The effect of mechanical treatment on kraft pulps produced from different softwood raw materials

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Keywords:
softwood, kraft pulping, mixing, strength properties, reinforcement, fiber properties

ABSTRACT

Fiber deformation is generally considered to be changes in the three-dimensional form of the fiber and fiber damage is considered to be changes in the strength properties of the fiber and fiber network. Usually, fiber deformation and fiber damage occur simultaneously and together are referred to as fiber damage. In this study fiber damage occurring in pulps made from pine and spruce round wood and sawmill chip raw materials were examined in the laboratory. Damage was carried out in the laboratory by mixing the pulp at the end of the cook (170^{o}C) for 15 minutes.

The curl index, kink index, fiber length and strength properties were measured for unbleached pulps made from these raw materials as a function of PFI beating. The damaged spruce pulps had lower wet zero-span tensile strength than the damaged pine pulps, although the strengths of the undamaged pulps were at the same level. Furthermore, this study showed that spruce fibers were more deformed than pine fibers under the same mechanical treatment conditions.

The results also showed that the tensile index of unbeaten fibers was a good indication of fiber deformation. The curl of the deformed fibers decreased during PFI-beating whereas the curl of the undeformed fibers increased.

TIIVISTELMÄ

MEKAANISEN KÄSITTELYN VAIKUTUS ERI RAAKA-AINEISTA VALMISTETTUJEN HAVUPUUSELLUKUITUJEN OMINAISUUKSIIN

Kuitujen muodonmuutoksia pidetään yleensä kuitujen kolmidimensionaalisina muutoksina ja kuituvaurioita muutoksina kuitujen ja kuituverkoston lujuudessa. Kuitujen muodonmuutokset ja kuituvauriot ilmenevät usein yhdessä ja niihin viitattaessa puhutaan kuituvaurioista. Tutkimuksessa tarkasteltiin kuusipölli -ja kuusisahahakkeesta sekä mäntypölli -ja mäntysahahakkeesta valmistettujen massojen taipumusta vaurioitua laboratoriossa tapahtuvassa vaurioituskäsittelyssä. Kuitujen muodonmuutos- ja vaurioittamiskäsittely

suoritettiin laboratoriossa sekoittamalla massaa keiton lopussa (170 ^{o}C:ssa) 15 minuuttia ennen keiton päättymistä.

Kuitujen kiharuus, kink-indeksi, kuidun pituus ja lujuusominaisuudet mitattiin valkaisemattomista kuiduista PFI-jauhatuksen funktiona. Vaurioituneilla kuusikuiduilla oli alhaisempi märkä zero-span vetolujuus kuin vaurioituneilla mäntykuiduilla, vaikka vaurioitumattomien kuitujen lujuudet olivatkin samalla tasolla. Tutkimus osoitti lisäksi kuusikuitujen muodonmuutoksen olevan suurempi kuin mäntykuitujen samanlaisissa oloissa suoritetun mekaanisen käsittelyn jälkeen.

Tulokset osoittivat myöskin, että jauhamattomien kuitujen vetolujuus on hyvä indikaatio kuitujen muodosta. Muotonsa muuttaneet kuidut suoristuivat jauhatuksessa ja suorat kuidut kihartuivat jauhatuksen aikana.

INTRODUCTION

Changes in the three-dimensional forms of fibers (e.g. fiber curl, kinks and dislocations) are defined as deformations. Fiber deformations can arise in the tree as a result of growth stresses, or they can be induced in numerous ways during processing, for example in chipping, fiberization or in medium consistency unit operations /1, 2/. Fiber deformation is usually associated with fiber damage. It is considered undesirable and should be avoided where possible.

It has been reported that fiber deformations (curl, kinks and dislocations) influence the properties of a fiber network /3/. Fiber curliness mostly affects the tensile strength and the bonding ability of fibers in a network. According to Page /4/, high fiber curl affects the tensile index so that a sheet formed from such fibers will have a low tensile index but may have a high tear strength. This has been explained by the uneven distribution of stress along the length of a curled fiber in a fracture zone /5/. Curly fibers also tend to form sheets having a lower elastic modulus but higher stretch than sheets made from straight fibers /6/.

In a dislocated part of the cell wall the alignment of the microfibrils is locally disturbed /4/. A fiber with no dislocations is extremely stiff. A small number of dislocations are sufficient to significantly reduce the stiffness. Some delamination occurs in the dislocated regions, which at least partly explains the decrease in the bending stiffness. As a fiber containing dislocations bends it forms a polygon rather than a continuous curve /7, 8/. As with curl, the presence of dislocations reduces the elastic modulus of the sheet /6/. Dislocations can become weak sites in the fibers, causing a reduction in the breaking strength of the individual fibers and in the average fiber length /7, 8, 9/. As a result, the strength properties of the pulp, in particular folding endurance and burst strength, decrease /8/. It has also been suggested that an increase in the number of dislocations increases the tear strength and stretch /10/. Moreover, dislocations decrease bonding strength by creating discontinuities that are points of bond failure in stressed fiber networks /10/.

Fiber kinks have been reported to affect the wet strength of the pulp. The more kinked the fibers are the higher the wet rupture energy. It has been suggested that chlorine-caustic and chlorine dioxide bleaching cause kinks present in the unbleached fibers to be set into position. Fiber kinking is unaffected by pulp drying stresses /11/.

Most fiber deformations (curl, kinks and dislocations) vanish during pulp beating, and the strength properties return to those of the undeformed pulp. This has been recognized, for example, by Kibblewhite /10/, Mohlin /12/, Seth /13/.

The physical properties of the fiber wall have been reported to affect the development of fiber deformations. Medium consistency fluidization induces more curl and microcompressions in thick-walled fibers than in thin-walled fibers, /14/.

The definition of fiber damage is not as clear as that of fiber deformation, and both tend to occur together. Fiber damage is usually seen as a reduction in strength of the dry or wet fiber network. Since there are several factors other than the network properties affecting fiber damage, the effect of the damage is difficult to determine. Mohlin /15/ defines the terms irreversible damage and reversible deformation. Reversible deformations can be removed by PFI beating. Mohlin /15/ also suggested that the irreversible damage could be defined as the difference in zero-span tensile index between an undamaged and damaged fiber when both are straight. The damage occurs mainly as a result of chemical degradation during pulping, but it may also arise from mechanical treatment.

The objective of this study was to determine the susceptibility of pulps made from different softwood raw materials to deformation and damage by inducing the latter under laboratory conditions. Another goal was to study the effects of fiber deformation and damage on pulp sheet strength properties.

EXPERIMENTAL

Raw material

Two different wood raw materials were used in this study: Norway spruce (*Picea abies*) and Scots pine (*Pinus sylvestris).* For each wood raw material, two types of industrial chips were used: normal roundwood chips and sawmill chips. These chip types were chosen to give a wide range of fiber dimensions. The chips were stored fresh but were not screened in the laboratory.

The cooking experiments were performed in two different types of digester. The undamaged pulps were produced in a 30 l forced circulation laboratory digester whereas the damaged pulps were cooked in a laboratory digester equipped with a mixer. The mixing treatment was chosen because it would simulate, in the most simple and effective way, the mixing, pumping and pipeline conditions in a kraft pulp mill fiber line. The authors of this study have shown that mixing treatment at high temperature results in both damage and deformation of the fibers /16, 17, 18/. The mixed pulps in this study are referred to as damaged. Table 1 summarizes the raw materials and cooking procedures used in this study.

Table 1. Raw materials and used legends.

Raw material	*Undamage*	*Legend*	*Damaged*	*Legend*
Spruce Roundwood	*Spruce RW*		*Spruce RWD*	
Pine Roundwood	*Pine RW*		*Pine RWD*	
Spruce Sawmill chips	*Spruce SC*		*Spruce SCD*	
Pine Sawmill chips	*Pine SC*		*Pine SCD*	

Cooking

The cooking liquor was prepared in the laboratory from NaOH and Na_2S of industrial grade. Deionized water was used in all experimental steps. The liquor to wood ratio was 4/1 in all cooking experiments. The effective alkali charge in each cook was 4.5 mol NaOH/kg dry wood. The sulfidity used in all cooks was 35%.

The following temperature profile was used in all experiments: heating from room temperature to 80^{o}C in 30 minutes; heating from 80^{o}C to 170^{o}C in 90 minutes; cooking at 170^{o}C for 2 hours. This temperature profile gave a kappa number of 28 ±2.

In the cooking experiments carried out in the forced circulation digester 4.5 kg of wood, calculated as oven dry, were used. In the cooking experiments done in the reactor equipped with the mixer 2.5 kg of wood were used.

The pulps cooked in the digester with the mixing propeller were stirred throughout the cook at 30 rpm in order to ensure even alkali and temperature distribution. Mixing at 170^{o}C started 15 minutes before the end of the cook and was carried out at a speed of 350 rpm. The total amount of energy fed into the system during mixing was approximately 20 kWh/t.

After the cook the pulp was washed with deionized water, disintegrated with with rod disintegrator at room temperature and 3% consistency for 2 min. and screened. The screening was carried out using a plane screen with a slot width of 0.25 mm. The pulps were never spin-dried and the dry solids content was never greater than 12% during treatment.

Testing

The pulp kappa number and viscosity were measured according to SCAN C-1:77 and SCAN-CM 15:99, respectively.

Sheets for testing were made according to ISO 5269-1 from pulps which included fines. Fiber lengths and widths were measured using a Kajaani FS-200 and a Kajaani FiberLab. Fiber curl and kink index were measured with a FiberExpert. Beating was performed using a PFI beater according to ISO 5264-2 to 0, 1000, 2000 and 2500 revolutions. The apparent bulk density was measured according to EN ISO 5270. Tensile properties were measured according to standard EN ISO 5270, tear index was measured according to standard ISO 5270 and zero-span tensile index (from rewetted sheets, Pulmac) according to ISO 15361. Light scattering was measured according to ISO 9416 and Scott bond was determined according to TAPPI T833 modif. The water retention value (WRV) was measured according to SCAN-C62.

RESULTS AND DISCUSSION

The pulp and fiber properties of damaged and undamaged pulps made from different softwood raw materials were measured, and the effect of the mechanical treatment on these properties is discussed below.

Cooking results

Table 2 shows the cooking results from the experiments carried out in this study.

Table 2. Cooking results.

Raw material	Yield, %, total	Kappa number	Viscosity, ml/g	Brightness, %	Rest EA, g/l	Viscosity at kappa 28, ml/g
Pine RW	50.4	29.5	1220	31.1	3.5	1200
Pine RWD	46.9	26.3	1150	29.3	3.9	1175
Pine SC	49.1	27.6	1320	28.1	4.0	1325
Pine SCD	48.6	26.3	1200	29.8	3.7	1225
Spruce RW	51.6	28.4	1220	28.0	5.0	1215
Spruce RWD	49.7	27.4	1100	28.5	5.0	1110
Spruce SC	50.6	27.9	1260	31.4	4.2	1260
Spruce SCD	48.3	27.0	1140	28.4	4.9	1155

Results in the table show that there were small differences in kappa numbers between the raw materials. The average kappa number was 27.5 and kappa numbers of all pulps were in the range: average +/- 2 units. Also, the residual alkali after cooking was comparable for the undamaged and damaged pulps. There were, however, differences in residual alkali between the different raw materials. As mentioned earlier, the dry content measurement was not very exact because the pulps were not spin-dried. The yield determination, therefore, was not very reliable. If compared at the same kappa number the differences in viscosity between the undamaged and damaged pulps from the same raw material were moderate. What was clear, however, was that damaged pulps had slightly lower viscosities.

Fiber properties and deformations

In Figure 1 the fiber length of the raw materials studied (measured with a Kajaani FS-200) is shown at two beating levels (0 and 1000 PFI revolutions).

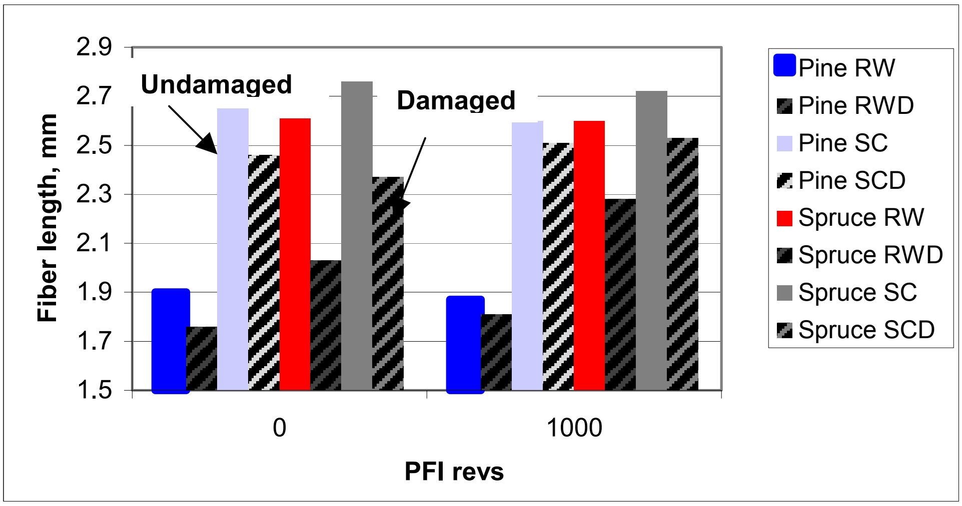

Figure 1. Length weighted fiber length for the studied pulps at 0 and 1000 PFI-revolutions. Measured with Kajaani FS200.

Figure 1 shows that the fiber length of the Pine RW raw material was considerably shorter than the fiber lengths of the other raw materials tested. One reason for this was that the Pine RW chips were shorter. Figure 1 also shows that for all the raw materials studied the length of the damaged fibers at 0 PFI revolutions was lower than that of the undamaged fibers. For the pine pulps, however, the difference in fiber length had diminished at 1000 PFI revolutions. The reason for this is that the damaged fibers were probably curly but straightened during beating. The results suggest that for the spruce pulps 1000 PFI revolutions were not enough to straighten the fibers; there was still a difference in fiber length after 1000 PFI revolutions.

In Figure 2 the length-weighted fiber length (measured with the FiberExpert) is shown for the raw materials studied at two beating levels (0 and 2500 PFI revolutions).

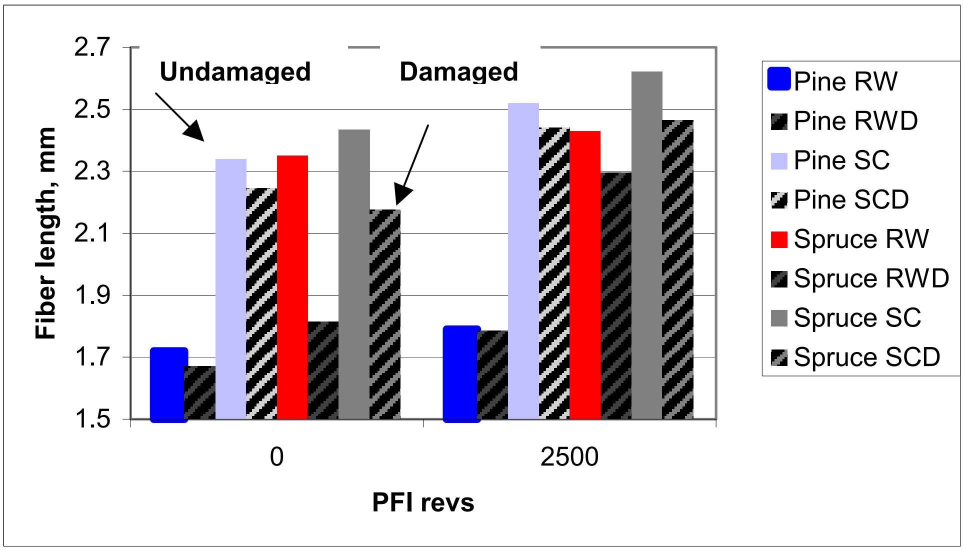

Figure 2. Length-weighted fiber length for the pulps at 0 and 2500 PFI-revolutions. Measured with a FiberExpert.

Figure 2 shows that the difference in fiber length at 2500 revolutions between the undamaged and damaged pine pulps was low, and that the difference between the undamaged and damaged spruce pulps had diminished but was still higher than for the pine pulps. Figures 1 and 2 indicate that 1000 PFI revolutions were enough to straighten the fibers in the damaged pine pulps (small difference in fiber length between undamaged and damaged pulps) but that not even 2500 PFI revolutions were enough to straighten the spruce fibers. Another possible explanation for the damaged spruce pulps having a shorter fiber length than the undamaged pulps could be that the spruce fibers had been straightened at 2500 PFI revolutions but that damage had shortened the fibers. Figure 2 also shows that fiber length measured with the FiberExpert was significantly greater for the beaten pulps (2500 revolutions) than for the unbeaten pulps, and also for the undamaged and straight fibers. This was not seen in results from the Kajaani FS-200 measurements. It is difficult to explain because the undamaged fibers had very little curl and therefore increased fiber length could not be a result of the latter. The reason for the different fiber length results is that two different instruments/measurement techniques were used and the absolute fiber lengths from these instruments should therefore not be compared.

The fiber cell wall thicknesses of the unbeaten, damaged and undamaged fibers were measured using a Kajaani FiberLab. The results are shown in Figure 3.

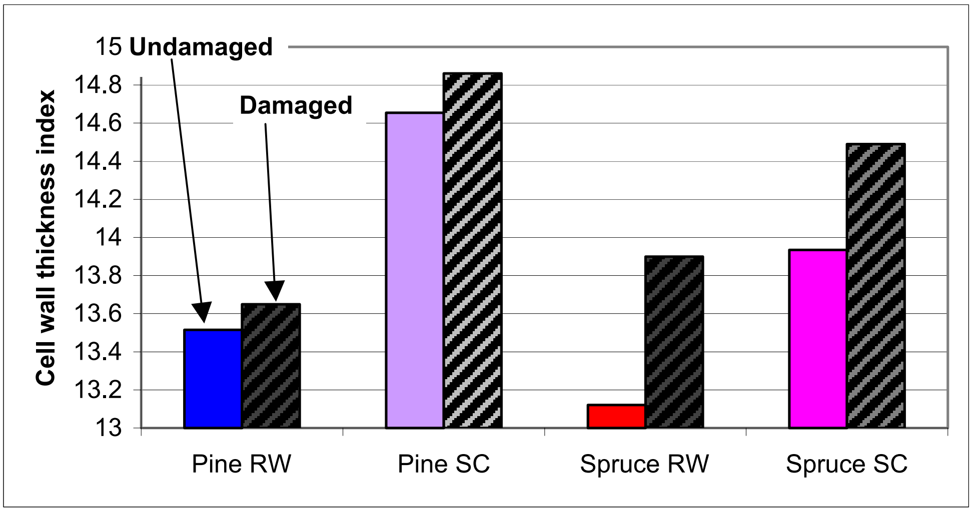

Figure 3. The fiber cell wall thickness index of the unbeaten, damaged and undamaged fibers measured with a Kajaani FiberLab.

Figure 3 indicates that the fiber cell wall thickness of the damaged fibers was higher than that of the corresponding undamaged pulps. This was particularly noticeable with the spruce pulps. One possible explanation for this could be the differences in the fiber wall structure between spruce and pine. The lignin-rich, dense S_1 fiber wall layer of spruce fibers is thinner than that of the corresponding pine fibers /19, 20/. The thicker S_1 layer of the pine fibers might protect the S_2 layer from loosening. The loosening of the spruce fiber S_2 layer might be seen as a thicker fiber wall.

PFI beating is a gentle process and it is known that curled fibers are usually straightened during the beating. This is usually seen as an increase in fiber length during beating. In this study fiber curl and fiber kinks were measured at different beating points with the FiberExpert. All the data from the measurements are collected in the Appendix. Figures 4a and 4b show an example of curl development of damaged and undamaged pulps made from pine sawmill chips. Figures 5a and 5b show the same for pulps made from spruce sawmill chips.

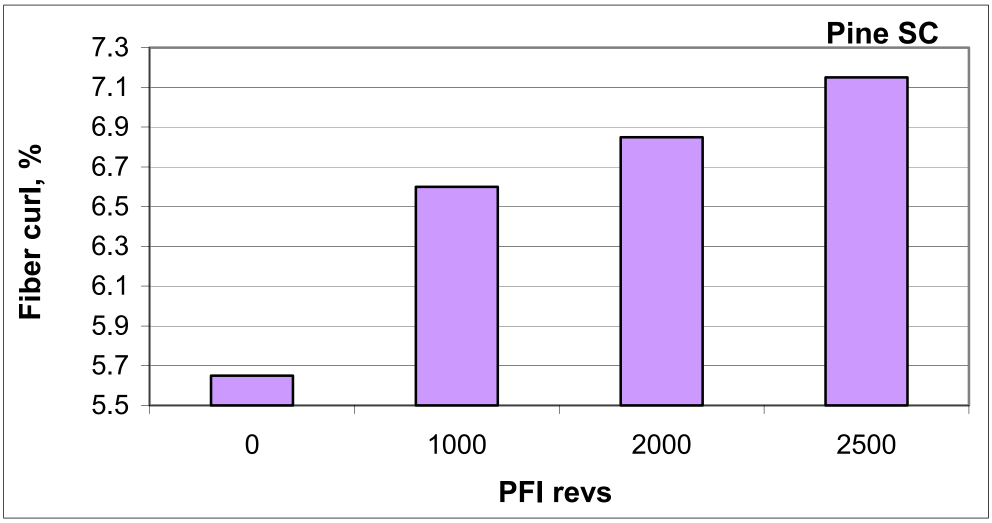

Figure 4a. Fiber curl as a function of PFI revolutions for the undamaged pine pulps made from sawmill chips. Measured with a FiberExpert.

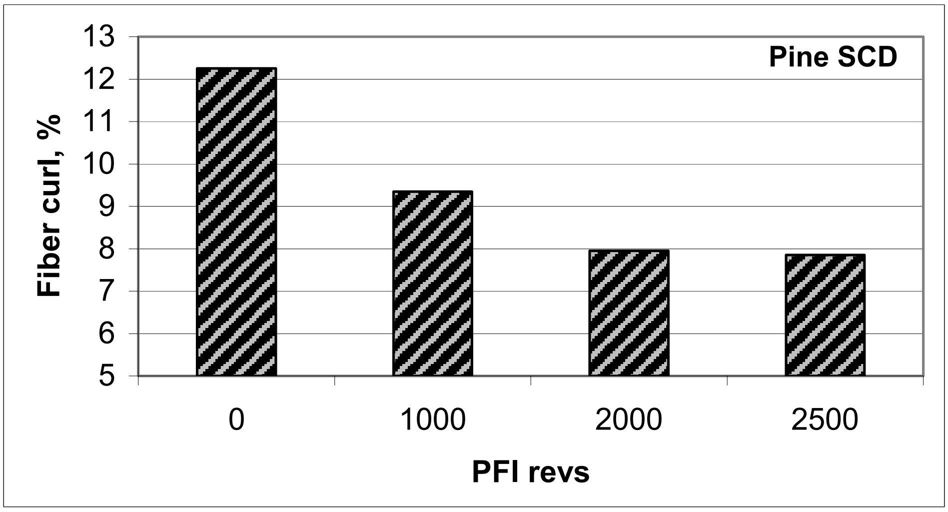

Figure 4b. Fiber curl as a function of PFI revolutions for the damaged pine pulps made from sawmill chips. Measured with a FiberExpert.

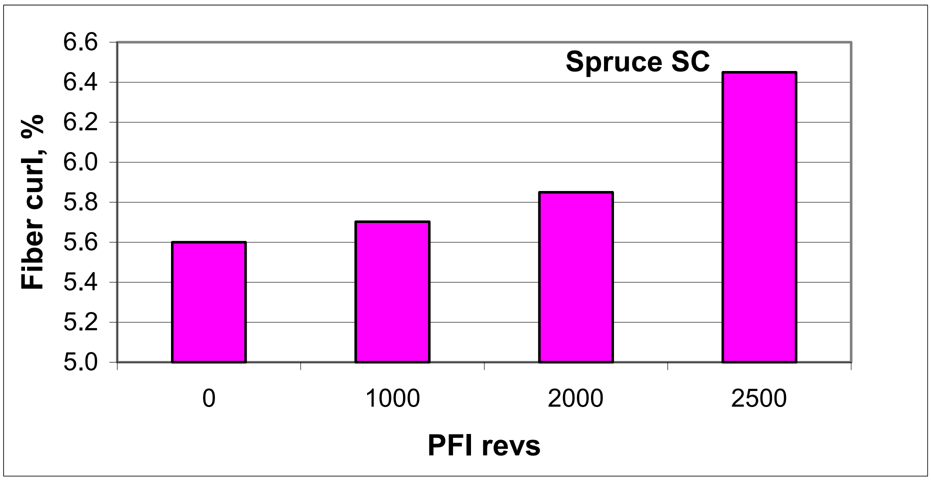

Figure 5a. Fiber curl as a function of PFI revolutions for the undamaged spruce pulps made from sawmill chips. Measured with a FiberExpert.

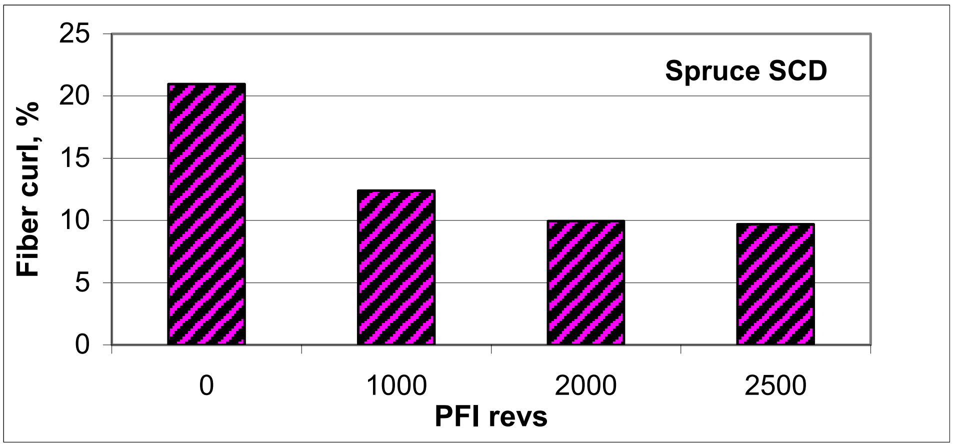

Figure 5b. Fiber curl as a function of PFI revolutions for the damaged spruce pulps made from sawmill chips. Measured with a FiberExpert.

Figures 4 and 5 show that curl development during beating was reversed in the undamaged and damaged pulps. The curl of the undamaged fibers increased during beating whereas that of the damaged fibers decreased. The fiber curl of the damaged pulp made from pine sawmill chips approached a level of 8% whereas that of the damaged pulp made from spruce sawmill chips approached a level of 9%.

When the fiber curl results are compared for the different raw materials it may be concluded that under the same damaging conditions the curl for the spruce pulps was considerably higher for the unbeaten pulps than for the corresponding unbeaten pine pulps.

Pulp properties and fiber damage

All results from the testing of the brown pulps are collected in the Appendix. In Figure 6 the tear index is plotted as a function of tensile index for the different pulps.

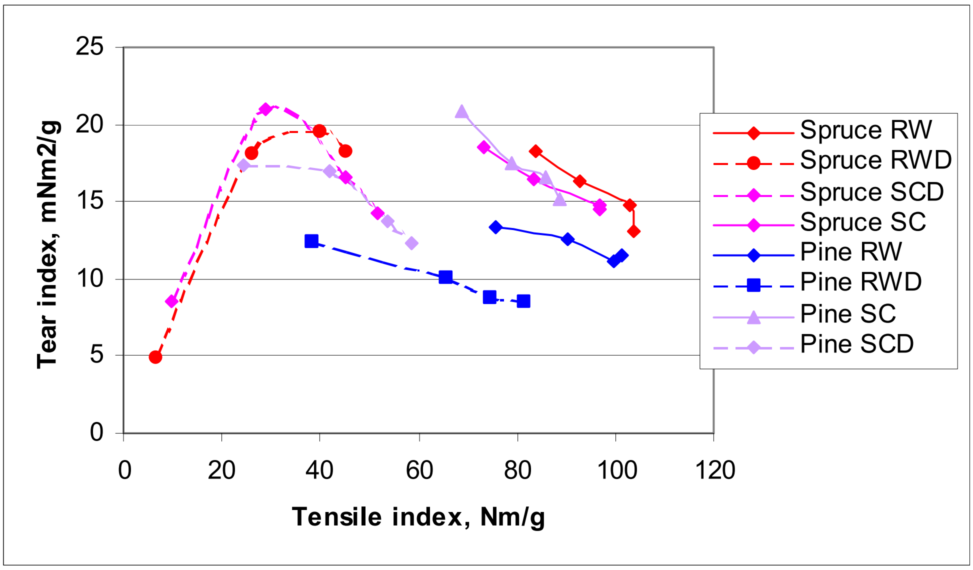

Figure 6. Tear index as a function of tensile index for the different pulps.

Figure 6 shows that the unbeaten tensile index decreased more for the spruce pulps than for the pine pulps. The reason for this was probably that the spruce pulps were much more curled than the pine pulps. Page obtained similar results and reported that increasing fiber curl decreased tensile index /4/. It is difficult from Figure 6 to compare tear indices at a particular tensile index because the undamaged and damaged spruce pulps had totally different tensile index levels. However, there does not seem to be any significant difference between the susceptibility to damage of the different raw materials. The effect of fiber length was clearly seen: Pine RW having the shortest fibers suffered least in the mechanical treatment.

Figure 7 shows the WRV values as a function of beating for the undamaged and damaged pulps.

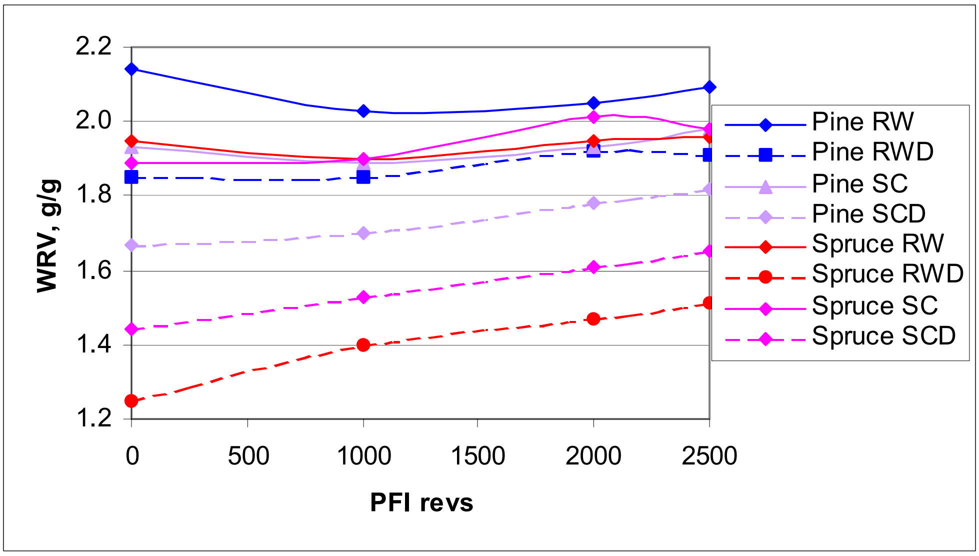

Figure 7. Water retention value as a function of beating for the different pulps.

Figure 7 shows that the WRVs were lower for the damaged pulps than for the undamaged ones. The results indicate that the decrease in WRV of the spruce pulps was greater than for the pine pulps. This is interesting because there were no significant differences in the tear – tensile relationship due to damage between the different raw materials. There were, however, large differences in the deformation behavior which correlated well with the reduction in WRVs.

The WRVs for the undamaged pulps were almost constant for all the different pulps tested

Figure 8 shows the wet zero-span tensile values as a function of PFI beating for the undamaged and damaged pulps.

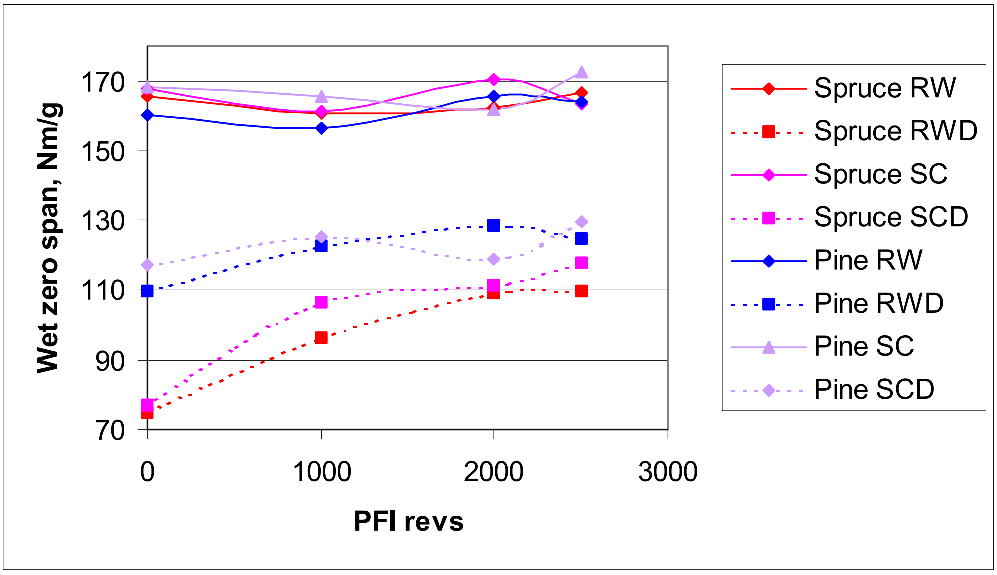

Figure 8. Zero-span tensile indices as a function of PFI revolutions for the different pulps.

Figure 8 shows that the wet zero-span tensile index decreased more for the spruce pulps than for the pine pulps. Seth /13/ and Molin /14/ have pointed out that zero-span should not be measured for curly fibers. In this case the damaged spruce fibers were more curled than the damaged pine fibers, which might account for the low zero-span tensile index of the damaged spruce fibers.

CONCLUSIONS

In this study the behavior of four raw materials after deformation and damage was tested in the laboratory. Curl index, kink index, fiber length and strength properties of the unbleached pulps were measured as a function of PFI beating. The main results were:

- There were differences in behavior between spruce and pine fibers following damage. The differences were obviously due to structural differences in the fiber walls of spruce and pine.
- Spruce fibers were more deformed than pine fibers under the same damaging conditions.
- Unbeaten tensile index was a good indicator of fiber curl.
- Deformed fibers: curl decreased during PFI-beating.
- Undeformed fibers: curl increased during PFI-beating.

The results of this study showed that the behavior of different raw materials following fiber damage differed, and that fibers seemed to have a “natural” curl.

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APPENDIX. Table 1. Fiber and sheet properties of PFI beaten pulps.

Sample ID	Revs.	Kajaani FS-200. L.w. av. fibre l. mm	Kajaani FS-200. Fines %	CSF ml	WRV g/g	Tens. ind. Nm/g	Tens. stiffn. ind. kN m/g	Elong. %	Zero-span (wet) Nm/g	Tear ind. mNm2/g	Density kg/m3	Scott bond J/m2	FiberExpert. L.w. av. fibre l. mm	FiberExpert. Curl index	FiberExpert. Kink index
Pine RW	0	1.90	3.01	625	2.14	75.6	8.48	2.1	160.0	13.3	662	167	1.72	5.1	2.47
Pine RW	1000	1.87	2.80	605	2.03	90.2	8.65	2.7	156.4	12.6	727	306	1.81	5.7	2.45
Pine RW	2000			540	2.05	99.7	8.89	3.1	165.3	11.1	766	429	1.82	5.7	2.40
Pine RW	2500			535	2.09	101.1	9.02	3.2	164.1	11.5	771	464	1.79	5.9	2.39
Pine RWD	0	1.76	3.08	715	1.85	38.2	5.23	2.0	109.6	12.4	557	94	1.67	9.4	2.89
Pine RWD	1000	1.81	2.93	670	1.85	65.4	7.12	2.9	122.8	10.1	694	255	1.79	7.2	2.64
Pine RWD	2000			640	1.92	74.3	7.81	2.9	128.5	8.8	730	380	1.79	7.1	2.56
Pine RWD	2500			615	1.91	81.4	7.98	3.1	124.6	8.5	752	467	1.79	6.9	2.54
Pine SC	0	2.65	2.94	685	1.93	68.8	8.43	1.8	168.4	20.9	605	107	2.34	5.7	2.55
Pine SC	1000	2.60	2.74	685	1.89	79.1	8.34	2.5	165.6	17.5	677	212	2.48	6.6	2.41
Pine SC	2000			665	1.93	85.8	8.39	2.8	161.5	16.6	705	273	2.49	6.9	2.33
Pine SC	2500			645	1.98	88.8	8.18	3.1	172.7	15.2	716	320	2.52	7.2	2.35
Pine SCD	0	2.46	2.78	730	1.67	24.5	3.67	1.8	117.1	17.4	497	77	2.25	12.3	3.10
Pine SCD	1000	2.51	2.75	730	1.70	41.9	5.73	2.1	125.4	17.0	629	150	2.38	9.4	2.73
Pine SCD	2000			710	1.78	53.8	6.66	2.4	118.8	13.7	649	218	2.38	8.0	2.56
Pine SCD	2500			690	1.82	58.4	7.15	2.3	129.4	12.3	676	245	2.44	7.9	2.52
Spruce RW	0	2.61	1.80	670	1.95	83.9	9.50	1.9	165.4	18.3	630	133	2.35	5.6	2.43
Spruce RW	1000	2.60	1.65	660	1.90	92.8	9.52	2.3	160.9	16.3	706	248	2.43	6.4	2.36
Spruce RW	2000			620	1.95	102.9	9.56	2.7	162.1	14.8	724	317	2.45	6.2	2.28
Spruce RW	2500			595	1.96	103.7	9.60	2.7	166.4	13.1	737	336	2.43	6.4	2.25
Spruce RWD	0	2.03	1.74	740	1.25	6.4	1.09	1.4	74.9	4.9	418	65	1.82	25.5	3.67
Spruce RWD	1000	2.28	1.70	735	1.40	26.2	3.72	2.5	96.4	18.1	564	127	2.20	15.9	3.22
Spruce RWD	2000			730	1.47	39.7	5.39	2.8	108.9	19.6	621	189	2.28	12.5	2.99
Spruce RWD	2500			720	1.51	45.1	5.95	2.7	109.7	18.3	634	227	2.30	11.7	2.94
Spruce SC	0	2.76	2.55	705	1.89	73.4	9.17	1.7	167.4	18.5	629	138	2.44	5.6	2.54
Spruce SC	1000	2.72	2.50	670	1.90	83.4	9.25	2.1	161.1	16.5	706	257	2.61	5.7	2.32
Spruce SC	2000			630	2.01	97.0	9.80	2.4	170.4	14.8	723	333	2.59	5.9	2.26
Spruce SC	2500			605	1.98	96.7	10.04	2.3	163.1	14.5	743	378	2.62	6.5	2.27
Spruce SCD	0	2.37	2.32	745	1.44	9.7	0.91	4.6	76.9	8.5	446	74	2.18	21.0	3.54
Spruce SCD	1000	2.53	2.27	730	1.53	29.0	4.58	2.2	106.7	21.0	594	155	2.42	12.4	3.01
Spruce SCD	2000			715	1.61	45.2	6.22	2.7	111.1	16.6	656	255	2.48	10.0	2.77
Spruce SCD	2500			705	1.65	51.8	6.53	2.9	117.6	14.3	668	280	2.47	9.7	2.71