CELLULOSE CHEMISTRY AND TECHNOLOGY

WHEAT STRAW PULP FRACTIONATION
PART 1. THE EFFECT OF CELLS, VESSELS AND FINES ON PAPER PROPERTIES

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*

Received May 24, 2012

A study on the effect of fractionation of wheat straw pulp shows the effects of various wheat straw pulp components on paper strength. An industrial type pressure screen and hydrocyclones of two different sizes were used to produce fines and coarse fractions containing different amounts of parenchyma, vessel and epidermal cells. The vessels were found to behave more like fibers in the fractionation process, and this made it possible to create parenchyma and epidermal cell-rich fractions. By gradually replacing the original pulp with the different fractions, it was seen that certain paper physical properties do not necessarily follow the expected trends. For instance, the fines fractions behaved very differently and, by fractionating the suspension, better bulk-strength ratios were obtained. The coarsest fiber fraction had the highest tensile and tear strengths, but the finest fines fraction gave the highest Scott bond values. By utilizing this information, the fractionation process and dosing ratios can be used to obtain high-strength papers without any negative effects on dewatering or densification.

Keywords: non-wood, straw pulp, parenchyma cell, epidermal cell, vessel, paper property

INTRODUCTION

In non-wood plants the different cells have special functions and have obviously different physical and physico-chemical properties. The basic structure of the non-wood plant consists of vascular bundles and parenchyma tissue. The role of the vascular bundles is to transport water and nutrients, and these bundles contain vessels, sieve tubes, fibers, tracheids, parenchyma cells, and sclereids. The size of the parenchyma cells varies substantially and they have different shapes, such as thin-walled and sac-like. The epidermis exists in the outermost layer of the entire plant. Epidermal cells are typically small, although long (proper epidermal cells) and short (cork and silica cells) and other cells (e.g. hair and stomata) exist.[1] Typically, the components of a non-wood plant can be categorized into the following main groups: fibers, parenchyma cells, epidermal cells, and vessel elements.

Both small and large cells from non-wood plants may cause problems if these plants are pulped for use in papermaking. Grass pulps in particular contain a large amount of fines, composed mostly of epidermal cells and small parenchyma cells. A high concentration of small particles retards dewatering.[2-7] The largest and the smallest particles are expected to be the most challenging components when preparing paper from non-wood pulp. The relationship between the size, shape and bonding properties resulting from physical and chemical properties is not fully clarified in non-wood based papers. The large amount of fines and the existence of large cells in non-wood pulps are usually associated with a linting tendency in the paper and picking in the printing press. Large vessels and parenchyma cells, as well as fine cells, may cause picking, linting and dusting problems, if they are not well-

Cellulose Chem. Technol., ***47*** *(5-6), 443-453 (2013)*

bonded in the fibrous network.[8-11] These phenomena may be due to a lack of surface strength, leading to faults in the print and deposits on the ink transfer rolls, although surface wetting phenomena are also important. Linting is, however, difficult to measure under laboratory conditions with simulated printing devices. According to Sountausta, over 1000 sheets are required to test linting and about 200 for pick-strength assessment.[12] In this study, physical paper properties, such as tensile strength, tear strength and Scott bond, were used as an indication of the bonding properties of the wheat straw pulp components.

However, there is a lack of scientific literature on the effect of non-wood pulp fractions and, particularly, of cell-rich fractions on the relationship between the physical properties of paper, such as the strength properties and picking and dusting. Tang *et al.* presented a list of ways to decrease the picking tendency of papers made from non-wood pulp.[13] Although refining is a common way to reduce vessel-picking problems with wood-based fibers,[13-17] it is not suitable for wheat straw pulps, since they typically have poor dewatering properties, even without refining.[18-20] Instead, surface treatments have proven to be more efficient.[21]

It is evident that there is a lack of information about the effects of different non-wood pulp fractions on pulp and paper properties with respect to the above-mentioned problems. In particular, the effects of different fine and coarse non-wood pulp fractions containing different cell types and concentrations require more attention. In this study, non-wood pulp was fractionated on a large scale, using industrial types of equipment. Different fractionation steps were evaluated and developed to create pulps enriched with different types of cells in order to clarify: 1) how different non-wood cell types and the sizes of these particles affect paper properties and 2) what synergetic effects the components may have. Sheets were prepared from the different fractions and the optical and technical properties of the sheets were evaluated. Fractionation conditions were selected so that fibers, parenchyma, epidermal and vessel cells could be enriched in different fractions.

EXPERIMENTAL

Pulp fractionation

A commercial once-dried Chinese wheat straw pulp prepared by the soda method was used. The pulp was disintegrated in a low consistency (LC) vat pulper at a temperature of 50 °C. The pulp suspension was fractionated by different methods in order to achieve an enrichment of different cell types in different pulp fractions. Industrial pressure-screen and hydrocyclone fractionation devices were used to produce large quantities and to offer an insight into the up-scale ability of the fractionation concept of wheat straw pulps. Pressure-screen fractionation is based mainly on differences in particle dimensions, whereas hydrocyclone fractionation is based mainly on differences in specific surface area.[22] The aim was to enrich fibers, parenchyma cells, epidermal cells and vessel cells in different fractions. The hydrocyclone was used to separate the pressure-screen reject and thus to obtain fractions enriched with particles of high specific surface area. The epidermal-cell-rich fraction is assumed to be enriched in the accept flow from the pressure screen, due to the low specific surface area of these cells. A diagram of the fractionation procedure is presented in Fig. 1.

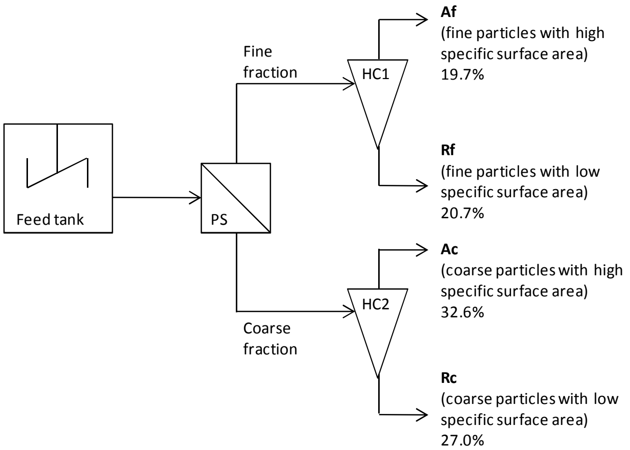

Figure 1: Fractionation procedure used in the study

The pulp was fractionated first with a pressure screen (Metso FS 03) with a smooth perforated screen plate having 200 μm holes. The total mass reject rate (RRm) in the pressure screen fractionation was 60%. The accept fraction from the pressure screen (fines fraction) was further fractionated using a 2-inch hydrocyclone (Mozley C124) into an overflow fraction (Af) and an underflow (Rf) fraction with a total mass reject rate of 51%. The reject fraction from the pressure screen (coarse fraction) was further fractionated with a 60-mm hydrocyclone (GL&V Celleco Cleanpac 270) 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 as follows: Ac = 32.6%, Rc = 27.0%, Af = 19.7% and Rf = 20.7%.

Analyses of the fractions

The different cell types in the pulp fractions were identified and counted based on microscope images, according to ISO 9184-1-7. The results are given as number proportions of the whole sample. Identification was achieved using Fiber Atlas.[1] Over 5000 cells were counted in each sample in order to provide statistical reliability. Fiber and other cell dimensions were determined with a Kajaani Fiber Labanalyzer. Cell widths in the wet pulp were determined from light microscope images. Laboratory paper sheets were imaged by scanning electron microscopy (JEOL 5800), using a 10 kV accelerating voltage and 12 mm working distance. The samples were coated with gold before the imaging.

Experimental design

The experimental design for different paper sheet compositions is shown in Table 1. The proportion of each fraction in the pulp furnish was varied from 0 to 100 percent and the rest of the furnish consisted of the other three fractions in their original proportions. The experiments were designed to illustrate the effects of each fraction on the paper properties and the possible synergetic or negative effects of the components on these properties. Besides obtaining information about different pulp mixtures, it is thus possible to draw conclusions regarding the effect of the absence of a certain fraction on the paper properties.

Table 1
Composition of the prepared laboratory sheets

	Ac	Rc	Af	Rf
Exp 1	**0.0**	40.1	29.2	30.7
Exp 2	**25.0**	30.0	21.9	23.0
Exp 3	**50.0**	20.0	14.6	15.4
Exp 4	**75.0**	10.0	7.3	7.7
Exp 5	**100.0**	0.0	0.0	0.0
Exp 6	44.7	**0.0**	27.0	28.4
Exp 7	33.5	**25.0**	20.2	21.3
Exp 8	22.3	**50.0**	13.5	14.2
Exp 9	11.2	**75.0**	6.7	7.1
Exp 10	0.0	**100.0**	0.0	0.0
Exp 11	40.6	33.6	**0.0**	25.8
Exp 12	30.4	25.2	**25.0**	19.3
Exp 13	20.3	16.8	**50.0**	12.9
Exp 14	10.1	8.4	**75.0**	6.4
Exp 15	0.0	0.0	**100.0**	0.0
Exp 16	41.1	34.0	24.8	**0.0**
Exp 17	30.8	25.5	18.6	**25.0**
Exp 18	20.6	17.0	12.4	**50.0**
Exp 19	10.3	8.5	6.2	**75.0**
Exp 20	0.0	0.0	0.0	**100.0**

Note: There was a long drainage time in the forming of sheets from the Af fraction. The formation of these sheets was not perfect and the final sheets contained small holes

Handsheet preparation

Laboratory handsheets were prepared (ISO 5269-1) from the original pulp, the pulp fractions and mixtures of the pulp fractions, as indicated in Table 1. A retention chemical was used to ensure retention of all the fines in sheet preparation. The dose and type of retention chemical were selected according to pre-tests and were kept the same in all cases, although the charge of the system was slightly different in various experimental points. The retention chemical selected was a cationic polyacrylamide flocculant having a molar mass of about 2×10^6 g/mol (Percol, BASF). The drainage properties of the pulp were measured as SchopperRiegler (SR number) (ISO 5267-1) and the drainage time in a sheet mould (T = 20 °C) manually with a stop watch. The following paper properties were evaluated: density (SCAN-P 7), tensile index, elastic modulus, tensile energy absorption and tensile strain (SCAN-P 38:80), tear index (SCAN-P 11:96), Scott Bond strength (TAPPI 569), roughness, air permeability (SCAN-P 21:67) and optical properties (ISO 2470).

RESULTS

Analysis of pulp fraction composition

Table 2 shows the compositions of the pulp fractions, including fiber and cell types and concentrations, and Fig. 2 shows micrographs of the fractions. The average cell dimensions of the original pulp and of the pulp fractions are shown in Tables 3 and 4.

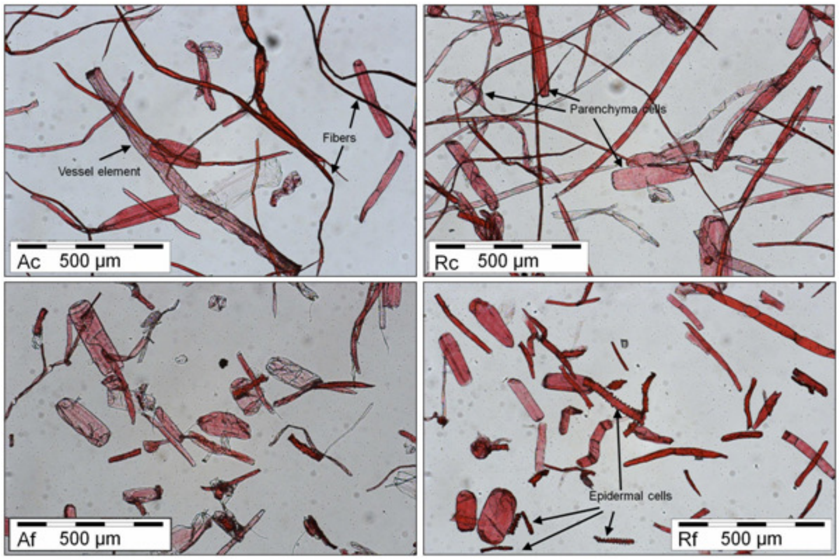

Figure 2: Photomicrographs of the Ac, Rc, Af and Rf fractions of wheat straw pulp

Table 2
Cell types in pulp fractions

	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%

Table 3
Particle dimensions of the original pulp and pulp fractions obtained using a Kajaani FiberLab analyzer

	Original pulp	Ac	Rc	Af	Rf
L(n), mm	0.41	0.57	0.53	0.2	0.19
L(l), mm	0.74	0.89	0.87	0.36	0.32
Fines L(n), %	38.31	21.66	25.49	63.56	68.26
Fines L(l), %	10.76	4.6	5.67	32.97	38.98
Coarseness, mg/m	0.088	0.062	0.073	0.135	0.142
Fiber width, µm	17.4	19.01	19.51	15.74	17.63

The pressure screen had a very fine perforation and clearly rejected fibers, while allowing fine material to pass the screen. The Ac and Rc fractions were fiber-rich fractions with less than

25% other cell types. The Ac fraction had the highest proportion of vessel elements, and the Af and Rf fractions contained a higher amount of fines. The Rf fraction had the lowest fiber content, but the highest content of parenchyma cells and epidermal cells. The lowest amount of parenchyma cells was found in the Ac and Rc fractions and the smallest amount of epidermal cells in the Ac fraction.

Ac and Rc had a greater fiber length and width, but the coarseness values of Ac and Rc were lower than those of Af and Rf. The fines fractions had a greater coarseness than the fiber fractions as a result of the higher cell-wall area of short particles than that of long fibers and possibly due to the higher ash content. In any given fractionation stage, the underflow (R) had a higher coarseness value than the overflow (A).

The quantities of the cell types were calculated for each experimental point. These quantities were calculated by multiplying the original cell quantities in the fractions Ac, Rc, Af and Rf with the proportions of the fractions in the experiments (Table 1). The cell-type analysis was based on the numbers of particles (not weight-based values), so that accurate numerical values cannot therefore be guaranteed and are not presented, but they can be regarded as indicative.

Typical cell dimensions measured on photomicrographs (Fig. 2) show clear differences in fiber width. Data for the visual analysis of the individual cell types in the photomicrographs are shown in Table 4. The fines appeared visually to be much narrower than indicated by the fiber analyzer. In the fiber-rich fractions, the difference was smaller. The difference in fiber width is due to the large number of wide parenchyma and epidermal cells, which raises the average width values. It must be emphasized, however, that the optical fiber detection method is not necessarily calibrated for the fine fraction, and this may have affected the results.

Table 4
Typical widths of cells measured on photomicrographs

Cell widths	Original pulp, µm	Ac, µm	Rc, µm	Af, µm	Rf, µm
Fibers	10-27 (11-16)	10-20	10-27	5-11	10-14
Vessel elements	50-85	40-60	40		
Parenchyma cells (etc.)	20-110	30-100	35-95	20-110	27-110
Epidermal cells (etc.)	10-30	27	21-27	11-21	16-30

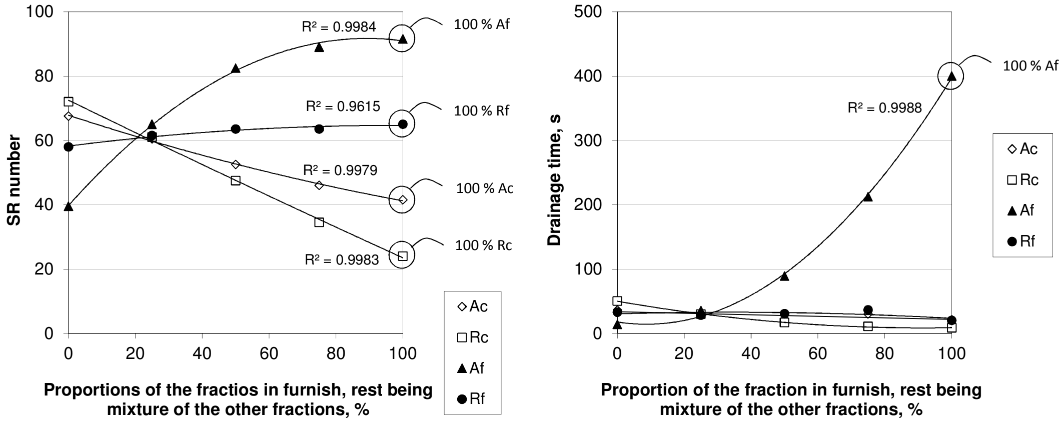

Figure 3: SR number and drainage time as a function of the proportions of different fractions in the wheat straw pulp furnishes

Table 5
Physical properties of the samples

	SR number	Drainage time, 20°C, s	Tensile index, Nm/g	Tensile strain, %	Tensile energy absorption, mJ/g	Tensile stiffness index, kNm/g	Tear index, mNm^2/g	Scott bond, J/m^2	Air permeance, Bendtsen, mL/min	Roughness, felt side, Bendtsen, mL/min	Roughness, wire side, Bendtsen, mL/min	Bulk, cm^3/g	ISO-brightness, R457 C, %	Opacity, %	Light scattering coefficient, m^2/kg	Light absorption coefficient, m^2/kg
Exp 1	67.5	36.1	46.59	1.27	411.22	6.69	2.05	791.2	26.2	894	47.3	1.21	65.58	85.37	31.69	1.33
Exp 2	60.5	29.0	44.28	1.38	415.79	6.52	2.79	396.7	155.9	860	85.8	1.44	69.82	86.48	39.30	1.18
Exp 3	52.5	22.4	56.96	1.80	722.91	7.74	2.66	712.7	38.4	761	34.3	1.20	68.81	82.98	31.64	0.99
Exp 4	46.0	30.0	55.68	1.74	685.86	7.75	3.25	482.2	120.8	810	65.9	1.35	69.86	82.67	33.61	0.99
Exp 5	41.5	21.0	64.65	2.35	1090.00	7.97	3.29	770.7	28.2	809	61.6	1.16	70.45	81.21	29.20	0.77
Exp 6	72.0	50.4	56.24	1.53	592.34	7.86	2.16	894.7	19.7	771	32.2	1.18	65.67	82.97	29.50	1.20
Exp 7	61.0	29.9	59.36	1.82	762.40	7.84	2.64	806.2	39.3	802	55.6	1.21	67.21	84.40	32.20	1.16
Exp 8	47.5	17.0	58.69	1.85	771.50	7.86	2.71	693.2	61.4	859	52.8	1.23	68.84	83.34	32.35	1.02
Exp 9	34.5	10.8	50.68	2.03	736.72	6.86	2.61	516.2	133.7	894	76.8	1.25	70.20	82.44	28.41	0.80
Exp 10	24.0	8.6	53.61	2.04	797.16	7.49	3.62	471.4	238.1	908	97.7	1.31	72.13	84.67	33.64	0.80
Exp 11	39.5	14.0	47.69	1.42	492.10	7.50	2.71	602.9	80.2	784	65.2	1.25	69.24	83.20	32.33	1.01
Exp 12	65.0	35.2	60.89	1.78	762.67	8.08	2.52	893.6	24.4	807	36.8	1.19	67.30	85.55	32.39	1.17
Exp 13	82.5	89.3	57.70	1.43	549.74	7.80	2.12	1170.8	5.5	806	44.1	1.16	64.16	82.89	28.76	1.29
Exp 14	89.0	212.5	44.08	0.87	228.43	7.30	1.98	795.1	0.5	773	40.0	1.16	62.11	79.17	24.78	1.33
Exp 15*	91.5	399.9	40.77	0.76	180.18	7.21	1.80	NM	155.9	1319	253.9	1.16	57.06	76.35	21.04	1.58
Exp 16	58.0	33.0	56.78	1.69	675.19	7.71	2.81	761.7	37.3	825	37.7	1.21	68.72	83.03	30.47	0.95
Exp 17	61.5	28.4	56.79	1.99	808.52	7.48	2.53	924.4	31.0	701	36.6	1.20	67.26	83.91	31.92	1.16
Exp 18	63.5	30.4	48.31	1.80	623.17	6.71	2.43	802.2	41.8	807	42.7	1.24	66.36	86.51	33.50	1.35
Exp 19	63.5	36.4	40.17	1.32	357.37	5.98	1.91	763.1	48.6	756	43.1	1.27	65.35	90.45	34.47	1.56
Exp 20	65.0	20.2	31.81	1.15	244.16	5.22	1.43	693.3	97.7	771	65.4	1.27	65.49	84.91	33.65	1.53

*Due to long drainage time, the formation of the sheet was not perfect and the final sheets had pinholes which affected the physical properties
NM = Not measured since the sample was too strong for the equipment

Table 6

Correlations between the measured properties of the pulp fractions and cell types. Significant correlations marked with an asterisk and bold type

	Effect of fraction				Effect of cell type			
	Ac	Rc	Af	Rf	Fibers	Vessels	Epidermal	Parenchyma
Drainage time (N=20)	-0.307	-0.364	0.925**	-0.254	-0.251	-0.081	0.381	0.150
SR (N=20)	-0.318	**-0.661****	**0.818****	0.161	**-0.618****	-0.121	**0.711****	**0.516***
Tensile index (N=17)	**0.653****	0.137	0.048	**-0.766****	**0.783****	**0.675****	**-0.772****	**-0.819****
Breaking strain (N=17)	**0.527***	0.384	**-0.544***	-0.466	**0.707****	0.426	**-0.759****	**-0.674****
TEA (N=17)	**0.646****	0.292	-0.386	**-0.597***	**0.782****	**0.578***	**-0.818****	**-0.774****
Tensile stiffness index (N=17)	-0.745**	-0.830**	0.782**	0.644**	**0.782****	**0.644****	**-0.745****	**-0.830****
Tear index (N=17)	0.455	**0.582***	-0.374	**-0.720****	**0.900****	0.387	**-0.925****	**-0.866****
Scott bond (N=17)	0.166	**-0.618****	**0.585***	0.037	-0.267	0.287	0.319	0.178
Brightness (N=17)	0.341	**0.642****	**-0.734****	-0.414	**0.726****	0.198	**-0.793****	**-0.653****
Opacity (N=17)	-0.368	0.005	-0.434	**0.646****	**-0.500***	-0.462	0.446	**0.557***
s (N=17)	-0.205	0.157	**-0.709****	**0.547***	-0.285	-0.353	0.204	0.363
k (N=17)	**-0.491***	**-0.577***	0.317	**0.789****	**-0.949****	-0.435	**0.967****	**0.922****
Density (N=17)	**0.530***	**-0.576***	**0.677****	-0.403	0.157	**0.676****	-0.092	-0.273
Bulk (N=17)	**-0.534***	**0.566***	**-0.670****	0.412	-0.169	**-0.680****	0.105	0.284
Roughness (N=17)	-0.291	**0.752****	-0.146	-0.374	0.438	-0.326	-0.431	-0.369
Air permeance (N=17)	-0.296	-0.141	0.250	-0.490*	0.250	**-0.490***	-0.296	-0.141

* Correlation is significant at the 0.05 level (2-tailed); ** Correlation is significant at the 0.01 level (2-tailed)

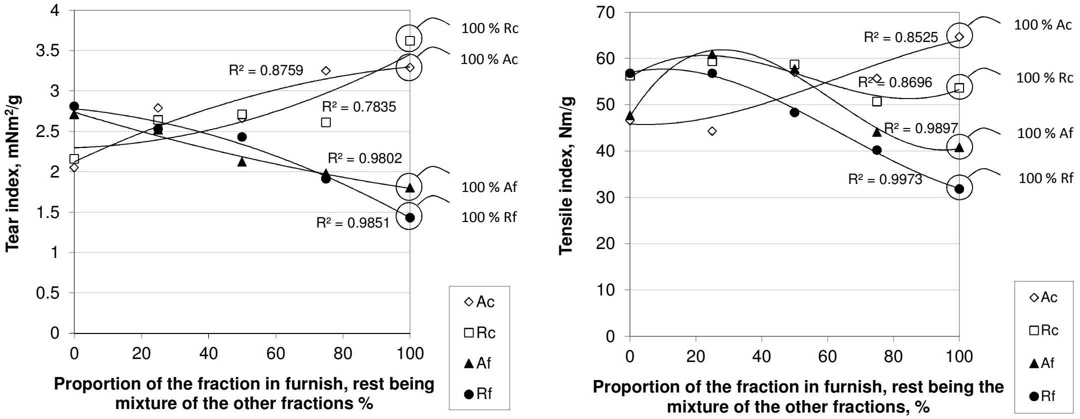

Figure 4: Tear index and tensile index as function of the proportions of different fractions in the wheat pulp furnishes

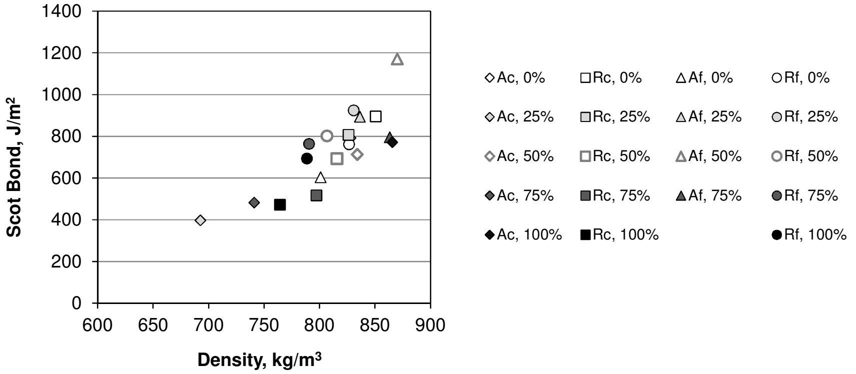

Figure 5: Relationship between Scott Bond strength and density of wheat straw pulp furnishes

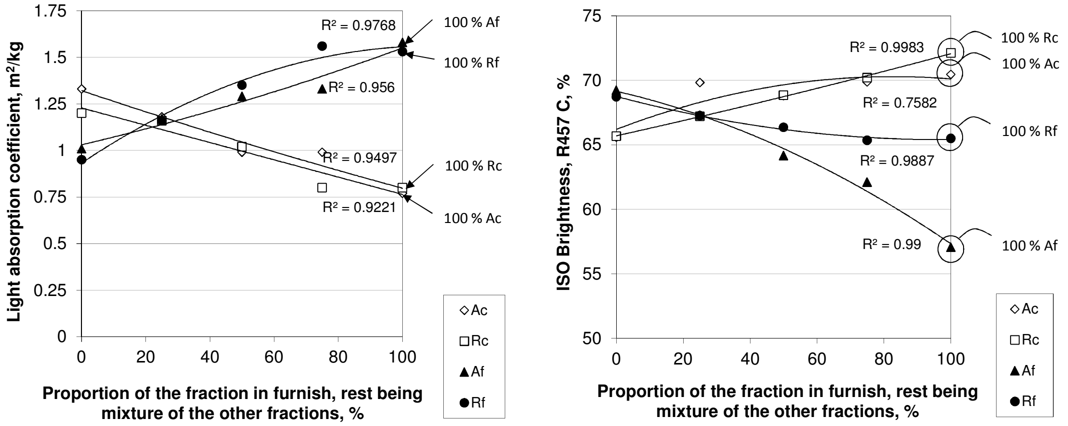

Figure 6: Brightness and light absorption coefficient as a function of the properties of different fractions in the wheat straw pulp furnishes

Effects of pulp fractions on paper properties

The proportions of the pulp fractions in the furnishes were gradually varied. 0% indicates an experimental point totally lacking the fraction in question and consisting of the three other fractions in their original proportions. 100% means a sample consisting purely of the fraction in question. 25%, 50%, and 75% indicate experimental points having the stated amount of the fraction in question, the rest consisting of other fractions in their original proportions. Figs. 3-6 show the most significant differences between the pulp fractions.

Figure 3 shows significant differences between the fines fractions Af and Rf with respect to SR number and drainage time. The Rf fraction had only a slight effect on the drainage, while the Af fraction strongly increased the dewatering resistance having the highest SR number and drainage time (Fig. 3 and Tables 5-6). The subsequent addition of other fractions to the Rf fraction had no significant effect on the drainage properties, revealing the synergistic effects between the fractions. The lowest dewatering resistance was seen with the coarsest fraction, Rc, which was expected to give a permeable structure and low water-holding ability, in agreement with the results of Guo *et al.*[23] It is, however, interesting to see that both the Rc and Af fractions are very dependent on the final pulp mixture composition for their SR values.

The highest tear strength was achieved with the Ac and Rc fractions. Having the highest tensile strength, the Ac fraction was also capable of reinforcing the whole furnish. All the fractions had comparatively high tensile strengths, although the accept fractions from the hydrocyclones clearly formed stronger structures than the corresponding reject fractions.

The accept fractions Af and Ac densified the paper structure, whereas the reject fractions Rf and Rc produced bulkier structures (Fig. 5). For bulky grades, the pure Rc and Rf fractions are thus interesting. In the graph showing Scott bond strength as a function of density, it appears that all the fractions with a large amount of fines have a higher Scott Bond strength at a given density (note Af, 100% fraction, gave the highest Scott Bond value, but it is not shown in the graph due to the lack of a numerical value). The Af fraction had thus good bonding properties, seen as a positive effect on the Scott bond value and a negative effect on the light scattering coefficient (Table 6). Obviously, the Af fraction promoted inter-fiber bonding.

The coarsest fraction Rc had a positive effect on brightness, so that the pulp brightness could be increased by reducing the proportions of Af and Rf in the furnish. The positive effect of the Rf fraction on the light scattering coefficient (Table 6) is in line with what was expected, e.g. from the tensile strength data (the Rf fraction had a negative effect on tensile strength).

DISCUSSION

Effects of cell type on paper properties

Table 7 summarizes the effects of the cell type on pulp and paper properties, based on correlations shown in Table 6.

The cell dimensions explain most of the findings on the compositions of the fractions, but significant exceptions were also found. Dewatering and strength properties benefited from fibers, whereas epidermal and parenchyma cells had a positive impact on paper smoothness. The Af fraction had a high amount of fines and cells in the suspensions and it obviously had the highest specific surface area, which provided the water-holding ability. Thus, the most harmful components for dewatering were the small parenchyma cells, forming a dense fiber network, and due to their low length-width ratio, they increased the distance through which the water needs to flow through a pulp pad. The dense structure was also evident in the very low air permeability of the Af fraction. These large differences between the Af and Rf fractions were not however visible in the cell dimensions measured by the optical analyzer (Table 3). In addition to characteristic fractions, the pulp probably contains different levels of microfibrils and microfibril aggregates, and these might also have a significant effect on the bonding ability and fixing in the paper sheet. Differences in surface area presumably also have some effect on the charge level and behavior of the components, but these effects were not evaluated.

Table 7

The effects of wheat straw cell types on pulp and paper properties

	Effect of cell type			
	Fibers	Vessels	Epidermal	Parenchyma
Drainage time*	+		-	-
SR*	+		-	-
Tensile index	+	+	-	-
Tear index	+		-	-
Brightness	+		-	-
k**	-		+	+
Bulk***		-		
Smoothness	-		+	+

* "+" means better dewatering; ** "+" means higher k values; *** "+" means higher bulk and lower density

Role of fine and large particles on paper structure and strength

All the fractions and cell types gave very high Scott bond values, indicating that all the components (fibers, parenchyma cells, epidermal cells and vessels) bonded fairly tightly in the sheet structure. According to the particle dimension analyses (Tables 3-4), the largest vessel cells existed in the Ac fraction. The Ac fraction also had the highest fiber content (Table 2), the highest tensile strength (64.65 Nm/g, Exp 5 in Table 5) and the highest tensile energy absorption (1090 mJ/g, Exp 5 in Table 5). In addition, the vessels-rich fraction had a positive effect on tensile index, tensile energy absorption, tensile stiffness index and density (Table 6). The photomicrograph analyses showed that the vessels of the wheat straw pulp were narrower and longer than those in typical hardwoods (Fig. 3, Table 4). Although fractionation with hydrocyclone clearly affected the bonding behavior measured as tensile strength, it did not have a significant effect on tear index, which seemed to depend on the fiber length.

According to the strength measurements, the various wheat straw fractions did not bond poorly in general, but small and large particles can still be problematic components. Oshawa *et al.* have reported that small and slender vessel elements have not been found to cause vessel-related picking problems.[13-14] Results presented elsewhere[1-2] show that large vessel cells may bond poorly in the paper structure causing picking, linting and dusting problems. All the results presented here indicate that the vessel-cell-rich fractions and elements of wheat straw pulp seem to be less harmful for the bonding/strength than expected. Known picking problems related to wheat straw pulp may have partly resulted from web formation in the paper machine, whereas another possibility may be infiltration of uneven surface sizes. Twin-wire machines or machines having top formers rather than fourdriniers, as well as high wet press loads, can produce printing papers with a lower tendency for vessel picking.[11,15]

Bonding of the components strongly depends on the material with which they are accompanied. Colley reported that neither their size, nor their proportion, can explain the differences in vessel picking.[10] It is claimed that it is influenced by other factors, such as the morphology of the associated pulp fibers. It is known that the vessel picking tendency is high if only a few fibers cover the vessel elements in the paper surface.[11] According to SEM micrographs, the parenchyma cells seem to bond well in the paper structure, ascribed to their good physical contact. The Rf fraction as well as the parenchyma and epidermal cells had a negative effect on all the tensile strength parameters (Table 6). Instead, the Af fraction had a positive effect on the Scott bond strength, but none of the cell types had any significant correlation with the Scott bond strength. Interestingly, both Af and Rf gave high Scott bond values; with Af, it was so high that it was impossible to be measured with the equipment (Table 5). According to the SEM micrographs, epidermal cells seem to bond most loosely in the paper structure. The fines fractions, including the highest parenchyma and epidermal cell contents, had the poorest tensile strength properties, but a high bonding degree and a low paper elasticity. Epidermal cells seem to be less conformable and to bond more loosely than the thin-walled parenchyma cells. This finding is also in line with the observations that the wax layer of epidermis inhibits hydrogen bonding of particle boards prepared from wheat straws.[24]

In the present study, surface properties, such as fiber charge or wetting, were not studied, nor were vessel picking or absorption tests performed. The results shown here are based solely on bonding and strength measurements, which can be regarded merely as an indicative with strength-related picking tendency. In addition, the wheat straw pulp cells have been categorized into only four main groups and these groups may contain cells that behave differently from the average components within the groups.

As illustrated in Table 5, the Af fraction was beneficial for the Scott Bond strength, but both fines fractions had lower tear and tensile strengths than fiber-rich fractions. However, Af fraction had a non-linear effect on tensile strength; only high proportions of Af were harmful for tensile strength. Even though the dose of retention chemicals was kept constant and surface charges were not measured and evaluated, these findings provide more detailed information. It clearly seems that the fines are not homogeneous in physical appearance and that each component type had a different effect on bonding and strength properties. Nevertheless, the actual mechanisms of the cells and vessels on the strength model are lacking.

CONCLUSION

The work demonstrates the role of the fractionation process and the effect of the composition of wheat straw fractions on paper properties. If the pulp mixture were optimized by blending different fractions, bulky and strong paper could be made without causing too high a SR number or high dewatering resistance.

Vessel cells in straw pulp are longitudinal and narrow and behaved more like fibers than parenchyma and epidermal cells in the fractionation process. The bonding ability of different cell types depends on the components they accompany. Vessel cells and fibers had a positive effect on tensile strength, whereas epidermal and parenchyma cells had a negative effect on the tensile and the tear strengths. Parenchyma cells are the most detrimental for dewatering properties. Both parenchyma and epidermal cells are harmful components for pulp brightness, since they have high light absorption coefficients. Even though negative effects were pointed out for parenchyma and epidermal cells, they have a significant impact on bonding behavior and paper structure. The fraction containing a large number of parenchyma cells showed good bonding properties and gave high Scott Bond values.

The results provide further insight into the possible effects of fluctuations in the furnish composition on the product properties. The pulping and especially the refining process affect the paper composition and subsequently the inter-fiber bonding. Picking and dusting problems that may arise when using straw pulp can be reduced by optimizing the papermaking process, including equipment, chemicals and accompanying fibers, without disturbing the process and runnability of the machine.

ACKNOWLEDGEMENTS: We would like to thank the Academy of Finland for funding this study and Kati Turku for various consultations. Dr Anthony Bristow is gratefully thanked for the linguistic revision of the manuscript.

REFERENCES

[1] M.-S. Ilvessalo-Pfäffli, “Fibre Atlas. Identification of Papermaking Fibres”, Springer-Verlag, Berlin, 1995.

[2] J.-H. Ma, L.-S. Xie and S.-Z. Zhang, in *Procs. The Second International Nonwood Fibre Pulping and Papermaking Conference*, Shanghai, China, 1992, pp. 834-843.

[3] S. V. Subrahmanyam, R. D. Godiyal, T. K. Roy, and R. P. Kibblewhite, in *Procs. IPPTA Convention Issue*, 1999, pp. 41-48.

[4] Z. Cheng and H. Paulapuro, in *Procs. The Third International Non-wood Fiber Pulping and Papermaking Conference*, Beijing, China, 1996, pp. 514-523.

[5] Z. Cheng and H. Paulapuro, *Procs. The Third International Non-wood Fiber Pulping and Papermaking Conference*, Beijing, P. R. China, 1996, pp. 431-523.

[6] P. P. Rousu and K. J. E. Hytönen, in *Procs. 2007 TAPPI Engineering, Pulping & Environmental Conference*, Jacksonville, FL, USA, October 21-24, 2007, Paper 50-3.

[7] P. Rousu and J. Niinimäki, *Appita J.*, **60**, 217 (2007).

[8] Anon., *Pap. Asia*, **November**, 30 (1986).

[9] S. Bi, Z. Cai, H. Dai, D. Li, Z. Li, B. Qian and P. Wu, in *Procs. The Second International Nonwood Fiber Pulping and Papermaking Conference*, Shanghai, China, April 6-9, 1992, pp. 816-824.

[10] J. Colley, *Pap. Technol.*, **14**, 293 (1973).

[11] J. Ohsawa, in *Procs. Tropical Wood Pulp Symposium ‘88*, Singapore, June 21-23, 1988, pp. 220-233.

[12] O. Suontausta, in “Papermaking Science and Technology”, edited by J.-E. Levlin and L. Söderhjelm, FapetOy, 1999, pp. 183-211.

[13] F. Tang, R. Yang, F. Liang and Y. Gong, in *Procs. The 2nd International Symposium on Emerging Technologies of Pulping & Papermaking*, Guangzhou, China, October 9-11, 2002, pp. 637-643.

[14] J. Ohsawa, K. Wakai, Y. Yoneda and Y. Nagasawa, in *Procs. International Symposium on Wood Pulping Chemistry*, Japan, Tappi, Supplement volume, May 23-27, 1983, pp. 250-255.

[15] J. Ohsawa, M. Wakai, Y. Komatsu, Y. Yoneda and T. Nagasawa, *J. Jpn. Wood Res. Soc.*, **30**, 742 (1984).

[16] H. U. Heintze and P. M. Shallhorn, in *Procs. The 81st Annual Meeting Technical Section*, Montreal, Canada, 31 Jan.-3 Feb., 1995, pp. B333-B337.

[17] F. H. Phillips and A. F. Logan, *Appita J.*, **30**, 29 (1976).

[18] J.-H. Ma, L.-S. Xie and S.-Z. Zhang, in *Procs. The Second International Nonwood Fibre Pulping and Papermaking Conference*, Shanghai, P. R. China, 1992, vol. 2, pp. 834-843.

[19] X. Zhao, L. Ödberg and G. Risinger, *Tappi J.*, **75**, 153 (1992).

[20] S. V. Subrahmanyam, R. D. Godiyal, T. K. Roy and R. P. Kibblewhite, *Procs. IPPTA Convention Issue*, 1999, pp. 41-48.

[21] L. Paavilainen and R. Torgilsson, in *Procs. TAPPI Pulping Conference*, November 6-10, 1994, pp. 611-617.

[22] J. Niinimäki, A. Ämmälä and H. Jokinen, in *Procs. PulPaper Conference*, Helsinki, Finland, June 5-7th, 2007.

[23] S. Guo, H. Zhan, C. Zhang, S. Fu, A. Heijnesson-Hultén, J. Basta and T. Greschik, *BioResources*, **4**, 3, 1006 (2009).

[24] A. S. Schmidt, S. Mallon, A. B. Thomsen, S. Hvilsted, and J. M. Lawther, *J. Wood Chem. Technol.*, **22** (1), 39 (2002).