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Characterization of mechanical and chemical pulp fibers

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ABSTRACT

Basic fiber properties can be classified into four categories: Size distribution, shape, structure of the cell wall and the fiber surface. This approach was used when long fiber fractions separated from 10 different mechanical pulps and unrefined and refined chemical pulp samples were compared in order to shed light on the different reinforcing abilities of chemical and mechanical pulp fibers. The long fiber fractions were analyzed using a variety of fiber analyzers and testing methods. The commercial analyzers for determining the size distribution and shape of the fibers were the FS-200, MorFi, FiberMaster and CyberSize analyzers. In addition, light microscopy was used for several purposes. The structure of the cell walls was studied using the CyberFlex analyzer (flexibility was analyzed using the Steadman method) and the FSP (fiber saturation point), FBW (free bound water), NFW (non-freezing water) and WRV (water retention value) were analyzed. The internal fibrillation was evaluated using Simons staining (light microscopy). The zero-span method was used for fiber strength analysis and the RBA (relative bonded area) was determined using the a CyberBond analyzer. The chemical composition (lignin and extractives coverage) of the fiber surfaces was analyzed using ESCA.

The results indicate that the most essential differences between chemical and mechanical pulp fibers can be found in the cell wall structure rather than in the fiber dimensions. The cell walls of chemical pulp fibers are more porous and internally fibrillated and, as a result, more flexible, conformable and swollen than those of mechanical pulp fibers. They are also stronger when analyzed using the zero-span method. In addition, surface lignin or extractives do not limit bonding as in the case of mechanical pulps. Thus, chemical pulp fibers can be more active in sheet forming and consolidation than mechanical pulp fibers. The possibilities for modifying the properties of mechanical pulp fibers in order for them to perform more like chemical pulps will be studied in the further research.

INTRODUCTION

Wood-containing papers are usually reinforced with chemical pulp fibers in order to ensure that the paper web is durable enough during the manufacturing process and downstream operations. Long-fiber mechanical pulp can be used to partially substitute chemical pulp in order to obtain the same toughness. However, there is evidence that mechanical pulp fibers have relatively worse reinforcement properties than chemical pulp fibers. One indication of this is that coated papers that contain TMP as a mechanical pulp component contain almost the same amount of chemical pulp as those composed of GW or PGW, even though the average fiber length in a TMP-based furnish is much higher than in a groundwood-based one.
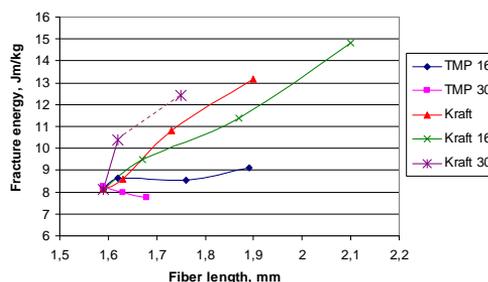

Figure 1. The fracture energy as a function of the average fiber length of a pulp furnish that contains TMP and different long fiber fractions. Chemical pulp (SW kraft) and its long fiber fractions increase the fracture energy much more than do mechanical pulp fibers.

In the previous study (1), it was shown that chemical pulp fibers give the pulp furnish a much higher tear index and fracture energy than do mechanical pulp fibers, even at equal fiber length. In the study in question, the fiber properties were characterized only by rather conventional methods such as fiber length and coarseness analysis and standard hand sheet testing. This approach enabled speculation as to the possible reasons for the differences in the reinforcement ability but no definite answer.

Heikkurinen et al. (2) have suggested that the basic fiber properties can be classified into four classes.

-     Size distribution
-     Shape
-     Structure of the cell wall
-     Fiber surface

This classification has been used in this study.

The objective of this study was to investigate in which respects chemical pulp and mechanical pulp fibers differ the most from each other and, in that way, to get ideas as to the reasons for their different abilities for reinforcing mechanical pulp.

MATERIALS AND METHODS

The long fiber fractions were separated from different mechanical pulps as well as from refined and unrefined chemical pulps. All the pulps were mill-scale pulps. The mechanical pulps were thermomechanical pulps (TMP; five different pulps, of which three were from Finland and two from France), groundwood (GW) pulp, pressure groundwood (PGW) pulp, pulp for medium density fiberboard (MDF) and TMP reject (abbreviations in the graphs: unrefined and refined; TREJu and TREJr). One of the TMP pulps (no. 5) had been manufactured in the RTS process. The TMP pulps were sampled from the second refining stage outlet. The chemical (kraft) pulps were sampled prior to and after a mill refiner (abbreviations in the graphs: BKPu and BKPr; bleached kraft pulp unrefined and refined).

Fractionation was performed using a Bauer-McNett classifier with 10-mesh, 16-mesh and 30-mesh sieves. The amount of pulp was 40 g and the fractionation time 30 minutes. The shives were removed from the 10-mesh fraction using a Somerville apparatus (a screen plate with 0.15-mm slots) before being admixed to a mixture of the 16- and 30-mesh fractions. Thus, the long fiber fraction of this study could be labelled as the R30 fraction.

The fractions pulps were analyzed at various institutes for their properties as shown in Table 1.

The sample preparation and FS-200 and WRV analyses were performed at UPM-Kymmene's Kaukas Research Center in Lappeenranta, Finland. The FiberMaster analyses were performed by PFI, Norway, and the MorFi, CyberSize, CyberFlex and CyberBond analyses by CTP, France. KCL, Finland, carried out the light microscopy analyses for internal and external fibrillation and performed the zero-span measurements and the flexibility analysis using the Tam Doo & Kerekes method. The FSP, FBW, NRW and ESCA analyses were performed at Helsinki University of Technology.

All the test methods and analyzers used in this study, are discussed in detail in the thesis by Huurre (3). In addition, some of the commercial analyzers used in this study were recently described and compared in the paper by Turunen et al. (4).

Table 1
The measured fiber properties and analyzers or methods classified according to the basic fiber property category.

Basic fiber property category	Measured property	Analyzer or method
Size distribution	Fiber length	FS-200, FiberMaster, MorFi
	Fiber width	CyberSize, FiberMaster, MorFi
	Cell wall thickness	Light microscopy
	Coarseness	MorFi
Shape	External fibrillation	Light microscopy, CyberSize
	Curl	CyberSize, FiberMaster (Shape factor), MorFi
	Kinks	CyberSize, FiberMaster, MorFi
Structure of cell wall	Flexibility, stiffness	CyberFlex (Steadman), Tam Doo & Kerekes
	Fiber wall porosity	FSP, FBW, NFW, WRV
	Internal fibrillation	Simons staining, light microscopy
	Fiber strength	Zero-span
	RBA	CyberBond
	Conformability	CyberFlex (Steadman)
Fiber surface	Chemical composition	ESCA (Extractives and lignin coverage)

RESULTS

Size Distribution

Fiber Length

The fiber length was analyzed using several different analyzers. The results obtained using the FiberMaster and MorFi correlated well with each other but those obtained using the FS-200 differed from those obtained using the two previously mentioned analyzers.
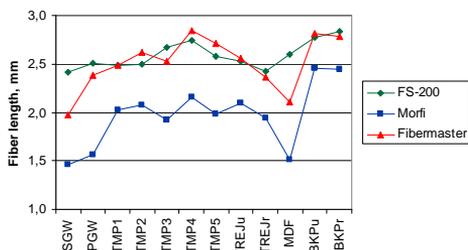

Figure 2. The weighted average fiber length of the pulp fractions.

As can be seen, the results depend on the analyzer used. The MorFi results show that the chemical pulp fibers are clearly longer than any of the mechanical pulp fibers, while the FS-200 or FiberMaster results indicate that the mechanical pulps can have as long fibers as the chemical pulp.

TMP3, which was found to have a long average fiber length using the FS-200 analyzer, is a relatively coarse newsprint grade pulp. TMP4 is produced mainly from long-fiber saw mill chips. In the previous study, from which Figure 1 is taken, the used pulp was sampled from the same line as TMP2.

Fiber Width

The long fiber fractions were analyzed for the fiber width using four different methods. The results were quite contradictory. MorFi and FiberMaster gave reasonably parallel results, while the results of neither the light microscopy method nor the Cybersize analysis correlated with each other or with the former two. It is clear that the methods are not directly comparable because, for instance, in the Cybersize analysis, the fibers are pressed against a glass plate and are dry when analyzed. In the MorFi and FiberMaster analyses, on the other hand, the fibers are in a wet state. Perhaps, the Cybersize test gives the best indication of the fiber width in a dry paper sheet.
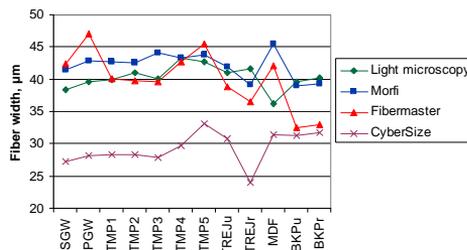

Figure 3. The fiber width analyzed using four different methods.

The results given by the MorFi and FiberMaster analyzers show that chemical pulp fibers are narrower than mechanical fibers; light microscopy (wet sample) supports this claim, while Cybersize tells a different story.

Cell Wall Thickness

The cell wall thickness was analyzed under a light microscope from a wet sample only.
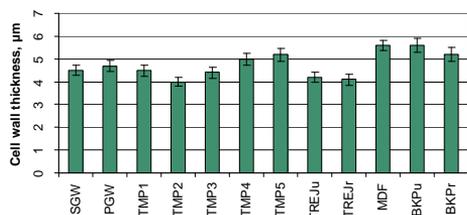

Figure 4. The cell wall thickness analyzed using light microscopy.

The pulps were not made from the same raw material, which, along with the different processes, explains the differences. The high saw mill chip content of TMP4 and TMP5 seems to be reflected in the high cell wall thickness of these pulps. TMP2 and both TMP rejects have thin cell walls, which is well in line with the fact that the TMP reject is derived from TMP2. The thick cell walls of MDF pulp probably contain the remains of the middle lamella. The thick cell walls of chemical pulp are either the result of the raw material that contains a large proportion of sawmill chips or are swollen.

Coarseness

Coarseness was analyzed using both the MorFi and FiberMaster analyzers. The results given by these analyzers correlated with each other, but neither the results given by the MorFi nor those given by the FiberMaster analyzer correlated with the thickness of the cell wall measured using light microscopy.
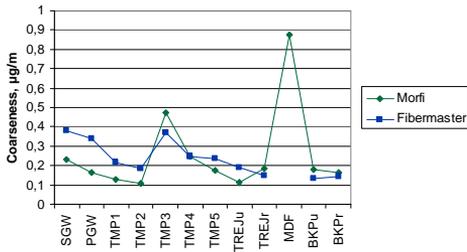
Figure 5. Coarseness analyzed using the MorFi and FiberMaster analyzers.

A very high coarseness value was obtained for MDF using the MorFi analyzer. Although it is clear that the MDF fibers are coarse, it is hard to believe that the difference between MDF and normal fibers is that great. As for the difference between mechanical and chemical pulps, the MorFi analysis indicated that chemical pulp fibers do not differ from mechanical fibers. The results of the FiberMaster analysis, on the other hand, indicated that chemical pulp fibers are less coarse.

Shape of Fibers

External Fibrillation

The degree of external fibrillation was evaluated using light microscopy and CyberSize analysis. The results given by these two methods do correlate with each other, although there are marked differences in the analysis principles. However, as can be seen in Figure 6, the microscope analysis showed that the two French TMPs (TMP4 and TMP5) are clearly different from the rest; about 70 % of the fibers are classified as being fibrillated. In the CyberSize analysis, they do not deviate from the rest.
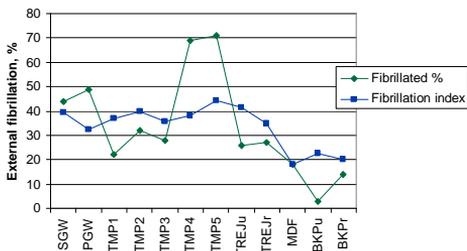
Figure 6. External fibrillation. The percentage of fibrillated fibers obtained using light microscopy (a KCL method), the fibrillation index analyzed using the CyberSize analysis.

The CyberSize analysis is made for fiber dried against a glass plate, and it may be that during the drying stage the fibrils have been aligned on the fiber surface and are, therefore, not detected in the analysis. Both methods showed chemical pulp to be less fibrillated than mechanical fibers. The microscopy analysis revealed the effect of beating on fibrillation, while CyberSize analysis did not.

The low level of external fibrillation of MDF is a sensible result taking the nature of the process into consideration, as it is well-known that fiber separation in the MDF process takes place in the middle lamella, which means that the possibilities for fibrillation are limited.

Curl

The curl index was analyzed using MorFi and is inversely proportional to the shape factor, which was analyzed using FiberMaster. The curl index profile by Cybersize has common features with MorFi but ranks chemical pulp differently in comparison to mechanical pulps.
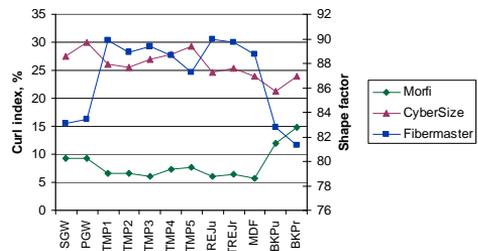

Figure 7. The curl index given by MorFi and CyberSize and the shape factor given by FiberMaster.

In a slurry, flexible chemical pulp fibers take a more curled configuration than stiff mechanical pulp fibers. The test set-up of CyberSize is different from that of MorFi and FiberMaster, which may explain the differences between the behaviors of these analyzers.

According to Mohlin and Alfredson (5), mill refining does not change the curl index of chemical pulp. Thus, no major changes should take place in the measured kinks either.

Kinks

The percentage of kinked fibers and curl measured using MorFi correlate with each other very strongly (r=0.97). It is obvious that distinguishing between a curl and a kink is difficult in image analysis. In any case, the MorFi analysis showed that chemical pulp fibers are markedly more kinked than mechanical fibers. The CyberSize analysis showed that chemical pulp fibers do not differ from mechanical fibers; therefore, the results for the refining of chemical pulp using CyberSize and MorFi are in contradiction with each other.
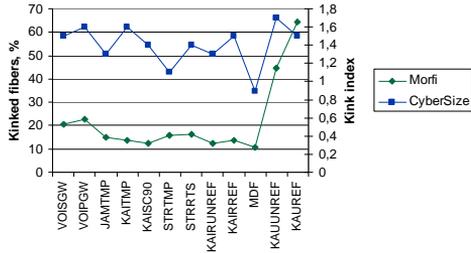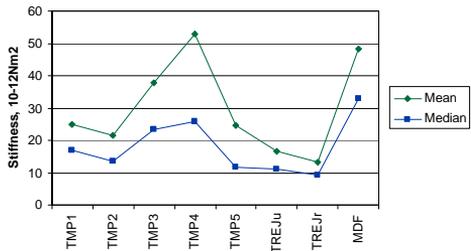
Figure 8. The kinks analyzed by MorFi (kinked fibers, %) and CyberSize (kink index).

Structure of the Cell Wall

Stiffness and Flexibility

The fiber stiffness was analyzed at KCL using the Tam Doo & Kerekes method. Unfortunately, it was not analyzed either for groundwood or chemical pulps.

Figure 9. The stiffness results given by the Tam Doo & Kerekes method.

The mean and median curves follow each other quite closely. However, the median is perhaps a better indicator of stiffness, because it rates MDF as being the stiffest pulp, as one would expect. The effect of refining TMP rejects looks very moderate. One can also ask why unrefined TMP reject fibers are less stiff than the parent pulp.

When stiffness is evaluated in terms of flexibility or conformability values (the correlation between these indicators is almost by 100 %) using CyberFlex, one can see that all the mechanical and chemical pulps are in different categories. The term conformability is analyzed simultaneously with flexibility; the only difference is that in conformability the fiber width is not taken into consideration.
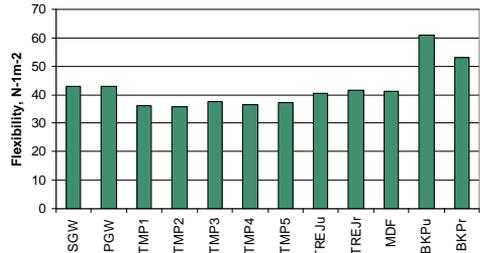

Figure 10. Flexibility measurements obtained using the Steadman method (analyzed using CyberFlex).

Groundwood fibers seem to be some more flexible than TMP fibers, which might be true considering that groundwood fibers are typically more damaged than TMP fibers. The result that MDF was more flexible than the other refiner pulps sounds unconvincing. The refining of the TMP reject increased its flexibility only marginally. For some reason, the refining of chemical pulp decreased the flexibility of that pulp.

Swellability and Cell Wall Porosity

The swellability of fibers was evaluated using FSP (Fiber Saturation Point) and WRV (Water Retention Value). FSP was determined using solute exclusion techniques. Cell wall porosity was evaluated using DSC (Differential Scanning Calorimetry) based on the method developed by Maloney (6).
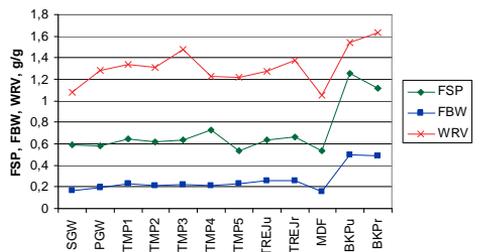

Figure 11. Fiber saturation point (FSP), freezing bound water (FBW) and water retention value (WRV).

The correlation between FSP and WRV is significant (r=0.76). However, the correlation of FSP with FBW is even higher (r=0.96). The correlation coefficients are somewhat misleading, because much of the correlation value is due to the grouping of the observations in two categories; mechanical pulps and chemical pulp. For the mechanical pulps, the correlation coefficients are markedly lower.

All the three analyses distinguish chemical pulp from mechanical pulps. MDF differs from the rest in that it has the lowest values in all the analyses. Only the WRV method reveals the effect of refining in an expected manner.

Cell Wall Deformations

External fibrillation can be described as macro-fibrillation. The Simons staining technique offers a good possibility to obtain an idea of the small-scale deformations (delamination, fibrillation or damages) in the outer fiber wall. One can also talk about internal fibrillation in this context. In Simons staining, the areas of the fiber surface that are fibrillated or damaged stain yellow. Interestingly, the number of yellow stained fibers does not correlate with the number of fibrillated fibers. Instead, it correlates significantly with FSP, FBW and WRV, which means that all these analyses provide indications of the same phenomena.
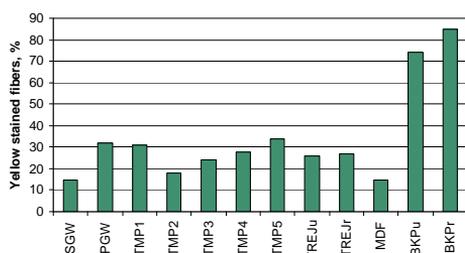

Figure 12. Internal fibrillation as indicated by Simons staining.

Figure 12 shows how most of the chemical pulp fibers stain yellow, which indicates that their fiber surface is markedly more open or porous than that of mechanical fibers. The refining of chemical pulp increases the number of yellow-stained fibers, although perhaps surprisingly, the refining of the TMP reject seems to have virtually no effect. MDF and GW fibers are the least damaged. As for GW, this result is in line with that of WRV but not with those of FSP and FBW.

Relative Bonded Area (RBA)

The relative bonded area (RBA) is not actually a basic fiber property in the original model of Heikkurinen et al. (1). However, it can be kept an indirect indicator of the cell wall structure, since it is evident that it is influenced by internal fibrillation, swellability and flexibility together with the cross-sectional dimensions of the fiber.
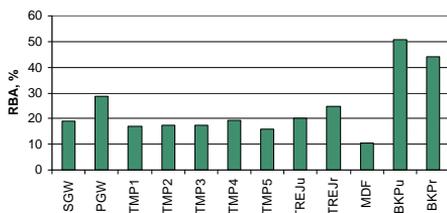

Figure 13. The relative bonded area (RBA, analyzed using CyberBond).

RBA correlates well with, for instance, yellow-stained fibers. Yet, a few contradictory results were observed; one such result was that RBA decreases during the refining of chemical pulp although one would assume the the opposite. On the other hand, flexibility and conformability also decreased at the same time.

Fiber Strength

The zero-span method was used to evaluate the fiber strength.
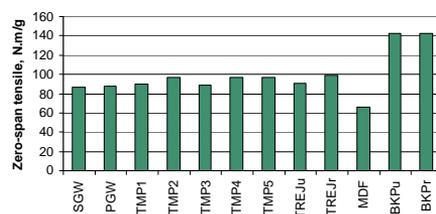
Figure 14. The zero-span tensile index for dry sheets.

No major differences were observed between mechanical pulp fibers with the exception that MDF is much weaker than the other pulps. The test sep-up of the zero-span method is designed to ignore the effect of bonding between fibers. In this case in which MDF has a very low bonding ability, one can ask whether or not this affects zero-span as well. Virtually all the properties related to bonding (such as the tensile index and Scott bond) correlate with zero-span. Therefore, does zero-span measure the fiber strength or bonding? Refining the TMP reject almost doubles the tensile index but improves the zero-span tensile strength by only 10 %, and accordingly, the refining of chemical pulp increases the tensile index by 60 % but does not affect zero-span at all. Thus, the impact of bonding cannot be fully ignored, while on the other hand, it does not explain all the changes that occur in the zero-span tensile strength. The low zero-span of MDF is likely to be not only due to its low bonding but also due to its high coarseness, which means that the relative amount of molecules that cannot carry the load in the fiber properly is higher than in the other pulps. In chemical pulp, the share of cellulose molecules is the highest, and consequently, zero-span tensile srength the best.

Fiber Surface
ESCA Analysis

The results of the ESCA (Electron Spectroscopy for Chemical Analysis) analysis can be translated into extractives and the lignin coverage of fibers.
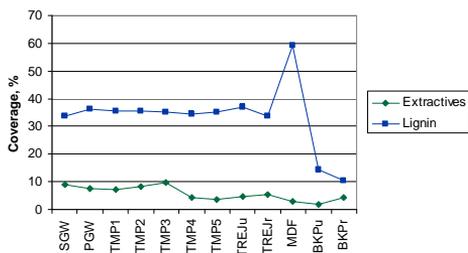
Figure 15. The fiber coverage by extractives and lignin as indicated by the ESCA analysis.

The extractives coverage of normal mechanical pulp varies from 3.5 % to 9.7 %. It is obvious that different process and raw material parameters influence the result, and it is difficult to say, for instance, whether or not the relatively low coverage degree of the French TMP samples is due to a different wood species or a different white water system. The very low extractives coverage of MDF might have resulted from the high process temperature that causes extractives to evaporate to a greater extent than in other mechanical processes.

Also, the high lignin content of MDF can also be explained by the high process temperature together with minute refining. The fibers are separated along the lignin-rich middle lamella and the cell wall layers that contain less lignin are not exposed by refining.

The low lignin coverage of chemical pulp fibers is a natural result. However, it is probably higher than one might expect when taking into consideration the low bulk lignin content of these fibers. The coverage of extractives is also relatively high. Evidently, chemical pulp, particularly when refined, effectively adsorbs extractives from the process water.

Conclusions

Size Distribution

The differences between the mechanical and chemical pulp fibers were rather limited in terms of the size distribution. The fibers of the chemical pulp were somewhat or clearly longer (the results depend on the analyzer used) than mechanical pulp fibers, which naturally explains the better reinforcement ability of chemical pulp in practical situations but not in the case in which mechanical pulp and chemical pulp fibers are compared at the equal average fiber length of a pulp furnish.

Chemical pulp fibers had about the same or lower coarseness, were narrower (excluding CyberSize) but had thicker cell walls than mechanical fibers. Obviously, chemical pulp fibers are more swollen than mechanical fibers. The coarseness of the different mechanical pulps varies a lot and, at its lowest, comes quite close to or is even less than that of chemical pulp in spite of the

difference in yield. In mechanical pulping, the outer layers peel, which decreases coarseness.

Shape

Chemical pulp fibers are less externally fibrillated than mechanical pulp fibers, and under a microscope they look more or less intact. This can be interpreted to mean that large-scale, clearly visible external fibrillation cannot be the only key to a good bonding and reinforcing ability.

Both analyzers (MorFi and FiberMaster) that measure curl from diluted pulp slurry indicated that chemical pulp fibers are more curled than mechanical fibers. It is likely that flexible chemical pulp fibers just get bent in the turbulent flow of the analyzers and the results tell more about flexibility than anything else. The more pronounced curliness of chemical fibers could partially explain the high stretch at break which is typical for chemical pulp.

When curl is determined using an analyzer (CyberSize), in which the fibers are allowed to filtrate on a wire, the result is the opposite; chemical pulp fibers are less curled than mechanical fibers. This analysis also gives a much higher level of curl than the other two.

As for kinks, the MorFi results indicate that chemical pulp fibers are much more kinked than mechanical fibers. However, because MorFi's curl and kink results have a very high mutual correlation, one can question if it really detects kinks correctly. Based on the CyberSize results, chemical fibers do not differ from mechanical fibers essentially.

Cell Wall Structure

The stiffness and flexibility measurements are prone to different disturbing factors. The stiffness given by the Tam Doo & Kerekes method could not be analyzed for groundwood or chemical pulp fibers. The former fibers were too broken and the latter too flexible. The Steadman-Mohlin method (CyberFlex) indicated that chemical pulp fibers are definitely more flexible than mechanical pulp fibers.

Several analyses show that the walls of chemical pulp fibers are more porous than those of mechanical fibers. For instance, the fiber saturation point (FSP) is about double for chemical pulp fibers in comparison to that of mechanical fibers. The same is true for freezing bound water (FBW). The water retention value (WRV) is also much higher for chemical pulp fibers. The results for Simons staining strongly support the observation that the cell walls of chemical pulp fibers are more porous or, in a word, looser than those of mechanical fibers.

The relative bonding area (RBA) is likely to depend on several dimensional and structural factors. Thus it is not a basic property by definition. However, it supports the

idea that chemical pulp fibers are more flexible or conformable than mechanical fibers.

The fiber strength determined by the zero-span method is, in a way, comparable with RBA, because other factors as well, such as bonding or fiber damages, can affect it. The zero-span tensile index of chemical pulp fibers was more than 40 % higher than that of mechanical fibers. This does not necessarily mean that individual chemical pulp fibers were stronger than mechanical fibers. In any case, a given amount of chemical pulp fibers definitely gave a higher zero-span tensile strength for a furnish than mechanical pulp fibers ever could. This is a distinctive difference between chemical and mechanical pulps. Fortunately, the fact that the degree of bonding of a typical printing paper is not very high may mean that the fiber strength, as such, is not the decisive factor that prevents the use of mechanical pulp fibers as the reinforcement fibers.

Fiber Surface

The fiber surfaces of mechanical and chemical fibers are certainly different, especially with respect to lignin coverage, which is round 10 % for refined chemical fibers in comparison to 35 % for mechanical fibers. A high lignin coverage is likely to have a significant effect on the bonding ability of mechanical fibers. The difference in the extractives coverage is much smaller. In addition, it is obvious that the effect of the extractives coverage is much smaller, because it varies within a wide range between different mechanical pulps without any correlation with bonding ability (determined by tensile index).

In summary, what are, then, the biggest differences between chemical and mechanical pulp fibers according to this study? Briefly, we can say that the differences are rather of a structural than of a dimensional nature. In addition, there are differences in the surface chemistry. All this means that chemical pulp fibers can be much more active in sheet forming and consolidation. This study has indicated that the fibers should simply be made more flexible and conformable without sacrificing their strength.

As for the commercial fiber analyzers that were used in this study, it is very hard to say which of them is the most useful and reliable. Generally speaking, their results correlate with each other and they give a roughly similar general picture of the different fibers. Nevertheless, several cases were observed in which one cannot be sure of what device gives the correct result. One can only wish that such versatile and easy-to-use analyzers as the FiberMaster and MorFi are developed so that they give the same results in all cases.

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