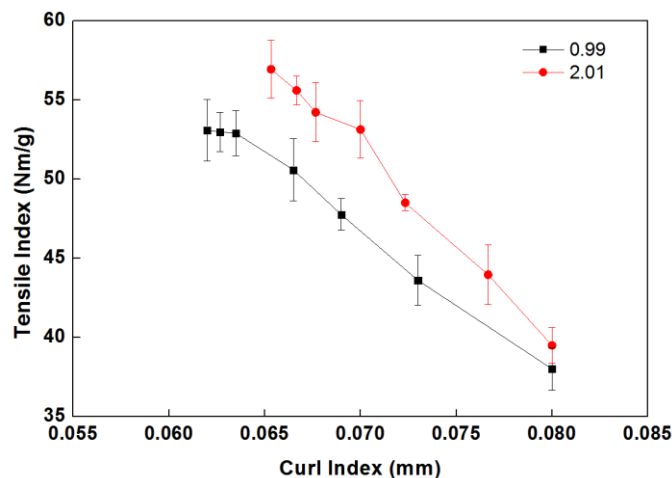**Fig. 6.** Tensile strength as function of sum SRE at 1200 RPM

Fig. 7. Tensile strength as function of curl Index

The effects of fibre deformations (curl and kinks) on tensile strength were also studied. Figure 7 shows the correlation between tensile development and curl index. As shown, the tensile strength decreased when the AOCC fibres in the fibre network were deformed. This could have been attributed to the fact that the deformed fibres (curl index, kink index) formed a fibre network where the load distribution was non-uniform (fibre activation was not uniform) compared to a situation with straight and un-deformed fibres. The nonuniform load distribution caused local stress points, which broke when fibre network was drawn and resulted in low tensile strength values (Zeng *et al.* 2012).

The correlation between freeness and tensile strength is shown in Fig. 8. As shown, the tensile strength was inversely proportional to the freeness, indicating that the refining process decreased the freeness and increased the tensile strength. The interim 2.01 BEL plate yielded higher tensile strength than the wide 0.99 BEL plate. The higher tensile index at a given freeness with the 2.01 BEL plate was probably related to the observation that this treatment produced pulps with longer fibre length and lower fines content compared to the 0.99 BEL plate. As clearly shown, the difference of tensile index between two plates was larger at lower freeness than higher freeness of the refined pulp. For example, at the freeness value of 130 mL Canadian standard freeness (CSF), the tensile indexes were 53.0 Nm/g and 56.8 Nm/g for 0.99 BEL plate and 2.01 BEL plate, respectively. In contrast, at the pulp freeness of 350 mL CSF, the tensile difference between two plates was 2.7 Nm/g (40.1 Nm/g for 0.99 BEL plate and 42.8 Nm/g for 2.01 BEL plate). It was also noticed from Fig. 8 that in the range of low freeness (lower than 180 mL CSF), the tensile strength decreased slowly with increasing freeness. By contrast, in range of high freeness (higher than 180 mL CSF), the tensile strength was reduced rapidly.

This work preliminarily compared the effect of LC refining with wide 0.99 km/rev BEL plate and interim 2.01 km/rev BEL plate on the pulp properties and tensile strength of AOCC pulp. The refining intensities of 0.24 J/m and 0.48 J/m were investigated for the 2.01 BEL plate and the 0.99 BEL plate, respectively. Based on the preliminary results, interim 2.01 km/rev BEL plate is considered to be suitable for the refining of AOCC pulp. To provide deep understanding of the refining of AOCC pulp, further work will be focused on the refining of AOCC pulp with interim 2.01 km/rev BEL at different intensities and investigate the effect of the refining process on the fibre properties, including fibre length, fines content, curl, and kink.
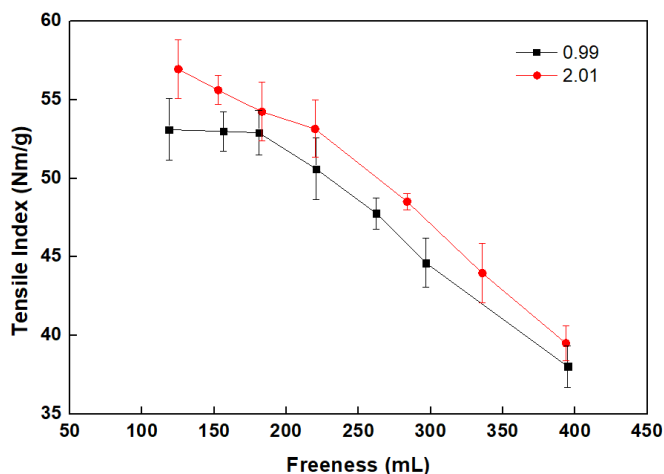

Fig. 8. Tensile strength as function of freeness

CONCLUSIONS

The fibre properties, freeness, tensile strength, and refining energy input were determined during the LC refining process of American old corrugated container (AOCC) pulp with two different refiner plate patterns.

1. During LC refining with both interim 2.01 km/rev BEL and wide 0.99 km/rev BEL plates, with increasing the SRE, the fibre length, curl index, kink index, and freeness values of the pulp decreased, while fines content and tensile strength of the produced handsheets increased.

2. LC refining with 2.01 BEL plate at low intensity of 0.24 J/m showed less reduction in fibre length than that obtained with 0.99 BEL plate at an intensity of 0.48 J/m when refining at the same specific energy.

3. Under the same SRE, refining with 2.01 km/rev BEL plate generally resulted in higher fibre length, curl index, freeness, and tensile strength of AOCC pulp than the refining with 0.99 km/rev BEL plate.

4. Compared to the wide 0.99 km/rev BEL plate, less energy was required for the interim 2.01 km/rev BEL plate to achieve a given tensile strength of AOCC pulp. Moreover, the interim 2.01 km/rev BEL plate achieved higher tensile strength than 0.99 km/rev BEL plate at the same pulp freeness.

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