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# TMP long fibres as reinforcement pulp
# Part 2. Pilot tests

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**KEYWORDS:** Fracture energy, Chemical pulp, Mechanical pulp, Refining, Reinforcement, Rejects, Sulfonation, Zero span tensile strength

**SUMMARY:** The target of this research was to study whether long-fibre mechanical or chemimechanical pulps could be used as a reinforcement pulp to replace softwood chemical pulp.

The reinforcement pulps were evaluated according to standard paper strength testing, runnability on KCL AHMA device, developed for studying the runnability of running paper webs and by damage analysis.

Mechanical and chemimechanical pulps did reinforce paper, but the present results showed that their capability was clearly less than that of chemical pulp. The low fibre strength of mechanical and chemimechanical pulps seemed to be a basic reason why the reinforcing capability of chemical pulp could not be achieved.

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Mechanical pulp in LWC paper is usually seen as a component that gives desired quality properties, like surface smoothness, opacity, bulk and good formation to the paper sheet. The role of long fibre chemical pulp in LWC paper is to reinforce paper, that is, to give necessary strength properties to the paper. Different mechanical pulps contain long fibre in varying amounts. Particularly in refiner mechanical pulps the share of the long fibres can be significant and therefore they have also a considerable reinforcement potential. Using thermo-mechanical pulp (TMP) instead of groundwood pulp (GW) has enabled a considerable decrease of the share of chemical pulp in SC and LWC papers. However, the decrease has not been as big as could be expected based on the fibre length of TMP. It can be shown by a simple calculation that if the fibre length were the only factor affecting the required chemical pulp content, TMP based LWC paper could easily be made without chemical pulp (Lehto et al. 2010). Since this is not the case in practice and chemical pulp is needed even when TMP is used as raw material for LWC, it is obvious that the performance of long mechanical pulp fibres is not as good as that of chemical pulp. In spite of the somewhat varying opinions, high fibre length is regarded as an important property for TMP. Reme et al. (1997) have speculated that split long fibres should be favourable for paper runnability and quality; splitting fibres improves surface smoothness and reduces the roughening tendency. If the fibre length is maintained, a high strength should be also reached.

Mechanical pulp fibres can almost reach the fibre length of chemical pulp. This can be achieved by selecting a long fibre fraction (in practise rejects pulp of a TMP line) as a starting point and by developing that fraction. In the first part of this study (Lehto et al. 2010) it was described how long fibre mechanical and chemimechanical reinforcement pulps, called MRP and CMRP, were produced and what kind of paper technical properties they possessed. The pulps were reported to have an average fibre length of 2.2 mm, an excellent tensile strength, a high tear strength and a high fracture energy index. The tensile strength was comparable with chemical pulp but the fracture properties were worse.

In this second part of the study a pilot test, where LWC base paper was manufactured on a pilot scale using the developed pulps as reinforcement pulp, is described. The reference paper was made using chemical pulp as the reinforcement pulp. In addition, paper without any reinforcement pulp was made from commercial TMP. Special emphasis was put on testing the runnability of the papers.

The target of this research was to study whether long-fibre mechanical or chemimechanical pulps could be used as a reinforcement pulp to replace softwood chemical pulp. The wider perspective was to study to what direction mechanical pulp development should be headed. In other words, should long fibres be preserved and developed to be as strong as possible, even by spending some extra energy or would it be more cost-efficient to make a low energy mechanical pulp with reasonable optical and surface properties, and let the strength properties suffer and compensate the reduced strength with chemical pulp?

## Experimental

This research concentrated on studying spruce TMP reject pulp because as a long-fibre pulp, it offered a good starting point for further development. Moreover, the share of rejects can be considerable in a TMP process and it is easy to increase the share of it by existing means; e.g. by increasing the freeness level of the main line refiners and by increasing the rejects ratio.

The experimental pulps were made starting from unrefined rejects (secondary screen rejects) of a commercial TMP mill in Finland. The reject pulp was first refined in three stages at Metso's pilot plant in Anjalankoski to a freeness of 83 ml. The energy usage in the rejects refining was 1840 kWh/t. Then a considerable share of fines was removed by pressure screening at KCL, Espoo, such that the remaining fines fraction P200 was only 10.9% in the rejects before further treatments. The extensively refined, fines-poor reject pulp with a freeness of 150 ml was developed further by refining it once more (SEC 434 kWh/t) or alternatively by sulphonating it (sulphite charge 150 kg/t pulp, cooking at 150°C for 30 minutes) and completing the treatment with light refining (SEC 149 kWh/t). The treatments are described in more detail in Part 1 of this study (Lehto et al. 2010).

The test papers were manufactured using KCL's pilot paper machine at a web speed of 100 m/min. The papers were machine calendered (one hard nip, line nip pressure 30 kN/m, moisture 4.5%) to simulate the base paper manufacture on an off-machine LWC line. The trial points are shown in *Table 1*. The pulps and papers were tested using standard test methods (see Appendix 1 of Part 1 for pulp tests and *Table 2* of this paper for paper tests).

The pilot papers were analysed for the damage properties using the techniques presented by Kettunen and Niskanen (2000). The paper sample is first impregnated with silicone. The specimen is then broken in the in-plane tear test. Siliconizing makes the fracture process zone visible whose size is measured using image analysis.

Table 1. Furnish composition (% of paper) of pilot papers. TMP: LWC TMP from a Finnish paper mill. Kraft pulp: Mill refined bleached softwood kraft pulp from a Finnish pulp/paper mill. Filler: Intramax JR by Imerys. Wood raw material of mechanical pulps: Norway spruce (*P.abies*).

| Test point | TMP | Kraft | MRP | CMRP | Filler |
|---|---|---|---|---|---|
| "Reference" | 63 | 27 | 0 | 0 | 10 |
| "MRP" | 63 | 0 | 27 | 0 | 10 |
| "CMRP" | 63 | 0 | 0 | 27 | 10 |
| "TMP" | 90 | 0 | 0 | 0 | 10 |

The runnability of LWC base papers was evaluated using the KCL AHMA device that was developed for studying the runnability of running paper webs (Niskanen et al. 2003). The most innovative part of the KCL AHMA equipment is the one-meter long test draw section from the brake nip (12) to the pulling nip (13), see *Fig 1*.

When analyzing the paper strength, the tension of the web is increased by increasing the speed difference between the brake nip and the pulling nip, until the web breaks. The breaking tension and breaking strain are recorded. The KCL AHMA recovers automatically from web breaks within a few seconds and the break sequence immediately starts again. The sequence is typically repeated for 30-100 times which enables the collection of reliable probability distributions of the dynamic breaking strain and breaking tensions. The KCL AHMA is equipped with a device for making notches to the running paper web. It makes it possible to study the effect of defects of different shapes, sizes and positions on the runnability of paper. The moistening units allow the investigation of the moisture content on the runnability.

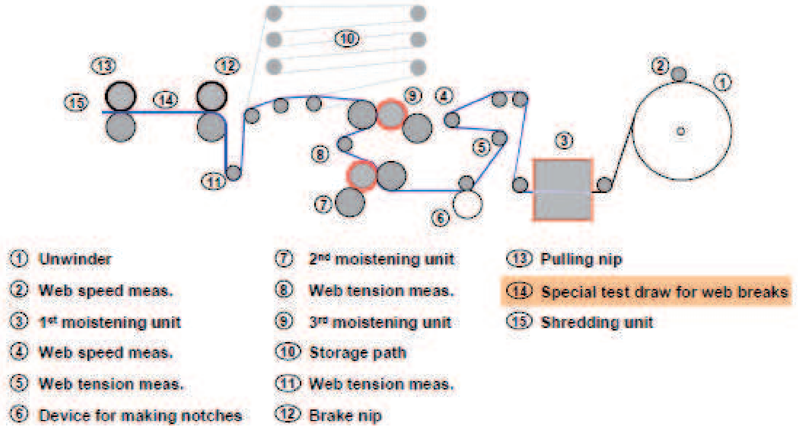

Fig 1. Main components of KCL AHMA. Unwinding tension T1 is measured at point 5, tension between moistening units T2 at point 8 and pre-tension T3 at point 11. Web speed refers to brake nip (12).

The following settings were used on the KCL AHMA (cf. *Fig 1*):

| | |
|---|---|
| Web speed | 3 m/s |
| Pre-tension (T3) | 50 N |
| Tension between moistening units (T2) | 35 N |
| Unwinding tension (T1) | 20 N |
| Max speed difference | 2.9% |
| Min speed difference | 0.1% |
| Ramp time | 20 s |
| Moistening | 3 g/m² (lower moistening unit) |
| Defects | 2 cm centre cut in CD |

A minimum speed difference of 0.1% is needed in the test draw section to keep the web under control. The steepness of the tension increase ramp is defined by the difference of the minimum and maximum speed difference and the ramp time.

For each test point two 5000 m paper rolls were available. The two rolls were cut from a pilot paper machine reel 1 m in width. One roll was used for dry tests (roll B) and the other one (roll A) for tests using the moistening unit.

The wetted sheets had a moisture content of about 10% after moistening. This corresponds roughly to the moisture level at a 4-colour offset printing.

Table 2. Analysis methods for paper tests and their repeatability (coefficient of variation, CoV). Repeatability figures are given by the laboratory based on repeated measurements (n=30).

| Property | Standard | CoV, % |
|---|---|---|
| Grammage, g/m² | ISO 536:1995 | 0.3 |
| Bulk, cm³/g | ISO 534:2005 | 0.9[1] |
| Tensile index, Nm/g | ISO 1924-3:2005 | 3.9 |
| Tear index, mNm²/g | ISO 1974:1990 | 6.3 |
| TEA index, J/kg | ISO 1924-3:2005 | 3.6 |
| Tensile stiffness index, kNm/g | ISO 1924-2:1994 | 2.9 |
| Fracture energy, J/m | SCAN-P 77:95[2] | 10[3] |
| Light scattering coefficient, m²/kg | ISO 9416:1998 | 0.7 |

[1] For thickness
[2] Measured using the L&W tensile tester for fracture toughness
[3] Estimated from the standard

# Results

## Fibre and pulp properties

The properties of MRP and CMRP differed significantly from those of chemical pulp (mill refined, commercial softwood kraft pulp) and also from TMP properties, see *Table 3* (wet pulp properties) and *Table 4* (handsheet properties).

Although a fines removal stage (pressure screen fractionation) preceded the final refining and sulphonation stages, it was not very effective and both the MRP and CRMP still contained a considerable amount of fines. A more selective fractionation would have increased the average fibre length, but it was seen more sensible to keep the process simple rather than try to maximize the selectively using a complex fractionation system. Due to the fines and the high fibrillation degree, indicated by WRV, freeness of the MRP and CMRP was low. The coarseness of CMRP approached that of the chemical pulp, but in the case of MRP it was about equal with TMP.

Table 3. Some pulp and fibre properties of trial pulps. Fibre length and coarseness analysed using Metso FiberLab. BMN = Bauer-McNett. L-factor = the sum of the 16, 28 and 48-mesh fractions. Fibre stiffness analysed using the method by Tam Doo and Kerekes (1981).

| | Kraft | TMP | MRP | CMRP |
|---|---|---|---|---|
| CSF, ml | 505 | 42 | 94 | 88 |
| Water retention value, g/g | 1.92 | 1.54 | 1.57 | 1.62 |
| Fiber length*, mm | 2.51 | 1.74 | 2.21 | 2.20 |
| Coarseness, mg/m | 0.182 | 0.252 | 0.243 | 0.207 |
| L-factor, % | 93.1 | 55.0 | 75.1 | 77.4 |
| BMN 16, % | 72.4 | 24.1 | 46.7 | 50.4 |
| BMN 28, % | 7.9 | 11.1 | 10.8 | 9.4 |
| BMN 48, % | 12.8 | 19.8 | 17.6 | 17.6 |
| BMN 200, % | 6.8 | 18.2 | 13.3 | 12.2 |
| BMN P200, % | 0.1 | 26.8 | 11.6 | 10.4 |
| Fibre stiffness, $10^{-12}$Nm$^2$ | 1.3 | 30.4 | 60.1 | 22.2 |

*Length weighted average

Table 4. Handsheet properties of pure trial pulps.

| | Kraft | TMP | MRP | CMRP |
|---|---|---|---|---|
| App. density, kg/m³ | 702 | 529 | 478 | 583 |
| Tensile index, Nm/g | 77.7 | 50.5 | 65.5 | 71.3 |
| Tensile stiffness index, MNm/kg | 8.2 | 5.3 | 6.2 | 7.8 |
| Stretch at break, % | 3.4 | 1.9 | 2.2 | 2.4 |
| TEA index, J/kg | 1586 | 829 | 943 | 1179 |
| Tear index, mNm²/kg | 15.5 | 6.9 | 8.4 | 7.5 |
| Fracture energy index, mJm/g | 21.3 | 8.0 | 10.6 | 11.3 |
| Scott Bond, J/m² | 359 | 301 | 207 | 271 |
| Light scattering coefficient, m²/kg | 23.8 | 58.0 | 40.6 | 28.3 |
| Zero-span tensile strength dry, Nm/g | 152.5 | 94.5 | 100.3 | 109.1 |
| Zero-span tensile strength wet, Nm/g | 138.3 | 74.6 | 91.5 | 97.5 |

The average fibre length of the MRP and the CMRP was relatively high. However, the Bauer-McNett fractionation showed that those two pulps contained less very long fibres (BMN 16-mesh fraction) than the chemical pulp. Still, about 75% by weight of those pulps were fibrous particles as the L-factor indicated.

The fibre stiffness most clearly reveals how different the pulps actually were. Sulphonation decreased the stiffness of the CMRP markedly but it was still 17 times stiffer than the chemical pulp. Fibre stiffness is known to have a major influence on the sheet consolidation (Corson 1989). The degree of sulphonation was estimated to have been ca. 1.5% based on the tests that Nurminen and Sundholm (1995) carried out in comparable conditions in the same pilot plant. The sulphonation level in this trial can be regarded as high and it undoubtedly was high enough to have a strong influence on the pulp and fibre properties (Heitner, Atack 1982, Gummerus, Rath 1986).

The chemical pulp strength properties were much better compared to the other pulps. For the tensile strength the difference was smallest and the strength of the CMRP approached that of the chemical pulp. The tensile stiffness index of the CMRP was close to that of the chemical pulp. Obviously, the increased fibre flexibility due to sulphonation, even though much lower than chemical pulp, enhanced inter-fibre bonding and sheet consolidation giving a relatively dense sheet with high tensile stiffness and strength. The high stretch at break of the chemical pulp contributed to the high TEA and fracture energy indices of it.

The fracture energy and the tear index of mechanical and chemimechanical pulps suffered on one hand from the low fibre length (compared to the chemical pulp), and on the other hand, low fibre strength that can be deduced from the zero-span tensile strength.

The relatively high fibre flexibility and the low fines content, explain the low light scattering coefficient of the CMRP.

### Paper properties

The differences between the properties for the pilot papers (*Table 5*) were much smaller than for the handsheets made from the single trial pulps since in all papers the main component was the same TMP. In addition, the mineral filler diminished bonding which evened out differences between the papers.

The tensile strength of the paper with CMRP as reinforcement pulp was equal with the reference paper. The kraft pulp gave a good tear index for the reference paper but the difference to the other papers was significantly smaller than the difference between the pure pulps. For the TEA index the relative difference was also reduced. For the fracture energy the difference in paper was markedly smaller than in pure pulps. Interestingly, all papers excluding the chemical pulp containing paper had an almost equal MD fracture energy. The chemical pulp gave 24 -27% higher MD fracture energy to paper than the other options.

The tensile stiffness was particularly clearly dependent on the direction of stress due to fibre orientation. The CMRP-reinforced paper had somewhat higher tensile stiffness than the chemical pulp-reinforced paper. The MRP and TMP papers had a lower tensile stiffness than the other two.

The TMP paper with no reinforcement pulp gave the highest light scattering coefficient. The CRMP containing paper showed the lowest value even though CMRP's light scattering coefficient was somewhat higher than that of the chemical pulp. Generally speaking, most of the measured pulp properties could be predicted with a reasonable accuracy from the properties of the component pulps.

Table 5. Properties of pilot papers (laboratory analysis).

| | Reference | MRP | CMRP | TMP |
|---|---|---|---|---|
| Grammage, g/m² | 47.4 | 46.0 | 45.8 | 45.0 |
| Bulk, cm³/g | 1.54 | 1.57 | 1.58 | 1.57 |
| Tensile index MD, Nm/g | 67.9 | 63.2 | 68.1 | 58.1 |
| Tear index CD, mNm²/g | 7.8 | 5.9 | 5.4 | 5.2 |
| TEA index MD, J/kg | 922 | 724 | 697 | 664 |
| TEA index CD, J/kg | 399 | 345 | 364 | 304 |
| Fracture energy MD, J/m | 0.56 | 0.44 | 0.45 | 0.44 |
| Fracture energy CD, J/m | 0.39 | 0.31 | 0.32 | 0.26 |
| Tensile stiffness index MD, kNm/g | 7.5 | 7.1 | 7.8 | 6.5 |
| Tensile stiffness index CD, kNm/g | 2.6 | 2.4 | 2.7 | 2.3 |
| Light scattering coeff. avg of TS & WS, m²/kg | 49.5 | 49.8 | 46.2 | 53.9 |

### Damage analysis

The damage width characterizes the extent of the fibre debonding from the crack line, i.e. the area where plastic deformation during the paper fracture occurs. The results of the analysis are shown in *Table 6*.

Table 6. Results of damage analysis of pilot papers.

| | Reference | MRP | CMRP | TMP |
|---|---|---|---|---|
| Damage width MD, mm | 2.27 | 1.94 | 2.00 | 1.73 |
| Damage width CD, mm | 2.00 | 1.54 | 1.63 | 1.39 |
| Damage width (geom. mean), mm | 2.13 | 1.73 | 1.81 | 1.55 |
| Pull-out length MD, mm | 1.23 | 1.03 | 1.02 | 0.96 |
| Pull-out length CD, mm | 1.07 | 0.88 | 0.86 | 0.80 |
| Pull-out length (geom. mean), mm | 1.15 | 0.95 | 0.94 | 0.88 |

The differences between the pilot papers in the damage width and pull-out length were clear. The chemical pulp containing paper showed the highest values, the MRP and CMRP papers were quite similar with each other and the TMP paper showed the lowest values.

### Runnability with KCL AHMA

The strength analyses made with the KCL AHMA differ in many respects from standard laboratory testing. The straining speed is essentially faster than in standard testing (with settings used in this trial 252 mm/min vs. 100 mm/min in the lab, ISO 1924-3), the test piece is wider, a higher number of loadings can be done and it allows testing the effect of defects and the web can be moistened. All these features were utilized in the current research. In addition to the faster straining speed, the loading geometry (the draw between the two nips) makes the breaking situation more dynamic than in the ordinary laboratory test set-up. Contrary to what one might intuitively think, in an open draw, the major part of the strain occurs within a short distance immediately at the beginning of the open draw.

The reference point with chemical pulp had the highest breaking strain and highest breaking tension, both dry and wet (*Tables 7* and *8*). The elastic modulus of the CMRP paper was as high as that of the kraft reference.

Moistening the web lowered the breaking tension and increased the breaking strain for all the papers. The CMRP containing paper maintained its properties best so that the drop from dry to wet was smallest. Pure mechanical papers (MRP and TMP) lost strength and elastic properties similarly

The breaking tension and the breaking strain levels of the webs with defects were essentially lower than those of intact webs (*Tables 9* and *10*). In the tests on the webs with defects, only the breaking strain and the breaking tension values are reported, since the intentional defects overrule the effect of other factors (like formation and shives) in the paper structure and the Weibull m, $\varepsilon_{1/100}$ and $\sigma_{1/100}$ results become meaningless.

The results with the webs with defects, both dry and wet, were well in line with the furnish composition of the test papers. The test paper with chemical pulp as reinforcement pulp had the highest breaking strain and tension values and the TMP paper with no reinforcement pulp had the lowest ones. The papers reinforced with mechanical or chemimechanical fibres were almost equal.

When the grammage of the trial papers was taken into consideration by converting breaking tension to tensile index, the MRP and CMRP came close to the chemical pulp, especially for the wet webs (*Fig 2*). This makes sense because a wet web is weak and the importance of fibre strength vanishes. Thus, in wet webs, the length of long mechanical or chemimechanical pulp is fully utilized. In dry webs, where fibres are more tightly bonded to the matrix, the single fibre strength has a more significant role and mechanical or chemimechanical pulp lose some of their performance.

The relative position of different trial points in terms of the tensile index in different stages was fairly consistent. However, the MRP and to some degree also the CMRP had a much lower threshold tension and threshold strain values than expected (*Figs 2* and *3*).

Table 7. Test results of dry, intact webs.

| | **Breaking strain, %** | **95% conf. for strain** | **$\varepsilon_{1/100}$, %** | **Weibull m (for strain), %** | **Breaking tension mean, kN/m** | **95% conf. for tens** | **$\sigma_{1/100}$, kN/m** | **Weibull m (for tension), kN/m** | **Elastic modulus, kN/m** | **No of breaks** |
|---|---|---|---|---|---|---|---|---|---|---|
| Reference | 1.30 | 0.01 | 0.77 | 23.59 | 3.31 | 0.02 | 2.41 | 44.03 | 331 | 84 |
| MRP | 0.99 | 0.03 | 0.28 | 7.47 | 2.59 | 0.05 | 0.85 | 12.25 | 305 | 103 |
| CMRP | 1.01 | 0.03 | 0.48 | 11.03 | 3.08 | 0.06 | 1.61 | 20.70 | 338 | 100 |
| TMP | 1.21 | 0.02 | 0.75 | 21.74 | 2.85 | 0.03 | 2.11 | 46.16 | 289 | 89 |

Table 8. Test results of wet, intact webs.

| | **Breaking strain, %** | **95% conf. for strain** | **$\varepsilon_{1/100}$, %** | **Weibull m (for strain), %** | **Breaking tension mean, kN/m** | **95% conf. for tens.** | **$\sigma_{1/100}$, kN/m** | **Weibull m (for tension), kN/m** | **Elastic modulus, kN/m** | **No of breaks** |
|---|---|---|---|---|---|---|---|---|---|---|
| Reference | 1.66 | 0.03 | 0.92 | 17.77 | 2.27 | 0.03 | 1.45 | 30.20 | 165 | 45 |
| MRP | 1.47 | 0.06 | 0.60 | 10.45 | 1.78 | 0.05 | 0.82 | 16.75 | 137 | 80 |
| CMRP | 1.39 | 0.05 | 0.64 | 16.18 | 2.10 | 0.04 | 1.12 | 21.03 | 176 | 79 |
| TMP | 1.57 | 0.02 | 0.86 | 18.57 | 1.80 | 0.02 | 1.09 | 26.63 | 128 | 64 |

$\varepsilon_{1/100}$ =threshold strain; one roll out of 100 rolls (10 km long) is predicted to break at this strain level

$\sigma_{1/100}$ =threshold tension; one roll out of 100 rolls (10 km long) is predicted to break at this tension level

Threshold values are derived from the break frequency distribution by first fitting a 2-parameter Weibull distribution to it and then extrapolating web tension (or strain) to a level where one break per 100 10-km long rolls can be expected.

The 2-parameter Weibull distribution has been successfully used to describe the experimental distributions gained with the KCL AHMA (Wathén, Niskanen 2006). A 2-parameter Weibull distribution for the failure probability $W_2(\sigma)$ of a paper web at a given web tension σ is expressed in the following way (*Eq 1*):

$$W_2(\sigma) = 1 - \exp - \left(\frac{\sigma}{\sigma_0}\right)^m \qquad [1]$$

where $m$ is the Weibull modulus and $\sigma_0$ is the scale parameter for the measurement geometry. The Weibull $m$ modulus is a parameter that measures variability; high $m$ means low variation and a narrow distribution, and vice versa.

Particularly in the case of the MRP the large scatter in the breaking strain and breaking tension values produced small Weibull m parameters and consequently low threshold tension and threshold breaking strain values.

Table 9. Test results of dry webs with defects.

| | **Breaking strain, %** | **95 % conf.** | **Breaking tension mean, kN/m** | **95 % conf.** | **No of breaks** |
|---|---|---|---|---|---|
| Reference | 0.46 | 0.01 | 1.38 | 0.03 | 32 |
| MRP | 0.40 | 0.01 | 1.22 | 0.02 | 33 |
| CMRP | 0.38 | 0.01 | 1.22 | 0.03 | 32 |
| TMP | 0.39 | 0.01 | 1.13 | 0.02 | 31 |

Table 10. Test results of wet webs with defects.

| | **Breaking strain, %** | **95 % conf.** | **Breaking tension mean, kN/m** | **95 % conf.** | **No of breaks** |
|---|---|---|---|---|---|
| Reference | 0.85 | 0.01 | 1.13 | 0.03 | 34 |
| MRP | 0.84 | 0.07 | 1.05 | 0.05 | 23 |
| CMRP | 0.65 | 0.02 | 1.09 | 0.04 | 23 |
| TMP | 0.56 | 0.07 | 0.94 | 0.02 | 22 |

An interesting question is whether the fracture energy of paper can predict the web strength in dynamic conditions. Indeed, the fracture energy of paper ranked the papers similarly (CD more accurately than MD) than the breaking tension of the webs with defects. The essential observation is that both the MRP and CMRP enhanced the defect resistance both dry and wet contrary to the breaking tension of intact webs that was improved by CMRP but not by MRP.

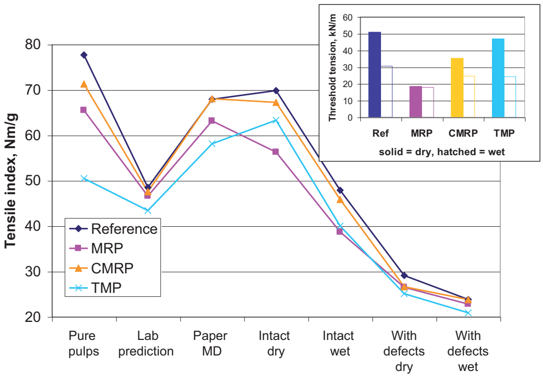

Fig 2. Tensile index in different stages. Lab prediction is based on a nonlinear dependence of furnish components properties as shown by Mohlin and Ölander (1985). "Paper MD" refers to laboratory analysis of pilot papers in machine direction. "Intact dry", "Intact wet", "With defects dry" and "With defects wet" refer to KCL AHMA tests. (*Tables 7-10*). The breaking tension values from are converted to indexes. The threshold tension values for dry (solid bars) and wet (hatched bars) are shown in the inserted bar diagram. A typical mean web tension on a printing machine is up to 450 N/m which translates to 10 Nm/g if the basis weight is 45 g/m².

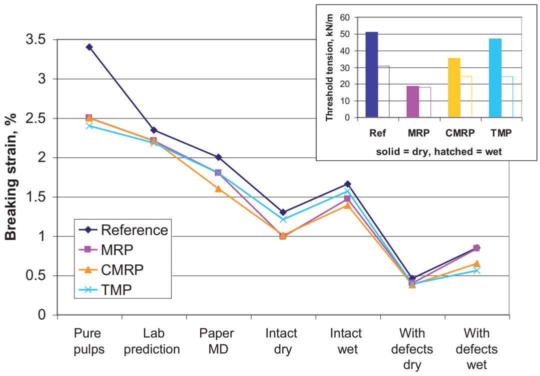

Fig 3. Breaking strain in different stages. Lab prediction is based on the linear mixing rule of pulp components. Threshold strain values are shown in the inserted bar diagram for dry (solid bars) and wet (hatched bars) sheets. Abbreviations as in *Fig. 2*.

## Discussion

The mechanical and chemimechanical reinforcement pulps, MRP and CMRP, of this study represent one possible approach to produce such pulps. The pulps differed so much from the normal TMP in the direction of kraft pulp in terms of fibre length, flexibility and strength that they surely gave more than indicative results on what could be achieved with mechanical or chemimechanical reinforcement pulps. The pulps produced were basically realistic and their manufacture on a full industrial scale would be possible.

One of the most striking differences between the chemical pulp and the MRP and the CMRP was the fibre flexibility which was much higher for the chemical pulp. The flexibility of chemical pulp fibres can be increased by beating (Hattula, Niemi 1988, Ljungqvist et al. 2005), but due to principal differences in the fibre structure after the manufacturing process, it is apparent that the flexibility of mechanical pulp fibres, even after a moderate chemical treatment, cannot reach the level of chemical pulp in this respect. According to Waterhouse and Page (2004), the shear modulus (G) of chemical pulp fibres is only a fraction of the longitudinal modulus E in the wet stage. This enables a very effective conformation around adjacent fibres in wet pressing.

The effective conforming of chemical pulp fibres in the paper network means that the end-to-end length is markedly reduced giving increased extension potential for the chemical pulp. This phenomenon must be distinguished from the fibre curl that tells what shape fibres take in a water suspension.

Since the high stretch at break has a positive impact on the fracture strength of paper (Seth 1996), chemical pulp has a marked advantage over mechanical and chemimechanical pulp thanks to its flexible and conformable fibres. Besides these factors, there are other ones that may contribute to the stretch at break of paper. The fibre length is likely to be one of them for obvious reasons. The chemical pulp definitely had an advantage from its high fibre length compared to other fibres of this study. The bond strength has been shown to affect the point where the rupture takes place (Seth, Page 1983). The high tensile index and Scott bond of the chemical pulp mean that it had an advantage also here. The high zero-span value of the chemical pulp gives an indication of a high fibre strength that enhances both tensile strength and stretch (Kärenlampi, Yu 1997, Page 1969, 2009).

The damage analysis of the pilot papers revealed interesting results. The chemical pulp gave the longest average fibre length to the furnish and as a consequence the highest $w_d$ and $w_p$ to the paper. According to Kettunen et al. (2000), the damage width $w_d \approx 2w_p \approx l_l$ where $w_p$ is the pull-out length and $l_l$ the weighted average fibre length. The results of this study were in reasonable agreement with their results, as *Fig 4*depicts. The mechanical and chemimechanical reinforcement pulps, MRP and CMRP produced somewhat lower $w_d$ and $w_p$ than could be deduced from their fibre length. This is an important observation since it supports the idea that chemical pulp fibres are stronger which explains why they reinforce paper better than mechanical pulp fibres.

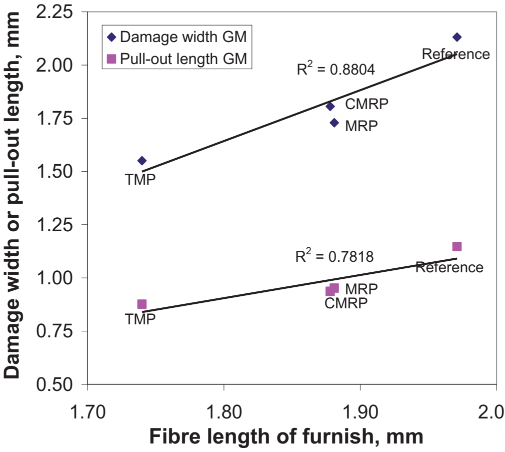

Fig 4. Damage width and pull-out length of base paper vs. fibre length of paper furnish (calculated from the length weighted average fibre lengths of component pulp). GM = geometric mean of CD and MD.

The ratio between $d_w$ and $w_p$ was less than two (1.77-1.93) which means, based on Hiltunen's work (2003), that the paper sheets of the different trial points were well activated by wet straining during the paper manufacture process.

Kettunen (2000) has shown that the fracture energy (determined as the in-plane tear index) is linearly dependent on the damage width when the paper web is reasonably well bonded and activated. The results of this research also support his observation, *Fig 5*.

The same kind of slight underperformance of MRP and CMRP could not be noted in the fracture energy/damage width relation (*Fig 5*) as could be seen in the damage width (and pull-out width)/fibre length relation in *Fig 4*. This is because the damage width actually includes the effect of fibre strength. Therefore, no underperformance of mechanical fibres was noted. Instead, the reduced ability to produce damage width at a given fibre length can be explained with the fibre strength. If the fibre length of the furnish components is scaled with the zero-span strength (ZS), *Fig 6*, the correlation between the fibre length and the damage width becomes very obvious. Here, by the zero-span scaling is meant the weighing of the fibre length of the pulp components by their zero-span tensile strength. The zero-span strength of the chemical pulp was chosen as the reference level. For example, the zero-span tensile strength of the MRP was 100.3 and that of the chemical pulp 152.5. The zero-span scaled fibre length of the MRP becomes 100.3/152.5*2.21 = 1.45 mm. It could be characterized as an effective

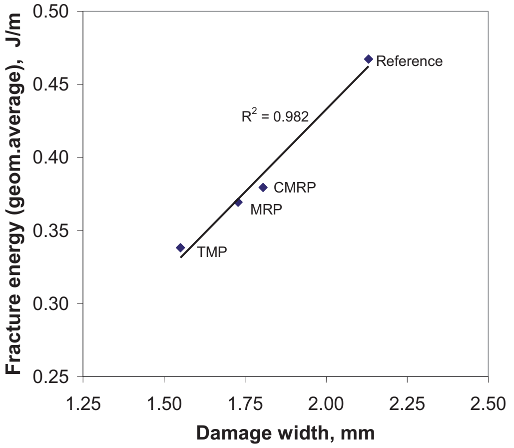

Fig 5. Fracture energy (geometric mean of CD and MD) vs. damage width of base paper.

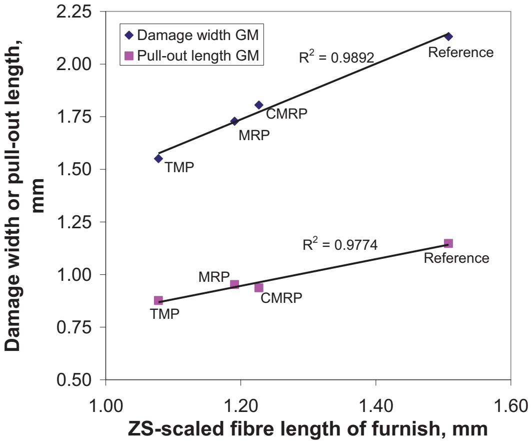

Fig 6. Damage width and pull-out length vs. zero-span -scaled fibre length of paper furnish (calculated from the length weighted average fibre lengths of the component pulps). GM = geometric mean of CD and MD.

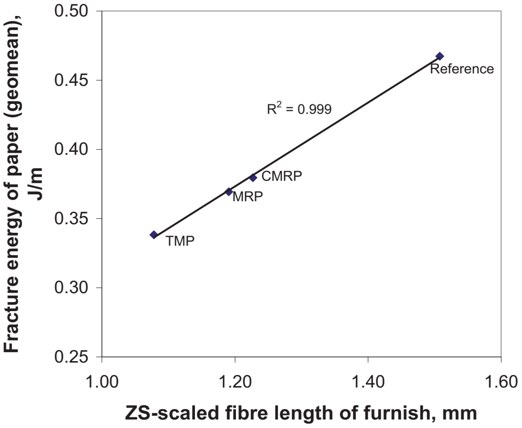

Fig 7. Fracture energy of paper (geometric mean) vs. zero-span -scaled average fibre length of paper furnish.

fibre length. Since the damage width and the fracture energy correlated with each other, it is also natural that the ZS-scaled fibre length and the fracture energy have a good mutual correlation, *Fig 7*.

The fracture energy could be predicted only by two variables, fibre length and fibre strength. The high fibre strength together with its high fibre length explains why the chemical pulp has much higher fracture energy than the MRP or the CMRP. In principle, a single mechanical pulp fibre can be stronger than a chemical pulp one but not at a given coarseness. If the coarseness is equal, mechanical fibres inevitably contain more components that do not carry load as effectively as cellulose. Moreover, decreasing coarseness by mechanical peeling of fibre wall layers, without causing any extra damage, cracks, microcompressions etc., is practically impossible. In this study, the low fibre strength of the MRP and the CMRP fibres reflected in the damage width that was narrower than could be deduced from their fibre length. In a poorly bonded sheet the single fibre strength might not be that important but in normal printing papers, like in this study, the bonding degree is so high that fibre strength surely has a marked contribution to the paper strength. The current results are analogous with the results of Kärenlampi and Yu (1997) who showed that weakening fibres by acid treatment decreased zero-span tensile strength and fracture energy of handsheets made of soft wood chemical pulp.

In a wet sheet, the interfibre bond strength is essentially lower than in a dry sheet and it can be concluded that the single fibre strength is less important. That means that even though mechanical and chemimechanical fibres did not give as good strength as chemical pulp fibres, they may be useful, because they may improve the wet web strength. In this research, the sheet was wetted to about 10 % moisture content which decreased the bonding level markedly. The breaking tension of the wet sheets with defects (*Table 10*) was about equal with the papers reinforced with the chemical pulp, MRP or CMRP whereas the strength of the pure TMP paper was below those. This observation can be regarded as an indication of a diminished importance of the fibre strength when the bonding degree is lowered by wetting. In this research, the main focus was not on wet sheets and it is hard to say at which moisture content level the effect of fibre strength disappears. Wetting the paper sheet to about 90% dry solids content decreased the dynamic tensile strength of intact sheets by about 30%. Kouko et al. (2006) have reported that the dynamic tensile strength of handsheets made of a blend of TMP and kraft pulp at 40% dry solids content is less than 1/10 of that of dry handsheets. Thus, it can be concluded that in coating, the moisture penetrating into the paper can drop the strength so much that tensile strength of paper is drastically reduced.

The runnability tests with the KCL AHMA were thought to give a clear answer to the ultimate question of what pulp reinforces best. It was a surprise that the dry, intact MRP paper had a lower breaking tension than the TMP paper with no reinforcement pulp. It seems that there were structural differences between the pilot papers and it is likely that the question is rather about the variability of the web strength than about the strength level as such. The breaking tension histograms (*Fig 8*) clearly show that for the reference and the TMP paper the distribution was essentially narrower than particularly for the MRP paper and also for the CMRP paper.

A wide distribution leads to a low Weibull m parameter. The MRP paper had a very wide distribution and, as a consequence, an exceptionally low m even though no significant differences in the pilot paper machine running conditions were recorded. Also the distribution of the CMRP paper differed from that of the references. A long tail towards low breaking tensions was characteristic to it. The Weibull modulus m characterizes structural variation of the sheet (Wathén, Niskanen 2006). Basically the variation could explain the poor strength characteristics of the MRP paper. The Weibull modulus m is affected by formation and potential weak points like CD oriented shives. The formation values of the trial points were in good agreement with the crowding factor values that were calculated using the equation originally presented by Kerekes and Schell (1992). The reference paper with the longest fibres had the worst, and the short fibre TMP paper the best formation. The papers containing MRP or CMRP located in between, *Fig 9*. Although the MRP and the CMRP papers had almost an equal formation index, the MRP was visually judged to be clearly worse than CMRP.

Since the formation of the MRP point was almost at the same level as the TMP paper with a low crowding factor and good formation, the formation hardly explains the bad result with MRP. The MRP and CMRP pulps were not pressure screened but in spite of this their shives content were modest, at 0.5% and ca. 0.6%, respectively. The shives content for the TMP was 0.15% (see Part 1, Lehto et al. 2010). The furnishes were not analysed for the shives content, but based on the shives content of the component pulps, the shives content can be estimated to have been the following: Reference 0.10%, MRP 0.23%, CMRP 0.27% and TMP 0.14% (chemical pulp supposed to be free of shives, 10% of filler). The RMP and CMRP containing papers contained more shives than the other two, but the absolute level still remained low. Thus, it is not likely that the shives content had a major impact on the paper structure. However, the possibility that it had some contribution cannot be fully ignored.

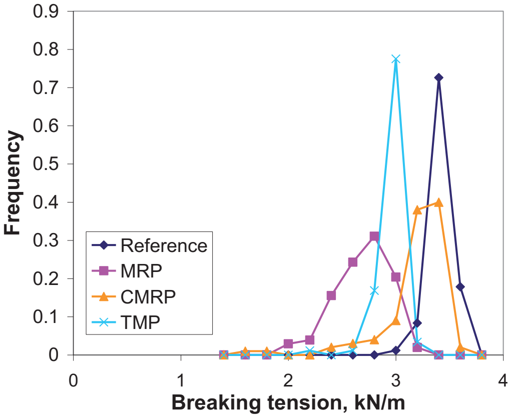

Fig 8. Breaking tension distribution of different pilot papers (dry, intact webs).

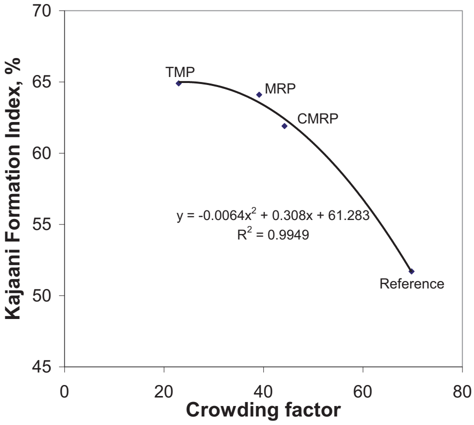

Fig 9. Optical formation (Kajaani) vs. crowding factor of the pulp furnishes. Formation index: higher is better. Crowding factor: flocculation tendency increases with increasing value. Crowding factor was calculated at head box consistency.

The manufacture of paper with the pilot paper machine succeeded well without any discrepancies. It can be stated that there probably were unidentified defects (holes, wrinkles, bad profile, big shives etc.) in the MRP and CMRP papers that caused those papers to break at an unexpectedly low web tension in the KCL AHMA tests. The variation obviously decreased the averages but above all, it affected the threshold tension and the threshold strain at which a given number of web breaks occur. It is evident that the KCL AHMA results did not allow a fair break frequency comparison in this study. Still, the results are by no means without value, since they show how important constant quality of paper is. The strength of paper with high variability would be unrealistically high to give the same break frequency than a weak paper with low variability.

As stated before, the reason why the variability was that high in the MRP and CMRP remained unclear. It is hard to believe that the pulps as such could generate so much variation as what was observed. For instance, the result that the threshold tension for the MRP is the same both dry and wet is obviously misleading (Tables 7 and 8). It is likely that if the variation in the paper structure were eliminated, the ranking of the papers in terms of threshold tension would be the same as in the other tests.

Improving the strength of the paper web so that it would be strong enough to tolerate different stresses during paper manufacture and different end uses, is by definition the reason why reinforcement pulp is used. The applicability of the fracture mechanics to characterize the strength of paper has been under an intense discussion during the past few decades. It has been suggested that fracture resistance (or fracture toughness, fracture energy, tenacity - terminology varies) is a relevant measure to forecast general runnability of paper (Seth, Page 1975, Page, Seth 1982, Seth 1996, Swinehart, Broek 1996 and many others). Later the usefulness of the fracture toughness has been questioned e.g. by Uesaka (2005). He emphasises the significance of strength uniformity in press room breaks. Fracture toughness is a valid parameter when failure is driven by macro cracks or defects. In press room breaks, the share of breaks caused by defects is minor. Although web uniformity is important, the average strength also contributes to runnability. According to Uesaka (2005), MD tensile strength and MD strain-to-failure are the most important factors. He refers to earlier work by Page and Seth (1982) showing that the fracture resistance correlates with the break rate in pressroom. Since fracture resistance can be empirically related to tensile strength and strain-to-failure (Seth 1996), the results of Uesaka and Page and Seth are consistent with each other, that is, the fracture toughness tends to correlate with pressroom breaks. Obviously, pressroom breaks, or breaks in general, depend on the level and variation of strength properties of paper on one hand and on the stress level and variation in the process on the other hand. The relation between these factors is not linear, which makes drawing conclusions often difficult. All in all, it is clear that decreasing the strength level of a paper web increases the likelihood of web breaks. The increase is not dramatic if the uniformity of paper is good and the process is stable.

## Conclusions

Chemical pulp proved to be the best reinforcement pulp. Carefully developed mechanical and chemimechanical pulps did reinforce paper, but the present results showed that their capability was clearly less than that of chemical pulp. The tensile strength and tensile stiffness of chemical pulp containing paper could be reached when sulphonation was included in the process. However, other strength properties (fracture energy, tear index) of the chemical pulp containing paper were not reached.

The damage width analyzed from the paper predicted the fracture energy of paper well, and on the other hand, the damage width could be predicted from fibre length and fibre strength. Thus, there was a direct link from the fibre length and fibre strength to the fracture behaviour of paper. Because the fibres of MRP and CMRP were shorter and weaker than chemical pulp fibres, it can be said that these two factors limited their reinforcement ability. In addition, it is likely that the high stretch at break of the chemical pulp containing paper improves its ability to tolerate defects and local stresses in the paper web.

The runnability tests with the KCL AHMA demonstrated tangibly the importance of low variability in the properties of the paper web. Since the low variability in paper, in the paper making process and in the pressroom operations may be even more important than the strength level of paper as such, plenty of emphasis must be put on improving the process stability and reducing the variability in pulp and paper. Only that allows for wider usage of mechanical or chemimechanical reinforcement pulp.

One implication is that seeking the highest possible length for mechanical pulps in every way may not be sensible because a long-fibre chemical pulp is more effective to give desired strength properties. On the other hand, when the proportion of chemical pulp is reduced the role of mechanical pulp becomes more pronounced again. In the end, the question is about cost and quality optimization.

## Literature

**Corson, S.R.** (1989): Aspects of mechanical fibre separation and development in a disc refiner, Int. Mechanical Pulping Conf. 1989, Vol. 2, Helsinki, Finland, June 6-8, 1989, FPPRI, Helsinki, Finland, pp 303-319.

**Gummerus, M., Rath, B.** (1986): Sulphite treatment of TMP rejects. Part 2. Effect of different treatment conditions and refining on properties of reject pulp. Paperi Puu 68(4), 269.

**Hattula, T., Niemi, H.** (1988) Sulphate pulp fibre flexibility and its effect on sheet strength. Paperi Puu 70(4), 356.

**Heitner, C., Atack, D.** (1982): Ultra-high yield pulping of eastern black spruce. Part 3. Interstage sulfonation. Svensk Papperstidning 85(12), R78.

**Hiltunen, E.** (2003): On the beating of reinforcement pulp. Doctoral thesis, Helsinki University of Technology, Espoo, Finland.

**Kerekes, R.J., Schell, C.J.** (1992): Characterization of fibre flocculation regimes by crowding factor. J.Pulp Paper Sci. 18(1)1, J32.

**Kettunen, H**. (2000): Microscopic fracture in paper. Doctoral thesis, Helsinki University of Technology, Espoo, Finland.

**Kettunen, H., Niskanen, K.** (2000): Microscopic damage in paper. Part I: Method of Analysis. J. Pulp Paper Sci. 26(1)1, 35.

**Kettunen, H., Yu, Y., Niskanen, K.** (2000): Microscopic damage in paper., Part II; Effect of fibre properties. J. Pulp Paper Sci. 26(7), 260.

**Kärenlampi, P., Yu, Y.** (1997): Fiber properties and paper fracture - fiber length and fiber strength. In: C.F.Baker (ed.), The Fundamentals of Papermaking Materials. Transactions of the 11th Fundamental Research Symposium, Cambridge, September 1997, Vol.1, Pira International, Leatherhead, pp.521-546.

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

**Lehto, J., Hiltunen, E., Paulapuro, H.** (2010): TMP long fibres as reinforcement pulp. Part 1. Laboratory tests. Nord. Pulp Paper Res. J. 25(3), 328.

**Ljungqvist, C-H., Lyng, R., Thuvander, F.** (2005): Evaluation of PFI beating on the strain to failure of spruce fibres using single fibre fragmentation. Nord. Pulp Paper Res. J. 20(4), 370.

**Niskanen, K., Mäkinen, J., Ketoja, J., Kananen, J., Wathén, R.** (2003): Paper industry invests in better web runnability. Paperi Puu 85(5), 274.

**Nurminen, I., Sundholm, J.** (1995) Chemimechanical treatments of coarse fibres - a way to reduce fibre roughnening of TMP-based LWC. 1995 Int. Mechanical Pulping Conf., Ottawa, Canada, June 12-15, 1995, CPPA, Montreal, Canada, pp 243-255.

**Mohlin, U-B., Ölander, K.** (1985): The influence of mechanical pulp quality on the properties of paper containing fillers. Int. Mechanical Pulping Conf., Stockholm, Sweden, May 6-10, 1985, SPCI, Stockholm, Sweden, pp. 231-241.

**Page, D.H.** (1969): A theory for tensile strength of paper. Tappi 52(4), 674.

**Page, D.H.** (2009): The distribution of stress in a fibre in a sheet under tensile load. J. Pulp Paper Sci. 35(1), 24.

**Page, D.H., Seth, R.S.** (1982): The problem of pressroom runnability. Tappi J. 65(8), 92.

**Reme, P.A., Helle, T., Johnsen, P.O.** (1997): Fibre characteristics of various mechanical pulp grades. 1997 Int. Mechanical Pulping Conf., Stockholm, Sweden, June 9-13, 1997, SPCI, Stockholm, Sweden, pp. 297-307.

**Seth, R.S.** (1996): Optimizing reinforcement pulps by fracture toughness. Tappi J. 79(1), 170.

**Seth, R.S., Page, D.H.** (1975): Fracture resistance: a failure criterion for paper. Tappi 58(9), 112.

**Seth, R.S., Page, D.H.** (1983): The stress strain curve of paper., In: Brander, J. (ed.) The role of fundamental research in paper making, Transactions of the symposium held at Cambridge, September 1981, Vol. 1, Mechanical Engineering Publications Ltd, London, UK, pp. 421-452.

**Swinehart, D.K., Broek, D.** (1996): Tenacity, fracture mechanics, and unknown coater web breaks. Tappi J. 79(2), 233.

**Tam Doo, P.A., Kerekes, RJ.** (1981): A method to measure wet fibre flexibility. Tappi J. 64(3), 113.

**Uesaka, T.** (2005): Principal factors controlling web breaks in pressroom - Quantitative evaluation. Appita Journal 58(6), 425.

**Waterhouse, J.F., Page, D.H.** (2004): The contribution of transverse shear to wet fiber deformation behaviour. Nord. Pulp Paper Res. J. 19(1), 89.

**Wathén, R., Niskanen, K.** (2006): Strength distributions of running paper webs. J. Pulp Paper Sci. 32(3)3, 137.

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