Influence of Jack pine earlywood and latewood fibers on paper properties

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KEYWORDS: Jack pine, Earlywood, Latewood, Paper property

SUMMARY: The morphological differences of EW and LW fibers influence the papermaking characteristics of the resulting pulps, namely the physical and optical properties. For a given freeness, thanks to their better fiber conformability, the fibers of EW whole pulps produce handsheets with higher sheet density, lower roughness and porosity than those of LW pulps. Mainly due to highly fibrillated fibers and fibril-rich elements in the fines, the fibers of LW whole pulps yield handsheets with better physical strengths, such as tensile, burst, and tear indices when compared to the EW counterparts. On the other hand, the EW pulps show higher light absorption coefficient because they have higher lignin content when compared to the LW pulps. However, EW pulps have better light scattering coefficient than LW pulps because the fines in EW pulps contain more flake-like particles which increase the scattering of light in the sheet structure. In the fiber network, the thin-walled EW fibers have better collapsibility and conformability, thick-walled LW fibers produce sheet with higher bulk and have greater fiber twists and fibrils in the network.

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Wood is a heterogeneous material in which the chemical and physical characteristics vary between species, between trees of the same species, and even between different parts of the stem within a tree. However, in temperate zone, the most distinguishable variability in fiber morphology exists between earlywood (EW) and latewood (LW) of softwood. When the atmospheric temperature rises in the spring, tree growth activities begin with cambium cells division. This activity is believed to be regulated by a growth hormone, auxin (Uggla et al., 2001). The early growth is fast and gives rise to fibers or tracheids in conifers (softwood) with large diameter and relatively thin cell wall. This wood tissue is called springwood or EW. As the late summer approaches the temperature falls and the tree growth gradually slows down, producing fibers with smaller cell lumen and thicker cell wall. This zone of thick-walled fibers is called summerwood or LW. The tree growth season ends in the fall as the trees begin to shed leaves or needles. The most visible differences between the EW and LW fibers are that the former tend to have larger diameter, thinner cell wall than the latter (Reme, Johnson, 1999; Law, 2001). Generally, EW fibers are more flexible (Agut et al., 1987; Luner, 1986), and collapsible (Uhmeier, Salmén, 1996; Mohlin, 1975; Hartler, Nyren, 1970) than those of LW; the latter being stiffer and less collapsible (Huang et al., 2012; Huang et al., 2011). During the thermomechanical pulping (TMP), the LW fibers exhibit a greater reduction in cell wall thickness. The EW fibers tend to split especially in the 1st stage refining (Reme, Helle, 2001), and they require more refining energy to reach the same freeness as compared to the LW fibres (Murton et al., 2001). In addition, previous studies also indicated that the thick-walled LW fibers break more readily than do the more flexible EW during the refining (Koljonen et al., 1995; Corson, Ekstam, 1993). These findings indicate that EW and LW respond differently to mechanical actions.

Fiber morphology plays an important role in determining the properties of paper. Doubtlessly, the morphological differences between EW and LW fibers would have dissimilar impacts on handsheet properties. Studies (Hattula, Niemi, 1988; Aspler, Beland, 1994) suggested that EW fiber increases some physical strength, such as density, tensile and burst strength, while the stiffer LW fiber produces bulky sheet with rough surface. Since EW fiber is much more flexible and conformable than LW fiber, it has larger bonding surface, giving better paper strength. However, LW fiber improves tearing resistance.

Although previous research indicated the EW and LW fibers had different impacts on paper properties, few studies were reported on the papers made from individual EW or LW pulps. In this study, the Jack pine EW and LW pulps were produced through the thermomechanical pulping. The physical and optical properties were examined for the handsheets prepared with EW and LW mechanical pulps, and the mixed furnish. Scanned electronic microscopy (SEM) was also employed to examine the fiber bonding and collapse in the paper cross-sections. With the analysis information we hope to establish some possible interrelations between the fiber characteristics and paper properties.

Materials and Methods

Logs of freshly felled Jack pine (*Pinus banksiana* Lamb.) were used in this work. The Jack pine trees were taken from a 30-years old plantation in St. Maurice region of Quebec. The logs were sawn into disks of about 2.5 cm thick in longitudinal direction. The disks were then debarked manually by means of a chisel. Chips were prepared from the sapwood portion, excluding the heartwood to minimize the possible effects of its high extractives content on pulp properties. The chips of EW and LW, approximately 2-3 cm in width and length, were also prepared manually using a chisel. The thickness of the chips varied depending on the width of the growth rings and the proportion of EW and LW in the growth increment. The separation of EW from LW was based on the difference in colour: LW in Jack pine was relatively broad and much darker than the EW counterpart. About 10 kg o.d. woodchips were prepared for EW and LW samples, respectively.

Physical and chemical properties analysis of EW and LW

In this study, the dichloromethane extractives, Klason lignin, holocelluloses, α- cellulose and ash of EW and LW chips were determined following the Tappi test methods T204 cm-97, T222 om-98, T9 wd-75, T203 om-99 and T211 om-02, respectively. The basic density (weight o.d./volume) of the EW/LW chips was measured following Tappi method T258 om-02. The dry content of woodchips was measured by drying samples in an oven of 105°C.

To study the fiber characteristics, such as fiber length, and cell wall thickness, it is necessary first to liberate the fibers from the wood matrix by means of chemical maceration (Franklin, 1945). The fiber length was measured using fiber quality analyzer (FQA, OpTest Equipment Inc.) and cell wall thickness measurement was conducted by means of light microscope.

Refining

A Sunds Defibrator 300 CD pilot plant (Metso Paper) was used for refining the chips. The refining capacity is 2 t/day. The models of this refiner rotor and stator plate are R3809BG and R3803, respectively. EW and LW chips were either separately refined or in blend according to the initial proportion of each exiting in the wood. In the process, the chips were pre-steamed atmospherically for 10 min and then screw-fed into a digester using a 2:1 compression ratio.

The refining was carried out in two stages. The first-stage was pressurized at 160ºC and the pulps were produced with a freeness of about 500 ml. The Canadian standard freeness (CSF) was measured following Tappi method T227 om-04. These pulps were refined atmospherically to a freeness range of 50-200 ml and the specific energies were recorded for the pulps at each freeness level. The 1st stage refining consistency was about 20-24%, while the 2nd stage was around 10-14%. In addition, the refiner plate clearance was different between the refining stages: 0.40-0.60 mm was in the 1st stage refining while 0.25-0.50 mm for the 2nd stage refining. After refining, all the pulp samples were disintegrated by means of 90ºC water to remove latency prior to further analysis (Bently et al., 1994).

Fractionation of Pulps

The experimental first-stage and second-stage pulps were fractionated in a Bauer-McNett classifier to obtain 6 fractions denoted as R14, R28, R48, R100, R200, and P200 (fines). The gravimetric percentage of each fraction was calculated based on the o.d. whole pulp weight. The Bauer-McNett fibre classification is a commonly used method to characterize the fibre length distribution of mechanical pulps. The fibres in different Bauer-McNett fractions are morphologically different and have different effects on paper properties. In addition, the length-weighted mean fiber lengths of all the pulps were analyzed by the fiber quality analyzer (FQA, OpTest Equipment Inc.).

Handsheet formation and characterization

Standard handsheets of 60 g/m^2 (Tappi method T205 sp-02) were made from EW, LW pulps and the mixture furnish (MIX) which was based on the initial EW/LW dry weight ratio in the whole solid wood. The handsheet physical and optical properties were determined based on standard Tappi test methods as follows: density (T220 sp-01), tensile strength (T220 sp-01), tear strength (T220 sp-01), burst strength (T220 sp-01), porosity (T547 om-97), roughness (T538 om-01), light scattering coefficient (T425 om-96), and light absorption coefficient (T425 om-96).

Scanning electron microscopy (SEM) and image analysis

Scanning electron microscopy (SEM) was employed to quantitatively examine the EW and LW fiber collapsibility in the handsheet cross-section. An ImageJ algorithm (Image Processing and Analysis in Java) (http://rsb.info.nih.gov/ij/) was employed to directly measure the following fiber properties in SEM images: cell wall thickness, cell wall area, lumen area, outer fiber perimeter of cell wall (Fjerdingen, Houen, 1997). It should be noted that the fibers were randomly chosen for the measurement. Some abnormal and non-aligned to the handsheet plane fibers were also included in the tests. The reported results were the average values of 200-300 measurements. Form Circle (*FC*) was used to evaluate the fiber collapsibility in the fiber network (handsheet) (Jang, Seth, 1998; Johnson et al., 1995). Higher *FC* value means lower collapsibility. *FC* is defined as the following equation, *Eq 1*.

$$FC = \frac{4\pi A_t}{P^2} \quad [1]$$

where

At = area of filled fibers (fiber wall area + lumen area);

P = outer perimeter of cell wall.

Due to the tedious work in the SEM sample preparation, only the handsheets made from 150 ml freeness pulp were applied in the analysis. The sample preparation was based on the reported method (Huang et al., 2011). The images were observed using a SEM (JOEL, JSM-500).

Twist angle determination

The twist angle was the angle measured between the longest dimension of the fiber cross section and the horizontal frame of the image obtained from the SEM analysis (He et al., 2003). As showed in *Fig 1*, β is the twist angle, which indicates the rotation extent of fiber cross-sectional major axis towards to the paper plane. The orientation of the fiber with respect to the paper plane (fiber twisting) could strongly affect the structure of the paper. Decreasing the number of twist in fibers will increase sheet strength. The reduction in fiber twist would reduce the amount of space taken by the fiber in the paper structure, thereby reducing the void space and increasing the density of paper. The reduction in fiber twist could also increase the potential bonding surface area of the fibers, especially for collapsed fibers (Mohlin

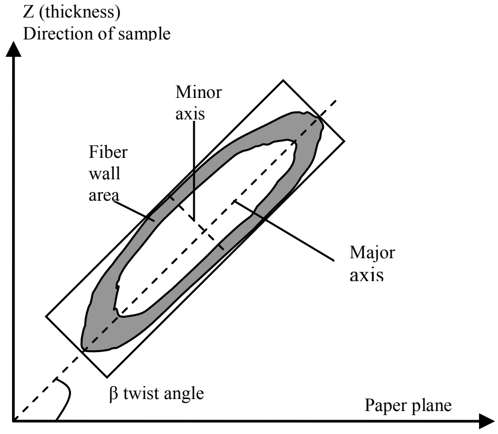

Fig 1 Definition of fiber twist angle (He et al. 2003)

et al., 1996). It should be noted that twist angle determination was originated to deal with kraft pulps. It is also important for mechanical pulps since it reflects the fiber-fiber bonding in the network, which is critical for the pulp strength.

Statistical analysis

For the statistics reason, at least 300 fibers per sample were measured for the microscopy analysis. The standard error for each analysis was ±5%. The standard error associated with the chemical composition analysis was ±2.0%. Multiple measurements (3-10 runs) were conducted for all the handsheet physical testing, and a mean value was reported.

Results and discussion

Physical and chemical analysis of EW and LW fibers

Table 1 indicates the cell wall thickness of LW (4.75 µm) is more than 2 times as that in EW (2.12 µm). The LW density (0.49 g/cm^3) is 63.3% greater than that of EW (0.30 g/cm^3). In addition, the LW fiber (3.55 mm) is longer than EW fiber (3.34 mm). These findings are well in line with those reported earlier (Hatvani et al., 1999). In addition, there are no significance differences of dry content between EW and LW woodchips.

The experimental data of chemical components of EW and LW of Jack pine are given in *Table 2*. Due to its thicker cell wall, LW has about 5.2% more α-cellulose when compared with EW. The EW has 4.5% higher lignin content in comparison with the LW. This is probably attributed to its relatively thicker lignin-rich CML as explained by Fengel (1969). Interestingly, the EW shows 20.4% higher dichloromethane (DCM) extractives than LW does. This difference in DCM extractives might probably due to the fact that the EW contains more resin-rich canals than LW (Huang et al., 2011). In addition, there are no significant differences in the ash content between EW and LW.

Pulp properties in each refining stage

After each refining stage, the pulp properties, including pulp freeness, specific energy consumption, length-weighted mean fiber length and the gravimetric percentage of each Bauer McNett fraction, were analyzed, as shown in *Table 3*. It can be seen that EW

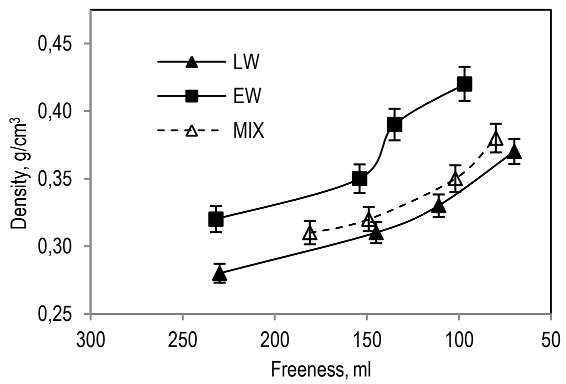

Fig 2. Handsheet density as a function of freeness.

needed more energy than the LW to get similar freeness, i.e. 90 ml after the 2nd refining stage, which was in accordance with previous study (Murton et al., 2001). Moreover, for a given freeness (90 mL), the LW pulp contained more long fiber fractions (43.00% in R14+R28) than the EW pulp (31.20% in R14+R28). However, this tendency was reversed in the short fiber fractions (R48+R100+R200): 39.35% in EW and 27.98 % in LW. This might be due to the fact the initial fiber length and cell wall thickness of LW fibers were greater than the EW fibers and they were more resistant to the mechanical actions in refining (Huang et al., 2012). In addition, there is no significant difference of fines content (P200) between the 90 mL EW and LW pulps.

Physical properties of handsheet

Density, roughness and porosity

Due to the superior collapsibility and conformability of EW fibers as compared to LW counterparts, the handsheets prepared from EW pulps were denser than those made of LW pulp at a specific freeness, as *Fig 2* showed.

Surface smoothness is an important property for printing paper. Jack pine is known to produce sheet with high roughness due to its thick-walled fibers (Law, Valade, 1994). For the same reason, thick-walled LW fibers produce handsheets with high roughness as compared to those of thin-walled EW fibers (*Fig 3*). Since the mixed furnish contains both LW and EW fibers, it makes handsheets with roughness inferior to that of LW sheet but higher than that for EW sheet.

The porosity of handsheets is mainly influenced by collapsibility of individual fibers within the sheet structure or the sheet density. The fines content in the pulp also plays an important role in determining the handsheet porosity. The fibril elements in the fines could positively influence the sheet physical strength (e.g. tensile, burst strength and porosity) while the flake-like elements in the fines play less important role in determining the paper strength (Luukko, Paulapuro, 1997; Alince et al., 2001).

Table 1. Basic property of Jack pine EW and LW

	Basic density	Fiber length	Cell wall thickness	Dryness
	g/cm^3	mm	µm	%
EW	0.30	3.34	2.12	91.14
LW	0.49	3.55	4.75	90.95

Table 2. Major chemical components of EW and LW fibers

	Klason lignin, %	Holocellulose, %	α-cellulose, %	DCM extractive, %	Ash, %
EW	28.30	68.68	42.34	1.95	0.17
LW	27.09	71.01	44.55	1.62	0.17

Table 3. Pulp properties from each refining stage

	1st refining stage		2nd refining stage	
Pulp type	EW	LW	EW	LW
Freeness, ml	411	660	90	90
Specific energy consumption, MJ/kg	6.51	3.48	12.73	11.05
Length-weighted mean fiber length, mm	1.57	2.07	1.40	1.82
Bauer McNett, R14, %	2.18	12.03	0.72	7.12
Bauer McNett, R28, %	39.32	45.07	30.48	35.88
Bauer McNett, R48, %	21.06	17.56	19.57	16.01
Bauer McNett, R100, %	11.34	6.14	11.03	7.09
Bauer McNett, R200, %	6.27	12.81	8.75	4.88
Bauer McNett, P200, %	19.83	6.39	29.45	29.02

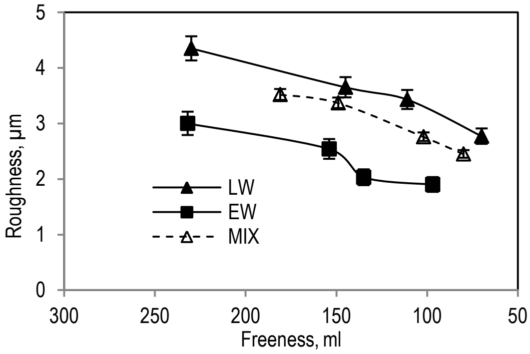

Fig 3. Roughness as a function of freeness

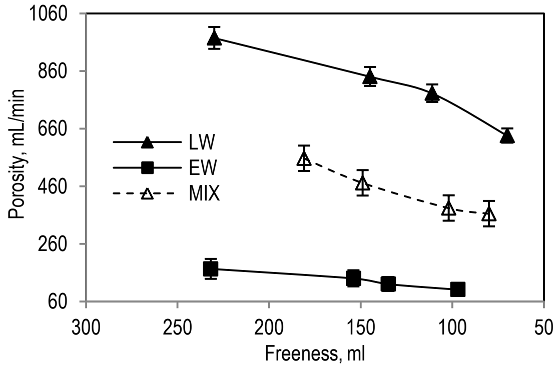

Fig 4. Porosity as a function of Freeness

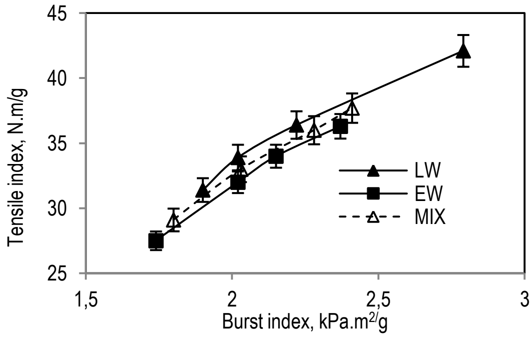

Fig 5. Tensile index as a function of burst index

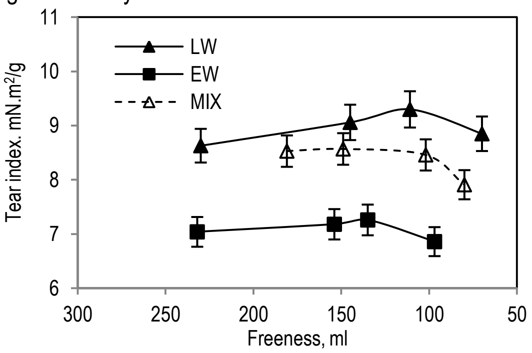

Fig 6. Tear index as a function of specific energy

As indicated in *Fig 4*, the EW sheet has lower porosity than that of LW, which is due to its higher collapsibility and conformability of the EW fibers. In addition, thin-walled EW fibers tend to break up more easily and yield more fines in refining (Huang et al., 2011), which could also reduce sheet porosity.

Tensile and burst indices

Fig 5 showed the burst index was plotted against the tensile index. As indicated in this figure, LW fibers exhibited a higher tensile and burst strength when compared to those prepared from EW and mixed furnish. As reported in previous research, LW produces more fibril-like fines in the pulps, which favours the fiber bonding in the fiber network (paper) (Murton et al., 2001; Huang et al., 2012). This might be the reason why LW pulps had better tensile and burst indices than EW as well as the mixed pulps.

Tear strength

Fig 6 shows the tear index as a function of freeness. Noted that LW pulp yields greater tear strength when compared to EW component since the former has longer fibers than the latter. Also, the LW yields more fibrils during the refining, which also favors the fiber bonding (Shallhorn, Karnis, 1979).

Light scattering coefficient

The light scattering coefficient of paper prepared from mechanical pulp is mostly influenced by the fines contents: higher fines contents yield greater light scattering coefficient (Lindholm, 1980). *Fig 7* showed the light scattering coefficient against the pulp freeness.

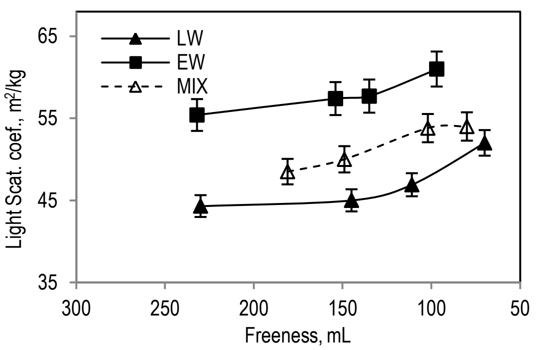

Fig 7. Light scattering coefficient as a function of freeness.

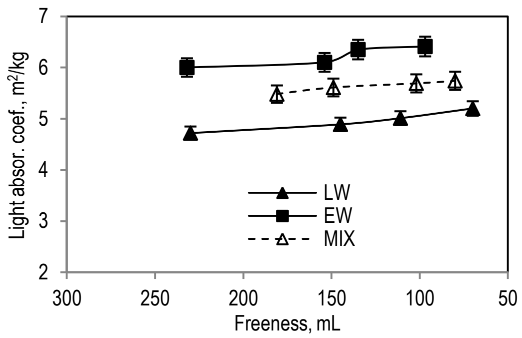

Fig 8. Light absorption coefficient as a function of freeness.

Optical properties

It can be seen the EW pulp had higher light scattering coefficient than those of LW because they contained less fibrils in their fines, as discussed earlier. A recent research work indicated that the fibril-like fines have greater specific surfaces than those of flake-like components. The fibril components contribute to the increase in physical properties of paper, as indicated in *Table 3* (Luukko and Paulapuro, 1997; Alince et al., 2001). The fibril-like elements in the fines influence positively the physical strength of sheet (e.g. tensile and burst indices) and negatively the light scattering coefficient of paper. The flake-like fines particles, namely, ray cells and tiny pieces detached from the outer layers of cell wall may play a less important role in determining the paper strength, but have considerable influence on the optical properties of paper. Due to their extremely high conformability, the fibril-like fines could be bonded tightly to the fiber surface, having little contribution on the light scattering coefficient (Sirvio and Nurminen, 2004). Therefore, the fibril-like fines have negative effect on the light scattering coefficient in contrast to the flake-like fines. Since EW fibers produce more flake-like fines in the pulps (Huang et al., 2011), they give higher light scattering coefficient in relation to the LW pulps.

Light absorption coefficient

The light absorption coefficient of paper is mainly influenced by the chemical nature of the wood components, such as cellulose, hemicelluloses, lignin and extractives. Cellulose and hemicelluloses are practically uncoloured. While the lignin is coloured since its chromophores absorb light and make the lignin coloured. The contribution of the chemical components of wood to the light absorption coefficient can be expressed by the following equation *Eq 2* (Sundholm, 1999):

$$k_p = c_C \cdot k_C + c_L \cdot k_L + c_E \cdot k_E \qquad [2]$$

where,

k_P = light absorption coefficient of the pulp;

c_C, c_L and c_E = relative amounts of carbohydrates, lignin, and extractives, respectively in the pulp;

k_C, k_L and k_E = light absorption coefficients of carbohydrates, lignin, and extractives.

Previous study (Norrström, 1969) reported that more than 90% of the coloured matter in Norway spruce (*Picea abies*) originates from the lignin, which contributes most to the light absorption coefficient among the wood chemical components (carbohydrates, lignin and extractives). It should be noted that the light absorption coefficient of the extractives is also relatively high, but their contribution to the light absorption coefficient of the pulp is limited because of the low content of extractives in wood. As discussed in *Table 2*, the Jack pine EW contains more lignin (28.30%) than the LW (27.09%). This might be the reason that EW sheet has higher light absorption coefficient than that of LW (*Fig 8*).

Table 4. Contribution of fibril and flake fines to paper properties (Luukko and Paulapuro, 1997; Alince et al., 2001)

Attribution	Physical strength	Light scattering coefficient
Fibril-like fines	++++*	-**
Flake-like fines	+	++++

*: Positive effect
**: Negative effect

SEM image analysis

Collapsibility and fiber bonding

The Form Circle (*FC*) was employed to quantitatively measure the collapsibility of EW and LW fibers in handsheets. Lower *FC* value indicates higher collapsibility. Due to their thin cell wall fibers, the EW handsheets collapsed more (*FC* = 0.45) than the thick-walled LW (*FC* = 0.63), and the MIX handsheet lay between (*FC* = 0.56).

The SEM image analysis (*Figs 9* and *10*) indicate that EW fibers show better conformability and collapsibility than LW fibers. Thus, the former has better fiber bonding than the latter due to its higher potential in bonding surface area. While the LW fibers (*Figs 9* and *10*) have a large amounts of fibrils, which also favours the fiber bonding.

This finding reveals that EW and LW fibers have their own distinct advantage in relation to the inter-fiber bonding. Although EW fibers have less fibrillations, they have thinner cell wall and, therefore, higher collapsibility and conformability, which are useful for fiber bonding. On the other hand, despite their thick cell-wall, LW fibers are more readily fibrillated or developed during refining, which also benefit fiber bonding. The shortcoming of the EW fiber is their lower fibrillation while that for the LW fiber is its poor conformability.

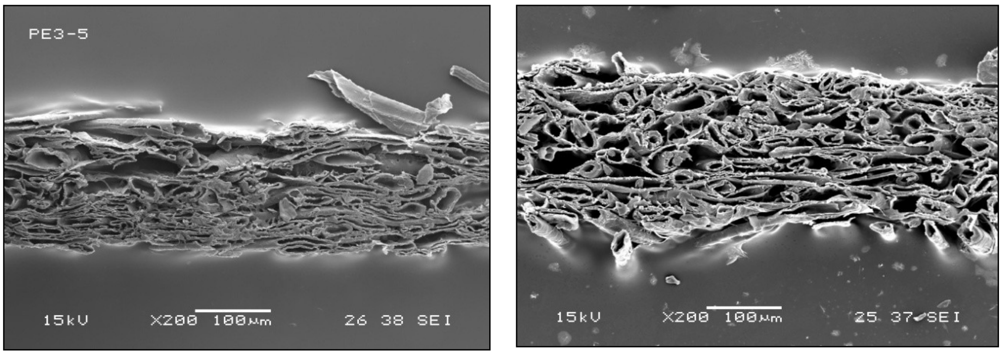

Fig 9. SEM micrograph showing a cross-section of EW (Right) and LW sheet (Left)

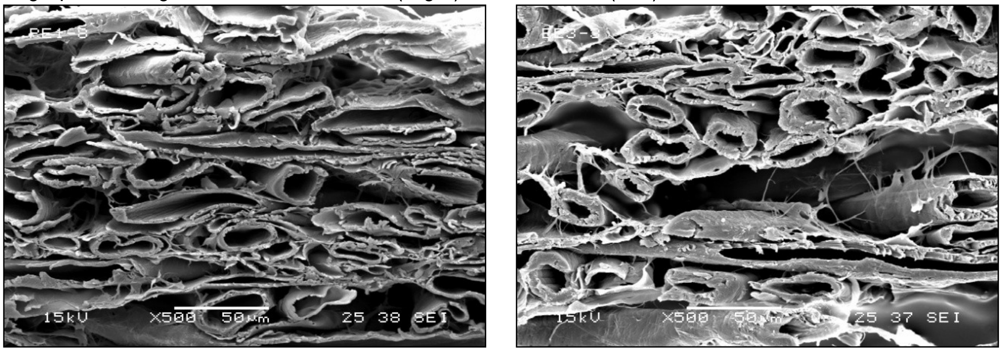

Fig 10. SEM micrograph showing fiber bonding of EW (Right) and LW sheet (Left)

Twist angle

The twist angle analysis showed the LW fibers (β = 11.3) had higher twist angle than those of EW (β = 3.9). In the mixed furnish, which contained LW and EW fibers, the twist angle (β = 10.1) was greater than that for EW fibers but not significantly lower than that for LW fibers. This is because LW fibers are stiffer than thin-walled EW fibers, and have less conformability and more twists than the latter. Owing to their less twists, the EW pulps have higher sheet density than that of EW sheet, as indicated in *Fig 2*.

Conclusions

The morphological differences of EW and LW fibers influence the papermaking characteristics of the resulting pulps, namely the physical and optical properties. For a given freeness, thanks to their better fiber conformability, the fibers of EW whole pulps produce handsheets with higher sheet density, lower roughness and porosity than those of LW pulps. Mainly due to highly fibrillated fibers and fibril-rich elements in the fines, the fibers of LW whole pulps yield handsheets with better physical strengths, such as tensile, burst, and tear indices when compared to the EW counterparts. On the other hand, the EW pulps show higher light absorption coefficient because they have higher lignin content when compared to the LW pulps. However, EW pulps have better light scattering coefficient than LW pulps because the fines in EW pulps contain more flake-like particles which increase the scattering of light in the sheet structure. In the fiber network, the thin-walled EW fibers have better collapsibility and conformability, rending the sheets with higher density. While the thick-walled LW fibers produce sheet with higher bulk and have greater fiber twists and fibrils in the network.

Acknowledgements

The authors would like to acknowledge the financial support from the Natural Science and Engineering Research Council of Canada (NSERC).

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Manuscript received April 4, 2012
Accepted June 20, 2012