Publication I

Lehto, J.H. 2003. Mechanical fibers as reinforcement pulp. 2003 International Paper Physics Conference. Victoria, B.C., Canada, 7-11 Sept. 2003, Montreal, Canada, PAPTAC, 323-331.

Note! The page numbering of this copy differs from the original paper due to technical reasons.

MECHANICAL FIBERS AS REINFORCEMENT PULP

Jouko H. Lehto
UPM-Kymmene Corp.
R&D
Valkeakoski Research Center
P.O. Box 51
FIN-37601 Valkeakoski, Finland

Modern thermomechanical pulp (TMP) offers one possibility of making pulp furnishes that have long average fiber lengths. However, there still remains the question of whether or not TMP fibers are as valuable as kraft pulp fibers as reinforcement pulp. Long-fiber fractions, which were separated from a thermomechanical pulp (TMP) and a commercial kraft pulp, were admixed with the TMP in proportions of 5, 20 and 50 parts by weight in order to compare the reinforcing capabilities of the mechanical pulp fibers with those of the chemical pulp fibers. The observation, according to which mechanical pulp fibers did not improve or improved, only slightly, the strength properties in the TMP furnish, while the kraft pulp fibers simultaneously exhibited both strength properties and rupture strain, means that kraft pulp fibers are superior as a reinforcement pulp.

INTRODUCTION

The strength properties of modern thermomechanical pulps (TMP) are good compared to those of ground wood (either conventional atmospheric groundwood, GW, or pressure groundwood, PGW) pulps. Thanks to this, less chemical reinforcement pulp can be used in the base paper when the furnish is based on TMP instead of on groundwood. Typically, 30 – 50 % of an LWC paper fiber furnish is made up of kraft pulp and 10 – 30 % of a SC furnish, the remaining content consisting of mechanical pulp. When the furnish is based on TMP, the share of kraft pulp is 5 – 10 % lower compared to when the furnish is based on GW. If the need for kraft pulp could be predicted from the strength properties of the components, the difference between TMP and GW would be greater. For instance, based on data presented by Lehto et al. [1], TMP- and PGW-based LWC base papers would have equal tensile and tear indices if kraft pulp made up 30 % and 43 % of their contents, respectively. It is not known why the good strength properties of TMP cannot be fully utilized in papermaking. Due to cost and quality reasons, it would be critical to further decrease the amount of expensive softwood chemical (kraft) pulp.

Using an excessive amount of kraft pulp in TMP-containing base paper leads to over-strong paper, especially with respect to the tear index of the dry web. This hints that the tear strength does not predict the runnability of paper web sufficiently well. Indeed, the out-of-plane tear strength indicator has been criticized as a runnability indicator [2]. In-plane properties, such as fracture toughness and in-plane tear, are considered to be more relevant [2, 3], but not without criticism from other authors [4]. In any case, both the fracture energy and out-of-plane tear indices are usually improved with an increase in the fiber length.

A simple calculation shows that TMP-based furnishes have higher average fiber lengths than do GW-based ones. Let us presume that we have a TMP pulp, a GW pulp and a kraft pulp with weighted average fiber lengths of 1.5 mm, 0.6 mm and 2.3 mm, respectively. Alternative pulp blends of 30/70 kraft/TMP or 40/60 kraft/GW would have fiber lengths of 1.74 mm and 1.28 mm, respectively. Although this calculation is not fully correct, because the different coarseness values have not been taken into account, we still have good reason to believe that the average fiber length of a TMP-based paper is higher than that of a GW-based one. Thus, this would suggest that the long average fiber length that is obtained from mechanical pulp is not as valuable as that obtained from chemical pulp.

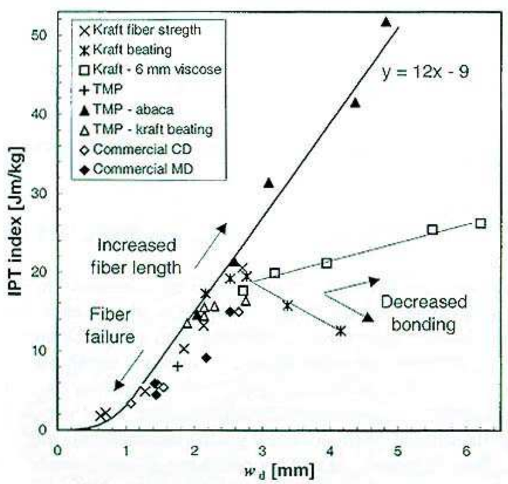

Fig.1.The in-plane tear index vs. the damage width. The data consists of different pulps and their mixtures [5].

Kettunen [5] has shown how the in-plane-tear work depends on the damage width, Fig. 1. According to him, a common trend can be observed for reasonably well-bonded papers. The measured variation in the fracture energy (IPT work) is caused mainly by the fiber length and fiber strength. In pulp mixtures, the average fiber length varies with the mixing ratio, which results in an almost linear change in the IPT work (see for instance TMP – abaca blends in Fig. 1.). A similar variation can be observed when the chemical pulp component has been weakened with hydrochloride acid treatment [5]. Fiber failures reduce the damage width, which for its part, decreases the fracture energy; however, fiber failures do not contribute to the fracture energy in other respects. If the reinforcement fibers have poor bonding abilities, as is the case in unbeaten kraft or viscose fibers, the IPT work is lower than the general trend would predict. However, it is important to note that adding long viscose fibers to kraft pulp improves the fracture energy. Thus, if the base pulp is well bonding, also poorly bonding fibers are able to contribute to the fracture energy. The refining of pure kraft pulp decreases the damage width but increases the fracture energy.

Based on the aforementioned, it is evident that the fiber length plays a crucial role as a reinforcing property in pulp. What, then, is the case with fiber strength? As shown in Fig.1, the fracture energy and damage width decrease linearly when the fibers are weakened. Kärenlampi and Yu [6] have shown that the fracture energy decreases drastically when the fibers are weakened using the same techniques (HCL vapor) as those used by Kettunen. Since the decrement of the fracture energy is much faster than that of the fiber failure probability, Kärenlampi and Yu deduced that the energy consuming contributions, the pull-out energy and the energy consumed in fiber failure, are correlated, possibly because of variations in the width of the fracture process zone. Due to extremely harsh processing, mechanical pulp fibers are much more damaged and weaker than are chemical pulp fibers. Therefore, one can justifiably presume that weak fibers might be one reason for the poor performance of mechanical pulp fibers.

The elastic modulus is an important property of paper. It determines how the web tension depends on the web strain that is brought about by the speed difference in open draws. The paper web must be kept under a certain tension to keep it stable throughout the process. Since the elastic modulus is not directly applicable to paper, the tensile stiffness index is used instead in practice [7]. The tensile stiffness, TS, is related to the elastic modulus, E, as follows:

$$TS = E \times t,$$

where t is the thickness of the sheet. The tensile stiffness is, therefore, a property of the sheet, but the elastic modulus is a property of the material. The tensile stiffness increases with the basis weight, while the elastic modulus remains basically the same. [8]

Refined chemical pulp has higher tensile stiffness (indices) than does mechanical pulp (TMP) [7]. This probably influences the behavior of TMP-based paper in the paper machine.

It is well known that mechanical pulp fibers are much stiffer than chemical pulp. This affects the crack propagation of the paper. Kettunen and Niskanen [9] have demonstrated that PGW fibers debond before kraft fibers do. Stiff fibers make the damage width wider than do flexible fibers. Poorly bonded stiff fibers debond as 'rigid bodies', so that all the bonds along the fibers open almost simultaneously. As a result, the fracture energy is consumed in bond openings and not in the plastic elongation of the fibers. Thus, the total fracture energy remains lower than in the case where both the plastic elongation of single fibers and the opening of bonds occur.

Low fiber coarseness has been seen as being an advantageous property of a reinforcement pulp. Ebeling [10] refers to some Finnish studies, according to which the reinforcement potential is proportional to the average fiber length and inversely proportional to the fiber coarseness. The more slender the fiber, the better its reinforcement potential is. In this respect, chemical pulp fibers enjoy a big advantage, because their coarseness is much lower than that of mechanical pulp fibers. Excessively low fiber coarseness may reduce the reinforcement potential if fiber failures increase in frequency [11].

The high coarseness of mechanical pulps means that there are fewer fibers per weight unit. For this reason, there is a smaller number of load-carrying units in the furnish. One must also take into consideration the fact that the load is carried mostly by cellulose molecules and not by hemicelluloses or lignin. In chemical pulps, the cellulose content is much higher than it is in mechanical pulps, which means that their ability to carry loads is higher per cross sectional area of the fiber wall.

As can be deduced from the above discussion, there are several indications that chemical and mechanical pulp fibers are different in terms of their ability to reinforce a paper sheet. A high average fiber length is not sufficient; the origin of fibers is also very important. In addition to the fiber length, the fiber strength and its ability to bond contribute to the reinforcing ability of fibers.

The aim of this study is, on one hand, to demonstrate that mechanical and chemical pulp fibers really are different with respect to their reinforcing ability and, on the other, to try to ascertain if the above reasoning is consistent.

METHODS AND MATERIALS

Long-fiber fractions were separated from mill-scale TMP and kraft pulps, and then the separated fractions were admixed to the base pulp. The added amount (three levels) corresponds roughly to the proportion of kraft pulp added to lightweight newsprint, SC paper or LWC base paper; however, no existing production line was imitated.

The separation was performed using a Bauer-McNett classifier according to SCAN-M6:69. The R16 and P16/R30 fractions were collected and the collection had to be repeated several times in order to obtain enough pulp for testing.

The TMP was LWC-grade pulp from a Finnish mill (freeness 57 ml). The kraft pulp was sampled from another Finnish paper mill from paper machine proportioning

(freeness 670 ml). The TMP was also used as the base pulp, with which the separated fractions were blended.
The added proportions of the pulp blends of the fiber fractions and kraft pulp were 5, 20 and 50 parts (or 4.76 %, 16.7 % and 33.3 % of the blend) by weight.

60-g/m2 hand sheets were made from the pulp blends according to SCAN-CM26:99 using white water circulation. The fraction sheets were tested without white water circulation, but in order to get an idea of the influence of the fines, the Bauer-McNett 16 fraction sheets were also made using circulation. The hand sheets were tested according to SCAN standards. The tensile index, tensile stiffness index, elongation, TEA index and fracture toughness (fracture energy) were analyzed using an L&W tensile tester with fracture toughness. The testing velocity in these tests was 100 mm/min.

RESULTS

A table containing all the results can be found in Appendix 1.

Properties of the Original Pulps

The base TMP used in this study was typical TMP with a long average fiber length (1.75 mm), good tensile index (51.2 Nm/g) and high tear index (7.0 mNm^2/g). The kraft pulp was mill-beaten to about 70 Nm/g and its average fiber length was 2.36 mm and tear index 16 Nm/g.

According to the results of the Bauer-McNett analysis, the kraft pulp contained double the amount of long-fiber fractions (the sum of R16 and P16/R30 fractions) that the TMP contained, see Table I.

TABLE I.
BAUER-MCNETT ANALYSIS OF THE ORIGINAL PULPS

	TMP	Kraft pulp
BMN 16, %	32.5	73.3
BMN 30, %	11.6	8.0
BMN 50, %	11.3	5.8
BMN 200, %	13.7	3.9
BMN<200, %	30.9	9.1

Properties of the Pulp Fractions

The freeness of the R16 fractions was >700 ml for both the TMP and kraft pulp. The freeness of the P16/R30 fraction of TMP was 700 ml. The Bauer-McNett 30 fraction of the kraft pulp was not tested for freeness, but it is likely that the freeness for this fraction would have been <700 ml.

The Bauer-McNett 16 fractions of the TMP and kraft pulp have distinctly different fiber length distributions, see Fig.1. The average fiber length of the chemical pulp R16 fibers is much higher than that of the TMP fibers (2.86 mm vs. 2.54 mm). This is because in the TMP process, the fibers are broken to a much greater degree than in the kraft pulp process.

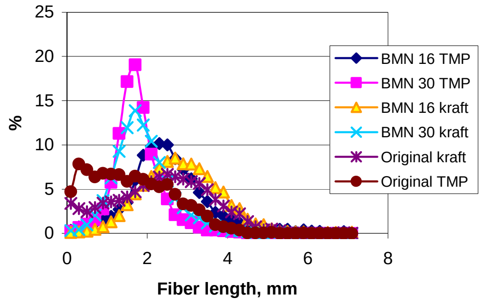

Fig. 1. The weighted average fiber length distributions of the original pulps and their long-fiber fractions analyzed using a Kajaani FS-200.

The Bauer-McNett 30 fractions of the TMP and kraft exhibit almost equal shapes, and the peak values are located at about the same fiber length. However, the kraft pulp's Bauer-McNett 30 fraction has a somewhat higher average fiber length (1.89 mm vs.1.75 mm) because it contains more long fibers than does the TMP. Obviously, some of the long and flexible kraft fibers can pass through the 16 mesh wire, which increases the average fiber length of the P16/R30 fraction. According to Petit-Conil et al. [12], flexibility affects the average fiber length of Bauer-McNett fractions.

In addition to the fiber length, the fiber coarseness was analyzed for the original pulps, pulp fractions and their mixtures. As assumed, the R16 fraction fibers of TMP were the coarsest. The fibers of the R16 fraction of kraft pulp were almost equally coarse, which may sound somewhat awkward when the difference in the pulp yield is taken into consideration. The explanation for this is probably that long fibers are usually also coarse and, as stated above, the R16 fraction of the kraft pulp did contain many more long fibers than did the TMP. In addition, the TMP was refined at a high energy level, which means that most of the fibers were no longer intact but that a lot of peeling and splitting of fibers had occurred. According to Karnis [13], the coarseness of mechanical pulp fibers at the energy levels required for producing papermaking pulp is quite similar to that of low-yield kraft pulp. The coarseness value of 0.314 mg/m observed for the base TMP must be erroneous, because it cannot be higher than the coarseness of its own R16 fraction. At least, part of the high value of the entire TMP can be explained by the high content of fines; not all the fines are detected by the optical analyzer but are included in the sample mass; thus, the basis of the coarseness analysis is not firm.

The paper technical properties of the TMP and kraft pulp fractions differ in all respects; hand sheets made of the fiber fractions of the kraft pulp have a much higher density, Scott bond, tensile index, fracture energy, TEA, elongation and tensile stiffness. In addition, they form a smoother sheet. The only drawback of the kraft fibers is their low light scattering coefficient.

The sheets made from the Bauer-McNett 16 fraction were tested both with and without using water circulation in a sheet mould. It is common practice to make paper sheets without the white water generated in the sheet mold, because collecting a sufficient amount of pulp for the hand sheets is so laborious with the Bauer-McNett fractionator. The white water fines had a clear and expected effect on the results; all the strength properties increased, and the sheets became smoother. The impact of water circulation was much greater for TMP fibers than it was for kraft fibers.

The Impact of the Addition of Long Fibers on the Properties of the Pulp and the Fiber Length Distribution

The addition of different pulp fractions had a clear impact on the fiber length distribution for added proportions that were sufficiently high. When the addition is only 5 parts, the change can hardly be observed. The fiber length distribution of TMP is affected the most strikingly by adding a Bauer-McNett 30 fraction of TMP or kraft pulp. This is due to the sharp distribution curve of the Bauer-McNett 30 fractions, see Figures 2 and 3.

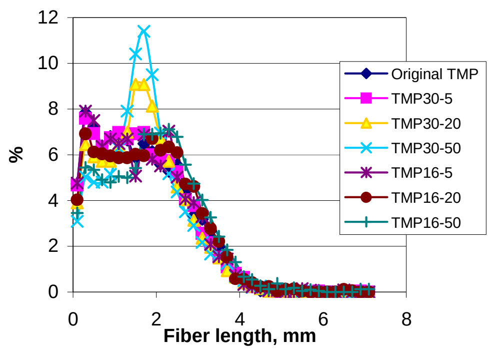

Fig. 2. The impact on the weighted average fiber length distribution of the blend of the addition of Bauer-McNett 16 and 30 fractions of TMP. The proportions added were 5, 20 and 50 parts on the base pulp.

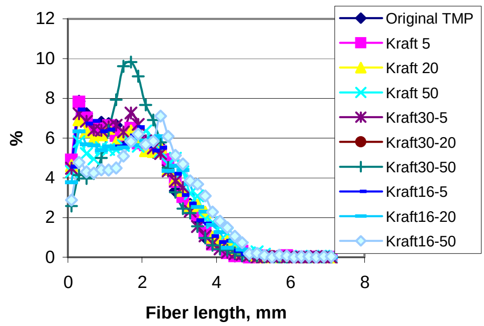

Fig.3. The impact on the weighted average fiber length distribution of the blend of the addition of kraft pulp or its Bauer-McNett 16 and 30 fractions. The proportions added were 5, 20 and 50 parts on the base pulp (the 30 mesh fraction of the kraft pulp at 20 parts is not included).

The effect of the R16 mesh fibers of the kraft pulp is more pronounced than that of the TMP due to the longer fiber of the former. The same can be seen in Figure 4, where the average fiber length is shown as a function of the added proportion. The effect of the P16/R30 fraction of either TMP or kraft pulp is rather limited. Kraft pulp and the 16 mesh fraction of TMP have an almost equal effect on the average fiber length. This makes it possible to make a paired comparison of these pulps, i.e. the BMN 30 fractions of TMP and kraft pulp can be compared with each other and the BMN 16 fraction of TMP can be compared with the whole of the kraft pulp. In this way, we may be able to answer the question as to the significance of the fiber type – rigid or flexible – as long as the average fiber length of the furnish is equal.

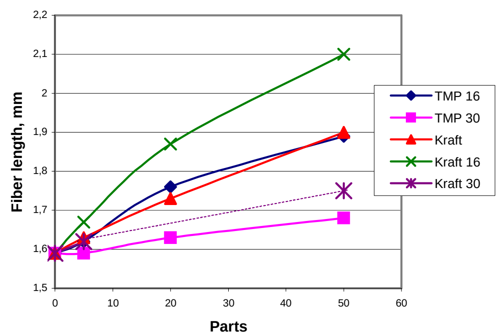

Fig. 4. The effect on the length-weighted average fiber length of different long-fiber fractions and the kraft pulp of the TMP/long fiber blend. The proportions added were 5, 20 and 50 parts on the base pulp (the 30 mesh fraction of the kraft pulp at 20 parts is not included).

The R16 fraction of the kraft pulp is clearly the most effective fraction in order to obtain a high average fiber length of the blend. This is more due to its high fiber length than to its low coarseness. Ring and Bacon [14] have derived equations for how the average fiber length of pulp depends on the fiber length and coarseness of the components of the pulp. Figure 5 shows that the average fiber length of the pulp blends could be predicted to a good degree of accuracy using the component values and the proportion of the components in the blend. Since the prediction is good, one can deduce that the basic data must be relatively correct. The contribution of coarseness was quite miniscule as, without it, R^2 dropped only slightly, from 0.975 to 0.967.

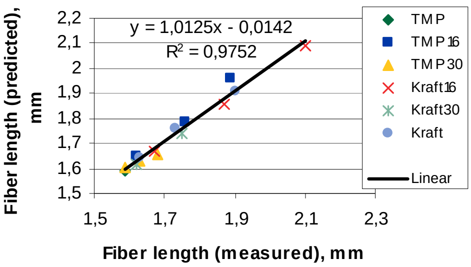

Fig. 5. The predicted vs. measured weighted average fiber length of the blends.

However, if the coarseness values of the components are studied more carefully, one immediately sees that there are certain illogical features in the results. The base TMP cannot have a higher coarseness than that of the R16 mesh fraction separated from it. Furthermore, it does not make sense that blending these long fibers with the base TMP decreases the coarseness of the blend. It is shown in literature [15] that there are some uncertainties in the coarseness analysis performed using the FS-200 analyzer and, in fact, measuring mechanical pulp for coarseness is not at all necessarily meaningful due to the considerable fiber fragments and fines; indeed, these problems occurred in this study. It seems that the coarseness values of the fiber fractions and of the whole kraft pulp are reasonably reliable and comparable with each other. Due to the problems with coarseness, the mean particle mass was calculated from the FS-200 raw data simply by dividing the mass of the sample by the total amount of measured fibers. The results are shown in Figure 6.

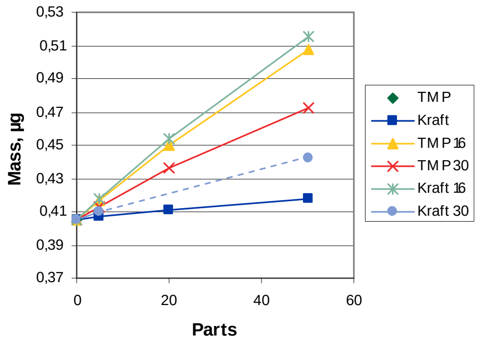

Fig. 6. The mean particle mass vs. the added proportion of different long-fiber fractions and kraft.

The mean particle mass increases the most with the R16 fraction fibers of the TMP and kraft pulps; the whole kraft pulp and its 30 mesh fraction have virtually no effect. The 30 mesh fraction of TMP is between these two groups.

Figure 7 illustrates how the fractions influence freeness. At a given added proportion, only the 16 mesh fraction of TMP differs clearly from the other fractions; it gives the highest freeness for the furnish. If analyzed from another point of view, Figure 7 shows how, at a given freeness, the average fiber length can vary within a wide range. It is also obvious that at a given fiber length, different pulp blends would behave differently on the forming section of a paper machine.

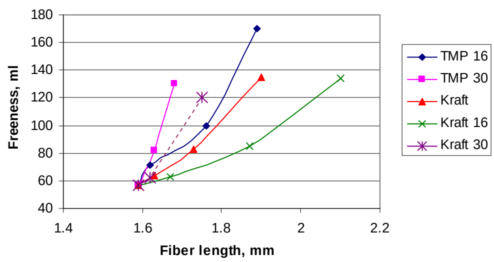

Fig. 7. Freeness vs. the average fiber length of TMP/fiber fraction furnish. The added proportions were 5, 20 and 50 parts (the 30 mesh fraction of the kraft pulp at 20 parts is not included).

The Impact of the Addition of Fiber on the Properties of Paper

Mechanical and kraft pulp fibers have a clearly distinctive effect on the paper technical properties of pulp blends. Figure 8 shows how whole kraft pulp has the biggest positive effect on the tensile index followed by the R16 and 30 fractions of kraft pulp.

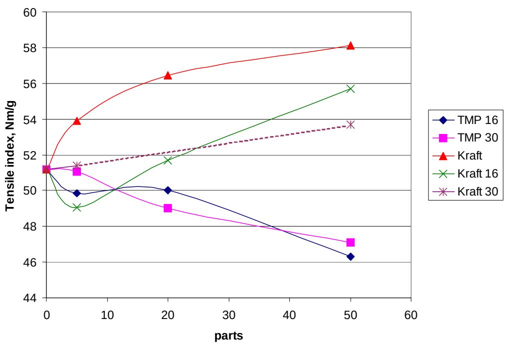

Fig. 8. The effect of the addition of long fiber on the tensile index.

The limited amount of available data prevents us from evaluating certain nonlinear features in the graph, but nevertheless, the basic message is clear: as a rule, mechanical pulp fibers decrease and kraft pulp fibers increase the strength of paper.

The apparent density of the hand sheets seems to determine properties related to tensile strength and elongation (the correlation coefficients range between 0.96 and 0.98). Figure 9 illustrates how close the relationship between density and tensile strength is based on the experimental data generated in this study. The lowest points are the long-fiber fractions of TMP and the four upper-most points of the whole kraft, its Bauer-McNett 30 and 16 fractions, the latter fraction having been prepared with and without circulation water. Chemical pulp fibers densify the hand sheets, whereas mechanical pulp fibers make it more bulky. This indicates that the contribution of chemical pulp fibers to the consolidation of the hand sheets differs from that of mechanical pulp fibers. The reasons for this are evident and are not discussed here. Even the small amount of fines that is retained in the sheet, when white circulation is used, is enough to increase the tensile index of the Bauer-McNett 16 fraction of kraft pulp by about 10 %.

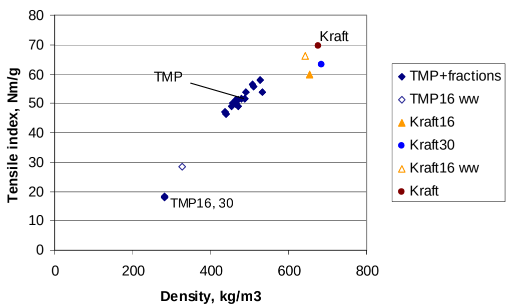

Fig. 9. Apparent density vs. the tensile index (ww = hand sheets made with white water recirculation).

In addition to properties related to tensile strength, the correlation between density and tear is also high (0.90). There is a marked difference between the fractions of mechanical pulp and those of chemical pulp fiber, the latter ones being in a class of their own. An interesting feature is that even though the fiber length increases drastically with mechanical pulp long fibers, they increase the tear of the furnish only a little.

Although the linear correlation between the density and the Scott bond is lower (0.74) than with other strength properties, the relationship is clear. Mechanical pulp fibers tend to decrease the Scott bond, whereas chemical pulp fibers increase it slightly. However, for high added proportions, the R16 mesh fibers of kraft pulp also begin to decrease the Scott bond. This is natural, because the Scott bond of the kraft pulp fractions is low in relation to their density.

A noteworthy observation is that elongation (stretch at break) drops with mechanical pulp already for low added proportions. The immediate drop may be a trial error, although in any case, the trend is evident. The elastic breaking strain, $\varepsilon_{elastic}$, can be calculated from the tensile index, σ, and tensile stiffness index, TSI, using Equation 2:

$$\varepsilon_{elastic} = \sigma / TSI \qquad (2)$$

The differences in $\varepsilon_{elastic}$ are relatively small, which means that the different fiber fractions mostly affect the plastic part of the breaking strain, see Figure 10. The addition of the R16 fraction of TMP seems to cause the plastic strain to fall, whereas adding the R16 fraction of kraft pulp increases it markedly. Neither of the two different long-fiber fractions has any effect on the elastic strain. The results for the P16/R30 fractions and whole kraft fully support the result that was obtained with the R16 fractions. Obviously, the kraft pulp fibers are not fully activated, even though the drying shrinkage is basically hindered in the preparation of the hand sheets.

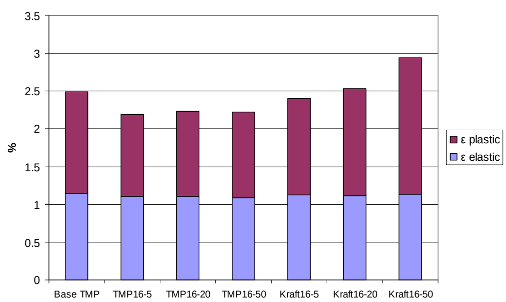

Fig. 10. The effect on the elastic and plastic strain of the addition of the R16 fractions of TMP and kraft pulp.

Since both tensile strength and elongation decrease with the addition of mechanical pulp fibers, it follows that TEA also decreases.

The fracture energy result is maybe the most interesting of all. Kraft pulp or its fractions increase it even at an addition of 5 parts. A 50-part addition of the R16 fraction of kraft pulp almost doubles the fracture energy, but fractions of mechanical pulp fiber only maintain the fracture energy at its original level. The tear index behaves almost identically to fracture energy. Here, also, it is very interesting to see that mechanical pulp fibers do not seem to improve the tear index whereas kraft or its R16 fraction almost double it. Somewhat surprisingly, at an addition of 50 parts, whole kraft pulp improves the tear index more than the R16 fraction does, even though R16 gives a markedly higher average fiber length.

Kraft pulp and its fiber fractions increase the tensile stiffness index of the furnish in contrast to mechanical pulp fibers that slightly decrease it. This result may be important in practical papermaking, as kraft pulp fibers seem to quicken the response of the web to draw and, thus, facilitate web control.

Optical properties (light scattering and light absorption coefficients) were calculated from the properties of the components with a reasonably good degree of accuracy. Similarly, the component properties can clearly be seen in the surface roughness of the hand sheets. Both mechanical pulp fractions increase roughness markedly. Kraft pulp fibers have only a marginal effect on roughness. All the blend fibers make the hand sheets more porous. Again, mechanical pulp fibers have the greatest effect. Whole kraft pulp seems to first close the sheet, although this might be an experimental error.

From the results presented above, it can be deduced that factors, other than the fiber length distribution or the average fiber length that the fraction contributes to the furnish, are decisive. A good example of this is fracture energy, see Figure 11. At a given fiber length, the Bauer-McNett 30 fraction of kraft gives the best result, but the respective TMP fraction hardly maintains fracture energy at its starting level.

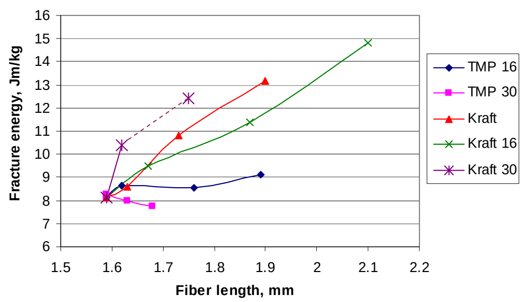

Fig. 11. Fracture energy vs. the weighted average fiber length of the TMP/fiber fraction furnish. The added proportions were 5, 20 and 50 parts (the 30 mesh fraction of the kraft pulp at 20 parts is not included).

This result is interesting, because it is not in accordance with the results reported by Kettunen [2] and Hiltunen et al. [16]. The fracture energy of reasonably well-bonded sheets is supposed to be linearly dependent on the damage width that, for its part, is dependent on the arithmetic fiber length. In this case, mechanical pulp fibers deviate from this rule. The low Scott bond values of the TMP fractions suggest that the main reason for this deviation might be their weak bonding properties. Another reason might be the low strength of the TMP fibers, which, as a result, would decrease the effective fiber length and damage width.

When two basic quality factors, elongation and the tensile index, are plotted against each other, we get the graph shown in Figure 12. In a way, it summarizes the results of the strength properties. The two long-fiber fractions of TMP are practically equal in terms of their elongation and tensile index, and both these values are very low. Obviously, the TMP fibers are relatively straight, which means that the bonds begin to break down rapidly when the paper is stretched. The tensile index is low either due to the low bonding strength or to minor conformability and the low bonded area of the fibers. The fiber strength has hardly any effect on the tensile index of the pure fractions because of the low degree of bonding. Kraft pulp fibers exhibit much more elongation and higher indices of tensile strength than do TMP fibers, which is also reflected in the properties of the blends. As stated earlier on, there is no big difference between the values of $\varepsilon_{elastic}$ of the pulps. Thus, taking into account the fact that kraft pulp fibers increase the tensile index, they must also increase the tensile stiffness, as is the case. In this respect, Fig. 8 may be misleading.

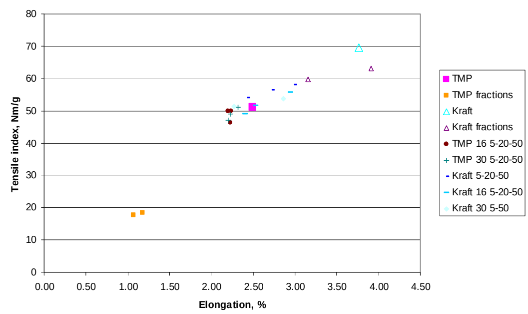

Fig. 12. Tensile index vs. the rupture strain. 5-20-50 refers to the added proportions.

Kraft pulp fibers simultaneously increase the tensile index, the tensile stiffness and the rupture strain, but mechanical pulp fibers have a reverse effect. There must be a lot of synergy between the added TMP long fibers and the base pulp, because the TMP series are located near the original TMP point for any added proportion.

CONCLUSIONS

The first part of this study, the separation of long-fiber fractions from TMP and from kraft pulp, brought forth one difficulty in this kind of approach; it is difficult to obtain fully comparable fiber fractions from different types of pulp. The Bauer-McNett 30 fractions of TMP and kraft had reasonably similar average fiber lengths and fiber length distributions. The slight difference in the fiber length distributions can be explained by the well-known fact that the Bauer-McNett classifier does not classify fibers solely based on their fiber length, but instead, other factors also have an impact; it is likely that fiber flexibility is the most important additional factor.

In spite of certain inaccuracies, we can conclude that the reason for any difference in the effects on paper properties that we observe when adding the Bauer-McNett 30 fraction must lie in fiber properties other than the length: the fiber width, cell wall thickness, cell wall structure etc.

The results for the Bauer-McNett 16 fractions are more difficult to evaluate, because there is a distinct difference in the fiber distribution. The Bauer-McNett 16 fraction of the kraft pulp contains much longer fibers than does the respective fraction of TMP. This is because the TMP process cuts fibers more than does the kraft process, and there was no upper limit for the length. Perhaps it would have been a good idea to include, for instance, a 10 mesh wire in the wire series to make the 16 fraction better defined.

The addition of separated long-fiber fractions to the base pulp changed the fiber length distribution of the furnish as expected. Due to its narrower distribution, the effect of the Bauer-McNett 30 fraction could be observed more easily than the Bauer-McNett 16 fraction. This visible difference is supported by the fact that the base TMP had a small Bauer-McNett 30 fraction, and thus, adding that fraction causes a large relative change. The change in the average fiber length is a different story. The Bauer-McNett 16 fraction of the kraft pulp increases the average fiber length the most (from 1.6 mm up to 2.1 mm at an added proportion of 50 parts) followed by whole kraft pulp and the R16 fraction of TMP. The Bauer-McNett 30 fractions do not have a major effect on the average fiber length, because their length is so close to that of the base TMP. These results enabled a comparison in which the pulp furnishes have an equal average fiber length, while at same time, the reinforcement fibers are certainly of a different type.

The main observations and conclusions of this study were:

- The apparent density of the fractions is reflected very clearly in the furnish and, on the other hand, the density correlates strongly with bonding-related properties analyzed by the tensile tester. Mechanical pulp fibers decreased the density, whereas chemical pulp fibers increased it markedly;
    - Although neither the fiber flexibility nor conformability was analyzed, we can presume that these properties explained a major part of the density, and thus, we can deduce that these properties are very important for bonding-related properties. Presumably conformable fibers form more fiber bonds or increase the relative bonded area more than do stiff fibers and, in that way, increase strength;
- The biggest relative changes occur in the strength properties, such as the TEA index, fracture energy and tear index, in which elongation plays a major role;
    - Kraft pulp fibers conform to the fiber matrix better than do mechanical pulp fibers and form a spring-like structure that has greater flexibility, even though drying shrinkage is hindered when making hand sheets in accordance with the ISO standard. In practical papermaking, to create the necessary tension in the web, there must be enough draw to straighten the kraft fibers and activate them;
- Kraft pulp fibers simultaneously increase rupture strain, the tensile index and the tensile stiffness, whereas mechanical pulp fibers decrease them;
    - This is possible, because $\varepsilon_{elastic}$ is not changed by the addition of kraft pulp fibers and the increase takes place in the plastic part;
- All the fiber fractions (including kraft pulp) increase freeness to about the same extent; the Bauer-McNett 16 fraction of kraft pulp is an exception, as it has a greater effect than the rest;
    - Taking into consideration that there was a large variation in other properties, one can conclude that freeness is not a good quality indicator in this kind of case;
- Kraft pulp is, in all respects, better than its Bauer-McNett 30 fraction and worse than its Bauer-McNett 16 fraction with respect to fracture energy;
    - This finding makes the fractionation of kraft pulp questionable. It seems that the fines and medium fraction of kraft pulp contribute advantageously to the consolidation of hand sheets.

The observations listed above simply mean that mechanical pulp fibers do not improve any strength properties in a TMP furnish or that kraft pulp fibers are superior as reinforcement pulp in comparison to mechanical pulp fibers even at a given fiber length of the blend. The observation that kraft pulp fibers exhibit rupture strain and tensile indices that are several times higher and that they are able to simultaneously increase elongation, the tensile index and the tensile stiffness are the most essential findings of this study, for they indicate the target when trying to utilize long mechanical pulp fibers better than they are utilized today.

This study demonstrated that the long fibers of mechanical and chemical pulp do have different reinforcement abilities, and some speculations as to the reasons for this could be presented; however, individual fiber properties were not studied in detail. In the follow-up to this study, this must be done in order to be able to explain the behavior of different fibers and, even more importantly, to be able to modify mechanical pulp fibers in a desired direction. One approach is to study the pulps from existing mechanical pulp processes and ascertain whether better mechanical reinforcement fibers than those studied here can be found. This would also help in envisioning the possibilities and development requirements.

REFERENCES

1. LEHTO, J., EBELING, K., HOLM, H., "Some aspects on silviculture of poplar species as raw material for paper grade pulps", The First ECOPAPERTECH Conference, Helsinki, June 6-9, 391–407 (1995).
2. NISKANEN, K., "Strength and fracture of paper", in Transactions of the tenth Fundamental Research Symposium, Vol. 2, Baker C.F., (Ed.), Waveney Print Services Ltd., Beccles, Suffolk, UL, 641–726 (1993).
3. PAGE, D.H., SETH, R.S., "The problem of pressroom runnability", Tappi 65(8), 641–726 (1982).
4. WIENS, M., GÖTTSCHING, L., "Das J-Intergral und seine Eignung zur Characterisierung des Risswiderstands von Papier", *Das Papier* 53(5), 305 – 313 (1999).
5. KETTUNEN, H., "Microscopic fracture in paper", Dissertation, Helsinki University of Technology, Espoo (2000).
6. KÄRENLAMPI, P.,YU, Y., "Fiber properties and paper fracture – fiber length and fiber strength". In Baker, C.F., (ed.) The fundamentals of papermaking material, Pira, UK, 521-545 (1997).
7. YU, Y., KETTUNEN, H., PAULAPURO, H., "On the reinforcement of straw pulp", *Nordic Pulp & Paper Research Journal* 15(2), 114 – 119 (2000).
8. LEVLIN, J-E., "General physical properties of paper and board", in Papermaking Science and Technology – 17. Pulp and Paper Testing. Ed. Levlin, J-E., Söderhjelm, L., Fapet Oy, Helsinki (1999).
9. KETTUNEN, H., NISKANEN, K.J., "Fiber debonding along a crack front in paper". Mat. Res. Soc. Symp. Proc., Vol 539, Beltz G.E., Blumberg Selinger R.L., Kim K.-S., Marder M.P. (Eds.), MRS, Warrendale (1999).
10. EBELING, K., "Role of softwood fibre form and condition on its reinforcement capability", Cellulosic pulps, fibres and materials. Woodhead Publishing Limited, Cambridge (2000).
11. YU, Y., KETTUNEN, H., HILTUNEN, E.J., NISKANEN, K.J., "Comparison of abaca and spruce as reinforcement fiber", *Appita J.*, 53(4):287–291 (2000).
12. PETIT-CONIL, M., COCHAUX, A., DE CHOUDENS, C., "Mechanical pulp characterization: a new and rapid method to evaluate fibre flexibility", *Paperi ja Puu*, 76 (10):657–662 (1994).
13. KARNIS, A., "The Mechanism of Fibre Development in Mechanical Pulping". *J. Pulp Paper Sci.*, 20(10): J280–J288 (1994).
14. RING, G.J.F., BACON, A.J., "Multiple component analysis of fiber length distributions", *Tappi* 80(1):224–231 (1997).
15. SETH, R.S., CHAN, B.K., "Measurement of fiber coarseness with optical fiber length analyzers", *Tappi* 80(5):217–221 (1997).
16. HILTUNEN, E., KETTUNEN, H., LAINE, J.E., PAULAPURO, H., "Behaviour of reinforcement fibres in TMP based paper", *Paperi ja Puu*, 84(4):269–273 (2002).

TABLE II.
TEST RESULTS

	BMN 16, TMP	BMN 30, TMP	BMN 16, kraft	BMN 30, kraft	Original kraft	Original TMP	BMN 16 fraction, TMP			BMN 16, TMP ww	BMN 30 fraction, TMP			Kraft pulp			BMN 16 fraction, kraft			BMN 16, kraft ww	BMN 30 fraction, kraft		
Parts added							5	20	50		5	20	50	5	20	50	5	20	50		5	20	50
Freeness, ml	723	703	740	x	670	57	71	100	170	x	57	82	130	64	83	135	63	85	134	x	62	x	120
Fiber length (Fs-200), mm	2,54	1,75	2,86	1,89	2,36	1,59	1,62	1,76	1,89	x	1,59	1,63	1,68	1,63	1,73	1,9	1,67	1,87	2,1	x	1,62	x	1,75
Coarseness (FS-200), mg/m	0,243	0,211	0,24	0,163	0,225	0,314	0,327	0,286	0,275	x	0,297	0,28	0,254	0,308	0,308	0,28	0,308	0,272	0,249	x	0,283	x	0,214
Basis weight, g/m²	61,5	62,3	60,5	60,3	57	59,6	60,4	59,2	59	62,1	60	60,3	60,3	60,1	60,6	58,2	57,7	59,2	61,6	70,4	56,6	x	63,5
Density, kg/m3	282	283	653	684	677	472	465	456	439	326	466	455	438	489	507	527	469	488	511	642	478	x	534
Tensile index, Nm/g	17,8	18,4	59,7	63,1	69,6	51,2	49,8	50,0	46,3	28,3	51,1	49,0	47,1	53,9	56,4	58,1	49,0	51,7	55,7	66,1	51,4	x	53,7
Rupture strain, %	1,07	1,18	3,16	3,92	3,76	2,50	2,20	2,24	2,23	1,30	2,32	2,23	2,20	2,43	2,72	2,99	2,40	2,54	2,95	3,41	2,28	x	2,86
Tensile stiffness, MNm/kg	2,41	2,44	6,52	6,30	6,68	4,47	4,49	4,53	4,25	3,50	4,61	4,40	4,30	4,82	4,97	5,21	4,34	4,64	4,92	6,83	4,67	x	4,98
TEA index, J/kg	114	135	1310	1735	1780	857	719	737	682	230	788	724	686	879	1050	1200	785	883	1125	1555	777	x	1070
Fracture energy, Jm/kg	2,7	2,5	23,5	18,1	23,8	8,1	8,7	8,5	9,1	5,0	8,3	8,0	7,7	8,6	10,8	13,2	9,5	11,4	14,8	25,6	10,4	x	12,4
Tear index, mNm2/g	7,5	4,6	20,7	12,8	16	7	7,1	7,3	7,3	8,9	6,4	7,1	7,5	7,1	8,3	12,3	7,5	9,3	11,4	24,7	7,3	x	9,1
Scott bond, J/m²	50	55	191	267	422	332	311	250	193	57	324	269	198	353	357	412	324	366	322	212	343	x	370
Light scattering coeff., m2/kg	31,7	32,5	22,2	27,3	24	59	57,3	54,1	49,2	31,4	57,3	55,6	51,5	55,5	54,6	46,8	56,6	52	45,8	24	55,8	x	47
Light absorption coeff., m2/kg	1,74	1,82	0,25	0,27	0,27	1,75	1,62	1,64	1,62	1,64	1,64	1,7	1,75	1,61	1,61	1,26	1,52	1,33	1,11	0,25	1,43	x	1,1
Roughness TS (Bendtsen 150/1), ml/min	3474	2918	1272	826	1171	1323	1612	1962	2106	2915	1543	1532	1830	1501	1538	1544	1766	1422	1500	1229	1582	x	1503
Roughness WS (Bendtsen 150/1), ml/min	3190	2686	454	215	201	109	135	172	230	1643	128	165	199	106	126	122	117	113	145	340	126	x	101
Thickness, µm	1090	1101	463	441	421	632	649	649	672	951	644	663	689	614	598	552	615	607	603	548	592	x	595
Air permeability (Gurley-Hill), s/100ml	*1,27*	*1,27*	1,5	4,3	8,2	179	145	107	59,1	*1,27*	150	109	59,8	204	181	129	151	127	84,7	2,9	159	x	114

ww = fraction sheets made with white water recirculation
x = not analyzed