EFFECT OF WHEAT STRAW FINES ON Z-DIRECTIONAL STRENGTH OF PAPER

PÄIVI P. ROUSU, MIKKO KARJALAINEN,[*] KAJ O. HENRICSON, JOUKO NIINIMÄKI,[*] ISKO KAJANTO and KAJ BACKFOLK

Laboratory of Fiber and Paper Technology, Lappeenranta University of Technology, P.O. Box 20, FI-53851 Lappeenranta, Finland
[*] *Fibre and Particle Engineering Laboratory, Department of Process and Environmental Engineering, P.O. BOX 4300, 90014 University of Oulu, Finland*

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The effect of adding different wheat straw pulp fractions on the z-directional strength of paper made from eucalyptus was studied. A pressure screen and hydrocyclones were used to fractionate wheat straw pulp in order to obtain fractions enriched in different components. The addition of wheat straw pulp and especially the enrichment of components in the hydrocyclone overflows were beneficial for the Scott bond strength and tensile strength properties of the papers. Parenchyma cells seemed to be beneficial for these properties, whereas epidermal cells seemed to have a more neutral impact on the pulp mixture.

Keywords: wheat straw, eucalyptus, Scott bond, fractionation, pressure screen, hydrocyclone

INTRODUCTION

The internal bond strength of paper is an important property, especially for printing papers and carton boards. Strong forces arise in the z-direction in, for instance, offset printing and board converting processes.[1] The z-directional strength of the paper can be influenced in several ways. Out-of-plane strength measures the ability of paper or board to withstand tensile stress in the thickness direction, it is therefore sensitive to the z-directional profile, e.g. density or composition. Fiber orientation in the z-direction has a strong effect on the z-directional strength: a layered structure lowers and an interwoven structure increases the energy required to pull or break fibers from the paper structure.[2]

Z-directional strength correlates well with paper density[3] and factors, such as wet pressing[4-5] or press drying,[2] which affect paper density and probably also affect the z-directional paper strength.

Z-directional strength is improved by chemical modification using additives, such as carboxymethyl cellulose (CMC), galactomannan and starch. Polyelectrolyte treatment and grafting are other routes.[6-14] These additives usually fill the interstices between the components, increase the bonding area and bond strength and are therefore beneficial for z-directional strength. The effects of polyelectrolytes, CMC and grafting are due to an increase in interfiber bonding, giving an increase in bond strength.[7,13-14] Pettersson[11-12] *et al*. and Eriksson[9] *et al*. have shown that polyelectrolyte multilayer treatment of a fiber suspension improves the Scott bond value without any significant change in density. This effect was ascribed to a greater amount of adsorbed starch on the fiber, the adsorbed starch layer conformation and the starch-cellulose boundary. Interfiber bonding and z-directional paper strength can also be affected by changing the hemicellulose content or by using other methods to change the surface charge of fibers, such as enzymatic pulp treatment.[10,15] Galactomannan especially has a high positive impact on the z-directional paper strength when sorbed onto fibers.[10]

Beating or other mechanical treatment usually improves the fiber bond area and hence the z-directional paper strength,[16-17] and this is usually associated with an increase in paper density, bonding degree, fiber flexibility and an increasing amount of fines.[18-19] Beating, which increases external fibrillation, is an efficient treatment to enhance fiber-fiber contacts.[19-20] Both mechanical and chemical pulp fines strongly affect paper properties.[21-22] In general, fines fill interstices between fibers and simultaneously densify the sheet and promote fiber bonding.[23] The bonding potential of chemical pulp fines increases as the size of the particles decreases and also when the raggedness and specific surface area increase.[24] The fines of mechanical pulp also have a positive effect on paper bonding, bond strength, and z-directional strength.[25] Fines are a heterogeneous material consisting mostly of flake- and fibrillar-type particles. Flake-type fines, such as fragments of cell walls (thick lamella and ray cells) do not participate in bonding due to their rigid and inflexible structure.[23] Instead, fibrils (filament-type particles, thin particles of lamella) increase bonding and improve the strength of the paper product. Fines can also be divided into primary and secondary fines. Primary fines are generated in the pulping process and secondary fines in beating.[26] Secondary fines are mostly fibrillar.

Non-wood pulps are generally used without beating and their fines are therefore mostly primary fines and behave partly differently from chemical and mechanical wood pulp fines. For instance, some of the finest fines can be removed from wheat straw pulp without affecting its strength properties, although this has a significant positive impact on dewatering and optical properties.[27] However, to our knowledge, there is very limited information available concerning the effect on paper properties of wheat straw pulp addition.[28-30] In particular, the effects of adding different fractions and components to eucalyptus pulp are relatively unknown. Wheat straw pulp components are usually divided into four classes: fibers, vessels, parenchyma cells and epidermal cells. The stem of wheat straw is build up of the parenchymatous ground tissue with vascular bundles containing the fibers embedded in it.[31] Epidermal cells cover the outer layer of the plant. The fiber length distribution in wheat straw pulp is wide, quite similar to that of softwood pulps, but the arithmetic mean fiber length is much lower. According to Ilvessalo-Pfäffli and Wettestein, the arithmetic mean fiber length is 1.3-1.4 mm and the mean fiber width is 15 µm.[31-32] Vessel elements are up to 1.0 mm long and up to 60 µm wide.[31] Parenchyma cells are thin-walled cells and vary in shape from rod-like to sack-like; the average parenchyma cell in wheat is 0.40 mm long.[31-32] Epidermal cells are elongated and up to 0.5 mm long.[32]

Pulp fractions and treatment of fractions can be used to improve certain strengths. For instance, the z-directional strength of the middle layer of three-ply carton board has been improved by replacing the mixture of chemi-thermomechanical pulp and long fibrous chemical pulp with a fines fraction of beaten birch pulp fractionated in a hydrocyclone.[33] Certain non-wood pulps have a positive impact on the z-directional strength of paper. High z-directional strengths have been reported for furnishes containing bagasse pulp and the fines fraction of bagasse pulp.[34-35] Nevertheless, the actual effect of different wheat straw fractions on the strength-density relationship for pulp mixtures containing eucalyptus needs to be clarified. In particular, there is a lack of knowledge about the effect of cellulose fiber-wheat straw interaction on strength properties.

The purpose of this study was to clarify the effect of adding wheat straw fractions to a eucalyptus furnish on the z-strength properties. High pressure screen and hydrocyclone fractionation were used to enrich different wheat straw pulp components. The fractions obtained were then analysed prior to being added to the eucalyptus furnish. Several pulp and paper properties were measured and microscopic analyses were made to explain the structural and bonding effects of the studied components.

EXPERIMENTAL

Pulp fractionation

A commercial Chinese bleached wheat straw pulp prepared with a soda process and a commercial bleached eucalyptus kraft pulp were used. Both pulps were once dried. The eucalyptus pulp was mill-refined to 27.5 SR. Wheat straw pulp was fractionated into four fractions in order to obtain fractions enriched with different cell types. A diagram of the fractionation procedure is presented in Fig. 1.

Wheat straw sheets were disintegrated in an LC vat pulper at a temperature of 50 °C. The pulp was fractionated first using a Metso FS 03 pressure screen with a smooth perforated screen plate having 200 µm holes. The total mass reject rate (RRm) in pressure screen fractionation was of 60%. The accept fraction of the pressure screen is here referred to as the "fine fraction" and the reject fraction as the "coarse fraction". The fine fraction was then fractionated using a 2-inch Mozley C124 hydrocyclone into overflow "Af" and underflow "Rf" fractions with a total mass reject rate of 51%, and the coarse fraction was fractionated with a 60-mm GL&V Celleco Cleanpac 270 hydrocyclone into overflow "Ac" and underflow "Rc" fractions with a total mass reject rate of 45%. The

Af and Ac fractions were thickened by settling and filtration using a 0.02-mm filter cloth. The proportions of the wheat straw pulp fractions were: Ac = 32.6%, Rc = 27.0%, Af = 19.7% and Rf = 20.7%.

Analyses of the fractions

The compositions of the pulp fractions were analyzed. Cell types were analyzed according to ISO 9184-1-7, using Fiber Atlas[31] for identification. Over 5000 cells were calculated in each sample. All cells cutting the calculation line were classified. The classes include the following cell types: "fibers": fibers and tracheids; "vessels": different types of vessels including annular, spiral and net-like cells; "parenchyma cells": cells from ground parenchyma including round-ended rod-like and sack-like cells, and "epidermal cells": cells from the outer surface of the plant including hair cells. Particle-based proportions were calculated and presented.

The fiber dimensions of the pulp samples were determined with a Lorenzen &Wettre FiberTester.

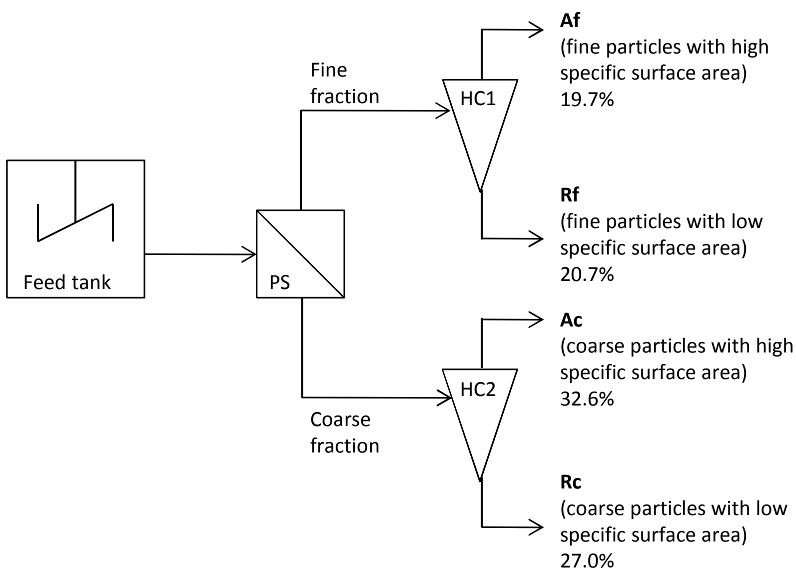

Figure 1: Fractionation procedure used in the study (PS: pressure screen, HC1: hydrocyclone used for the fine fraction and HC2: hydrocyclone used for the coarse fraction)

Table 1
Experimental design showing compositions of furnishes

		Euca, %	Ac, %	Rc, %	Af, %	Rf, %
Exp 1	Ref, Euca	100	–	–	–	–
Exp 2	Ref, 10%	90	3.26	2.70	1.97	2.07
Exp 3	Ac, 10%	90	10	–	–	–
Exp 4	Rc, 10%	90	–	10	–	–
Exp 5	Rf, 10%	90	–	–	–	10
Exp 6	Af, 10%	90	–	–	10	–
Exp 7	Af, 30%	70	–	–	30	–
Exp 0	Original	–	32.6	27.0	19.7	20.7

Euca = eucalyptus pulp; Wheat straw pulp fractions: Ac = reject of pressure screen and overflow of the subsequent hydrocyclone; Rc = reject of pressure screen and underflow of the subsequent hydrocyclone; Af = accept of pressure screen and overflow of the subsequent hydrocyclone; Rf = accept of pressure screen and underflow of the subsequent hydrocyclone

Experimental design

Refined eucalyptus pulp was the main component in the furnish and it was used as a reference for the test series. Part of the eucalyptus pulp (10% or 30%) was replaced with wheat straw pulp or a wheat straw pulp fraction. The experimental design is shown in Table 1.

Laboratory paper sheets were prepared according to ISO 5269-1 – Part 1 (Conventional sheet-former method) using the original pulps and pulp mixtures. The targeted grammage of the sheets was 60 g/m^2. A cationic polyacrylamide retention aid (Percol 63, BASF) was used in sheet preparation. After preliminary tests, 0.03% was selected as the most suitable dosage level and charge levels were not monitored thereafter in the sheet preparation.

Pulp and paper properties

The following paper properties were evaluated from laboratory hand sheets: SR number (ISO 5267-1), drainage time in a sheet mold (T = 20 °C), density (SCAN-P 7), tensile index, elastic modulus, tensile energy absorption, tensile stiffness and tensile strain (SCAN-P 38:80), tear index (SCAN-P 11:96), Scott bond strength (T 569 pm-00), roughness and air permeability (SCAN-P 21:67), bending stiffness (resonance method) (ISO 5629) and optical properties (ISO 2470, ISO 9416, ISO 9416, ISO 2471).

SEM micrographs

Laboratory paper sheets were imaged by scanning electron microscopy (SEM), using a JEOL 5800 SEM with 10 kV accelerating voltage and 12 mm working distance. The samples were coated with gold before the examination.

RESULTS

Wheat straw pulp fraction analysis

Wheat straw pulp was fractionated into four different fractions: Ac, Rc, Af, and Rf, where the subscript “c” refers to the coarse fraction after the pressure screen and “f” to the corresponding fine fraction. The cell compositions in the fractions are shown in Table 2 and the fiber dimensions of the original pulps and pulp fractions are shown in Table 3.

The results in Table 2 show that the cell compositions in the fractions varied significantly. Higher contents of parenchyma and epidermal cells were found in the pressure screen accept fraction (Af and Rf) than in the reject fraction, which contained more fibers (Ac and Rc). The hydrocyclone overflows (Ac and Af) contained more fibers and vessels than the hydrocyclone underflows, which contained more epidermal and parenchyma cells.

The fiber dimensions shown in Table 3 demonstrate that the length-weighted fiber length of eucalyptus and wheat straw pulps were at a similar level, although the values for the wheat straw pulp were slightly higher. The arithmetic mean fiber lengths of the wheat straw pulp and of the fractions were all significantly lower than that of the eucalyptus pulp. The mean shapes of all the samples were of the same order of magnitude.

Table 2
Compositions of wheat straw pulp fractions represented as particle-based proportions

	Ac	Rc	Af	Rf
Fibers, %	76 ± 5%	75 ± 5%	50 ± 5%	28 ± 5%
Vessel elements, %	7 ± 2%	3 ± 1%	4 ± 1%	3 ± 1%
Parenchyma cells (etc.), %	13 ± 3%	14 ± 3%	27 ± 5%	33 ± 5%
Epidermal cells (etc.), %	4 ± 1%	8 ± 2%	19 ± 3%	36 ± 5%

For the meaning of Ac, Rc, Af and Rf, see Table 1

Table 3
Fiber dimensions of original pulps and pulp fractions

	Euca	Original WS	Ac	Rc	Af	Rf
L(n), mm	0.605	0.494	0.528	0.525	0.362	0.361
L(l), mm	0.688	0.711	0.751	0.730	0.460	0.446
Relation of fines and fibers*	5.9	50.4	30.5	26.2	111.8	100.4
Mean shape, %	90.1	86.9	87.2	89.4	86.0	86.0

L(n) = arithmetic mean and L(l) = length weighted mean; values measured by optical fiber analyzer. For the meaning of Ac, Rc, Af and Rf, see Table 1

*In detection, the pixel size is 10 μm; an object must cover at least 5 pixels and have at least 4:1 length to width ratio and 50% shape factor to be counted as a fiber. All fines that are detected are counted. Fines are displayed as length weighted

Paper properties

Paper sheets were prepared using refined eucalyptus pulp as a reference pulp. 10 wt% or 30 wt% of the eucalyptus pulp was replaced by wheat straw pulp or fractions of wheat straw pulp as shown in Table 1. The physical properties of the pulp mixtures are shown in Table 4 and Figures 2-4.

The addition of wheat straw pulp improved the values of Scott bond strength of eucalyptus-based furnishes (Fig. 2a). The most effective additive was the Af fraction. At a 10% addition, the Scott bond strength of the eucalyptus-based furnish increased by more than 25% and at a 30% addition by almost 70%. However, the Af fraction had poor drainage properties measured as SR number (Fig. 2b), and this may restrict the utilization of this fraction.

In general, the drainage properties measured as SR number of the furnish of wheat straw pulp can be improved by reducing the fractions that contain a high proportion of fine parenchyma cells. Here, larger amounts of the Rf fraction (10%) in the furnish did not significantly change the SR value, whereas the Af fraction (10%) increased the SR number from 27.5 to 34.0. This effect cannot solely be ascribed to the parenchyma cells, but is probably a combined effect of dissolved species and the total amount of fines and cells.

The air permeability values of wheat straw pulp and all its fractions were lower than those of the eucalyptus reference pulp (Fig. 3). In particular, the Af fraction densified and consolidated the structure of paper, while the Rc fraction had the least effect.

Table 4
Physical properties of paper made from furnishes containing pure eucalyptus pulp and mixtures of eucalyptus and wheat straw pulp and wheat straw pulp fractions Ac, Rc, Af, and Rf

	Ref, Euca	WS, 10%	Ac, 10%	Rc, 10%	Rf, 10%	Af, 10%	Af, 30%
Scott Bond, J/m^2	279	315	305	266	277	351	472
Tensile index, Nm/g	57.28	60.18	60.80	58.54	54.45	60.47	66.31
TEA, mJ/g	1400	1510	1550	1440	1280	1630	1810
Breaking strain, %	3.29	3.39	3.45	3.32	3.16	3.63	3.64
Tensile stiffness index, kNm/g	7.03	7.19	7.2	7.15	6.78	7.06	7.45
Tear index, mNm^2/g	7.38	7.31	7.16	6.97	6.77	7.00	6.09
SR number	27.5	27.5	27.5	30.0	29.0	34.0	54.5
Air permeability, Bendtsen, mL/min	1033	679	787	990	883	513	87
Roughness (up side), Bendtsen, mL/min	531	517	516	522	509	500	488
Density, kg/m^3	720	733	730	715	715	744	782
Brightness, %	87.35	84.41	84.52	86.57	83.6	83.15	77.11
Opacity, %	77.31	77.53	78.56	77.26	80.05	78.79	81.08
s, m^2/kg	38.25	37.52	37.42	37.74	39.82	37.23	36.26
k, m^2/kg	0.16	0.24	0.25	0.19	0.30	0.29	0.56

Ref. = reference pulp; WS: original wheat straw pulp; For the meaning of Ac, Rc, Af and Rf, see Table 1

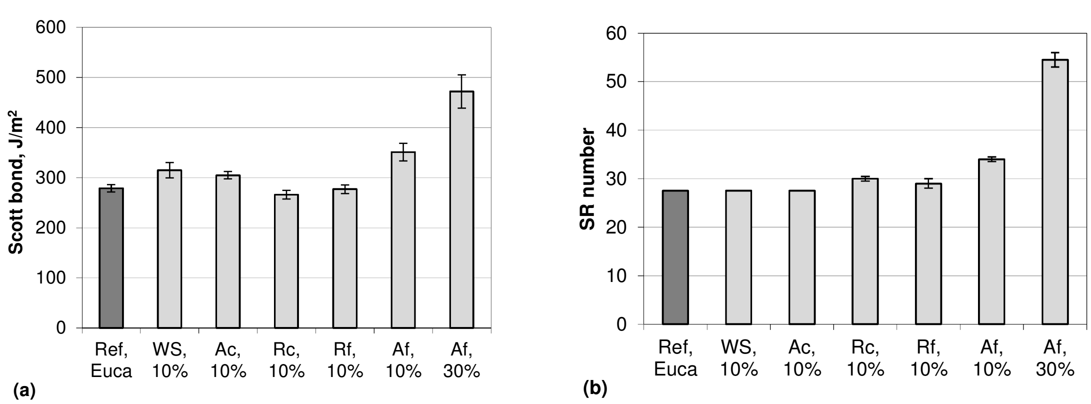

Figure 2: Scott bond values (a) and SR numbers (b) of papers made from furnishes composed of eucalyptus and wheat straw pulp and fractions of wheat straw pulp (Ref = pure eucalyptus (Euca) pulp; other samples contain eucalyptus pulp that is substituted for a given percentage of wheat straw pulp or pulp fraction; WS = original wheat straw pulp; for the meaning of Ac, Rc, Af and Rf, see Table 1)

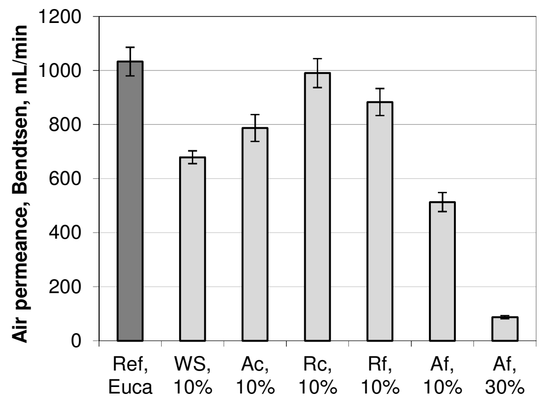

Figure 3: Air permeability of papers made from furnishes composed of eucalyptus and wheat straw pulp and its fractions (Ref = pure eucalyptus pulp; other samples contain eucalyptus pulp that is substituted for a given percentage of wheat straw pulp or pulp fraction; WS = original wheat straw pulp; for the meaning of Ac, Rc, Af and Rf, see Table 1)

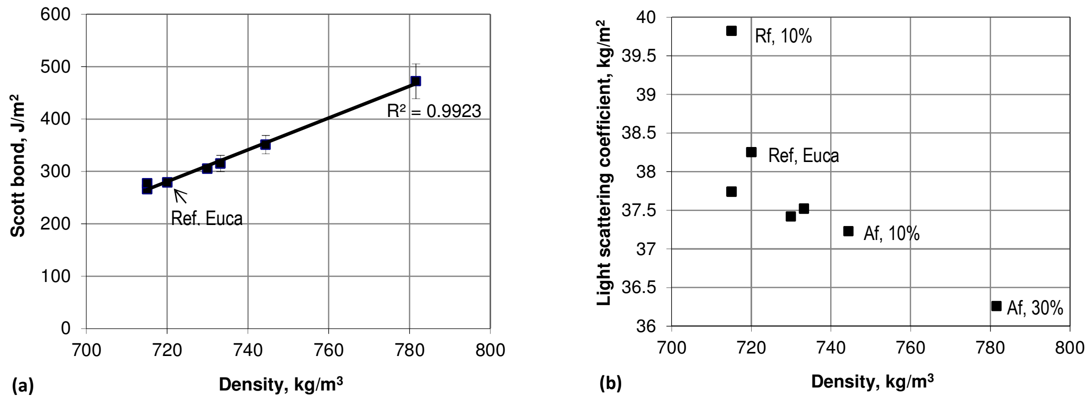

Figure 4: Scott bond *vs* density (a) and light scattering *vs* density (b) of papers made of furnishes containing mixtures of eucalyptus pulp and wheat straw pulp fractions

The wheat straw pulp underflows from the hydrocyclones gave papers with lower densities, while overflows gave papers with higher densities than the pure pulps (Table 4). The Scott bond value correlated well with the paper density (Fig. 4a), but there was no linear relationship between light scattering coefficient and density (Fig. 4b and Table 4). The light scattering power of the fiber fractions was at the same level as that of the reference, but the fine fractions showed significant differences in light scattering coefficient; the Af fraction being slightly lower than the reference and the Rf fraction significantly higher. The paper opacity did not decrease as a result of the increase in density, although the positive increase in opacity due to the fines fractions was associated with a slightly lower brightness for the wheat straw pulp (Table 4). The results in Table 4 show that wheat straw pulp and all the other fractions, apart from Rf, had a positive effect on the tensile index, tensile stiffness and tensile energy absorption of the eucalyptus and wheat straw pulp mixtures. Wheat straw pulp tended to reduce the tear index in all cases.

SEM micrographs of the paper sheets are shown in Fig. 5. SEM micrographs of the paper sheets show that wheat straw pulp overflows from the hydrocyclones (Af and Ac) give much better bonding than the underflows (Rf and Rc). The paper sheet containing the Rf fraction has the highest epidermal cell content, which did not seem to bond as well as parenchyma cells to the fibers.

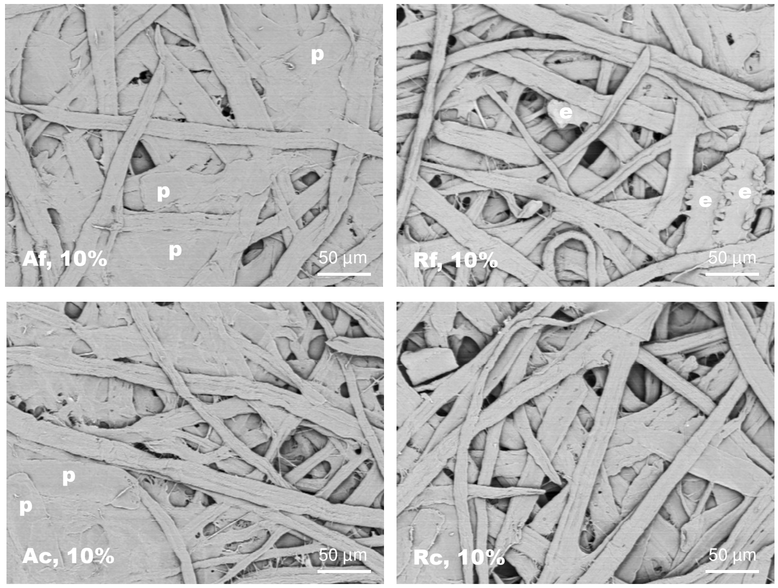

Figure 5: SEM Micrographs of paper sheets containing eucalyptus pulp and 10% of different wheat straw pulp fractions (e = epidermal cell, p = parenchyma cell)

DISCUSSION

Fractionation sequence

Pressure screen fractionation is based mainly on particle dimensions,[36] and in the present study the pressure screen efficiently separated large and small particles as expected (Table 3). Hydrocyclone fractionation is based mainly on specific surface area[36] and it was used to separate vessels from the pressure screen rejects. According to Ilvessalo-Pfäffli,[31] the vessels of wheat straw are thin-walled and have a high specific surface area, and it was therefore expected that they will be enriched in the Ac fraction (Table 2). Epidermal cells have small specific surface area and they therefore ended up in the Rf fraction. The shapes and sizes of parenchyma cells vary strongly and the fractionation of these components is not therefore simple. The efficiency of the fractionation could be possibly improved, if the number of fractionation stages was increased.

Several pulp and paper properties were measured to clarify the nature of the structural and bonding behavior. It was noticed that several eucalyptus-based paper properties benefited from the addition of a wheat straw pulp component. Wheat straw pulp and the hydrocyclone overflow fractions led to an increase in the Scott bond strength (Fig. 2a). The Af fraction in particular had a strong effect and can be used in small proportions without greatly impairing the drainage (Fig. 2b). The Scott bond strength showed a linear correlation with the paper density, which increases as a result of the increase in fiber bonding (Fig. 4a). The improvement in bonding is supported by the tensile test data, which showed an increase with the addition of each of the wheat straw pulp fractions, except for the Rf fraction, which was fiber-poor and epidermal cell-rich (Table 2). The light scattering coefficient was not linearly related to the density (Fig. 4b). With the same paper bulk, the Rf fraction leads to a higher light scattering coefficient than that attainable with pure eucalyptus pulp. Hou *et al.* demonstrated that co-refining eucalyptus and wheat straw requires less refining energy and has no negative effect on paper mechanical properties.[37] The present results show that small amounts can be used, while maintaining the SR number and mechanical properties.

Size effect of wheat straw components on strength properties

The length-weighted fiber lengths of the wheat straw and eucalyptus pulps were very similar (Table 3). However, the wheat straw pulp was much more heterogeneous and included more fine fibers and fines. The arithmetic mean fiber length of the wheat straw pulp was therefore significantly lower than that of the eucalyptus pulp.

The results suggest that it is worthwhile optimizing the mechanical fractionation of wheat straw fibers in order to produce different particle sizes and different size distributions. Guo *et al.* claim that removing fines from the wheat straw pulp increases the mechanical strength, whereas the present work demonstrates that small amounts (10-30%) of wheat straw fines, including a high proportion of cells, do not affect adversely the mechanical properties.[28] As shown here and concluded by Ljusgren *et al.*, a higher fraction of epidermal and parenchyma cells is likely to change the mechanical properties of the paper.[29] Another property that may reduce interfibrillar bonding is the presence of surface lignin, which may be higher in non-wood than in wood pulp.[38]

The Af and Rf fines fractions had similar dimensions when analyzed with an optical fiber analyzer (Table 3), although they behaved very differently when mixed with eucalyptus fibers. The cell type analysis showed significant differences in the fractions (Table 2) and the SEM studies (Fig. 5) confirmed the differences in bonding ability of parenchyma and epidermal cells. These components were also very different from the microfibrillated cellulose,[39] which has also been shown to have similar effects on pulp and paper properties. It is noteworthy that the degree of fibrillation of the wheat straw fibers is relatively low according to the SEM images and the strength is therefore expected to originate from fines. Wheat straw fines fractions, according to this study, cannot be regarded as being similar to fillers in general, as Guo *et al.* stated.[28] Instead, a fractionation method as described here can be used to produce a fines fraction having excellent bonding properties or a fraction having a higher light scattering power at a similar Scott bond level.

Effect of cell types on pulp and paper properties

The most valuable wheat straw components from the point of view of Scott bond strength were the parenchyma cells and fine fibers, which formed a strong network with the eucalyptus fibers. The parenchyma cells in particular were much wider[31] (see Fig. 5) than the other components. Parenchyma cells also have thin cell walls[31] and thus they are able to collapse easily. SEM micrographs (Fig. 5) confirmed the strong collapsibility of the parenchyma cells and that they formed flat and wide bonding surfaces. Thus, the improvement in Scott bond strength seems to originate from the greater bonding area due to higher fiber flexibility and not solely to the presence of larger amounts of fines. Small flake-like particles settled in the voids of the fiber network, which can be seen as a lower air permeance, and a higher density (Table 4, Figs. 3 and 4). The flake-like components also affect the dewatering properties: the network structure containing this type of fine particles has poor drainage properties because of the longer distance for the water to pass through the pad containing settled flakes rather than thin fibers.[40]

Since fines fractions Af and Rf had similar contents of parenchyma and vessel cells, but Rf had many more epidermal cells and Af more fine fibres, it can be concluded from the Scott bond and tensile strength data that epidermal cells contribute less to the strength. The Rf fraction with a high content of epidermal cells gave paper with a lower density and high light scattering properties (Fig. 4).

CONCLUSION

Wheat straw pulp was successfully fractionated into two different types of fines fractions capable of improving the mechanical properties of paper, such as Scott bond strength, tensile strength and smoothness. The parenchyma-rich fraction provided high Scott bond values for a furnish containing eucalyptus fibers, whereas the epidermal-rich fraction gave a higher light scattering power at a similar Scott bond level. The parenchyma-rich fraction was obtained from the pressure screen accept and the overflow of a subsequent hydrocyclone, while the epidermal-rich fraction was obtained from the pressure screen accept and the underflow of a subsequent hydrocyclone. A small fraction of a refined eucalyptus pulp was replaced by an unrefined wheat straw pulp fraction without any adverse effect on the dewatering properties, but a larger proportion of the parenchyma-rich fraction cannot be used without deterioration in drainage. This work thus encourages the use of wheat straw pulp in eucalyptus furnish in order to promote the mechanical or optical properties of eucalyptus paper.

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REFERENCES

[1] J.-E. Levlin, in "Papermaking Science and Technology 17, Pulp and Paper Testing", edited by J.-E. Levlin and L. Söderhjelm, Fapet Oy, 1999, pp. 137-161.
[2] I. Kajanto, in "Papermaking Science and Technology 16, Paper Physics", edited by K. Niskanen, Fapet Oy, Finland, 1998, pp. 193-221.
[3] U. Molin, and A. Teder, *Nordic Pulp Paper Res. J.*, **17**, 14 (2002).
[4] I. I. Pikulik, *Tappi J.*, **82**(**11**), 88 (1999).
[5] A. Vainio and H. Paulapuro, *Nordic Pulp Paper Res. J.*, **22**, 403 (2007).
[6] E. Kontturi, M. Mitikka-Eklund and T. Vuorinen, *BioResources*, **3**, 34 (2008).
[7] M. Rakkolainen, E. Kontturi, A. Isogai, T. Enomae, M. Blomstedt *et al.*, *Ind. Eng. Chem. Res.*, **48**, 1887 (2009).
[8] L. Frilund and H. Bruun, *Pap. Puu*, **67**, 609 (1985).
[9] M. Eriksson, G. Pettersson and L. Wågberg, *Nordic Pulp Paper Res. J.*, **20**, 270 (2005).
[10] A. Suurnakki, T. Oksanen, H. Kettunen and J. Buchert, *Nordic Pulp Paper Res. J.*, **18**, 429 (2003).
[11] G. Pettersson, H. Höglund and L. Wågberg, *Nordic Pulp Paper Res. J.*, **21**, 115 (2006).
[12] G. Pettersson, H. Höglund and L. Wågberg, *Nordic Pulp Paper Res. J.*, **21**, 122 (2006).
[13] K. Koljonen, A. Vainio, E. Hiltunen, J. Laine and P. Stenius, in *Procs. The 5th International Paper and Coating Chemistry Symposium*, Montreal, QC, Canada, 2003, pp. 223-227.
[14] D. Montplaisir, C. Daneault and B. Chabot, in *Procs. The 91st Annual Meeting Pulp and Paper Technical Association of Canada*, Montreal, QC, Canada, February 8-10, 2005, pp. C165-C169.
[15] C. Schönberg, T. Oksanen, A. Suurnäkki, H. Kettunen and J. Buchert, *Holzforschung*, **55**(**6**), 639 (2001).
[16] K. El-Sharkawy, S. Haavisto and H. Paulapuro, *Appita J.*, **61**, 41 (2008).
[17] P. Somboon, T. Kang and H. Paulapuro, in *Procs. The 93rd Annual Meeting of the Pulp and Paper Technical Association of Canada*, Montreal, QC, Canada, February 5-9, 2007, pp. A59-A64.
[18] E. Hiltunen, PhD Thesis, Helsinki University of Technology, Reports, Series A16, Espoo, 2003.
[19] X. Wang, T. C. Maloney and H. Paulapuro, *Pap. Puu*, **89**(**3**), 148 (2007).
[20] T. Kang and H. Paulapuro, in *Procs. The 91st Annual Meeting Pulp and Paper Technical Association of Canada*, Montreal, QC, Canada, February 8-10, 2005, pp. B177-B180.
[21] W. Brecht and K. Klemm, *Pulp Pap.-Can.*, **54**, 72 (1953).
[22] W. B. Campbell, *Tappi J.*, **42**, 999 (1959).
[23] K. Luukko and H. Paulapuro, *Tappi J.*, **82**(**2**), 95 (1999).
[24] E. Retulainen, K. Luukko, K. Fagerholm, J. Pere, J. Laine *et al.*, *Appita J.*, **55**, 457 (2002).
[25] A. Vainio, J. Kangas and H. Paulapuro, *J. Pulp Pap. Sci.*, **33**, 29 (2007).
[26] E. Retulainen, K. Niskanen and N. Nilsen, in "Papermaking Science and Technology 16, Paper Physics", edited by K. Niskanen, Fapet Oy, 1998, pp. 54-87.
[27] P. P. Rousu and K. J. E. Hytönen, in *Procs. The 2007 TAPPI Engineering, Pulping & Environmental Conference*, Jacksonville, FL, USA, October 21-24, 2007, Paper 50-3.
[28] S. Guo, H. Zhan, C. Zhang, S. Fu, A. Heijnesson-Hultén *et al.*, *BioResources*, **4**, 1006 (2009).
[29] I. Ljusgren, B. Wiberg, A. Tubek Lindblom, and T. Persson, in *Procs. The 5th International New Technologies in Non-wood Fiber Pulping and Papermaking Conference*, Guangzhou, China, 2006, pp. 281-286.
[30] H. Zhang, Z. He and Y. Ni, *Bioresource Technol.*, **102**, 2829 (2011).
[31] M.-S. Ilvessalo-Pfäffli, "Fibre Atlas. Identification of Papermaking Fibres", Springer-Verlag, Berlin, 1995.
[32] R. Wettestein, *Wochenblatt für Papierfabrikation*, **90**, 433 (1962).
[33] S. Panula-Ontto and A. Fuhrmann, Effect of fractionation and refining on board and tensile stiffness of board, SP-2 Sustainpack seminar, Latest innovation in cellulose packaging, Verona, Italy, Apr. 18, 2007.
[34] R. Subramanian, T. Maloney and H. Paulapuro, in *Procs. The 2004 Tappi Paper Summit, Spring Technical and International Environmental Conference*, Atlanta, GA, USA, May 3-5, 2004.
[35] K. El-Sharkawy, P. Rousu, S. Haavisto and H. Paulapuro, *Appita J.*, **60**, 404 (2007).
[36] J. Niinimäki, A. Ämmälä and H. Jokinen, in *Procs. PulPaper Conference*, Helsinki, Finland, June 5-7, 2007.
[37] Q. Hou, B. Yang, W. Liu, H. Liu, Y. Hong, and R. Zhang, *Carbohyd. Polym.*, Doi:10.1016/j.carbpol.2011.04.040, (2010).
[38] Y. Yu, K. Koljonen and H. Paulapuro, *Ind. Crop. Prod.*, **15**, 123 (2002).
[39] T. Taipale, M. Österberg, A. Nykänen, J. Ruokolainen and J. Laine, *Cellulose*, **17**, 1005 (2010).
[40] Z. Cheng, and H. Paulapuro, in *Procs. The Third International Non-wood Fiber Pulping and Papermaking Conference*, Beijing, China, 1996, pp. 431-444.