Publication III

Lehto, J., Koskenhely, K., Paulapuro, H. 2007. The role of chemical and mechanical pulp fibres in LWC base paper. PTS pulp technology symposium, Dresden, Germany, 27-28 Nov. 2007, Munich, Germany, PTS, Paper 9, 17 p.

9 Die Rolle von Zellstoff- und Holzstofffasern in LWC-Rohpapieren

The role of chemical and mechanical pulp fibres in LWC base paper

J. Lehto, Lappeenranta, Finnland
K. Koskenhely, Espoo, Finnland
H. Paulapuro, Espoo, Finnland

Zusammenfassung

Teure Zellstofffasern werden in LWC-Rohpapieren benutzt um das Fasernetzwerk so zu armieren, daß die Papierbahn stark genug für gutes Laufverhalten ist. Preiswerter Holzstoff wird benutzt um die Glätte und die optischen Eigenschaften des Rohpapiers zu verbessern. Wir haben untersucht, könnten die langen Fasern der Refiner-Holzstoffe erhebliches Armierungspotential geben, und dadurch den Bedarf an Zellstoff zu vermindern.
Die Absicht dieser Forschung war die Grundverschiedenheiten zwischen Holzstoff- und Zellstofffasern herauszufinden, ihren Einfluss auf die Festigkeit der Laborblätter zu messen und die möglichen Ursachen für die Verschiedenheiten in ihrem Armierungsverhalten zu klären.
Die Ergebnisse bestätigen, daß die Faserdimensionen von Holzstoff- und Zellstofffasern ziemlich verschieden, oder in gewissen Fallen beinahe gleichwertig sein können. Die wichtigsten Unterschiede zwishcen diesen zwei Fasertypen ihre Flexibilität, Zellwandstruktur, Faserfestigkeit und die Qualität der Faseroberfläche sind. Diese Unterschiede zwischen Fasern zeigen sich in ihrer Fähigkeit als Armierungsfasern in Laborblättern zu funktionieren. Im allgemeinen, wurde es bestätigt, daß die Ezsetzung von Zellstofffasern mit Holzstofffasern verschlechtert alle Festigkeitseigenschaften der Laborblätter, verbessert Durchlässigkeit und verschlechtert Rohdichte. Im dem gewissen Fall, wo 10 % von Zellstoff mit der langen Fraktion von thermomechanischem Holzstoffspuckstoff ersetzt wurde, es war wirklich möglich dasselbe Niveau der innerer Bindekraft und des Durchreissfaktors wie das Niveau von chemischem Armierungsstoff zu erreichen. Es scheint, daß man mit richtiger Behandlung von Holzstofffasern mindestens den Zugfestigkeitsindex und die Zugfestigkeit so verbessern könnte, daß das Niveau von Zellstoff erreichbar wäre. Das würde auch die Bruchenergie von Holzstoff zu verbessern helfen, die immer deutlich niedriger war als die Bruchenergie von Zellstoff. Es kann jedoch ganz unmöglich sein das Niveau von Zellstofffasern mit Holzstofffasern zu erreichen, weil die Holzstofffasern unbestreitbar schwächer sind und ihre Weiterbehandlung sie leicht noch schwächer macht.

Abstract

Expensive chemical pulp fibres are used in LWC base paper to reinforce the fibre network so that the web is sufficiently strong for good runnability. Less expensive mechanical pulp is used to improve the smoothness and optical properties of the base paper. We studied whether the long fibres of refiner mechanical pulps could provide a marked web reinforcement potential and so reduce the chemical pulp need. The aim of this study was to clarify the basic differences between mechanical and chemical pulp fibres, to measure their effect on hand sheet strength, and to develop possible reasons for the differences in the fibres' reinforcement performance. Results indicate that fibre dimensions of mechanical and chemical pulp fibres can be quite different or in certain cases be virtually equal. The most significant differences between the two types of fibre are the fibre flexibility, cell wall structure, fibre strength, and quality of the fibre surface. These differences as such reflect the fibres' capability to act as reinforcement fibres in the hand sheets. Generally, it was found that replacement of the chemical pulp fibres with mechanical pulp fibres decreases all of the hand sheet strength properties, increases the permeability, and decreases the bulking density. In the certain case when 10% of the chemical pulp was replaced with the long fibre fraction of a refined TMP reject, it was indeed possible to reach the same internal bond level and tear index as that of the chemical reinforcement pulp. It seems that with proper treatment of mechanical pulp fibres at least the tensile index and tensile stiffness could be improved to more closely approach that of the chemical pulp. This would also help to improve the fracture energy of mechanical pulp which was always clearly less than that of the chemical pulp. However, getting to the same level as that of the chemical pulp fibres may be an impossible task since mechanical pulp fibres are inevitably weaker than chemical pulp fibres and further treatment of them easily makes them even weaker.

Liz.sc.techn. Jouko Lehto
UPM-Kymmene Oyj
UPM Research Center
53200 Lappeenranta
Finnland
Jouko.H.Lehto@upm-kymmene.com

Dr.-Ing.Kari Koskenhely
Helsinki University ofTechnology
Paper Technology
P.O.Box 6300
O2015 TKK
Finnland
kari.koskenhely@tkk.fi

Prof. Hannu Paulapuro
Helsinki University ofTechnology
Paper Technology
P.O.Box 6300
O2015 Espoo
Finnland
hannu.paulapuro@hut.fi

1 Background

The role of chemical pulp fibres in LWC base paper is to reinforce the fibre network so that the desired paper strength and the runnability on the paper machine line and on the printing press is achieved. Though mechanical pulp is primarily used to improve the smoothness and optical properties of the base paper sheet, the long fibres that refiner mechanical pulps in particular contain, represent a major part of all fibres in the furnish. In addition, the average fibre length of a LWC paper furnish, based on refiner mechanical pulp (usually TMP), is much longer than that of a groundwood (GW) based furnish.

It can be estimated that in a TMP based LWC furnish (65 % TMP, 35 % soft wood kraft pulp) the weight share long fibres (Bauer-McNett +28 mesh) is about 47 %. If the mechanical pulp component is groundwood with an essentially smaller long fibre fraction, the weight share of long fibres is about 32 % (furnish: 60 % GW, 40 % kraft pulp). The share of mechanical pulp fibres is in the GW case roughly 10 % and in the TMP almost 50 % of all long fibres.

The fibre distributions of these two furnishes are illustrated in Fig. 1. From it, we can easily see that the amount of long fibres is much higher in a TMP furnish than in a GW one. Thus, a TMP containing furnish has in principle a marked reinforcement potential that should be realized in a low chemical pulp need.

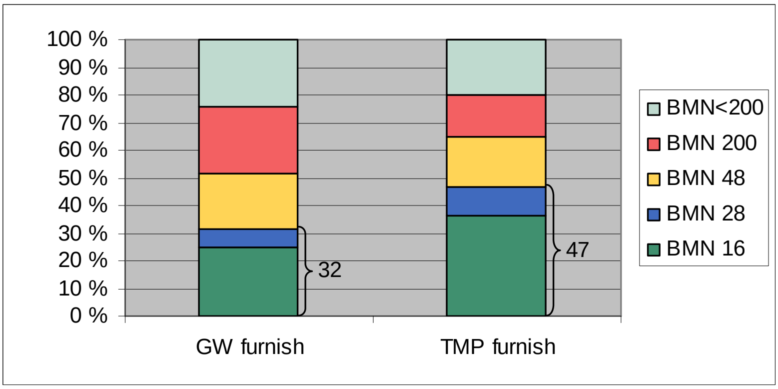


Figure 1. Bauer-McNett fractions two different furnishes. The result is calculated based on the following assumptions: GW furnish contains 60 % GW and 40 % softwood kraft pulp and TMP furnish 65 % TMP and 35 % softwood kraft pulp. The fractionation results of the single pulps are shown in Table 1 of Appendix 1.

However, the potential that the high average fibre length offers is not well utilized in practise. The difference in chemical pulp usage in GW and TMP based LWC mills is lower than one might assume based on the fibre length of the furnish. It seems that the reinforcement ability of mechanical pulp fibres really is less than that of chemical pulp fibres /1/.

The runnability of a paper machine line depends on several factors, not only on the strength of the paper web /2/. The development of the paper machine technology has no doubt changed the situation and probably diminished the relative importance of the furnish and its strength potential. It is clear that the strength of the dry web on the pope reeler is not the only factor to be looked at. Some researchers, like Kouko et al. /3/ emphasize the properties of wet web strength after the press section. According to them, clear differences can exist between wet and dry wet sheet properties. Some, like Koskinen et al. /4/ have emphasized the web's ability to tolerate faults on the drying section and in coating, either on-line or off-line, where large forces are projected on the rewetted paper.

In brief, it can be concluded that the paper machine runnability is still open for discussion. In this study, the focus is on the dry paper web properties but understanding that looking at them only, one gets only a limited view to the whole problem of the runnability. The aim of this study was 1) to clarify the basic differences in the microstructure of mechanical and chemical pulp fibres, and 2) to determine their effect on the handsheet strength, and 3) to discuss possible reasons for the differences in the fibres' reinforcement performance.

As stated before, mechanical pulp long fibres represent a considerable part of a TMP containing LWC base paper, but they seem to underperform as a reinforcing component. Therefore, production efficiency and product quality would benefit if their reinforcement cability could be increased. Knowing the basic differences between chemical and mechanical pulp fibres may help us to improve and to develop better mechanical and chemical pulp treatment processes.

2 Materials and methods

Pulp samples from several mills producing different mechanical pulps were collected and analysed for their pulp and paper properties. Pulps were also fractioned and the long fibres were tested by making handsheets and carrying out normal paper technical tests. Pulps and long fibre fraction were analysed using optical instruments and certain chemical analyses. In addition, long fibres were added to a base pulp (TMP).

In testing, mainly SCAN standards were followed.

Long fibre fractions were separated from different mill scale mechanical pulps and unrefined softwood chemical pulp. Mechanical pulps were thermomechanical pulps (TMP, five different ones, three from Finland, marked TMP1-3, two from France, marked TMP4-5), groundwood (GW), pressure groundwood (PGW), pulp for medium density fibreboard (MDF) and TMP reject (unrefined and refined). One of the TMP pulps (TMP 5) was manufactured with the RTS process (RTS, developed by Andritz, is a modification of TMP process; RTS stands for Retention, Temperature and Speed). The TMP pulps were sampled from the second refining stage outlet and groundwood pulps prior to the primary screens. Chemical (kraft) pulps were sampled before and after the mill refiners (BKPu and BKPr, respectively). The basic idea was that the pulps should represent a wide range of different pulps.

The separation was done 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 was 30 minutes. Shives were removed from the 10 mesh fraction with a Somerville apparatus (a screen plate with 0.15 mm slots) before adding it to the mixture of 16 and 30 mesh fractions. Thus the long fibre fraction of this study could be marked as the R30 fraction. A detailed description of the sampling procedure is given in /5/.

The fractions were used to partially replace the refined kraft pulp in a LWC furnish that consisted of a LWC-grade spruce TMP collected from a Finnish paper mill, a refined softwood kraft pulp, and a kaolin filler in varying ratios, see Table 1.

Table 1. Trial plan. Note that SGW, PGW, TMP1 etc. are long fibre fractions of those pulps.

Point	BKP refined	LWC TMP	SGW	PGW	TMP1	TMP2	TMP3	TMP reject unrefined	TMP reject refined	TMP4	TMP5	MDF	BKP unrefined	Filler
Ref 1	45	45												10
Ref 2	35	55												10
Ref 3	25	65												10
Ref 4	10	80												10
5	25	55	10											10
6	10	55	25											10
7	25	55		10										10
8	10	55		25										10
9	25	55			10									10
10	10	55			25									10
11	25	55				10								10
12	10	55				25								10
13	25	55					10							10
14	10	55					25							10
15	25	55						10						10
16	10	55						25						10
17	25	55							10					10
18	10	55							25					10
19	25	55								10				10
20	10	55								25				10
21	25	55									10			10
22	10	55									25			10
23	25	55										10		10
24	10	55										25		10
25	25	55											10	10
26	10	55											25	10

In order to see the effect of mechanical pulp fibres that were shown to have a different nature than chemical pulp fibres, softwood kraft pulp was partially replaced with different mechanical pulp fibres in the LWC furnish. The trial point Ref2 can be kept as a basic reference that represents a normal LWC furnish that contains 35 % SW kraft pulp and 55 % spruce TMP and 10 % filler. The point Ref1 has elevated kraft pulp content and Ref3 and Ref4 have a moderately and heavily reduced content, respectively. In the proper trial points (5-26), 10 % or 25 % of kraft pulp is replaced with long fibre fractions separated from different pulps. This means that the kraft pulp percentage is 25 % or 10 %, the balance being base TMP and filler. The share of TMP is 55 % in all trial points and in Ref2. In the last series (points 25 and 26), whole kraft pulp was partially replaced with the long fibre fraction of unrefined kraft pulp. In this series the total kraft pulp content was 35 %

The refined softwood kraft pulp (freeness 650 ml) used in these mixtures was sampled from UPM Kaukas Paper Mill.

LWC base paper was manufactured using a semi-automatic sheet mould. The target basis weight was 38 g/m². The sheets were tested as uncalendered and calendered to two different roughness levels but in this study only results from uncalendered sheets are evaluated.

In the series, where synthetic fibres were added to a pulp mixture, the used TMP was SC grade spruce TMP and the kraft pulp was mill refined softwood pulp, both pulps collected from Finland, and the synthetic fibre was Kevlar 29 supplied by Du Pont in the U.S.A.

3 Results

3.1 Properties of whole pulps

The pulps were tested for their basic properties. The most important properties are shown in Table 2.

Table 2. Properties of tested pulps (whole pulps). 'Fibre fractions' contain fibres that remained on 16 mesh and 30 mesh wires when 40 g of pulp was fractionated (see /5/).

		SGW	PGW	TMP1	TMP2	TMP3	TMP4	TMP5	TREJu	TREJr	MDF	BKPu	BKPr
CSF	ml	71	141	123	130	159	132	125	260	75	765	680	630
WAFL	mm	0,81	1,18	1,63	1,57	1,83	1,76	1,39	1,89	1,68	1,84	2,18	2,26
Fiber fractions	%	21,35	33,9	49,9	49,2	54,2	49,6	43,8	70,6	58,6	77	93,2	82,4
Tensile Index	Nm/g	31,2	33,5	42,1	41,02	36,93	38,9	37,1	44,23	63,96	-	49,56	74,81
Tear Index	Nm2/kg	3,33	4,86	7,35	7,32	8,29	7,73	6,49	9,06	7,51	0,79	21,87	16,04

The share of fibre fractions is somewhat higher than what would be given by a standard Bauer-McNett analysis due to the higher pulp amount that was used in the fractionation.

TMP1, TMP2 and TMP4 are from traditional TMP processes. TMP3 is from a unique full conical refiner line and TMP4 is from a RTS line. TMP rejects (unrefined and refined) are from the same where TMP2 was taken from. MDF is not meant for paper production but for manufacture of medium density fibreboard. It was included as a part of this study to widen the range and to see what kind of fibres come from a very low energy line.

3.2 Comparison of basic properties of different fibres

Pulps can be described in many ways; here we have used the methodology introduced by Heikkurinen et al. /6/ who suggested that basic fibre properties can be classified in four classes: size distribution, shape, structure of cell wall and fibre surface.

The size distribution describes the physical dimensions of the fibres, like fiber length and fibre width. The shape of the fibres describes the appearance, such as how they are kinked or curled or externally fibrillated. The structure of cell wall can be described with properties like stiffness or flexibility of fibres, swellability, cell wall porosity, cell wall deformations, and fibre strength. The fibre surface means both the chemical and physical nature of the fibre surface. The idea is that the four basic properties are independent of each other. This is in practise idealistic but in spite of that using the basic properties helps when trying to find cause-consequence relationships.

The long fibre fractions of the pulps listed in Table 2 were characterized by using analytical methods that represent the four basic properties in addition to standard physical properties. The results are shown in Table 3.

Table 3. Paper technical and some basic fibre properties of the studied pulps fractions.

		SGW	PGW	TMP1	TMP2	TMP3	TMP4	TMP5	TREJu	TREJr	MDF	BKPu	BKPr
Physical properties:													
Density	kg/m3	319	296	277	261	216	225	262	269	330	na	618	643
Tensile Index	Nm/g	13,6	15	13,7	10,5	7,1	8,6	11,5	12,9	23,7	na	35,7	56,5
Tear Index	Nm2/kg	4,53	5,26	5,01	3,71	3,16	3,62	4,68	5,59	7,58	0,47	24,85	23,88
Bonding Strength SB low	J/m2	61	58	50	41	38	43	43	46	48	na	135	161
Size distribution:													
WAFL (FiberMaster)	mm	1,97	2,38	2,49	2,62	2,53	2,85	2,71	2,56	2,36	2,11	2,82	2,78
Coarseness	ug/m	381	343	216	184	373	248	237	191	150		136	142
Fibre number	million/g	1,3	1,2	1,9	2,1	1,1	1,4	1,6	2,0	2,8		2,6	2,5
Shape:													
Fibrillated fibres (LM)	%	44	49	22	32	28	69	71	26	27	18	3	14
Curl index (MorFi)	%	9,3	9,35	6,55	6,6	6,05	7,3	7,6	6,05	6,5	5,75	12	14,9
Structure of cell wall:													
Water Retention Value	%	1,08	1,28	1,34	1,31	1,48	1,23	1,22	1,27	1,38	1,05	1,54	1,63
Zero-span Tensile Index Dry	Nm/g	87,2	87,7	89,5	96,8	89,1	96,6	97,3	90,8	99	65,6	142,5	142,5
Fibre surface:													
Extractives coverage	%	9,1	7,4	7,1	8,3	9,7	4,3	3,5	4,8	5,5	2,9	1,7	4,4
Lignin coverage (ESCA)	%	33,9	36,3	35,4	35,5	35,1	34,6	35,3	37	33,9	59,2	14,4	10,3

WAFL = Weighted Average Fibre Length, LM = Light Microscopy

Mechanical and chemical pulp fractions are different in almost all respects. The density of chemical pulp fractions is higher, their strength properties are much better, they have less fibrillated fibres (according to microscopy analysis), they have high water retention value (WRV), and their lignin coverage is clearly lower. The density is often used as an estimate of fibre flexibility or conformability. In addition to the fibre fraction density, fibre flexibility and conformability analyses (using the CyberSize analyzer) of different fibre fractions /5/ confirm that kraft pulp fibres really are more flexible. The average fibre length is high but not as high as in the longest TMP fraction (TMP4). In principal the fibre length figures should be about equal since the fractionation process mainly separates the fibres based on their length. Fibre flexibility also somewhat effects the separation on slotted screen plates. In Table 3, the fibre length is analysed with the FiberMaster analyzer. The widely used FS-200 analyzer gave results that correlate well with the FiberMaster but have a narrower range (smaller differences between different pulps). The fibre number was calculated from fibre length and coarseness by FiberMaster. The fibre number contains uncertainties in both of these analyses and it can be kept only as an indicative figure. In any case, it shows that the fibre number of the chemical pulp is not necessarily higher than that of a well-treated mechanical pulp (in this example, refined TMP reject). In mechanical pulp refining, outer layers of fibres are peeled off decreasing coarseness without any excessive fibre cutting.

The main conclusion is that chemical and mechanical pulp fibres can be surprisingly similar in terms of fibre dimensions. However, the main differences are in flexibility or conformability, cell wall structure, fibre strength, and fibre surface. These differences are then reflected in the paper technical properties of hand sheets made from their pulp fractions.

3.3 Replacing kraft pulp with different fibres

What happens when kraft pulp is replaced with mechanical pulp or synthetic fibres that are even as long as the chemical pulp fibres but deviate in other respects from them? In the following, the effects of their replacement on the most important paper technical properties are described.

3.3.1 Tensile index

In this study the kraft pulp was moderately refined but still had higher tensile strength than the base TMP. Moderate refining of kraft pulp is usual in LWC manufacture. In all cases where refined kraft pulp is replaced with different pulp fractions the tensile index is decreased. This is in accordance with the fiber fraction properties. The fibre fraction of the MDF pulp with a very low tensile index (<< 10 Nm/g; could not be analyzed) performed the worst and the strong refined reject performed the best. Groundwood fibres performed almost as badly as MDF fibres, which cannot be explained by their measured properties.

The unrefined kraft pulp fibre fraction performed worse than one would deduce from its pulp properties, particularly at the lower addition rate (25 % kraft pulp, 10 % unrefined kraft pulp long fibres, 55 % TMP). Its tensile index and Scott bond are much higher than those off any mechanical pulps, but this fact was not translated into good properties for the mixture.

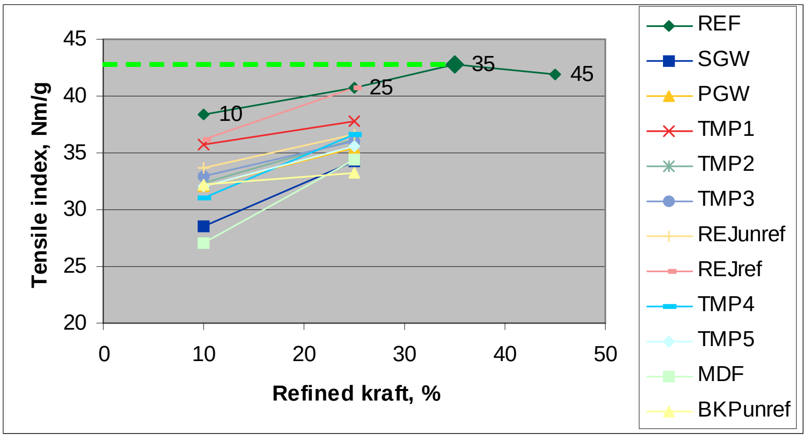


Figure 2. Tensile index as a function of refined pulp percentage when kraft pulp is replaced with different long fibre fractions.

Among TMP's, TMP1 was best what is in a good agreement with its relatively good fibre properties. However it is clear that the furnish behaviour of different fibres cannot be directly revealed from the properties of single pulp fractions.

3.3.2 Tensile stiffness

Tensile stiffness indicates how rapidly tension increases when the paper sample is stretched. Usually high tensile stiffness is appreciated since the web control is easier due to there needing to be less speed difference between the rolls. Interestingly, decreasing the percentage of kraft pulp results in an increasing tensile stiffness (see reference series in Fig. 3). This means reducing kraft pulp percentage can in certain cases bring strength properties in the desired direction. When kraft pulp is replaced with different fibre fractions, the tensile stiffness is markedly decreased with almost all of the pulps. Only the long fibre fraction of TMP1 (SC grade) and that of refined TMP reject reach the reference level.

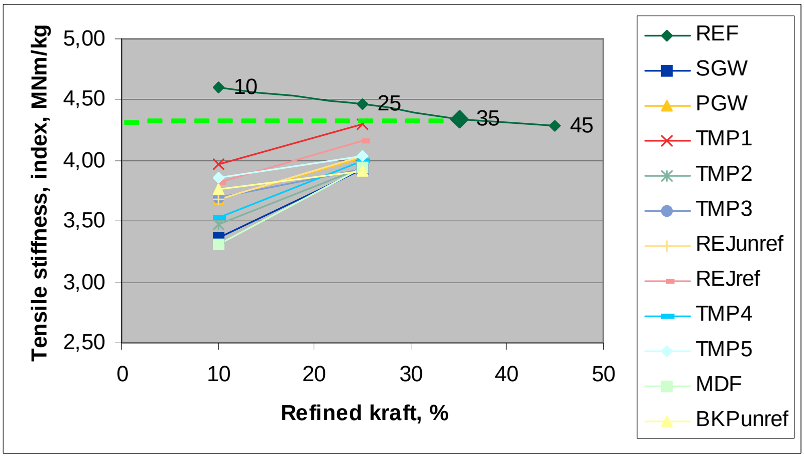


Figure 3. Tensile stiffness as a function of refined kraft pulp percentage when kraft pulp is replaced with different long fibre fractions.

3.3.3 Apparent density

Figure 4 clearly shows how stiff MDF fibres give the lowest density and how flexible kraft pulp fibres, even though unrefined, give a sheet with a relatively high density. However, it is somewhat lower than one might assume based on its pure fibre fraction density. In spite of having a much lower fibre fraction density than the unrefined kraft pulp fibres, refined TMP reject densifies the sheet even more than the unrefined kraft pulp at a 10 % replacement rate.

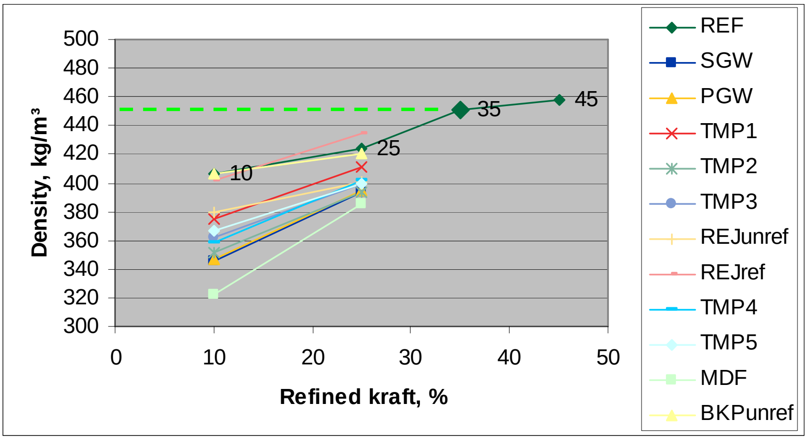


Figure 4. Density as a function of refined kraft pulp percentage when kraft pulp is replaced with different long fibre fractions.

The typical strong correlation between density and tensile strength was also seen in this study, as illustrated in Figure 5.

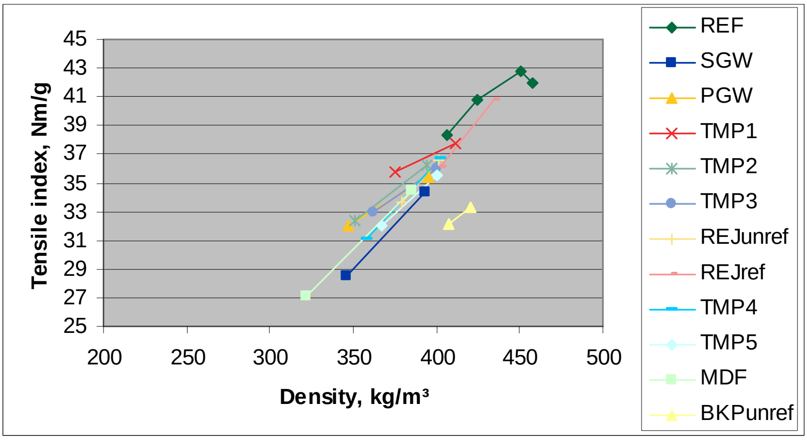


Figure 5. Tensile index vs. density with different pulp furnishes.

It is striking that unrefined kraft pulp deviates from the 'master curve' in that at specific density, it gives a low tensile strength. This observation is rather surprising taking into consideration that in spite of having relatively poor bonding as a pure fraction, it is far better than any of the mechanical pulp fractions.

We can speculate that the mechanism of bonding is different between various fibre types which then affects the sheet consolidation. Another explanation could be the different collapse of the fibres. Chemical pulp fibres collapse easier than mechanical pulp fibres resulting in a dense sheet with high a RBA (Relative Bonded Area) which in turn leads to good bonding properties (high Scott bond and tensile strength). Probably, in this case chemical pulp fibres do collapse but due to filler particles and stiff mechanical pulps in the mixture, fibre bonding is less than in a sheet made of pure pulp. As such, nonlinear behaviour in pulp blends is usual and it is pronounced when pulps with very different properties are mixed. According to Görres et al. /7/ collapse is dependent on the blend composition and is one the reasons for nonlinear behaviour of pulp blends. They stress that nonlinearity is due to the complex interactions between the different fibres in the fibre network and the evolution of average fibre properties as the blend composition changes.

Plotting Scott bond versus density summarizes the situation, as shown in Figure 6. Replacing kraft pulp with good LWC grade TMP (reference curve A) improves the Scott bond even though the density is decreased. Mechanical pulp fibres that generally can be kept as poorly bonding, markedly decrease both density and Scott bond (B). If the fibres are relatively flexible (based on density measurement of fibre fractions), but still relatively poorly bonding, as refined kraft pulp fibres and refined TMP reject are, density and Scott bond decrease slightly (C). Replacing TMP with moderately refined kraft pulp increases density and decreases Scott only very little (D).

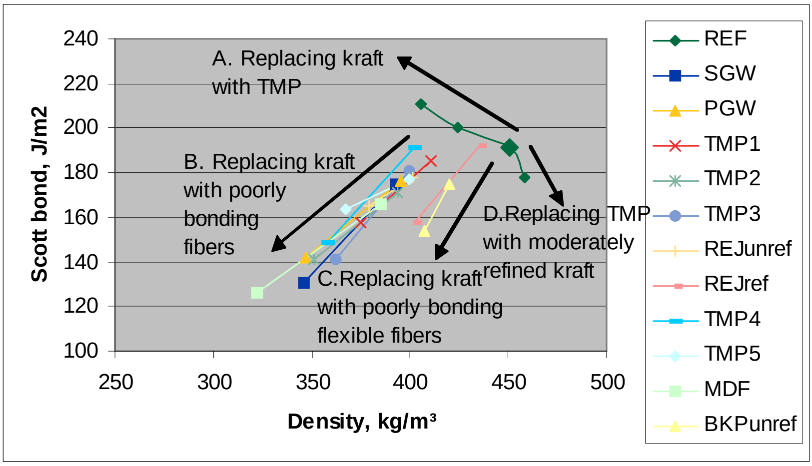


Figure 6. Scott bond vs. density with different pulp furnishes.

Permeability of the different furnishes increases with all the studied pulp fractions, Figure 7.

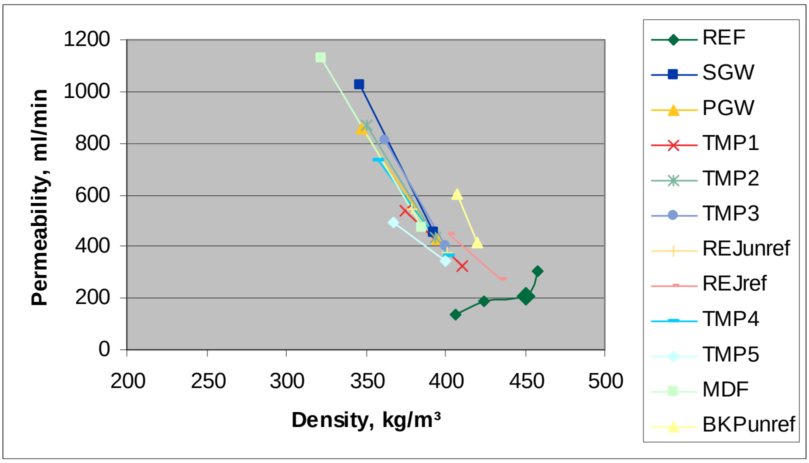


Figure 7. Permeability (Bendtsen) vs. density with different pulp furnishes.

Long fibres of the refined reject remain quite close to the basic reference point. Unrefined kraft pulp fibres increase permeability more than could be deduced from density. This is likely due to slight fibrillation and lack of fines.

From Figures 6 and 7, it is evident that replacing chemical pulp with different fibre fractions has a drastic effect on the sheet structure and the consolidation.

It is also clear that TMP accept fibres deviate from the reject fibres as Mohlin /8/ has reported already years ago. Fibres in the refined reject have higher bonding ability (tensile index) than the main line accept fibres.

3.3.4 Tear index

The importance of the tear index has been questioned by several authors, like Uesaka et al. /9/ and Fellers et al. /10/. However, so far the tear index cannot be put aside, because in practical life it is still followed very carefully in many paper mills. All fibre fractions gave higher tear index than the points where kraft pulp amount was just decreased without any compensation. This is obviously due to the fact that the long fibre fractions have higher average fibre length than the whole TMP which means that fibre length of the furnish increased with increasing replacement ratio.

It is surprising that MDF fibres maintain the tear index best for the mechanical pulps at the highest replacement ratio. Obviously poor bonding ability of reinforcement fibres is no limiting factor when targeting a high tear strength if the network is other wise well bonded. Neither does the low zero-span tensile strength of MDF fibres destroy the tear strength.

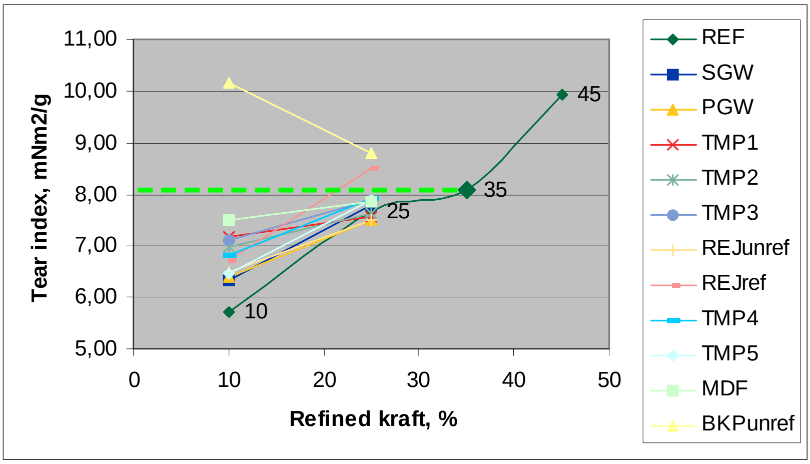


Figure 8. Tear index as a function of refined kraft pulp percentage when kraft pulp is replaced with different long fibre fractions.

The long fibres of refined reject give a high tear index (8.5 mNm^2/g) at the 10 % replacement ratio (25 % refined kraft pulp) but for some reason at the higher replacement ratio it did not perform well. Thus, none of the mechanical pulp fibres was particularly good. It is quite difficult to find a consistent explanation for this. The fibre number might offer one possible explanation but why then do the coarse and rather short MDF fibres perform so well?

Instead, unrefined kraft pulp fibres are very effective in generating tear index. At the 25 % replacement ratio (10 % refined kraft) they give the same tear index (ca. 10 mNm^2/g) at 10 % lower total kraft pulp content than does the whole kraft pulp (point '45').

3.3.5 Fracture energy

The fracture energy has been reported to forecast the runnability of a paper web better than the traditional out-of-plane tear index /11, 12/ and several papers have discussed the fracture mechanics of paper, as overviewed by Mäkelä /13/.

As expected, reducing the amount of kraft pulp in the reference series (TMP/kraft pulp mixture) results in a significant drop (from 0.45 J/m to 0.32 J/m) of fracture energy. Mechanical pulp and unrefined kraft pulp fibre fractions are in most cases better than the whole TMP. The most likely reason for this is that in the reference series fibre length decreases when kraft pulp percentage is decreased, yet in the trial series the average fibre length is increased because the kraft pulp is replaced with pulps having longer fibres (except SGW and MDF). These furnishes were not analysed for the average fibre length, but it can be estimated from the component values. Because the fibre length does not explain the lower fracture energy, there must be other reasons for the decrease. The main reason is likely to be decreased bonding degree of the hand sheets.

The fracture energy ranks the fibre fractions differently than the tear test. For instance, the long fibre fraction of refined TMP reject is the best and not the unrefined kraft pulp fibres as would be expected. Another interesting observation is that MDF falls down in the ranking. These observations are in accordance with what was seen when the reinforcement ability of Kevlar fibres was tested (see 3.3.6).

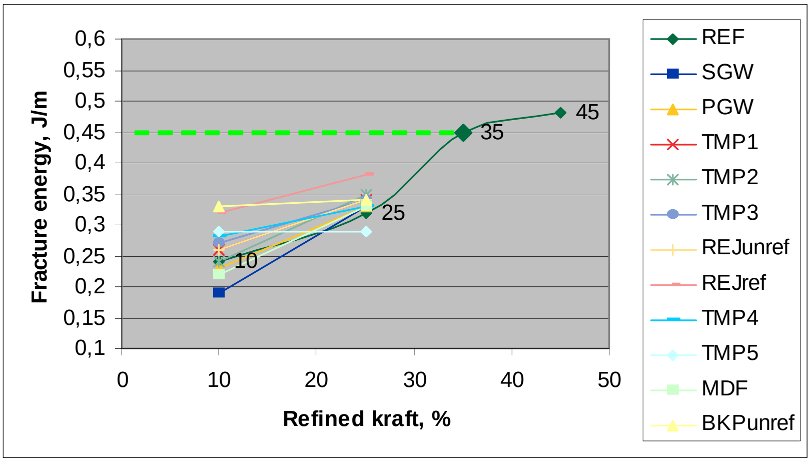


Figure 9. Fracture energy as a function of refined kraft pulp percentage when kraft pulp is replaced with different long fibre fractions.

The fracture energy analysis favours bonding as already shown by Åström and Nyström /11/. According to them, the fracture energy of a mechanical pulp/chemical pulp mixture increases with increasing degree of refining the chemical pulp component. According to Niskanen et al. there is a direct connection between fracture energy and tensile strength /14 /. Increasing the tensile index improves the fracture energy to the power of two whereas the increasing fibre length (through its effect on the damage width) improves fracture energy only in a direct relation. Kettunen /15 / has shown that the fracture energy decreases when fibre length, fibre strength, or bonding ability of fibres decreases. In this study the low tensile strength of the trial series likely explains most of the decreased fracture energy with the different fibre fractions.

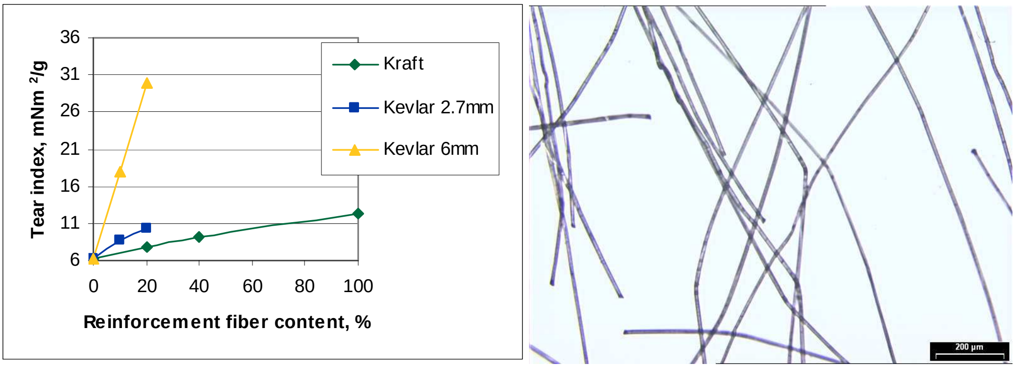
The differences in the average fibre length can explain some of the different positioning of the series in terms of the fracture toughness. In spite of the better tensile strength, the series with the refined TMP reject fibre fraction gives only roughly the same fracture energy than the series with the unrefined fibre fraction of kraft pulp. The clearly lower fibre length of reject fibres (2.36 mm and 2.82 mm for reject fibre fraction and kraft pulp fibre fraction, respectively) must have had an effect on this result. Also, the bad performance of SGW is likely to be partly due to short fibres.

The evaluation of the importance of the fibre strength is more difficult than that of fibre bonding or fibre length. Here, some speculation can be made. The Zero-span analysis revealed that all fibre fractions (excluding MDF) have much higher fibre strength than the sheet strength which leads to the conclusion that the fibre strength is not necessarily a decisive factor in most cases. It is reasonable to believe that the relative importance of the three hypothesized reasons depends on the pulp. Unrefined kraft pulp fibres are certainly strong, but in spite of that, deteriorate the fracture energy. Thus, their weak point must be in bonding (although all indicators show that they bond to each other better than any of the studied mechanical pulp fibres). As for mechanical pulp fibres, better bonding, and in some cases higher fibre length, would help. The role of the fibre strength is likely to become more pronounced, maybe even critical, after the bonding is raised to a higher level.

If the limiting factor is bonding ability, it should be possible by increasing that of mechanical pulp fibre to reach the level of kraft pulp! Damage analysis /15, 16/ would have offered one possibility to get information of the importance of the different factors but unfortunately it was not carried out in this study. E.g. low bonding ability should appear as a high wide damage zone.

3.3.6 Tests with synthetic fibres

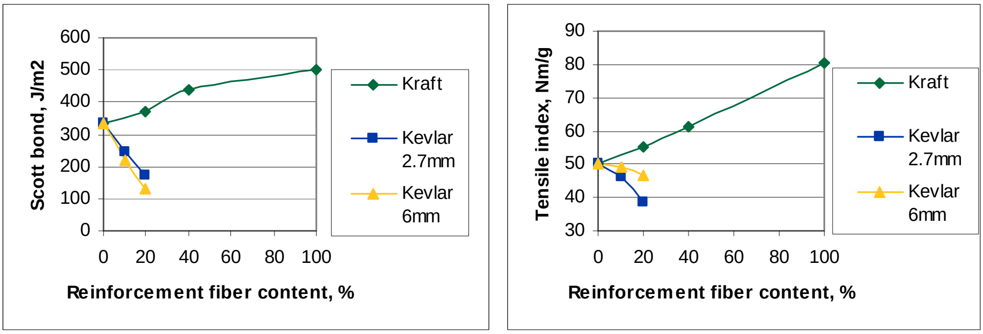
The role of the fibre nature (length, strength, bonding) was further examined by testing different synthetic fibres. Kevlar fibres (Kevlar fibres are aromatic polyamides, aramids) are known to be very stiff and strong, but as they are hydrophobic in nature they can be assumed to bond poorly in a fibre network.



A B

Figure 10. A. Tear index as a function of reinforcement fibre content in a TMP/kraft pulp blend. Kraft pulp is mill refined soft wood pulp for SC paper. Kevlar fibres are 2.7 mm and 6 mm in length and 15 µm in width. B. A micrograph (100x) of 6 mm long Kevlar fibres.

The tear index increases rapidly particularly with the 6 mm long Kevlar fibres. Low bonding (Figure 11 A and B) did not prevent Kevlar fibres from giving a good tear index. It is hard to speculate whether the tear would have been even higher if the Kevlar fibres had better bonding ability.



A B

Figure 11. A. Scott bond as a function of reinforcement fibre content. B. Tensile index as a function of reinforcement pulp content. Kraft pulp is mill refined soft wood pulp for SC paper in a TMP/kraft pulp blend. Kevlar fibres are 2.7 mm and 6 mm in length and 15 µm in width.

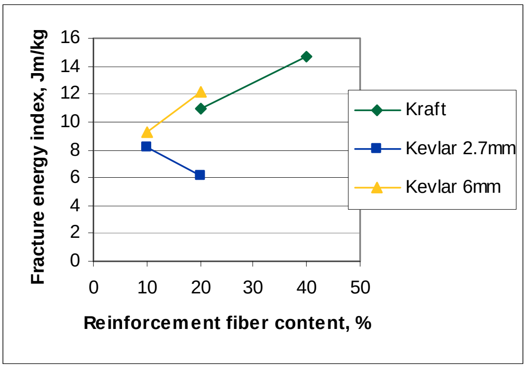


Figure 12. Fracture energy as a function of reinforcement fibre content in a TMP/kraft pulp blend. Kraft pulp is mill refined soft wood pulp for SC paper. Kevlar fibres are 2.7 mm and 6 mm in length and 15 µm in width.

Particularly, the fracture energy of the 2.7 mm long Kevlar fibres containing series suffers from the decreased bonding degree of the hand sheets. In that series, the tensile index was clearly lower than in the series with 6 mm Kevlar fibres. Even 6 mm long Kevlar fibres give only slightly higher fracture energy than the kraft pulp which has much shorter fibres.

This example confirms that at least a reasonable bonding level is needed when high fracture energy of a mixed fibre fraction sheet is targeted. Also, long and strong fibres must be bonded to the network if the stress mode is either in x-y (like in the fracture energy measurement in this study) or in z-direction (Scott bond).

4 Conclusions

This study showed that there are clear differences between basic fibre properties of chemical and mechanical pulps. They do not necessarily differ that much in terms of fibre dimensions but rather in flexibility or conformability, cell wall structure, fibre strength and the quality of fibre surface. This may sound self evident, but the point is that if the fibre dimensions were about equal, we might be able to treat mechanical pulp so that it has the same reinforcement potential as the chemical pulp. Particularly, a TMP based LWC furnish contains a marked share of long fibres that originate from the mechanical pulp component. Thus, the potential is there! Knowing what the differences are gives the possibility to focus the methods of further treatment in the right place.

The test series where kraft pulp was replaced with different mechanical pulp fibres and unrefined kraft pulp fibres revealed that replacement leads to drastic changes in the sheet properties and structure. With most of the tested pulp fractions the changes were negative as far as strength properties are concerned. The best long fibre fractions, especially the refined TMP reject, are in many respects quite near or even above the reference level when only 10 % of the kraft pulp is replaced with it. The greatest hurdle is that the fracture energy of the furnish inevitably decreases when chemical pulp is replaced with the studied fractions. The fracture energy is a combination of several important parameters like tensile strength, fibre length, fibre strength and fibre bonding. Many researchers keep it and variables derived from it as one of the best runnability indicators. The open question is whether TMP reject or some other mechanical pulp fraction could be developed so that it really could challenge chemical pulp.

Based on this study, it surely is possible that by better treatment of mechanical pulp fibres we can end up in a situation where sheet density, tensile strength, tensile stiffness, Scott bond, porosity and tear strength are at the reference level (or even higher) when 10 % of chemical pulp is replaced. However, reaching the desired fracture energy may be impossible because mechanical pulp fibres are more fragile, and have lower fibre strength, than chemical pulp fibres.

The tests with synthetic fibres supported the observation from the main test series that the fracture energy is much more dependent on bonding degree of the sheet than the out-of-plane tear strength that depends mostly on fibre length.

References

1. Lehto, J., Mechanical fibers as reinforcement pulp. 2003 International Paper Physics Conference. September 7-11, 2003, Victoria, British Columbia, Canada. Preprints, 323-331.

2. Gregersen, Ø.W., Runnability, fracture and pressroom breaks. Products of papermaking. Advances in paper science and technology. Trans. 13th Fund. Res. Symp., (ed. S.J. I'Anson), 797-825, FRC, Lancashire, UK, 2005.

3. Kouko, J., Kekko, P., Liimatainen, H., Saari, T., Kurki, M., Wet runnability of fibre furnish for magazine papers. Paperi ja Puu 88(2006)3, 169-174.

4. Koskinen, T., Kosonen, M., Ebeling, K., The impact of paper defects on paper strength requirements. The Science of Papermaking, Trans. 12th Fund. Res. Symp., (ed. C.F. Baker), 1441-1465, FRC, Lancashire, UK, 2001.

5. Huurre, J., Properties of single mechanical pulp fibers. Master of Science Thesis. Lappeenranta University of Technology, Laboratory of Paper Technology, Lappeenranta 2001. 125p.

6. Heikkurinen, A., Levlin, J-E., Paulapuro, H., Principles and methods in pulp characterization - Basic fiber properties. Paperi ja Puu 73(1991)5, 411-417.

7. Görres, J., Amiri, R., Wood, J.R., Karnis, A., The apparent density of sheets made from pulp blends. Tappi Journal 79(1996)1, 179-187.

8. Mohlin, U-B., Fibre bonding ability - a key pulp quality parameter for mechanical pulps to be used in printing papers. International Mechanical Pulping Conference. Helsinki 1989. Preprints. Volume 1, 49-57.

9. Uesaka, T., Ferahi, M., Hristopoulos, D., Deng, N., Moss, C., Factors controlling pressroom runnability of paper. The Science of Papermaking, Trans. 12th Fund. Res. Symp., (ed. C.F. Baker), 1423-1439, FRC, Lancashire, UK, 2001.

10. Fellers, C., Melander, J., Mohlin, U-B., Predicting the effect of reinforcement pulp characteristics in TMP papers for web breaks using fracture mechanics. Nordic Pulp and Paper Research Journal 16(2001)4, 257-260, 265.

11. Åström, A., Nordström, A., Fracture toughness as a pulp characterization method for runnability assessment of paper. Products of Papermaking. Trans. 10th Fund.Res.Symp., (ed. C.F.Baker), 807-823, FRC, UK, 1993.

12. Yu, Y., On the reinforcement of straw pulp. Nordic Pulp & Paper Research Journal 15(2000)2, 114-119.

13. Mäkelä, P., On the fracture mechanics of paper. Nordic Pulp and Paper Research Journal 17(2002)3, 254-274.

14. Niskanen, K., Sirviö, J., Wathén, R., Tensile strength of paper revisited. Trans. 13th Fund. Res. Symp., (ed. S.J. I'Anson), 563-589, FRC, Lancashire, UK, 2005.

15. Kettunen, H., Microscopic fracture in paper. Doctoral thesis. KCL Communications 1, Helsinki University of Technology, Department of Paper Technology, Espoo 2000, Finland 102p.

16. Niskanen, K., Kettunen, H., Yu, Y., Damage width: a measure of the size of fracture process zone. The science of papermaking, Trans. 12th Fund. Res. Symp., (ed. C.F. Baker), 1467-1482, FRC, Lancashire, UK, 2001.

Appendix 1.

Table 1. Bauer-McNett fractionation results of pulps of Fig. 1.

	GW	TMP	Kraft pulp
16 mesh, %	1.4	23.8	60.1
28 mesh, %	4.3	10.4	10.2
48 mesh, %	22.6	19.3	15.6
200 mesh, %	35.6	18.9	7.6
P200 mesh, %	36.1	27.6	6.5