PULP AND FIBER CHARACTERIZATION OF WHEAT STRAW AND EUCALUPTUS PULPS - A COMPARISON

Sanchuan Guo,[a] Huaiyu Zhan,[a] Chengfeng Zhang,[a] Shiyu Fu,[a] Anette Heijnesson-Hultén, *[b] Jiri Basta,[b] and Thomas Greschik [b]

The response to refining of wheat straw and eucalyptus pulps as well as the relationships between refining, fiber properties, and paper properties are described in this paper. Pulps were bleached applying different bleaching sequences and thereafter refined to varying degrees. Pulp and fiber properties were investigated and set into relation to the final sheet properties. The results show that wheat straw pulps respond to refining more easily than eucalyptus pulps and that the differences are due mainly to morphological and ultrastructural differences as well as fines content and xylan content. The development of strength properties of the different pulps was found to be strongly correlated to the number of dislocations, i.e. weak points in the fiber wall, as well as to the morphological appearance of the pulp fibers after refining. A higher initial number and a faster development of dislocations together with the creation of large amounts of fines explain the slower and lower development of strength properties of wheat straw pulps than of eucalyptus pulps. Removal of fines from wheat straw pulps improved not only the drainability of the pulp suspension but also the mechanical and optical sheet properties. This indicates that the fines in the wheat straw pulps act mainly as filler with low bonding properties. The fact that fractionated D(EOP)D wheat straw pulps can deliver good mechanical sheet properties at very good drainability with no or only minor refining is very interesting when evaluating the potential of replacing or partially replacing eucalyptus with domestic Chinese raw materials in furnishes for production of different paper products.

Keywords: Bleaching; Bleached pulps; Wheat straw; Eucalyptus; Fiber properties; Sheet properties; Dislocations; Fiber charge; Fines; Pulp properties; Fiber dimensions; Refining; ESEM.

*[a]State Key Laboratory of Pulp & Paper Engineering, South China University of Technology, Guangzho 510640, China; [b]Eka Chemicals AB, Sweden; *Corresponding author: anette.heijnesson-hulten@akzonobel.com*

INTRODUCTION

Although wood is the main raw material for paper production, non-wood plants are very important raw materials in many countries where wood is not available in sufficient quantities to meet the demand for pulp and paper. In China, non-wood plants account for about 20% of the raw material used for paper and paperboard manufacture. The explosion of paper manufacturing in China in recent years shows no signs of abating, and this has created an urgent need for research aimed at improving the present processes and bleaching technologies and also for using raw materials efficiently. In this paper, wheat straw fibers are compared with eucalyptus pulp fibers from a fiber point of view as well as with the regard to the effect of fiber properties on sheet properties. This is done to investigate the possibility of wholly or partially replacing eucalyptus with wheat straw pulps, particularly in uncoated papers.

Refining or beating of pulp fibers is an important factor in the papermaking process, and thus also for the final paper quality. The main purpose of refining is to obtain a higher sheet strength resulting from well bonded fibers. A few investigations have been carried out in order to determine the optimum refining conditions for non-wood pulp, especially bamboo pulps (Subrahmanyam et al. 2000; Wai and Murakami 1983; Rao et al. 1978; Mista 1975). It is generally concluded that non-wood fibers respond to refining more easily than wood fibers. The reason for the difference is not fully understood, although morphological and ultrastructural differences as well as differences in fiber dimensions, fiber classification, chemical composition, and initial Schopper-Riegler value certainly play an important role.

The aim of this investigation is to look more closely at the relationship between refining, fiber properties and paper properties for wheat straw and eucalyptus pulps. For this purpose, wheat straw and eucalyptus pulp were bleached applying different bleaching sequences and thereafter refined to different degrees. Pulp and fiber properties were investigated and set into relation to the final sheet properties.

EXPERIMENTAL

Pulp Raw Material and Bleaching

Unbleached soda-AQ wheat straw pulp was supplied by the Quanlin Pulp and Paper mill in the Shandong province in China. The wheat straw pulp was washed and thereafter bleached using CEH, D(EOP)D and DQP bleaching sequences as described by (Greschik et al. 2008). The eucalyptus chips came from the Leizhou Forestry Bureau (Guangdong, P.R.C) and were from a hybrid of *Eucalyptus Grandis* and *Eucalyptus Camaldulensis*, 6 years old. The chips were screened and air-dried. The knots and bark were removed prior to cooking, and the homogenized selected chips were stored at about 90% dry content. Kraft pulping of eucalyptus chips was carried out in a modified U.S. M/K609-2-1 digester controlled by a computer. The cooking conditions applied were: active alkali charge 23% (as NaOH), sulfidity 25%, wood to liquor ratio 1:4, temperature 165^{o}C, time to the cooking temperature 125 min, and time at the cooking temperature 120 min. After cooking, the pulp was thoroughly washed. The washed pulp was defibrated and then screened on a flat screen with 0.2 mm wide slots. The accept pulp was dewatered in a centrifuge and then homogenized. Two bleaching sequences were applied for the eucalyptus pulp, CEH and O(DQ)P, and the conditions used are given in Table 1. After each bleaching treatment, the pulp was thoroughly washed with deionized water.

Refining and Analytical Methods

All the pulp samples were refined in a laboratory PFI-mill at SCUT. Handsheets (60 g/m^2) were prepared with white water circulation (8 circulations prior to sheet preparation). Schopper-Riegler drainability and mechanical and optical properties of the paper sheets were determined according to standard ISO and SCAN test methods. Fiber dimensions and fiber defects (shape factor, number of kinks and segment length) were measured using the FiberMaster at STFI-Packforsk, Sweden. Fiber dislocations were determined using HCL-treatment (Ander et al. 2008). The content of carbohydrates was determined according to Dahlman et al. (2000). Morphological properties of pulp, fibers, and fine material were investigated by Environmental Scanning Electron Microscopy (ESEM). The samples were freeze-dried prior to ESEM investigations. The content of fines in the wheat straw pulp samples was determined as described in SCAN CM 66:0, except that a smaller amount of pulp was used (0.2g instead of 0.5g) and there was more deionized water (5-10 liters instead of 2.5 liters).

Table 1. Bleaching Conditions used for the Eucalyptus Pulp

Stage	Chemicals (%)	Temp. (℃)	Cons. (%)	Time (min)
C	4.2 act.Cl.	25	3.5	60
E	2.1 NaOH	60	10	60
H	2.1 act.Cl.	40	10	120
O*	2.0 NaOH 0.2 $MgSO_4$	100	10	60
(DQ)	2.0 act.Cl. 0.2 DTPA	60	10	45
P	1.2 H_2O_2 1.0 NaOH 0.05 $MgSO_4$	90	10	240

*O stage: 0.5 MPa

Table 2. Basic Properties of the Pulp Samples

Pulp	Kappa Number	Viscosity (mL/g)	Brightness (%ISO)
Wheat straw			
Unbleached	14.3	999	37.1
CEH	0.91	569	82.4
D(EOP)D	0.81	957	82.4
DQP	2.59	966	81.5
Eucalyptus			
Unbleached	17.1	1023	36.4
CEH	n/a	438	82.9
O(DQ)P	n/a	646	84.0

n/a: not available

RESULTS AND DISCUSSION

The results of the investigation are divided into three different parts. The first part deals with the response of the fibers to refining, the second part with the effect of fiber properties on paper properties, and the third part with the effect of fractionation of wheat straw pulps.

Impact of Pulp and Bleaching Sequence on the Response to Refining

Figure 1 shows that the two pulps differed totally from each other in their response to refining. The initial Schopper Riegler value for the bleached wheat straw pulps was very high, between 31 and 45 SR, compared to values between 18 and 22 SR for the eucalyptus pulps. The high SR values for the wheat straw pulp coincide with a very high content of fines, which was about 35%, and increased further to 47% during refining in the PFI-mill for 2000 revolutions. The extremely rapid development of the Schopper Riegler values observed for the wheat straw pulps compared to the eucalyptus pulp, is most probably due to creation of fines, i.e. a breakdown of the parenchymatous groups (*cf* Fig. 8). However, another or complementary explanation of the different response to refining between wheat straw and eucalyptus is their different chemical compositions, i.e a higher content of hemicellulose, especially xylan, in the wheat straw pulps than in the eucalyptus pulps.

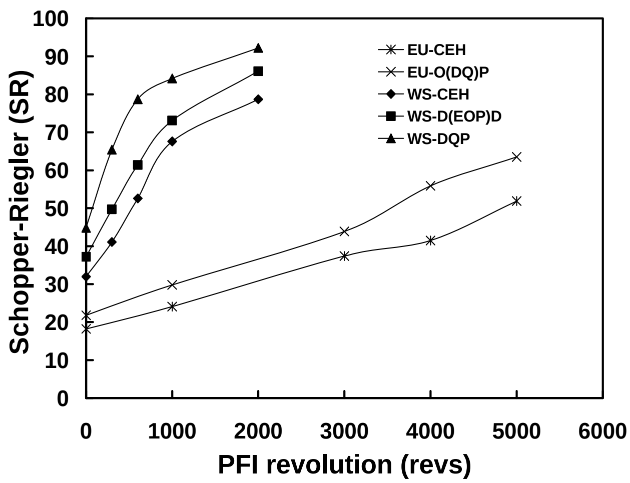

Fig.1. The effect of PFI refining on the Schopper Riegler

The presence of xylan is known to cause distinct swelling of the fiber walls and to facilitate response of the pulp to refining. In Fig. 1 it can also be seen that the response to refining differed between the bleaching sequences, i.e. the SR values of the CEH bleached pulps were lower than for the other bleached pulps. These differences may be explained by the different swelling behavior of the pulps. Complementary experiments on the CEH, D(EOP)D, and DQP wheat straw pulps showed that the WRV values of these pulps increased during refining with 13, 19 and 31 %, respectively.

Impact of Fiber Properties on Paper Properties

The results in Figs. 2-4 show that the development of strength properties (breaking length, burst and tear indexes) of the eucalyptus pulps was more pronounced and faster than that of the wheat straw pulps. When comparing Fig. 1 with Figs. 2-4 it can be seen that the sharp increase in SR values during refining of wheat straw pulps was not associated with any large increase in the breaking length and burst index values. On the other hand, on eucalyptus pulps, a modest increase in the SR values was accompanied with large increases in the corresponding pulp strength properties. This may imply that when refining eucalyptus pulps, internal and external fibrillation occur to a greater extent, and thus stronger fiber-fiber bonding is obtained in the paper sheet.

Table 3. Relative Carbohydrate Compositions (%) of the Pulp Samples (Normalized values to give 100%)

Pulp	Wheat straw			Eucalyptus	
	CEH	D(EOP)D	DQP	CEH	O(DQ)P
Xylose	25.1	25.8	25.9	15.9	14.7
Glucose	73.0	73.3	71.5	83.5	84.2
Mannose	0.2	<0.1	0.4	0.4	0.5
Arabinose	1.5	0.9	1.9	<0.1	<0.1
Galactose	0.2	<0.1	0.3	0.2	0.1
HexA	<0.1	<0.1	<0.1	<0.1	0.5
4-O-Me-glcA	<0.1	<0.1	<0.1	<0.1	<0.1

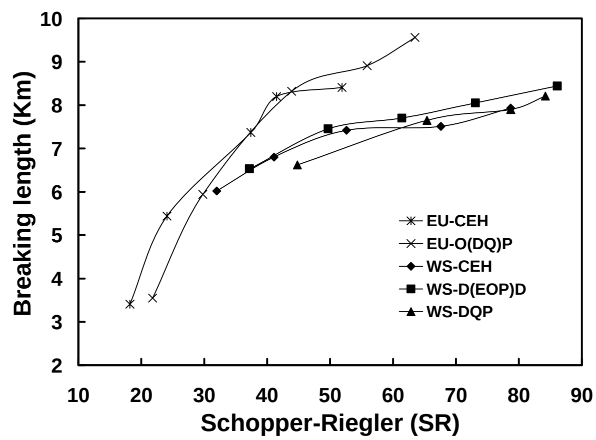

Fig. 2. The effect of PFI refining on breaking length

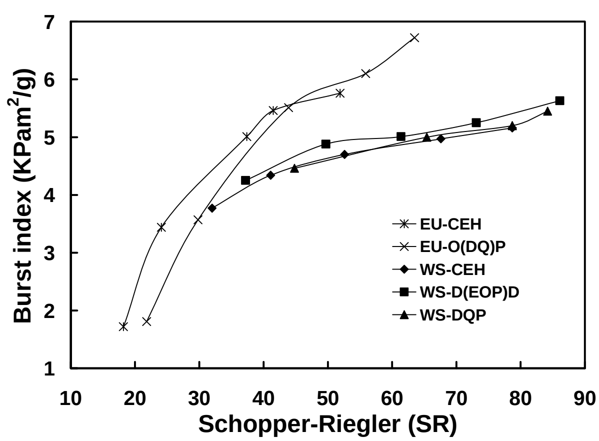

Fig. 3. The effect of PFI refining on burst index

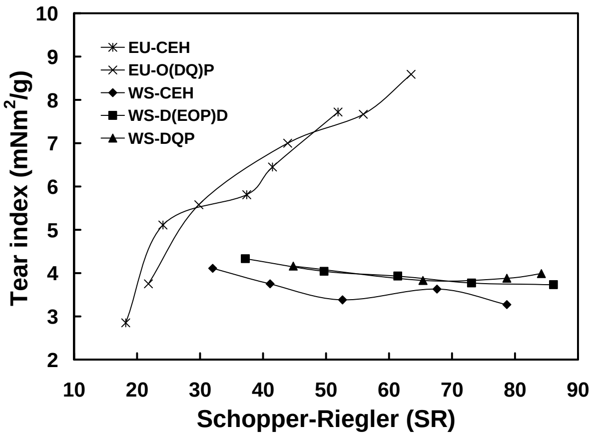

Fig. 4. The effect of PFI refining on tear index

ESEM observations of the samples indicate a higher degree of external fibrillation of eucalyptus pulps than of wheat straw pulps refined to the same Schopper Riegler value (Fig. 5). Furthermore, the greater external fibrillation of eucalyptus pulps is supported by the fact that the surface charge of the eucalyptus pulps increased more rapidly than that of wheat straw pulps (data not shown). It has been pointed out that differences in fiber dimensions are an important factor influencing the response to refining as well as the strength properties. In our study, the average fiber dimensions, i.e. length weighted fiber length and fiber width, of wheat straw fibers resemble those of eucalyptus pulps (Table 4). However, the wheat straw pulps were much more heterogeneous in character, with a considerably lager amount of fines than the eucalyptus pulps.

When pulp fibers are subjected to compression and/or mechanical stresses, as for instance in pulping, bleaching, or refining, fibers may be damaged, i.e. dislocations may be introduced into the fibers, and this certainly influences the strength properties. Figure 6 shows the development of dislocations/weak points in the fibers during refining for the different pulp samples. It can be noted that the initial number of weak points/dislocations was higher and that the number increased more rapidly during refining for wheat straw fibers than for eucalyptus pulps. These results may explain the lower and slower development of the strength properties of paper sheets prepared from wheat straw pulps than in that from eucalyptus pulps. Furthermore, pulps bleached applying the CEH standard showed more dislocations than when other bleaching sequences were applied.

The number of kinks per fiber is also a measure of fiber defects, and Table 4 shows that the kink value was lower for eucalyptus pulps than for the wheat straw pulps. However, during refining both the number of kinks per mm fiber and the kink angle decreased in all the pulp samples, indicating fiber straightening. The light scattering ability of the eucalyptus pulps was about 20 unites higher than that of the wheat straw pulps. The high content of fines in the wheat straw pulp certainly play a role in this matter, although other properties such as fiber wall thickness and fiber flattening, etc., are probably more important factors.

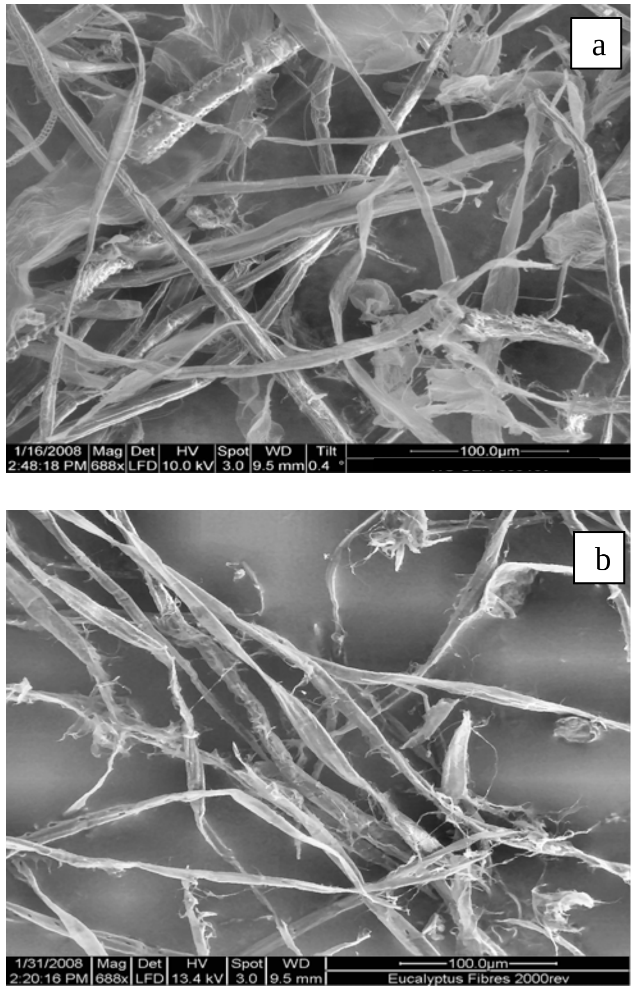

Fig. 5. Morphological appearance of fibers from a) wheat straw pulp and b) eucalyptus pulp refined to ~45 SR.

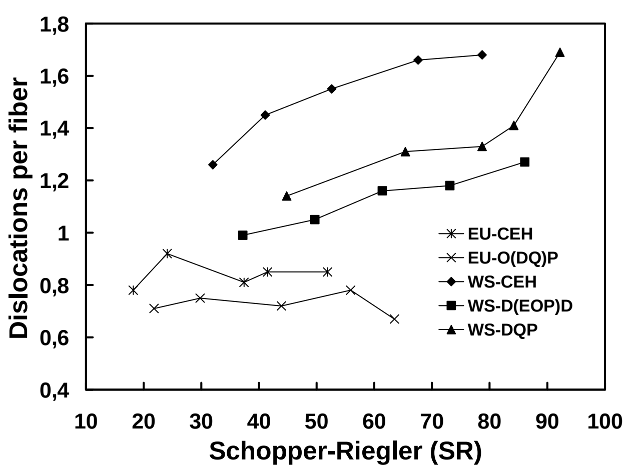

Fig. 6. The effect of PFI refining on dislocations

Table 4. The Fiber Dimension of Pulp Samples

Pulp/revs.	Fiber dimensions		Number of kinks		Kink
	Length weighted (mm)	Width (µm)	Per fiber	Per mm	angle (º)
Wheat straw					
CEH					
0	0.66	15.3	0.53	0.74	56.9
300	0.67	15.1	0.48	0.65	55.7
600	0.68	14.7	0.46	0.62	54.3
1000	0.68	15.1	0.45	0.60	55.9
2000	0.68	15.1	0.43	0.58	55.9
D(EOP)D					
0	0.66	14.9	0.51	0.70	56.6
300	0.70	14.8	0.48	0.63	55.2
600	0.69	15.1	0.44	0.59	55.2
1000	0.69	15.4	0.43	0.58	55.6
2000	0.68	15.4	0.44	0.59	56.7
Eucalyptus					
CEH					
0	0.67	14.4	0.31	0.47	52.2
4000	0.64	14.2	0.27	0.42	51.5
O(DQ)P					
0	0.67	15.1	0.32	0.49	52.7
3000	0.65	14.5	0.24	0.37	50.4

Effect of Fines on Pulp and Paper Properties

The content of fines in wheat straw pulps seems to play an important role both for the drainability of the pulp suspension and for the sheet properties. Therefore, wheat straw pulp samples were fractionated and thereafter analyzed for their properties. The content of fines (<76µm) in the wheat straw pulps was relatively high, between 35 and 47%, depending on degree of refining, compared with a content of between 8 and 10% in eucalyptus pulps (Mohlin and Hornotowska 2006). Unlike with wood pulps where fines usually contribute to pulp strength properties a removal of fines from wheat straw pulps by fractionation improved the strength properties of the paper sheets (Table 5) as well as the optical properties. This is in agreement with earlier reported results for wheat straw (Ljusgren et al. 2006). The difference in bonding capacity and thus in the strength contribution of the fines from wheat straw and eucalyptus pulps might be explained by the different morphological appearance of the fines (Fig. 7). The fines from wheat straw pulps consist mainly of vessels and epidermal cells whereas the eucalyptus fines consist of broken fiber parts, fibrils and material from the fiber wall. The appearance of wheat straw fines indicates that this fraction acts predominately as filler with limited bonding properties. When the fines were removed from the wheat straw pulps, the Schopper Riegler number decreased significantly and thus the drainability of the pulps increased (see Fig. 8).

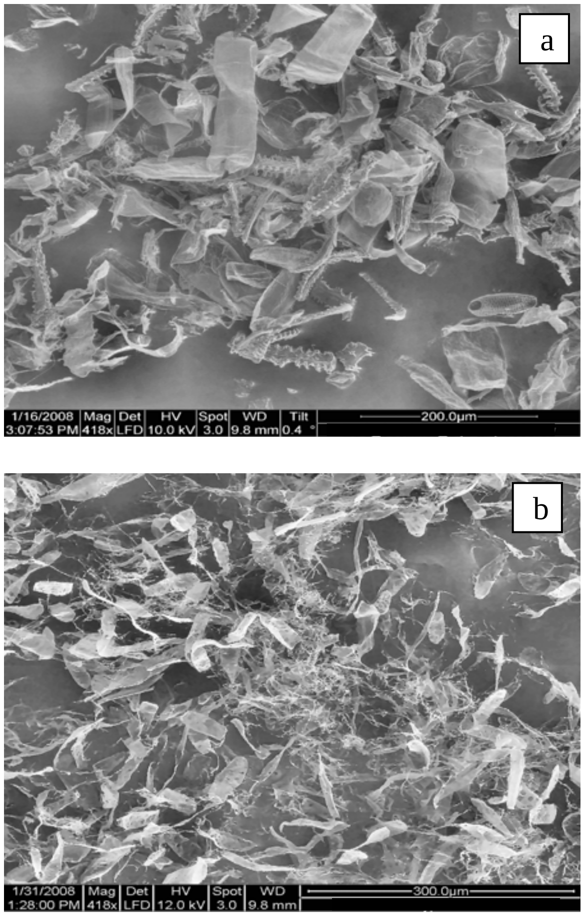

Fig. 7. Morphological appearance of fines from a) wheat straw and b) eucalyptus pulps

Table 5. The Properties of Fractionated* and Unfractionated Wheat Straw Pulp Samples

Pulp	Burst index (kPam^2/kg)	Break length (km)	Tear Index (mNm^2/g)	Light Scat. Coef (m^2/kg)
CEH				
0	3.77	6.02	4.11	27.0
0*	4.00	6.18	4.26	28.9
600	4.70	7.42	3.38	17.2
600*	4.71	7.74	3.71	21.3
D(EOP)D				
0	4.25	6.53	4.33	26.0
0*	4.66	6.87	5.24	27.6
300	4.88	7.45	4.04	21.6
300*	5.04	7.85	4.89	23.1

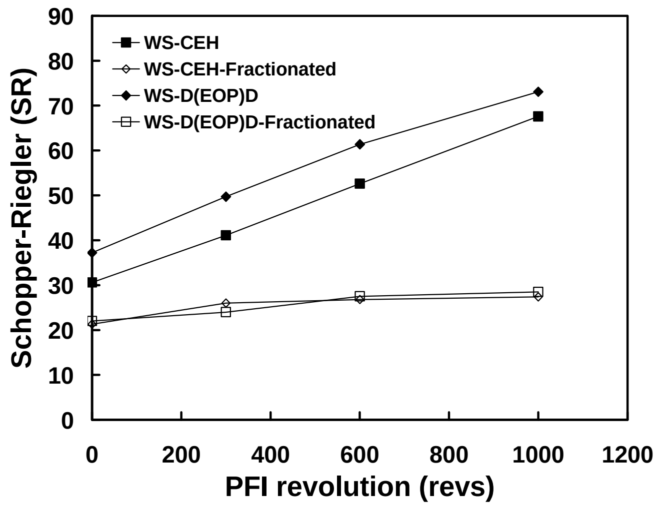

Fig. 8. The effect of removing fines on the Schopper Riegler value

CONCLUSIONS

In comparison with eucalyptus pulps, wheat straw responds more easily to refining. The differences in response to refining are due mainly to morphological and ultrastructural differences, as well as fines content and xylan content.

The slower and lower development of strength properties of wheat straw pulps compared to that of eucalyptus is explained by:

a) higher initial number and a faster development of dislocations, i.e. weak points in the fiber wall
b) creation of fines with limited bonding properties

Wheat straw pulps contain a lot of fines, between 35 and 47%, depending on Schopper-Riegler value and the removal of these fines leads to an improvement in the:

a) drainability of the pulp suspension
b) mechanical and optical sheet properties

The fact that fractionated D(EOP)D wheat straw pulps can deliver good mechanical sheet properties at very good drainability with no or only minor refining is very interesting when evaluating a potential of replacing or partially replacing the eucalyptus with domestic Chinese raw materials in furnishes for production of different paper products

ACKOWLEDGEMENT

Caterina Camerani is gratefully acknowledged for her assistance with ESEM analysis.

REFERENCES CITED

Ander, P., Hildén, L., and Daniel, G. (2008). "Cleavage of softwood kraft pulp fibres by HCl and cellulases," *Bioresources* 3(2), 477-490.

Dahlman, O., Jacobs, A., Liljenberg, A., and Olsson, A. I. (2000). "Analysis of carbohydrates in wood and pulps employing enzymatic hydrolysis and subsequent capillary zone elecrophoresis," *J. Chromatography* 891(1), 157-174.

Greschik, T., Basta, J., Zhang, C., Zhan, H., and Jiang, S. (2008). "Environmental aspects of wheat straw bleaching," *2nd International Papermaking and Environment Conference*, Tianjing, China.

Ljusgren, I., Wiberg, B., Tubek Lindblom, A., and Persson, T. (2006). "Papermaking potential scandinavian softwood pulp together with non-wood pulp," *5th International New Technologies in Non-wood Fiber Pulping and Papermaking Conference*, 5thINWFPPC, Guangzhou, China, 281-286.

Mista, D. K. (2006). "Industrial experiences & problems involved in stock preparation & paper utilizing non-wood fibrous materials," Non-wood Plant Fibre Pulping, Progress Rep. No 6., TAPPI CAR no. 58, 7-22.

Mohlin, U.-B., and Hornatowska, J. (2006). "Fibre and sheet properties of Acacia and Eucalyptus," *Appita Journal* 59(3), 225-230.

Rao, A. R. K., Srinivasan, G., and Maheshwari, H. K. (1978). "Effect of beating on bamboo fibres," *Indian Pulp and Paper*, February-March, 35-46.

Subrahmanyam, S. V., Godiyal, R. D., Sharma, A. K., Janbade, T., and Gupta, H. K., (2000). "Effect of refining energy on the pulp properties of nonwoods," *IPPTA* 12(2), 11-18.

Wai, N. N., and Murakami, K., (1983) "Characteristics of kraft pulp from Burmese bamboo," *International Symposium on Wood Pulping Chemistry*. Tsukuba science city, Japan, 23-27 May, 188-193.

Article submitted: July 17, 2008; Peer review completed: Nov. 17, 2008; Revised version received and approved: May 13, 2009; Published: June 10, 2009.