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FRACTURE PROPERTIES IN FILLED PAPERS

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ABSTRACT

The mechanical properties of paper are impaired by the addition of filler. The beating of kraft pulp and addition of starch are possible remedies for this. However, beating also has negative effects because it reduces opacity and bulk, and starch effects are limited by retention. Optimal use of the kraft pulp and starch is therefore important. We show that in pure kraft sheets beating alone can compensate for most of the adverse effects on mechanical properties caused by kaolin addition. In TMP-based sheets with kaolin, the mechanical properties are fairly insensitive to the kraft content unless very high beating levels are used. The primary role of kraft is to improve tensile stiffness, not tensile strength of paper. Starch and beating both improve inter-fiber bonding but beating also raises fiber segment activation. The latter mechanism contributes to tensile stiffness but reduces damage width. The other mechanical properties of paper appear to be insensitive to fiber segment activation.

INTRODUCTION

Filler is added to furnish to improve properties such as opacity, brightness, smoothness and printing properties, which are highly desirable in printing papers. Concurrent with these improvements, the strength properties of the paper can deteriorate substantially as a result of decreasing inter-fiber bonding. For example, poor inter-fiber bonding can lead to blistering in coated papers. Different ways to alleviate these strength losses have been studied. For example, it has been shown that beating kraft pulp to a greater extent partially compensates for the loss of tensile index and fracture energy [1].

Strength losses caused by filler can also be compensated for by using dry strength additives. Starch is a typical dry strength agent. It is considered to increase the inter-fiber bond strength per unit bonded area, but not to change the inter-fiber bonding area [2]. It has been found that dry-strength additives, including starch, improve strength properties without affecting sheet structure [3]. In one study, the reduction in tensile strength caused by filler addition was almost entirely compensated for by adding starch, even when the filler content was high [4].

The evidence reported in literature suggests that filler content acts on the mechanical properties of paper primarily through the inter-fiber bonding area. Starch and other strength additives in turn seem to influence primarily the strength per unit area of inter-fiber bonds. The mechanism active in beating is more complicated, combining different changes in network structure and inter-fiber bond properties. The mechanisms of filler addition and strength additives may also be more complicated because most studies have focused on the tensile strength of paper. Thus they offer only a rather limited view on the mechanical properties of paper.

In this paper, we compare the effects of kraft beating and starch addition on the in-plane and out-of-plane mechanical properties of papers containing filler. The z-directional fracture properties of paper are critical for, e.g., blistering in heatset printing. Depending on the relative importance of the mechanical properties of a printing paper, one should compensate for the negative effects of filler by either adding starch or increasing kraft beating.

EXPERIMENTAL

Sample material

We used lap-dried ECF-bleached softwood kraft pulp (KP). The length-weighted mean fiber length was 2.20 mm and coarseness 0.146 mg/m. The kraft pulp was used unbeaten and beaten for 5, 15 and 40 min in a Valley beater (SR 12, 13, 15 and 22, respectively). The other pulp component was a TMP with the mean fiber length 1.68 mm and coarseness (with fines screened out) 0.180 mg/m.

We made handsheets of the pure kraft pulp, its 50–50 mixture with TMP, and the pure TMP. Starch (ordinary cationic dry strength agent) was added to the unbeaten and 5 min beaten pure kraft handsheets and to the 50–50 mixture of TMP and unbeaten kraft. The amount of starch added to the pulp suspension was 1–4%, calculated on dry fiber weight. Filler was added only to the pulps with good bonding ability or the pure kraft beaten for 15 and 40 min, and to the mixture sheets of TMP and all three beaten kraft pulps. When adding filler, we held the fiber grammage constant.

The purpose of adding starch was to see if it would give the same effect as increasing beating. Hence starch was added to the unbeaten and 5 min beaten pure kraft handsheets and to the 50–50 mixture of TMP and unbeaten kraft. These fiber furnishes were expected to have the lowest level of "bonding" prior to starch addition. The amount of starch to the pulp suspension was 1–4%, calculated of the dry fiber weight. Since white water circulation was not used in the sheet making (pure chemical pulp), the actual amount of starch retained was lower than that added to the pulp. The starch retention was not measured, but it was assumed to be high.

The filler addition was expected to act in the opposite direction from beating. Hence the filler was added to the furnishes with the best "bonding" ability, or the pure kraft beaten for 15 and 40 min and to the mixture sheets of TMP and all the three beaten kraft pulps. It was then of interest to see if the filler addition would bring the mechanical properties back to a level obtained with the unbeaten kraft pulp. The final filler content in handsheets, determined from the ash content, ranged to 30% in the pure kraft sheets and to 20% in the mixture sheets.

Mechanical testing

We measured the ordinary in-plane sheet properties (tensile strength, breaking strain and tensile stiffness), and the in-plane fracture energy using the in-plane tear (IPT) test [5–9]. For out-of-plane fracture characterization, we performed the Scott bond test, nip-peeling test [10] and z-directional tensile test.

In the nip-peeling test, paper specimen is inserted into a nip system with two synchronized rolls, 25 mm in radius. A spring at both ends of the rolls applies a compressive linear load of about 2.5 kN/m on the paper specimen. Adhesive tape is used only at beginning of the specimen, to adhere the first 10–20 mm of the specimen length onto the rolls. After the beginning phase, delamination proceeds without the tape. Fracture energy per unit crack surface was obtained from the work done in the delamination.

Damage width and pull-out width were determined from "damage analysis" using silicone impregnated samples [5]. Damage width reveals the distance to which microscopic damage (inter-fiber bond openings and fiber failures) is created on both sides of the fracture line when paper fails in an in-plane test. Pull-out width tells how long fiber sections emerge from the fracture line. Both measures characterize the size of the in-plane fracture process zone.

RESULTS

All the measured results are in Table 1. We express the in-plane tensile index, tensile stiffness index, and in-plane tear (IPT) index using only the mass of the fibers and not the mass of the whole sheet grammage as reference. This means, for example, that the tensile index values that we use for filled papers are larger than the ordinary tensile strength divided by paper grammage. This normalization simplifies the discussion of results.

In order to characterize the strength of paper web we considered primarily tensile index and elastic breaking strain. According to Uesaka and Ferahi [11] these two factors are crucial for web breaks. These properties can in turn be related back to furnish properties if one considers tensile stiffness, in-plane tear energy (as a measure of fracture energy), and damage width [12]. As Figure 1 shows, there is a reasonably good agreement between the measured tensile index and that calculated from Equation 2 in Reference 12.

Pure kraft handsheets

Beating improved tensile stiffness index (specific tensile stiffness), tensile index and IPT index. For example, beating for 15 min almost doubled the IPT index and tensile stiffness index. In comparison, damage width decreased systematically as a result of beating and, at high levels of beating, also fracture energy decreased.

Kaolin impaired all in-plane properties except damage width. For example, adding 29% kaolin to pulp beaten for 15 or 40 min lowered the IPT index to half and tensile stiffness index to two-thirds. Damage width remained almost constant.

Starch affected mainly fracture energy and tensile strength. For example, adding 4% starch to unbeaten kraft pulp doubled the IPT index and almost

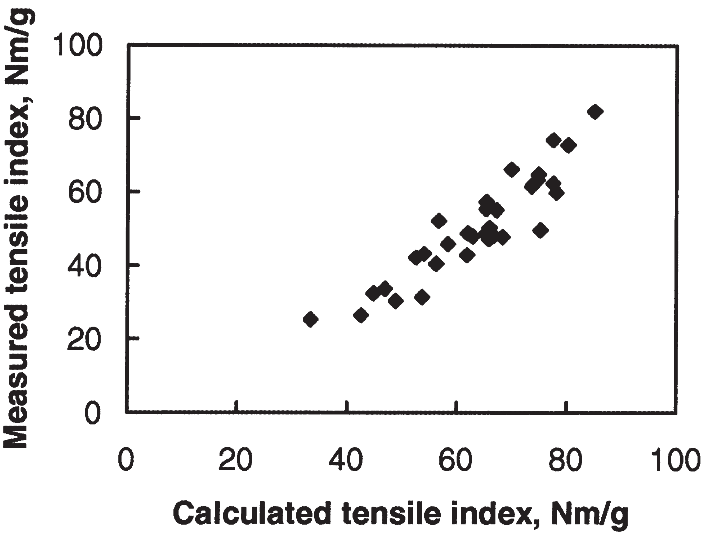

Figure 1 Measured vs. calculated [12] values of the tensile index for all samples.

doubled the tensile index. Tensile stiffness index and damage width changed little.

To summarize, the primary effect of beating appeared to be a concurrent increase in inter-fiber bonding and fiber segment activation [13]. As expected, kaolin and starch altered only the inter-fiber bonding but not the fiber segment activation or fiber failure probability.

Figure 2 illustrates the effect of furnish on the tensile index of the paper sheet. Figure 3 shows the corresponding data for the elastic breaking strain. In the tensile index of the paper sheet, the addition of 4% starch to the unbeaten kraft pulp is equal to 5 min of beating. In elastic breaking strain, starch addition is much more effective than beating.

If the 5 min beaten sheet is used as a reference, beating can fully compensate for the negative effects that adding filler causes in the tensile index and elastic breaking strain of the paper sheet.

The z-directional properties, Scott bond energy, nip-peeling energy (= z-directional fracture energy) and z-tensile strength increased with beating and starch addition, but decreased with kaolin addition (Figure 4). Of the three factors, starch addition had the largest effect. The 4% addition to the unbeaten kraft pulp made the nip-peeling energy 5 times higher. Scott bond energy behaved qualitatively in the same way as the z-directional fracture

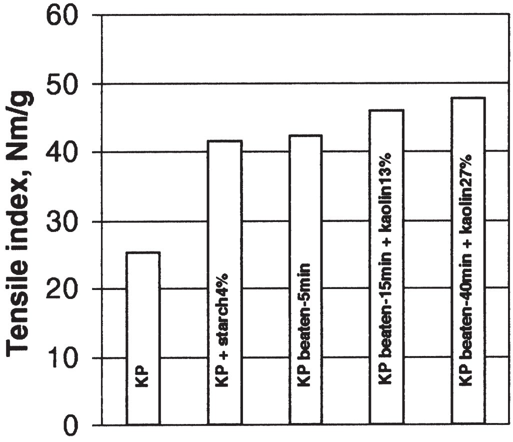

Figure 2 Effect of furnish on the tensile index of a pure kraft paper sheet. KP refers to the unbeaten kraft pulp.

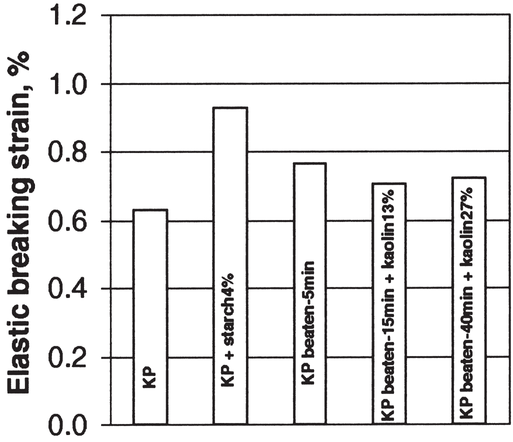

Figure 3 Effect of furnish on the elastic breaking strain of a pure kraft paper sheet, calculated by dividing the tensile index with tensile stiffness index.

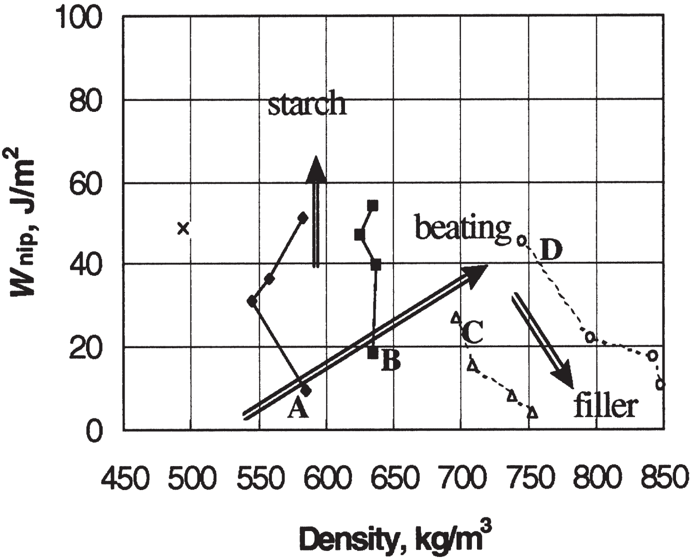

Figure 4 Nip-peeling energy (W_{nip}) against density for pure kraft handsheets; unbeaten kraft with different content of starch (closed diamond), lightly beaten with starch (closed square), medium beaten with filler (open triangle), and heavily beaten with filler (open circle). Increasing beating without starch or filler corresponds to points **A–D**. The ×-symbol indicates the pure TMP sheet.

energy but was 6–8 times larger. The relative change in z-tensile strength was smaller than even that of the Scott bond energy.

TMP and kraft mixture handsheets

The effects of kraft beating or kaolin addition on mixture sheets were only slightly different from those on pure kraft sheets. Firstly, beating had roughly the same effect as before on tensile stiffness index, tensile index, and damage width, but it had almost no effect on the IPT index. Secondly, unlike in the pure kraft sheets, kaolin addition did not change almost at all tensile stiffness index. The effects of starch addition were almost the same as for the pure kraft sheets.

Here, as in the pure kraft handsheets, the negative effect of kaolin filler can be fully compensated for by increasing the beating degree of the kraft pulp.

When the kaolin filler is present, tensile stiffness (Table 1) and the tensile

Table 1 Sheet properties.

	Beating of KP	Starch content	Kaolin content	Gram-mage	Thick-ness	Tensile index	Tensile stiffness index	IPT index, W_{plane}	Damage width, w_{d}	Pull-out width, w_{p}	Scott bond, W_{scott}	Nip-peeling, W_{nip}	z-tensile strength
	[min]	[%]	[%]	[g/m^2]	[mm]	[kNm/kg]	[MNm/kg]	[Jm/kg]	[mm]	[mm]	[J/m^2]	[J/m^2]	[kPa]
TMP	–	–	–	67.3	136	52.2	4.7	9.6	1.55	0.86	337	48.7	640
KP	0	0	–	62.0	106	25.3	4.0	10.2	3.09	1.98	72	9.4	292
KP	0	1	–	63.8	117	32.2	4.7	19.1	3.44	1.96	152	31.0	423
KP	0	2	–	63.6	114	32.9	4.2	21.3	3.32	1.92	221	36.3	449
KP	0	4	–	67.0	115	41.5	4.5	21.9	2.99	1.83	286	51.1	560
KP	5	0	–	60.8	96	42.1	5.5	17.2	2.96	1.95	129	18.6	438
KP	5	1	–	63.1	99	47.6	5.5	23.7	2.70	1.73	274	39.9	577
KP	5	2	–	58.6	94	60.4	6.1	22.9	2.49	1.52	382	47.1	620
KP	5	4	–	63.4	100	70.0	6.6	23.5	2.40	1.43	477	53.9	647
KP	15	–	0.0	64.7	93	66.2	7.1	20.1	2.66	1.67	227	27.0	598
KP	15	–	12.5	69.0	98	45.8	6.5	16.3	2.77	1.85	103	15.8	446
KP	15	–	21.9	78.2	106	30.3	5.4	12.6	2.62	1.86	56	8.2	258
KP	15	–	29.1	88.8	118	26.4	4.7	11.3	2.70	1.88	46	4.2	183
KP	40	–	0.0	62.8	84	82.1	7.8	19.7	2.14	1.40	472	45.7	652
KP	40	–	17.6	73.7	93	59.9	7.2	20.7	2.36	1.56	148	22.0	556
KP	40	–	27.0	83.6	99	47.8	6.6	17.1	2.36	1.61	103	17.6	374
KP	40	–	28.8	110.2	130	31.5	5.2	13.4	2.34	1.69	67	10.7	316

TMP+KP	0	0	–	66.1	115	40.5	4.1	15.7	2.10	1.43	234	44.0	499
TMP+KP	0	1	–	67.1	118	48.8	4.7	16.7	2.09	1.28	313	49.7	576
TMP+KP	0	2	–	67.8	121	42.8	4.5	17.2	2.07	1.28	458	64.7	611
TMP+KP	0	4	–	68.8	118	49.7	5.0	18.0	1.70	0.93	491	100.1	609
TMP+KP	5	–	0.0	65.5	112	55.5	5.1	16.9	2.07	1.26	314	47.8	574
TMP+KP	5	–	9.7	77.5	127	50.4	5.0	16.6	1.98	1.28	207	37.7	502
TMP+KP	5	–	13.7	81.9	129	47.9	5.1	16.8	2.17	1.39	195	33.8	503
TMP+KP	5	–	19.7	88.1	134	47.3	5.4	16.1	2.06	1.38	166	27.4	448
TMP+KP	15	–	0.0	66.5	107	62.0	5.4	15.7	1.70	1.03	369	47.2	596
TMP+KP	15	–	9.7	73.4	112	57.3	5.5	14.5	1.94	1.22	240	32.3	563
TMP+KP	15	–	15.5	78.8	116	55.2	5.6	15.9	2.02	1.23	221	31.5	535
TMP+KP	15	–	18.4	83.9	120	48.6	5.1	15.0	1.89	1.28	169	24.7	488
TMP+KP	40	–	0.0	65.1	102	74.2	6.3	14.6	1.66	0.89	445	57.2	620
TMP+KP	40	–	11.6	73.8	109	64.8	5.9	16.3	1.83	0.99	282	38.8	576
TMP+KP	40	–	15.9	78.4	112	63.3	6.1	16.8	1.93	1.16	256	30.1	553
TMP+KP	40	–	19.6	80.9	115	62.4	6.3	18.8	2.02	1.19	211	29.1	550

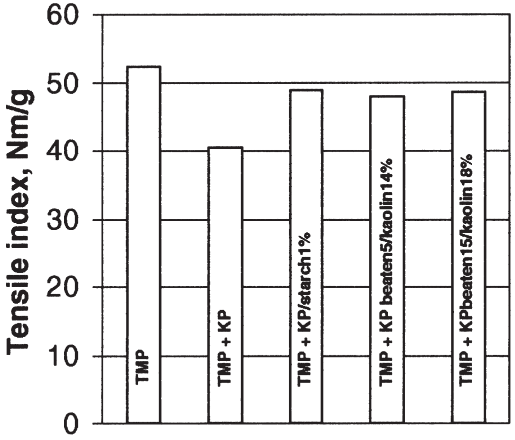

Figure 5 Effect of furnish on the tensile index of a TMP/kraft paper sheet. KP refers to the unbeaten kraft pulp.

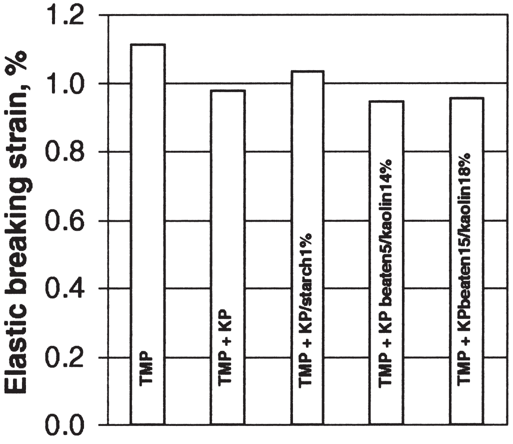

Figure 6 Effect of furnish on the elastic breaking strain of a TMP/kraft paper sheet, calculated by dividing the tensile index with tensile stiffness index.

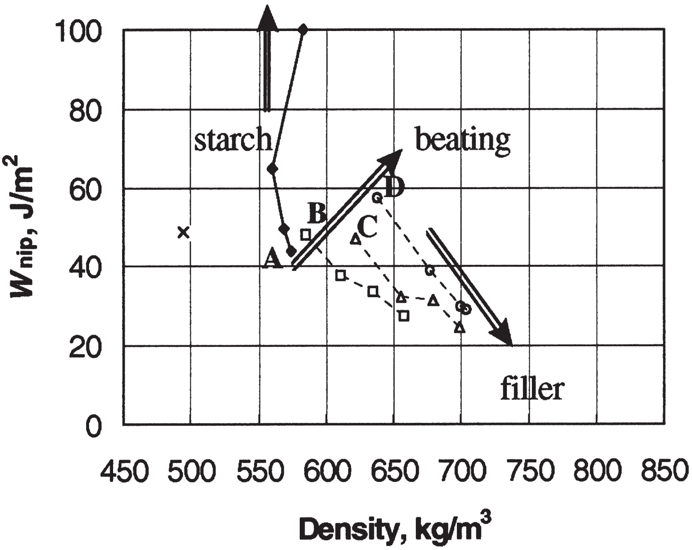

Figure 7 Nip-peeling energy (W_{nip}) against apparent density for a pure TMP sheet (×-symbol) and TMP/KP mixture sheets. Only KP was beaten into different levels. Unbeaten kraft with different content of starch (closed diamond), lightly beaten with starch (closed square), medium beaten with filler (open triangle), and heavily beaten with filler (open circle). Increasing beating without starch or filler corresponds to points **A–D**.

index of the paper sheet is fairly insensitive to changes in the relative proportions of TMP and the moderately beaten kraft pulp (compare Figures 2 and 5). The elastic breaking strain improves if the beaten kraft pulp is replaced with TMP (Figures 3 and 6). The kraft pulp has to be beaten heavily if the kraft pulp is to improve the in-plane mechanical properties of the paper. Even then the primary effect is in the tensile stiffness and the secondary effect is in the tensile index.

The out-of-plane properties behave qualitatively in the same way as in the pure kraft handsheets when kraft beating or starch content is increased (Figure 7). The quantitative effects of the kraft beating are smaller than in the pure kraft handsheets because the mechanical pulp alone gives already rather good out-of-plane properties to paper. However, starch addition still improved the out-of-plane properties a lot.

DISCUSSION

Pure kraft handsheets

The connection between fiber network density and tensile stiffness index is shown in Figure 8. We hypothesize that the factors that contribute to all the mechanical properties are drying stresses and inter-fiber bonding in the dry paper. Drying stress improves fiber segment activation and increases fiber stiffness in the restraint-dried handsheets that we consider. Increasing beating should contribute to the tensile stiffness through both increased bonding and increased swelling. The latter influences the drying stress.

Since filler does not alter fiber swelling, it should only reduce inter-fiber bonding. It is therefore reasonable that tensile stiffness did not decrease generally as rapidly with decreasing network density as it did when beating degree was the controlling factor. Starch addition had a small positive effect on the tensile stiffness, but not in the case of unbeaten fibers. Obviously the

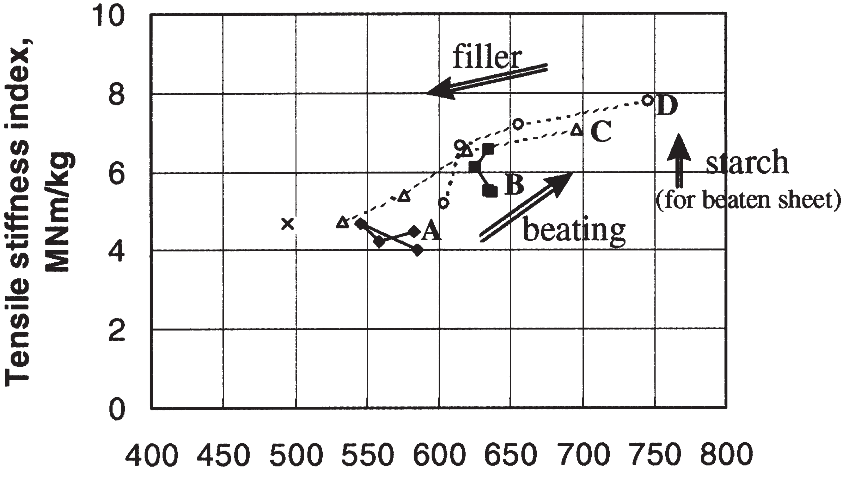

Figure 8 Tensile stiffness index against network density for pure TMP (×-symbol) sheet and pure KP sheets; unbeaten with different content of starch (close diamond), lightly beaten with starch (close square), medium beaten with filler (open triangle), and heavily beaten with filler (open circle). Increasing beating without starch/filler corresponds to points **A**–**D**.

eventual improvement of inter-fiber bonding by starch addition was of such nature that it had almost no effect on tensile stiffness.

The observed changes in tensile index were primarily accounted for by changes in the tensile stiffness. If any other effects exist, they are revealed by changes in the elastic breaking strain (= tensile index divided by tensile stiffness index). As Figure 9 shows, increasing filler content and increasing beating had precisely opposite effects on elastic breaking strain against fiber network density. The relative effects of filler, starch and beating on elastic breaking strain are different from their relative effects on tensile stiffness. The differences suggest that elastic breaking strain is more sensitive than tensile stiffness improvements in inter-fiber bonding.

Considering still the role of inter-fiber bonding, we notice that the pure TMP sheets have almost the same elastic breaking strain, 1.0 ± 0.1%, as the kraft sheets (with no filler) at the highest starch content or highest beating

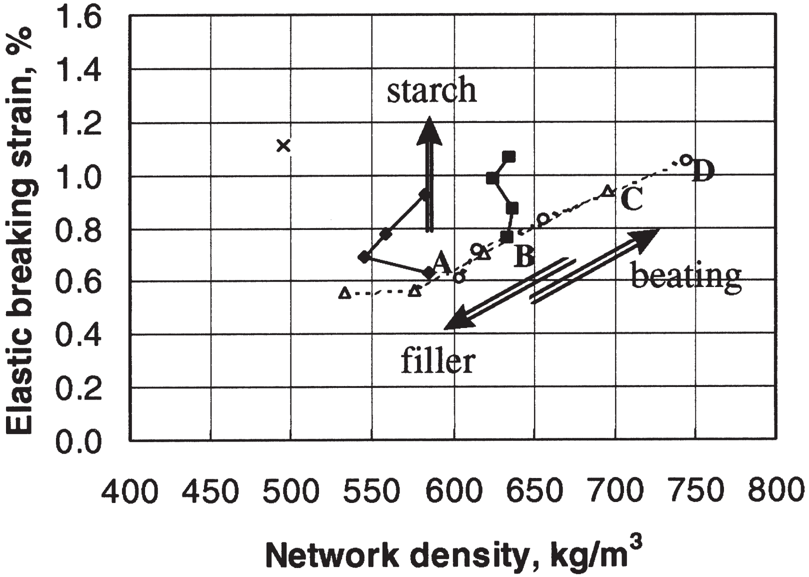

Figure 9 Elastic breaking strain against network density for pure TMP (×-symbol) sheet and pure KP sheets; unbeaten with different content of starch (close diamond), lightly beaten with starch (close square), medium beaten with filler (open triangle), and heavily beaten with filler (open circle). Increasing beating without starch/filler corresponds to points **A–D**.

level. In comparison, the tensile stiffness of the pure TMP sheets is lower than that of the kraft sheets. This indicates that lower tensile strength values with TMP are caused by low tensile stiffness of the paper and not by poor inter-fiber bonding.

The changes in inter-fiber bonding and fiber activation can also be seen in the in-plane fracture energy. It increased with beating and starch addition, but decreased with filler addition. The relationship between the in-plane fracture energy (W_{plane}) and damage width (w_d) is shown in Figure 10. From preceding experiments and theoretical analysis [14], we know that W_{plane} is usually roughly linearly related to w_d for sheets that are bonded at least reasonably well. The general trendline obtained from the preceding experiments is shown as the broken line in Figure 10. In the present case beating caused a clear decrease in w_d. The decrease in w_d can be explained to arise from higher rate of fiber failures when fiber segment activation reaches high enough a level. The increase in fiber breakage was seen also in the pull-out width (see Table 1).

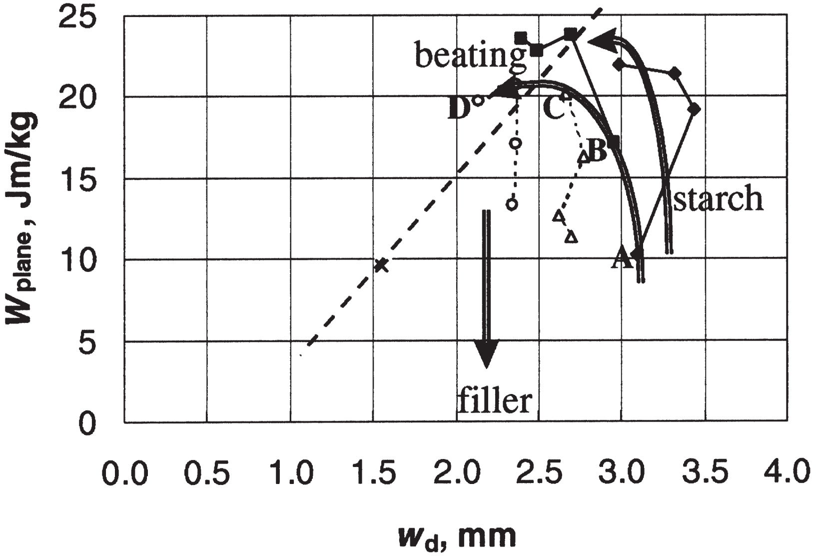

Figure 10 In-plane tear index (W_{plane}) against damage width (w_d) for pure TMP (×-symbol) sheet and pure KP sheets; unbeaten with different content of starch (close diamond), lightly beaten with starch (close square), medium beaten with filler (open triangle), and heavily beaten with filler (open circle). Increasing beating without starch/filler corresponds to points **A–D**.

We originally expected that increasing filler content would have lead to an increase in damage width since fiber failures might have been decreased with the reduced inter-fiber bonding. As one can see from Figure 10, this did not happen. As we inferred from tensile stiffness, filler content did not influence the activation of fiber segments. Thus adding filler only decreased the in-plane fracture energy. The reader should remember that the fracture energy values are indexed with the fiber network grammage. The ordinary fracture energy index of paper decreases even more than Figure 10 indicates. Returning to the effects of starch addition, one may speculate that the changes in both tensile stiffness and damage width arise from segment activation.

Finally, the z-directional fracture energy (Figure 11) is rather similar to the elastic breaking strain (Figure 9) when plotted against network density, although some of the samples do not rank in the same order. The starch addition is very effective in improving the z-directional properties. As in the

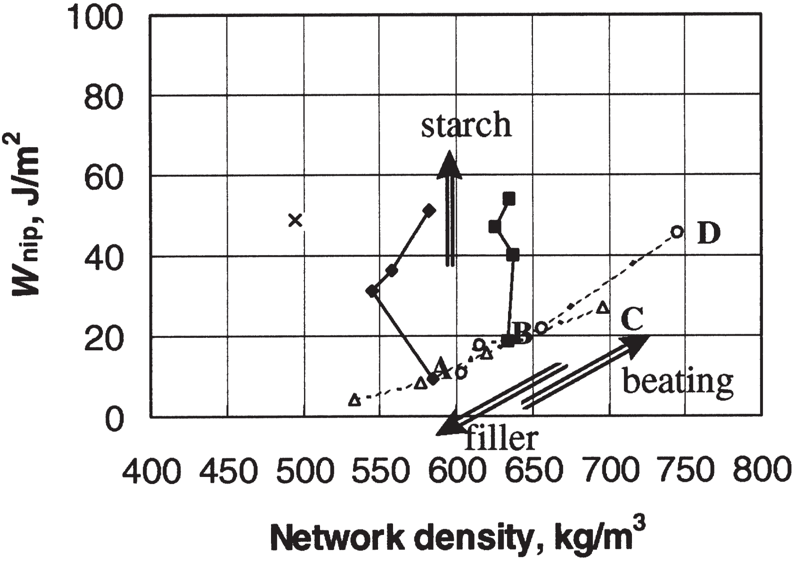

Figure 11 Nip-peeling energy (W_{nip}) against network density for pure kraft handsheets; unbeaten kraft with different content of starch (closed diamond), lightly beaten with starch (closed square), medium beaten with filler (open triangle), and heavily beaten with filler (open circle). Increasing beating without starch or filler corresponds to points **A–D**. The ×-symbol indicates the pure TMP sheet.

case of elastic breaking strain, the pure TMP sheets and the kraft sheets with the highest starch content or highest beating level and no filler all had approximately the same fracture energy of 50 J/m^2.

TMP and kraft mixture handsheets

The in-plane fracture energy and damage width of the mixture sheets were slightly affected by the beating of kraft and adding starch or kaolin filler (Figure 12). Damage width (and also pull-out width) was approximately equal to the mean value for the pure TMP and pure kraft. This derives from the shorter mean fiber length. In the pure kraft sheets damage width was primarily a decreasing function of the beating degree and, to a smaller degree, a decreasing function of the starch content. In the mixture sheets the situation was not as clear, but generally speaking higher beating or lower filler content both gave lower damage width. It also seems that the filler addition decreased the activation of fiber segments in the mixture sheets whereas it caused no change in the pure kraft sheets.

The in-plane fracture energy of the mixture sheets was generally larger than the mean value of the pure TMP and pure kraft sheets. The fracture energy was also slightly higher than we would have expected on the basis of the damage width values (dashed line in Figure 12). Higher beating level caused a reduction in fracture energy that followed the reduction in damage width. This is qualitatively the same effect as was seen for the pure kraft data along the same reference line (Figure 10). In the data along the line there were points of good inter-fiber bonding with either high beating level or low beating level combined with starch addition, but no filler. In the mixture sheets the fines material of TMP appears to have provided similar effective inter-fiber bonding as kraft beating does in pure kraft sheets.

Also the out-of-plane fracture energies of the mixture sheets were approximately equal to the mean of the pure TMP and pure kraft values. Scott bond energy (see Table 1) again behaved in a manner qualitatively similar to that of the fracture energy. (This notwithstanding, the clear difference between the 5 min beaten and 15 or 40 min beaten kraft mixtures was surprising as it could not have been foreseen from the pure kraft data.) The starch and filler addition were effective in changing the out-of-plane fracture energy. The effect of starch was particularly interesting because the in-plane properties suggested (Figure 12) that the fines material of TMP had already provided good bonding and hence starch gave no additional improvement.

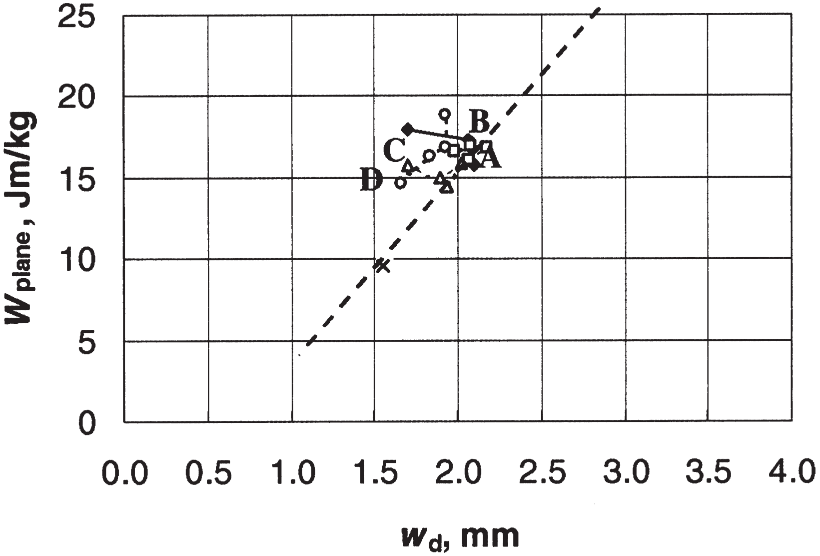

Figure 12 In-plane tear index (W_{plane}) against damage width (w_d) for pure TMP sheet (×-symbol) and TMP/KP mixture sheets. Only KP was beaten into different levels. Unbeaten with different content of starch (close diamond), lightly beaten with filler (open square), medium beaten with filler (open triangle), and heavily beaten with filler (open circle). Increasing beating without starch/filler corresponds to points **A–D**.

CONCLUSIONS

In the pure kraft sheets, adding filler acts in the direction opposite to beating in terms of almost all properties. They have precisely opposite effects on elastic breaking strain and z-directional fracture energy against network density. The role of beating and filler content in the TMP/KP mixture sheets is qualitatively similar to their role in the pure kraft sheets, only the range of variation is much smaller in the mixture sheets.

Starch addition to the kraft pulp leaves fiber network density unchanged but leads to a clear improvement in all the mechanical properties considered, including the tensile stiffness. The effect of starch is different in the mixture sheets where it does not alter the in-plane mechanical properties practically at all. This corroborates the conclusion presented elsewhere [15] that mechanical pulp fines can maximize inter-fiber bonding strength for in-plane loading.

Tensile stiffness is the property that changed less when adding filler than when reducing beating, compared at the same density of the fiber network. This supports the view drawn from literature that tensile stiffness is not controlled simply by the bonding degree but also by the effects of drying stresses [16].

The out-of-plane properties are more sensitive to beating, filler content and starch addition than are the in-plane properties. Starch addition improves the z-directional fracture energy also in the mixture sheets, even though the in-plane properties of mixture sheets do not change at all with the starch content. The sensitivity of the out-of-plane properties to starch content should derive from the different role of inter-fiber bonding.

A combination of moderate beating and starch addition is probably the best approach if out-of-plane strength properties are critical or if high levels of in-plane strength are required. Because of the limited retention, starch addition alone cannot secure in-plane strength. In the out-of-plane direction starch addition is more effective than kraft beating.

In the mixture sheets with kaolin filler, the relative proportions of TMP and beaten kraft pulp have relative small effects on the mechanical properties. The kraft pulp has to be beaten heavily if the kraft pulp is to improve paper properties compared to pure TMP. Even then the primary role of the kraft pulp is in improving the tensile stiffness of paper.

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Transcription of Discussion

FRACTURE PROPERTIES IN FILLED PAPERS

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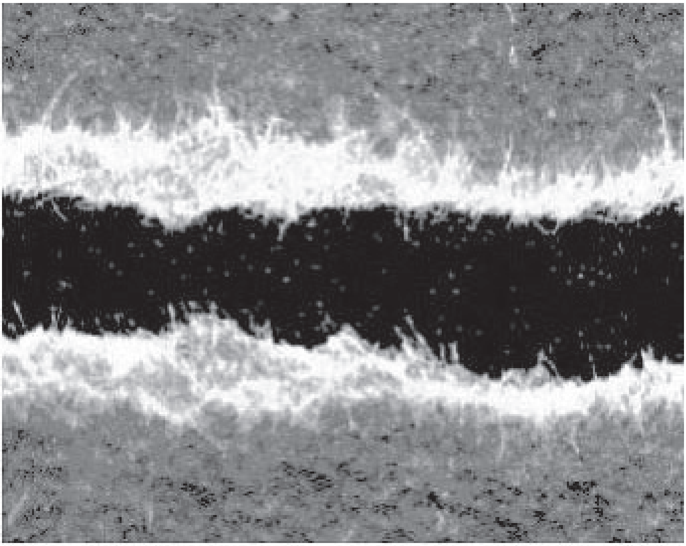
Editor's note: this data was sent in after the symposium by K Niskanen

During the discussion of Atsushi Tanaka's presentation in Oxford, I noticed that the picture of damage analysis that Atsushi showed was actually from an Elmendorf tear test, not from the usual in-plane tear test. I have now checked that this is really so. The picture is enclosed and may be included in the discussion with the following comment. "The picture shown in Dr Tanaka's presentation (see below) actually came from an Elmendorf tear test, not from the usual in-plane tear test that we use in damage analysis. We have used this picture (obtained by Heikki Kettunen) to demonstrate why one should be



very careful when using the Elmendorf tear test to deduce differences in inter-fibre bonding and fibre strength. What is seen on the left side of the picture is an area where the paper delaminates during the Elmendorf tear test. On the right hand side, the fracture has taken place through pull-out and failure of fibres. The paper was a standard hand sheet made of a well-beaten softwood Kraft."

Kari Ebeling UPM-Kymmene Corporation

One could say that in your picture the opposite is also visible due to the flocs. Inside the flocs you do not have a coherent equally loaded fibre structure. Instead you are loading the fibre segments unevenly and you are breaking the structure bond after bond and therefore you do not get up to it's maximum. You can see that the narrow fracture zone, which has more fibres extruding, perhaps exhibits less fibre breaks because they have been sliding past each other. In the case you have a wide fracture zone, you have a very blunt surface with very little fibres that have been pulled through, because they have all broken, which is opposite to what you were concluding in another picture.

Atsushi Tanaka

If we consider only using this picture it seems like you mentioned; but this is just one example. We can see many fibres are sticking out in many cases. Generally we have found it to be like that.

John Roberts Department of Paper Science, UMIST

You said that your network density was not affected by starch additions.

Atsushi Tanaka

Yes because starch affects inter-fibre bonding included in the structure, but different from filler.

John Roberts

In your opening slide it was assumed that starch has no structural effects on the sheet, I would be very surprised if unbeaten or very partially beaten softwood sheets without filler had no formation problem with cationic starch addition because it can be almost impossible to make sheets under those conditions. The question is did you use extremely high shear to try to control the formation in the presence of cationic starch with unfilled sheets.

Atsushi Tanaka

I don't follow exactly what you mean.

Eero Hiltunen

All the sheets including starch were prepared according to standard laboratory procedures so we didn't use any shear. All the sheets were made at standard conditions with extremely low consistency. So all of them had good formation.

Kaarlo Niskanen

We need to check one thing with regard to Kari Ebeling's question. The picture in the presentation was for an out-of-plane tear test not the in-plane tear test. The behaviour is different in the two cases.

Murray Douglas McGill University

You tend to attribute results to fibre binding effects certainly that is one factor. You have said very little about the structural aspects, particularly the starch addition as the previous questioner pointed out, likely changes the sheet structure as well there is nothing much specified about the forming. We have just heard about that, but forming of hand sheets of course is a very different process than machine formed sheets. You have also said that drying stresses influence some of the properties but I don't see in the paper where you have specified anything about how you have dried the sheets, the question of restraint during drying, can you comment on that please?

Atsushi Tanaka

We use a laboratory drying method for making sheets. Not in some special way, just standard drying.

Discussion

Murray Douglas

You dry it under total restraint in a circular frame?

Atsushi Tanaka

Not a circular frame but we used a rectangular plate.