METHOD FOR AUTOMATIC ANALYSIS OF WHEAT STRAW PULP CELL TYPES

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Agricultural residues are receiving increasing interest when studying renewable raw materials for industrial use. Residues, generally referred to as nonwood materials, are usually complex materials. Wheat straw is one of the most abundant agricultural residues around the world and is therefore available for extensive industrial use. However, more information of its cell types is needed to utilize wheat straw efficiently in pulp and papermaking. The pulp cell types and particle dimensions of wheat straw were studied, using an optical microscope and an automatic optical fibre analyzer. The role of various cell types in wheat straw pulp and papermaking is discussed. Wheat straw pulp components were categorized according to particle morphology and categorization with an automatic optical analyzer was used to determine wheat straw pulp cell types. The results from automatic optical analysis were compared to those with microscopic analysis and a good correlation was found. Automatic optical analysis was found to be a promising tool for the in-depth analysis of wheat straw pulp cell types.

Keywords: Particle size analysis, Cell type analysis, Nonwood, Wheat pulp

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INTRODUCTION

Nonwood materials derived from agriculture by-products are a promising source of renewable raw material not only for the pulp and paper industry, but also for biofuel, energy, and specialty chemical production. The industrial utilization of nonwood residues is, nowadays, small-scale. For example, compared to wood fibers, only a relatively small amount of paper is produced annually using nonwood raw material. Excess material is usually burnt in the fields or for household energy, which causes local air pollution problems (Gadde et al. 2009, Sahai et al. 2007, Yan et al. 2006, 2008).

Wood-based pulps contain only a few different cell types because only the debarked stem is used in pulp manufacturing. By contrast, various parts of the plant can be used when manufacturing nonwood pulps, even the whole plant apart from its ear and roots. A plant used as a nonwood raw material may contain in its entirety as many as 80 cell types (Sitte et al. 1998). Therefore, dozens of different cell types may be found in nonwood pulp. The role of fibres and fines in paper is quite well known for wood-based pulps, but the role of nonwood pulp components in paper is less established. Each cell type with a unique function in the plant and a unique morphology and chemical composition will presumably also have a unique effect on paper properties. The problem

in determining the particle role in nonwood pulp behavior is the difficulty of cell type identification. Standards (ISO 9184, SCAN G3 and G4, TAPPI T259 and T401) and guidebooks (e.g. Ilvessalo-Pfäffli 1995) have been published to help cell type identification, but the work is still time consuming and requires a lot of expertise. This prevents the analysis of a large number of samples even though cells are usually categorized only for four main cell categories (fibres, vessels, parenchyma cells, and epidermal cells).

Automatic optical fibre analyzers have been developed to measure fibre dimensions from wood-based pulps. Particles in a sample are photographed and the particle dimensions are measured using image analysis. Automatic analyzers have been proven to be reliable even though a small difference in results occurs between different analyzer manufacturers (Guay et al. 2005; Turunen et al. 2005). Wheat is one of the most important cultivated plants in the world, and, therefore, wheat straw is also one of the most abundant agricultural residues (Anon 2011). Wheat straw is used as a paper raw material mainly in small Asian paper mills. However, there is potential for a much wider use, not only in paper products, but also for various other applications in which lignocellulosic materials are used. Some microscopic studies of the proportions of wheat straw cell types (Wettstein 1962) and their dimensions exist, but studies are usually concentrated on the dimensions of certain cell class (Beemster and Masle 1996, Hua and Xi 1988, Kuo et al. 1974, Kuo and O'Brien 1974, Percival 1921). The analysis of wheat straw pulp by automatic fibre analyzers is hitherto limited on the determination of average cell dimensions, determined for the whole cell population.

The purpose of this work was to develop a method for automatic wheat straw pulp cell type analysis by using an optical fibre analyzer. First, the cell dimensions were measured for various cell types by microscopic analysis and cells were categorized in accordance with length, width, and aspect ratio into five classes with distinct cell types. The categorization was then applied for the data of an automatic optical fibre analysis device. The method was verified with standardized cell type analysis done by an accredited pulp and paper laboratory.

An automatic cell type analysis method allows the extensive studies of the effect of pulp constituents in paper properties, for example. It can also be used in process control and monitoring in the nonwood pulp and paper industry.

EXPERIMENTAL

The pulp used in the study was commercial bleached, once dried, Chinese wheat straw (*Triticum aestivum*), which had been delignified by the soda method. Pulp sheets were slushed in a vat pulper at a temperature of 50°C at a consistency of 0.7% for 2 hours.

The pulp was fractionated in order to generate pulp fractions with different cell types. A diagram of the fractionation procedure is presented in Fig. 1. The pulp was first size fractionated with a pressure screen into long and short particle fractions using a smooth perforated screen plate with a hole diameter of 0.2 mm. The mass flow split between the short and long fractions in pressure screen fractionation was 40/60. The long

particle fraction was fractionated further with a 60-mm Celleco Cleanpac 270 hydrocyclone into long underflow (Lu) (having a low specific surface) and long overflow (Lo) (having a high specific surface) fractions using a mass flow split of 45/55. The short particle fraction that passed through the screen plate were fractionated according to particle specific surface with a 50-mm Mozley C124 hydrocyclone into short underflow (Su) and short overflow (So) fractions using a total mass flow split of 50/50. The short particle fractions were thickened by settling and filtration using a 0.02 mm filter cloth.

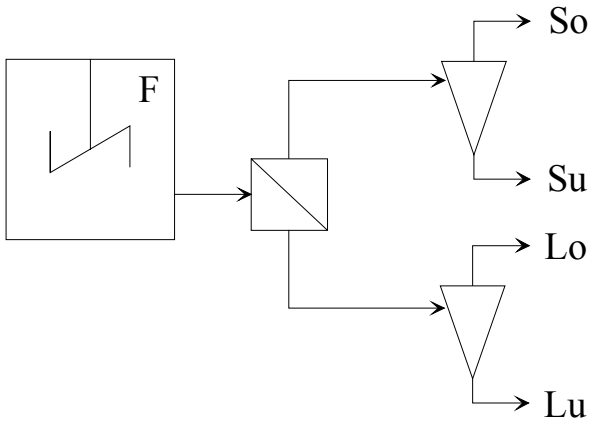

Fig. 1. Fractionation procedure used in the study

Optical analysis included cell type analysis and particle dimension analysis. Cell type analysis of the fractions was done in a Finnish pulp and paper analysis laboratory, KCL, according to the KCL method and ISO 9184 standard. Fiber Atlas (Ilvessalo-Pfäffli 1995) was used in cell type identification. In microscopic cell type analysis, the microscope slide is moved horizontally and particles crossing the mark in the microscope eyepiece are counted. When the edge of the slide is reached, the slide is moved vertically 5 mm and a new horizontal line is counted. If a particle crosses the line several times it is counted as a new particle every time. For cell dimension analysis microscope slides of low consistency were prepared, and pulp fractions were photographed using a Leica MZ FLIII stereomicroscope, moving the slide as described above. Cell length and width were measured from the pictures by hand using 'vector' and 'chain' tools in Measurement module in commercial Leica IM50 software.

To do a statistically representative analysis, a suitable amount of measured particles for average particle length analysis according to standard presented above is 500 particles. In this study, we were looking for the largest and the smallest particles on each cell type class and only particles that were clearly large or small in each cell type class were measured. Therefore, there was no need for 500 measured particles. Anyhow, several hundred particles were checked and dimensions for at least 155 particles were measured for each cell type. In addition to microscopic particle dimension analysis, the fractions were also analyzed using a kajaaniFiberLab fibre analyzer. Sample preparation was made according to the TAPPI T271-standard where recommended amount for the particles measured in analysis is 5000. In the analyzer, a sample with low consistency is prepared and individual cells passing through a narrow capillary are photographed. An automatic image analysis is used to determine various cell properties, fibre length and

width, for example. Centerline cell length was used in the study, such that a true length for bent fibres is reported, not the length of projection of the bent fibre.

RESULTS

Microscopic Analysis of Wheat Straw Pulp

A pulp sample was photographed and the cell dimensions were measured. Fibrous material was defined as elongated cells excluding vessels, parenchyma cells, and epidermal cells, which were counted as separate categories. The maximum and minimum cell dimensions measured (length and width) and calculated aspect ratios (i.e. length-to-width ratio) are presented in Table 1. Also the range of particle dimensions, within 95% of the particles belonged is presented. Small rings and unwound spiral thickenings, originating from annular and spiral vessels, were seen in the photographs. The diameter of the rings was in a range of 10-50 μm.

Table 1. Particle Dimensions Measured Using Microscopic Analysis

	Fibrous material	Vessels	Parenchyma	Epidermal
Length				
Min-Max (mm)	0.13-3.18	0.08-1.42	0.04-1.5	0.01-0.36
95% (mm)	0.2-2.4	0.2-1.1	< 0.5	< 0.30
Width				
Min-Max (μm)	10-40	10-200	10-170	10-50
95% (μm)	10-30	< 70	10-110	< 30
Aspect ratio				
Min-Max	5-133	2-120	1-30	1-20
95%	9-105	8-36	< 12.5	< 12.5

On the basis of a microscopic analysis and literature survey, wheat straw pulp components were divided into five categories according to the particle dimensions. The categorization is presented in Fig. 2 and the particle dimension limits for each category are presented in Table 2. Typical particles in each category are presented in Figs. 3 through 5. There are one or two dominating cell types in each category. Categories 1 and 2 (C_1 and C_2) include the material generally considered to be fibrous material: C_1 includes long fibrous material and C_2 short fibrous material. Wide and long vessel elements and parenchyma cells are in Category 3 (C_3), short wide parenchyma cells and vessel elements in Category 4 (C_4), and elongated epidermal cells, and short narrow parenchyma cells in Category 5 (C_5). The line between C_2 and C_5 was defined on the basis of the particle aspect ratio: the aspect ratio of the elongated epidermal and parenchyma cells were found mainly to be smaller than 12.5, while the aspect ratio for the fibrous material was higher. The finest material, for example, rings from annular vessel elements and small epidermal cells, is located in C_5.

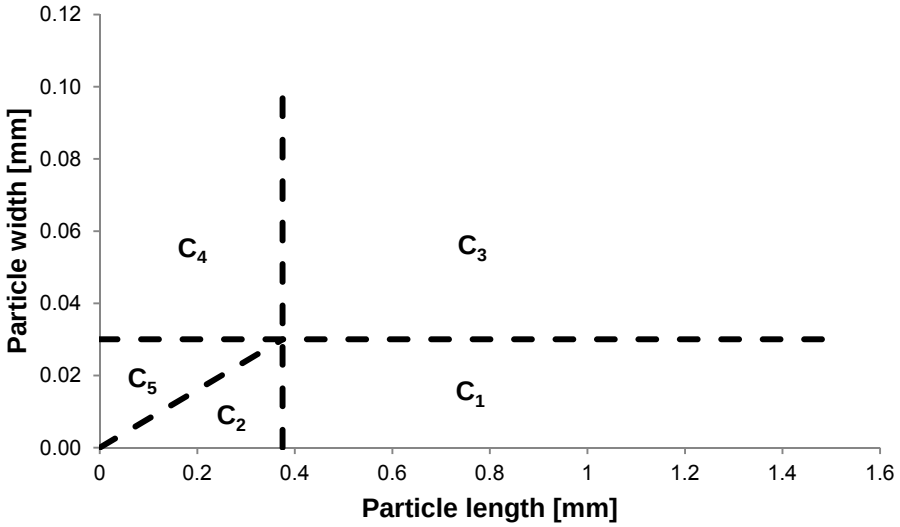

Fig. 2. Categorization of the particles according to the particle dimensions

Table 2. The Range of Particle Dimension for the Categories Presented in Figure 2

	Category 1	Category 2	Category 3	Category 4	Category 5
Length (mm)	≥ 0.375	< 0.375	≥ 0.375	< 0.375	< 0.375
Width (μm)	≤ 30		> 30	> 30	≤ 30
Aspect ratio		≥ 12.5			< 12.5

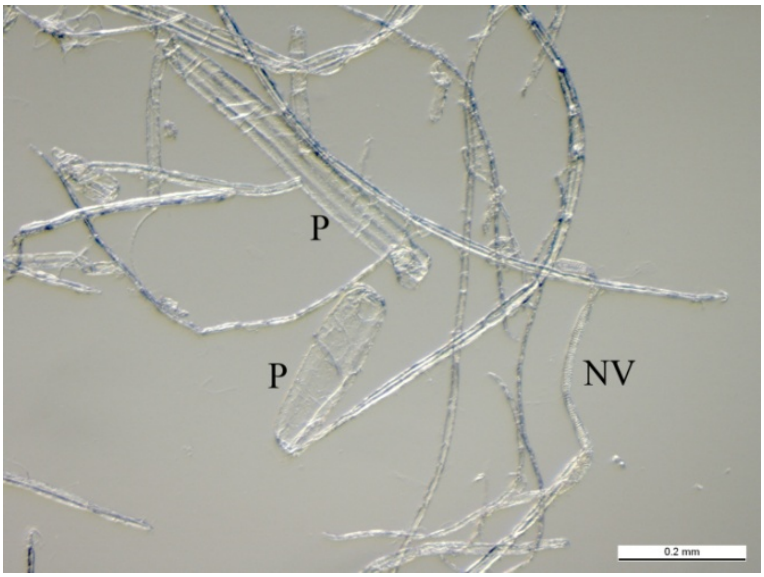

Fig. 3. Photograph of a wheat straw pulp. P = parenchyma cell, typical particle in C_3 and C_4. Narrow vessel element (NW) and other fibrous material in the picture are typical particles in C_1.

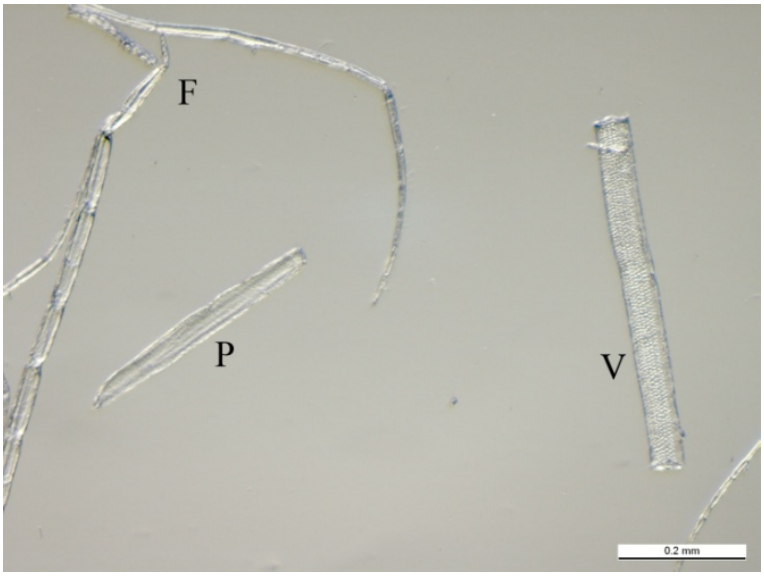

Fig. 4. Photograph of a wheat straw pulp. P = parenchyma cell, V = vessel element, typical particles in C_3, F = fibrous material, typical particles in C_1.

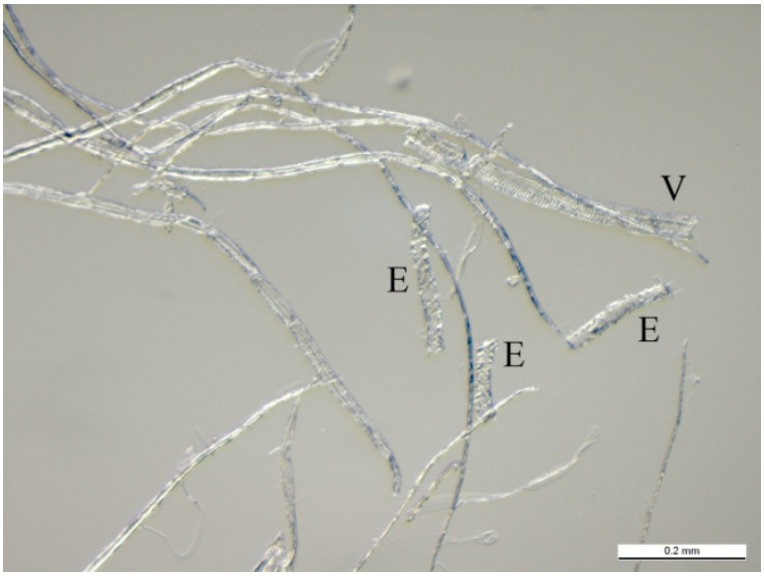

Fig. 5. Photograph of a wheat straw pulp. E = epidermal cell, typical particles in C_5, V = vessel element, typical particle in C_3. The fibrous particles in the picture are typical particles in C_1.

Analysis of Cell Types Using Automatic Fibre Analyzer

The categorization procedure presented above was used to divide data from automatic analysis, and the amount of the particles in each category was counted (Table 3). The automatic analyzer doesn't measure particle width for all cells and for the particles width less than 0.2 mm width weren't measured at all. Therefore, categories 4 and 5 were combined: the main components in the new combined category are parenchyma and epidermal cells. Only the particles with those widths were measured were taken into account in cell type analysis in other categories. Categories 1 and 2 were also summarized to determine the amount of fibrous material. The cell types of fraction-

ated pulp fractions were determined in KCL using microscopic analysis. Results from this analysis are also presented in Table 3. The measurement error for automatic analysis presented in Table 3 is calculated as the standard deviation of the mean for 95% confidence level for 10 replicates. Results from automatic optical analysis and microscopic analysis are compared in Fig. 6. A correlation between microscopic and automatic optical analysis for all cell classes is quite good, $r^2 = 0.875$. A categorization was not sensitive to the used category limits and the correlation remained when changes (±0.25 mm in length and ±5 μm in width) in the limits were made.

Table 3. The Cell Types of the Fractionated Pulps Determined by Microscopic and Automatic Optical Analysis (The Column 'Others' Includes Parenchyma and Epidermal Cells)

	Automatic optical analysis [%, number]			Microscopic analysis [%, number]		
	$C_1 + C_2$ Fibrous	C_3 Vessels	$C_4 + C_5$ Others	Fibres	Vessels	Others
Lo	67.2 ± 0.5	6.4 ± 0.2	26.4 ± 0.5	76 ± 5	7 ± 2	17 ± 3
Lu	62.0 ± 0.5	6.3 ± 0.2	31.7 ± 0.5	75 ± 5	3 ± 1	22 ± 5
So	33.5 ± 0.5	0.5 ± 0.2	66.0 ± 0.5	50 ± 5	4 ± 1	46 ± 5
Su	27.2 ± 0.5	0.6 ± 0.2	72.2 ± 0.5	28 ± 5	3 ± 1	69 ± 5

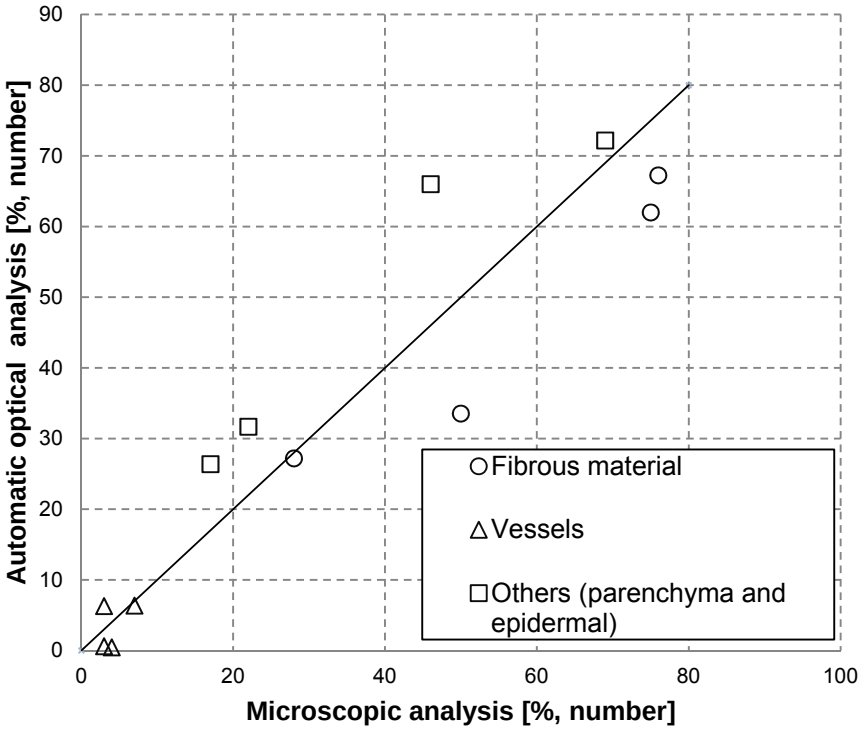

Fig. 6. Cell types of the fractionated wheat straw pulps measured by microscope and by automatic optical analysis

DISCUSSION

Microscopic Analysis of Wheat Straw Pulp

Wheat straw pulp was examined using a stereomicroscope. Various cell types exist in wheat straw pulp, some of which are easy to distinguish, but it requires a lot of experience to do extensive cell type identification. As a consequence, extensive microscopic analysis is time consuming to perform, and cells are usually only categorized into four groups: fibrous material, vessel elements, parenchyma cells, and epidermal cells.

Elongated cells with a high aspect ratio are usually referred to as fibres in wood-based pulps. These cells have a supporting function in the tree stem. Fibres also form the backbone of the paper and have a positive effect on paper strength properties. Wheat straw pulp contains various cell types that can be termed fibres, although a better term would be "fibrous material". These cells with a versatile function in the plant include fibres, tracheids, mestome sheath cells, collenchymas, and sieve tube members. A typical feature of the long fibrous material was that the cells were thin and the cell wall thickness was small in relation to fibres of the same length in wood-based pulps. The fibre width measured here was in the range of 10-30 μm; the average width is reported to be as small as 12.9 μm (Hua and Xi 1988). Slender morphology and a high microfibril angle (30-45º, Huo et al 1988) favour fibre flexibility, which can account for fibre curl values that were nearly double that of softwood pulp curl (data not presented). Previous works have shown that flexible thin-walled fibres are adaptive and have a large relative bonded area in the fibre network, thus forming a strong fibre network in paper (Paavilainen 1993, 1994). Increasing fibre flexibility is beneficial for sheet formation as flexible fibres form a more uniform fibre mat (Huber et al. 2008; Jokinen and Ebeling 1985).

It was noted that the particle length of the fibrous material of wheat straw pulp varies on a wide scale: fibrous material was measured from a fines fraction to long fibres with a length over 3 mm. Therefore, fibre length distribution is a somewhat intermediate form of softwood and hardwood pulp distributions and good papermaking properties of both pulps may be expected for wheat straw pulp fibres. Fibre lengths for wheat pulps have been reported by many authors, but most dimensions are measured using automatic optical analyzers and are, therefore, average values from the whole cell population. Average arithmetic lengths for wheat fibres (1.32 mm) have been reported by two authors (Wettstein 1962, Hua and Xi 1988). Dimensions for some special groups of fibre-like cells have also been reported: mestome sheath cells are fibrous cells that cover the vascular bundle in the wheat leaf. Kuo et al. (1974) reported that the mestome sheath cell length in a wheat leaf is in the range of 0.12 to 0.73 mm. Sieve tube members are elongated phloem cells that transport organic materials in the plant. Kuo and O'Brien (1974) reported that in wheat, both lignified and non-lignified sieve tube members exist. The diameter and length of sieve tube member lumen are 3 to 6 μm and 250 to 300 μm, respectively. They also observed that lignified sieve tube members have a thicker cell wall. Long fibrous material is in C_1 (see Fig. 2), while the short fibrous particles, for example sieve tube members, are in C_2.

Wide vessel elements were easy to recognize from wheat straw pulp due to the specific texture in the cell wall (see Fig. 4). The width of the wide vessel elements was similar to those reported in the literature (up to 60 μm, Ilvessalo-Pfaffli 1995). The vessel

element length measured here varied from 100 μm to 1.4 mm; Ilvessalo-Pfaffli (1995) reported vessel lengths of up to 1 mm. The function of the vessel element is to conduct water and dissolved minerals from the roots to the higher parts of plant. As a result, the primary cell wall is partly strengthened (annular rings and helical thickenings), or almost entirely covered (scalariform, reticulate and pitted vessels) with a lignified secondary wall. Large vessel elements cause a vessel-picking problem in papermaking when hardwoods are used (Ohsawa 1988; Panula-Ontto et al. 2007). Therefore, even though not reported, this vessel-picking problem may be expected when wheat straw pulp is used. It has also been reported that narrower vessel elements are located in the wheat leaf (diameter of 20 μm, Percival 1921). Long, narrow (width 10-20 μm) vessel elements with helical thickenings were found in microscopic observation. The cells were curly, which indicates that the cells are flexible. It may be assumed that narrow vessel elements can be entangled and form a network with fibrous material and are not harmful in papermaking, i.e. they do not promote vessel picking. In categorization, the narrow vessel elements are situated in C_1. Rings (diameter 10-50 μm), originating from the annular vessel elements, were found in the wheat straw pulp.

A diverse group of parenchyma cells exists in the aboveground part of wheat. The predominant parenchyma cell groups found in the samples were sac-like and elongated rod-like parenchyma cells. The function of these cells in the plant is to store water, nutrients, and assimilation products. The parenchyma cells full of water also support the plant with turgor pressure. A parenchyma cell has only a thin primary cell wall that, even though it is known that parenchyma cells with lignified wall exist, consists mainly of cellulose, hemicelluloses, and pectin. Pectin and hemicelluloses are known to work as glue that interlocks cellulose fibrils. (Evert 2006) Therefore, it may be expected that adaptable thin-walled parenchyma cells are beneficial for paper strength properties because they have a high specific surface area that increases the bonding area and they have a favorable chemistry for bonding. Unfortunately, at the same time a high specific surface area is detrimental to the dewatering of the paper web. The sac-like and rod-like parenchyma cell length was in the range of 0.04 to 1.5 mm, most of them being shorter than 0.5 mm. The width of these cells varied in the range of 10 to 170 μm. The results correspond with earlier studies: it has been reported that the diameter of parenchyma cells in a wheat stem is in the range of 35 to 100 μm and the length is in the range of 150 to 350 μm (Percival 1921), while the average parenchyma cell length in wheat is 0.40 μm (Wettstein 1962). Depending on the cell width, sac-like and rod-like parenchyma cells are situated mainly in C_4 and C_5, while the biggest cells are in C_3.

The epidermis is the outermost cell layer in the plant surface. The function of the epidermis is to control water balance and gas exchange, to support the plant body and to protect the plant from external threats. The epidermis is coated with a cuticle, which protects the plant and prevents water evaporation. The cuticle is a narrow waxy layer and, in consequence, very hydrophobic leaf surfaces are measured. It may be assumed that the wax-coated rigid bricklike hydrophobic cells are not beneficial to cell-to-cell adhesion in a paper web. It has been noted that small particles with low bonding ability cause a linting problem in paper and printing machines (Kleen et al. 2003; Westermark and Capretti 1988; Wood et al. 1999). The epidermis consists of several different kinds of cells: short and long cells, cells of stomata, and bulliform cells (Ilvessalo-Pfäffli 1995).

An elongated epidermal cell shape is characteristic of grasses but also other shapes, for example wavy and polygonal epidermal cells exist (Beck 2005). Elongated saw-edged cells (long cells) are the most easily identifiable of epidermal cells in wheat straw pulp (see Fig. 5). The length of the epidermal cells is reported to be in the range of 0.15 to 0.30 mm (Percival 1921) and up to 0.3 to 0.5 mm (Ilvessalo-Pfäffli 1995), while the average length of epidermal cells is 0.15 mm (Wettstein 1962). The width of an epidermal cell is reported to be in the range of 9 to 20 μm (Percival 1921). The dimensions measured here were 0.01 to 0.36 mm for length and 10 to 50 μm for width, which correspond well with earlier results. These short cells are located in the C5 in the categorization. Also, the existence of long elongated epidermal cells with lengths of up to 0.9 mm has been reported (Beemster and Masle 1996). In contrast to the shorter saw-edged cells, these long cells were not found among the fibrous material. A closer examination of undefibered epidermal cell plates revealed that the longest epidermal cells did not have any pattern in the cell wall and therefore the cells are very hard to identify.

Analysis of Cell Types Using Automatic Fibre Analyzers

Data from automatic analysis was categorized according to the method presented to determine the possibility of using this type of analysis in cell type determination. The results were compared to microscopic analysis, and quite a good correlation was found. The most detrimental issue that hinders cell type analysis according to cell dimensions is that the dimensions vary on a large scale; thus cell dimension distributions for different cell types partly overlap. Cell dimensions also vary slightly depending on the habitat and the weather conditions in which the plant lived in (e.g. Beemster and Masle 1996). As a result, compromises have to be made when the lines between the categories are drawn. In any case, categorization was not sensitive to the used category limits, and the correlation remained when changes in the limits were made. Therefore, the categories used may well be generalized for wheat straw pulps.

Automatic optical analysis seems to give a smaller proportion for fibrous material than microscopic analysis. By using the categorization based only on cell dimensions, long narrow particles, i.e. parenchyma cells, vessel elements and epidermal cells, were counted as long fibres with the category limits used. This does not cause a big error in cell type identification because the amount of long narrow parenchyma cells and vessel elements is small in relation to other particles, and long epidermal cells are probably counted as fibres in microscopic analysis, too. Exact identification is challenging in microscopic analysis too, and especially short wide fibres can be confused with parenchyma cells (Ilvessalo-Pfäffli 1995). Probably the biggest error in the fibre amount comes with short particles, where a large number of epidermal and different kinds of parenchyma cells exist. Hua and Xi (1988) reported a non-fibre material content of 37.9 percent in wheat, which is in the same order of magnitude as our value determined by automatic analysis for feed pulp, 45 percent.

Automatic analysis seems to give a higher proportion for fine material, i.e. parenchyma cells and epidermal cells, than microscopic analysis. In fact, when the fines proportion is high, automatic analysis may be better than microscopic method in particle counting: automatic analysis counts all the particles that pass the cuvette. In microscopic analysis, longer particles have higher probability to be counted. Most of the parenchyma

and epidermal cells are small cells, i.e. length of under 0.5 mm. Fibres with an average length of 1.3 mm have a higher probability of being counted. Therefore it is possible that the microscopic method overestimates the proportion of fibrous material and automatic analysis may give a more realistic picture of the short particle proportion. It should also be noted that cell type portions depends on defibering and other pulp processing, i.e. the quality of defibering and breaking of cells. Undefibered parenchyma and epidermal cell plates of many sizes were found in microscopic observation. Most of the plates were large, but small parenchyma and epidermal cell plates were also found. The cell plates were wide and situated in the automatic analysis in C_3 and C_4, i.e. in the vessel and parenchyma cell categories. The cell plates did not have a significant effect on cell type analysis because the amount of undefibered material is small. The undefibered cell plates cannot be recognized using only particle dimensions, and software that notices that the plate consists of several particles should be used. If the cell plates could be recognized, the category "undefibered material" could be used to characterize the wheat straw pulp cooking degree or demand for pulp further processing.

Epidermal cell dimensions partly overlap with other cell types. The saw-edged epidermal cells in wheat straw pulp can be distinguished from other cells using the characteristic pattern in the cell wall. Only saw-edged cells that are easy to identify are probably recognized in microscopic analysis; thus other epidermal cells are counted as fibres or parenchyma cells. The smallest cells, with a diameter of a few micrometers (silica, stomatal and cork cells), are probably omitted. On the other hand, automatic analysis cannot categorize cells better unless some specific identification marks for epidermal cells are used.

The amount of vessel elements was determined in automatic analysis as a particle amount in C_3. There are some factors that complicate vessel element identification. Other cell classes include a large amount of different cells, but the vessel element category is a small exactly defined group of cells with varying morphology. As the group is small, a small error in particle counting causes major errors in relation to other groups. Varying morphology is not a problem in microscopic calculation because the vessels can be identified using thickenings in the secondary wall, but identification does not work when morphology alone is used in automatic analysis. Large parenchyma cells have dimensions like large vessel elements and are counted as vessel elements in the categorization used. This caused inaccuracy in the Lo and Lu fractions that consisted of larger particles. In automatic analysis, narrow vessel elements are counted as fibres (C_1), and short vessel elements that have dimensions like short sac-like parenchyma cells (C_4), are counted as parenchyma cells. This diminished the vessel amount in small particle fractions (So and Su). Therefore, vessel element identification based only on cell dimensions cannot work absolutely. Other characteristic features, for example fibre transparency or thickenings in the secondary wall, have to be used in vessel element identification for wheat straw pulps. On the other hand, the total vessel amount may not be critical from the perspective of papermaking because the narrow vessel elements can be assumed to behave like fibrous material. The amount of short, wide vessel elements may be more critical, because they are more likely to contribute to the vessel-picking problem.

Particle staining is used to improve the contrast between the background and the cell in microscopic analysis. There are also many staining procedures for recognizing

cells with a certain surface chemistry. Staining procedures, for example, for lignified and cellulosic material, are presented in the standards, and more versatile procedures can be found from the literature. Unfortunately, staining is not as useful in automatic analysis when black-and-white cameras are used. The staining procedure also makes the analysis more complicated and slower to perform.

CONCLUSIONS

Wheat straw consists of a variety of cell types with wide distributions of cell dimension. A method is introduced to categorize wheat pulp cells into five main types based on length, width, and aspect ratio of particles, each category enriched with different type cells. The method could be applied in automatic optical fibre analyzers to determine wheat straw pulp cell types. Fibrous material, parenchyma, and epidermal cells as well as wide vessel elements can be identified and their amount monitored in various process stages and the effect of wheat straw pulp constituents on the properties on various end uses, e.g. on paper properties, can be studied.

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