Alkali Extraction of Kraft Pulp Fibers: Influence on Fiber and Fluff Pulp Properties

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ABSTRACT

The importance of hemicelluloses for the papermaking properties of pulp fibers is well documented. In the patent literature, it can be seen that there is also an interest in this type of modification of pulp fibers for use in absorption products. In this study, a Scandinavian softwood kraft pulp and a birch kraft pulp were alkali extracted at 3 different concentrations of NaOH (2%, 4% and 8% NaOH in the suspension). The alkali extraction removed a large part of the hemicelluloses from the pulp fibers and decreased the content of the charged groups. After extraction, the pulps were dried in the form of sheets (approx. 600 g/m^2). The alkali extracted pulp fibers exhibited a greater decrease in swelling when re-wetted than untreated pulp. A significant increase in the curl index after extraction with 4% and 8% NaOH was also noted. The tensile strength index of the formed sheets increased at the lowest concentration of NaOH and, at the higher concentrations, a decrease was observed. The pulp sheets were dry defibrated at different defibration intensities and the performance of the resulting pulps in fluff pulp applications was studied. The air-laid fiber networks of softwood pulp fibers showed higher network strength than the networks of birch pulps. The birch pulp extracted at the highest alkali level tended to give the highest network strength. The results from the network strength tests also indicated that the increased curl of the fibers from the softwood pulp extracted at the highest alkali level rendered a more flexible fiber network. In water absorption tests, the alkali treated softwood fibers tended to give networks with a somewhat enhanced water holding capacity under pressure.

INTRODUCTION

The term fluff pulp refers to pulp fibers intended for use in absorption applications, such as diapers and feminine hygiene products. In the past, the absorbent core of these products was exclusively composed of fluff pulp. With the introduction of super absorbing polymers (SAPs) in the 1980s the demands on the pulp changed. Some of the main functions of the fluff pulp fiber network are now to distribute liquid effectively throughout the product and to provide sufficient network strength to hold it together.

Bleached softwood kraft pulps, such as those from southern yellow pine, are often used in fluff pulp applications. [1-2] However, other raw materials and processes, such as softwood CTMP and hardwood kraft pulps, have and are being used. [2] Fluff pulp is dried before deliverance to the fluff pulp user. The dried pulp should be easy to dry defibrate (low knot content at low energy inputs), and the fiber network formed in a subsequent air-laid process should have good network strength and be resilient in the wet state. The resistance towards dry defibration of a fluff pulp sheet is to a large extent dependent on the strength of the bonding between fibers. High bonding strength within the sheet means that greater energy is needed during defibration to liberate fibers and reduce the amount of knots. Different types of debonders have been used to alleviate the defibration procedure by decreasing the strength of the interaction between the fibers in the sheet. [3] The use of debonders is also often mentioned in the patent literature. [4-5] The network strength in an air-laid product is also dependent on the forces that act between fibers. However, since the fluff pulp network is dry-formed, inter-fiber forces are mainly frictional in character. The most important factor that affects the impact of frictional forces within a fiber network is the length of the fibers, [6-7] although other properties such as flexibility and curl may also influence network strength. [6, 8] Furthermore, it has been noted that in wet networks [9] and when modelling dry networks, [10] fiber entanglement plays an important role. The ability to resist pressure in the wet state is largely dependent on the wet

flexibility of individual fibers, [11] but also, in this case, other factors such as fiber length most likely have an influence on pressure resistance. [12]

The extraction of hemicelluloses [13-14] and the importance of hemicelluloses for pulp and paper properties [15-16] have been thoroughly studied previously. Several patents and patent applications have been issued regarding the improved properties of fluff pulp by the extraction of hemicelluloses. [17-18] It has been claimed in, for example the patent issued by Chatterjee [17] that it is likely that fiber-fiber bonding potential would decrease when a large part of the hemicelluloses is removed. The resulting decrease in bonding would facilitate the dry defibration procedure. It is also possible that with the removal of hemicelluloses, fibers will undergo more extensive hornification during drying, a process where the fibrils in the fiber wall bond more strongly to each other. [19-20] When the fibers are rewetted, the swelling of the fiber walls becomes significantly less than for never-dried pulp fibers. This reduction in fiber swelling decreases wet fiber flexibility [21-22] and produces a fluff pulp more resilient to pressure.

In the present study, a Scandinavian softwood kraft pulp and a Scandinavian birch kraft pulp were alkali extracted at 3 different concentrations of NaOH. The extraction was done in order to remove hemicelluloses (especially xylans) from fiber walls. The performance of the pulps in fluff pulp applications was then evaluated.

MATERIALS AND METHODS

Starting Materials

The pulps used in this investigation were never-dried peroxide-bleached (totally chlorine free) kraft pulps: one produced from Scandinavian softwood (a mixture of *Picea abies* and *Pinus sylvestris*) and one produced from birch (*Betula pendula*). The pulps were obtained from a pulp mill situated in the southern part of Sweden.

Preparation of Pulps

Alkali Extraction

The extraction was carried out at room temperature using three different concentrations of NaOH, cf. *Table I*. The pulps were extracted for 1 h at room temperature at a pulp consistency of 5%. After completed extraction, the pulp was dewatered in a Büchner funnel and carefully washed with deionised water.

TABLE I. Concentration of NaOH in extraction of pulp.

	Softwood Kraft Pulp				Birch Kraft Pulp			
Denotation	S0	S2	S4	S8	B0	B2	B4	B8
NaOH (weight-% of suspension)	0	2	4	8	0	2	4	8

Formation of Sheets

Wet pulp was defibrated according to SCAN-C 18:65 (10,000 rev, 3000 rpm). A suspension of the defibrated pulp (94.5 g dry weight, 7 g/l) was then transferred to a 0.35 x 0.45 m box with a nylon web at the bottom. The suspension was stirred and then dewatered, by allowing it to drain for 10 minutes. Water was then removed from the sheet in three steps, with increasing pressure at each step. The first step, which involved putting 3 layers of blotting paper (Binzer & Munktell filter GMBH, grade 1600) on the sheet and gently rolling a plastic cylinder over, was repeated three times. The sheet was then put between new blotting papers and two wooden plates and a pressure of about 5 kPa was applied for about 30 s. This step was repeated twice. Third, the sheet was pressed between new blotting papers and wooden plates at 0.10 MPa for 7 minutes. The last step was also repeated twice. The sheets were then air-dried in a climate room (23° C, 50% RH).

Dry Defibration

The sheets were cut into strips (width=15 cm) and dry defibrated in a hammer mill (SMED, Norway) at 1500, 1700, 1900, 2100 and 2400 rpm. The rate of the inlet feed of the pulp sheets was 1.8 m/min and the disintegrated fibers had to pass a mesh with 10 mm openings before leaving the hammer mill.

Methods

Chemical Analysis of Pulps

The carbohydrate composition was analysed according to Theander and Westerlund. [23] The analysis protocol includes acid hydrolysis of the carbohydrates followed by reduction of the liberated monosaccharides and subsequent acetylation. The formed alditolacetates were then analysed using gas chromatography.

The content of charged groups was analysed using conductometric titration according to SCAN-CM 65:02, based on Katz et al. [24]

WRV (Water retention value)
WRV was analysed according to SCAN-C 62:00. Never-dried pulp and once-dried pulp before defibration were analysed. The analysis was performed in duplicates.

Tensile Strength Index
Tensile strength index tests were conducted with an EZ L2000R MTM from Lloyd Instruments. The width of the test strip was 1.5 cm. The distance between the clamps was 10 cm and the speed of the clamps during the test was 20 mm/min. The tests were done in a climate room (23° C, 50% RH).

Kajaani FS300
The fiber length and curl of the once-dried fibers, before and after defibration, were analysed with a Kajaani FS300.

Knot Content
Knot content was analysed according to SCAN-CM 37:85. The procedure in this study deviated from the standard in that 3 g of pulp were used and the analysis was duplicated for all samples. The method involved subjecting pulp to an oscillating air flow within a horizontal plastic tube. A pin mixer at the centre of the tube facilitated the liberation of fibers from fiber flocs. The knots were retained on the wire screens at the ends of the tube, while free fibers passed through.

Dry Forming of Pads
The equipment for the formation of pads (test piece former) is described in detail in SCAN-C 33:80 and shown schematically in *Figure 1*. Deviations in the present study from the SCAN method were the included plastic ball (d=37 mm) suspended in the lid 5.5 cm above the pulp pad holder (length of wire=23 cm), see *Figure 1* (the plastic ball enhances fiber separation), and instead of the wire screen at the bottom of the pad holder, a sintered metal plate with pore size of 0.4 mm and 140 pores/cm² was used.

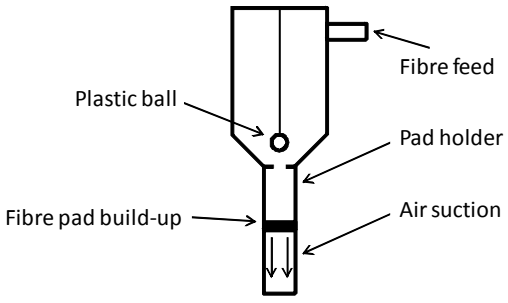

FIGURE 1. Schematic overview of test piece former.

1.2 – 1.3 g of defibrated fibers was fed into the fiber feed as outlined in *Figure 1*. Continuous air suction forced the fibers pass the small ball and down to the pad holder. The fibers were fed at a rate so that pads were formed in 20 ± 5 s. The pulp pads formed had a diameter of 50 mm and the air suction produced a pressure difference of 0.14 bar.

Network Strength
Network strength is the force needed to produce a rupture in a dry-formed test pad. The method used in this study is based on the one developed at PFI in Norway. [25] A schematic overview of the instrument used to measure the network strength is shown in *Figure 2*.

Test pads were formed according to the method described previously, cf. *Figure 1*. The height of the test pads was measured at a load of 6 kPa. The pad was then fastened in the pulp pad holder by pressing down the edges with a cylinder (inside cylinder in *Figure 2*). A piston (d=2 cm) was then forced through the pad and the highest force was recorded, which, in a typical case, is just before the pad ruptures.

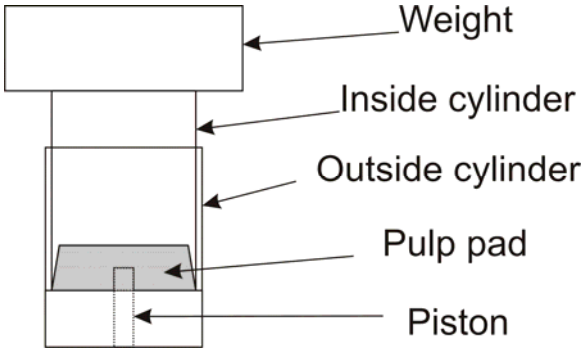

FIGURE 2. Schematic overview of instrument used to measure network strength.

Wet Compression Test
The pulp pads used in the compression test were formed as described previously and pressed at 0.37 MPa for 9 seconds before being put in the compression tester. The steps in the compression test procedure are outlined in *Table II*.

TABLE II. The different pressures in the compression test. The height of the test pad was measured before each change in pressure.

Time (min)	Pressure (kPa)	State
0	2	Dry
2	0	Wetting
12	0	Drainage
14	0.5	Wet
16	2	Wet
18	6	Wet
20	0	Wet
25	0.09	Wet

The height of the dry pulp pad was first measured at 2 kPa. An open water container was then put under the pulp and the pad absorbed water for 10 min after which excess water drained off for 2 min. The height of the wet pulp pad was measured at 0.5, 2 and 6 kPa, with a 2 min equilibration at each pressure. The pressure was then released and the sample was equilibrated for 5 min with no pressure applied and the height was measured at 0.09 kPa. The equipment used in the compression test is described elsewhere. [26]

RESULTS AND DISCUSSION

Alkali Extraction

Softwood and birch kraft pulps extracted with NaOH-solutions at 3 different concentrations were subjected to carbohydrate analysis along with untreated reference pulps. The relative anhydrosugar composition of the pulps presented in *Table III* shows, not unexpectedly, that xylan was removed most extensively during the extraction, both from the softwood pulp and the birch pulp.

TABLE III. Relative anhydrosugar composition and fiber charge of the different pulps after alkali extraction.

Pulp sample	**S0**	**S2**	**S4**	**S8**	**B0**	**B2**	**B4**	**B8**
Glucan (%)	85.7±0.5	87.0±0.5	89.4±0.5	93.9±0.5	76.9±0.5	79.3±0.5	88.3±0.5	95.7±0.5
Xylan (%)	7.1±0.1	6.1±0.1	3.9±0.1	1.1±0.1	22.0±0.2	19.5±0.2	10.5±0.2	3.2±0.2
Mannan (%)	5.9±0.1	6.0±0.1	5.9±0.1	4.5±0.1	0.6±0.1	0.6±0.1	0.7±0.1	0.6±0.1
Arabinan (%)	0.9±0.1	0.7±0.1	0.6±0.1	0.4±0.1	0.4±0.1	0.4±0.1	0.4±0.1	0.4±0.1
Galactan (%)	0.3±0.1	0.2±0.1	0.2±0.1	0.1±0.1	0.1±0.1	0.1±0.1	0.1±0.1	0.1±0.1
Yield (%)	-	98	95	89	-	94	84	75
Fiber charge (meq/kg)	68±1	57±1	46±1	28±1	110±1	89±1	55±1	24±1

TABLE IV. WRV of different pulps. Percentage hornification is calculated as (WRV of never-dried – WRV of once-dried) / (WRV of never-dried). The pooled standard deviation of the WRV values was 0.01 g/g.

	WRV (g/g)		**Hornification (%)**
Pulp sample	*Never-dried*	*Once-dried*	
S0	1.34	0.96	28
S2	1.36	0.96	30
S4	1.35	0.93	31
S8	1.30	0.87	33
B0	1.57	1.17	25
B2	1.63	1.15	29
B4	1.61	1.04	35
B8	1.48	0.90	39

A reduction in the relative content of mannose residues in softwood could also be seen, but only at the highest alkali concentration. This shows that hemicellulose of the glucomannan type was extracted at this alkali level. [Regarding the composition of different hemicelluloses in kraft pulps, see Dahlman et al. [27]]. The total charge of the fibers was shown to decrease as a consequence of alkali extraction. This was expected and is consistent with the removal of xylan, which contains uronic acid residues as substituents.

The WRV (water retention value) of the pulps was measured before and after drying, see *Table IV*. The extraction of alkali had a relatively minor influence on the WRV, i.e. the swelling, of the never-dried softwood pulp and a somewhat greater influence on the never-dried birch pulp. Nevertheless, alkali extraction using 2 and 4% NaOH tended to increase the WRV, whereas extraction with 8% lowered the value. This behavior is probably governed by two factors: the swelling of the fiber wall and hemicellulose removal during extraction due to a high pH and the resulting decrease in charged group

content. During alkali treatment, the fiber wall swells due to osmotic effects and the swelling pressure disrupts (hydrogen) bonds between the fibrils building up the fiber wall. This promotes a high WRV. The subsequent washing step with deionised water decreases the pH to a neutral level. Charged groups (e.g. uronic acids) in the fiber wall increase the WRV by giving rise to osmotic pressure. [28] The reduction in the charged group content of pulps extracted with 2% and 4% alkali is more than compensated for by the swelling effect of the alkali, and the WRV increases as a result. For pulps treated with 8% alkali, however, the level of uronic acid removal is high and the WRV drops.

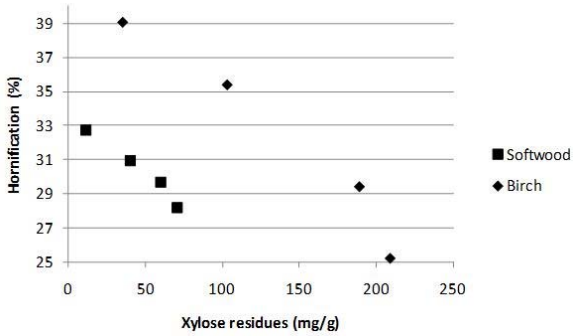

FIGURE 3. Hornification of fibers as function of content of xylose residues.

The water retention values of the once-dried pulps were lower than the corresponding values of the never-dried pulps. This well-known effect of drying is called hornification, and the degree of hornification can be defined as [WRV (never-dried) – WRV (once-dried)]/[WRV(never-dried)]. [29] Results in the literature demonstrate that decreased amounts of hemicelluloses and/or charged groups in the inter-fibrillar spaces reduce the tendency of irreversible bonds to form between adjacent cellulose fibrils. The presence of hydrated hemicelluloses in the fiber wall enhances, to a certain extent, the amount of water taken up by the fiber wall when re-wetted. Nevertheless, the content of charged groups is the dominant factor of the swelling behavior of the fibers. [30] *Table IV* and *Figure 3* show the WRV of the never-dried and once-dried fibers, as well as the percentage of hornification of the fibers. The trend is that with lower amounts of hemicelluloses (which in this case is mainly xylan) and charged groups, the fibers undergo a higher degree of hornification.

TABLE V. Curl index and fiber length of the alkali extracted pulps. Shown are the softwood pulps defibrated at 1900 rpm and the birch pulp defibrated at 2400 rpm. Shown are also the sheets before defibration. The pooled standard deviation for the softwood was 0.10 mm for the fiber length and 1.7% for the curl index. The pooled standard deviation for the birch was 0.01 mm for the fiber length and 0.6% for the curl index.

Pulp sample		**S0**	**S2**	**S4**	**S8**	**B0**	**B2**	**B4**	**B8**
Curl index (%)	*Sheets*	30.1	30.0	33.1	41.1	14.3	14.6	19.0	20.7
	Defibrated	30.4	30.8	35.4	44.0	14.8	14.9	18.4	20.8
Fiber length (mm)	*Sheets*	2.74	2.71	2.72	2.42	0.93	0.90	0.85	0.75
	Defibrated	2.62	2.70	2.74	2.45	0.94	0.92	0.85	0.78

Dry Defibration

One of the important properties for pulps used in dry-forming applications is their behavior during dry defibration. [8] The fibers need to be sufficiently liberated and the content of knots (fiber bundles) should be low. Excessive energy input during defibration, however, leads to fiber cutting. High bonding strength in the dried pulp to be defibrated produces a pulp with more knots at a given energy input. [31]

One indirect way to obtain an indication of the behavior of the pulp in dry defibration is to measure the tensile strength of the pulp sheets. [32] The tensile strength index of the alkali extracted pulps in the present study can be seen in *Figure 4*. The tensile strength index for both the softwood and the birch pulps was seen to increase at the lowest concentration of alkali and then to decrease at the two highest alkali concentrations. This trend follows the tendency seen for the WRV of the never-dried pulps in *Table IV*. The tensile strength index of paper is considered to be dependent on the conformability of the fibers, as well as on the structure and chemical composition of the fiber surfaces. [33] An increase in WRV indicates that the fibers are more flexible which leads to a higher degree of fiber bonding during sheet formation. This results in a higher tensile strength index. It has also been noted, however, that a lower charged group content reduces the tensile strength index of handsheets. [34] It is plausible that the increase in the tensile strength index seen for the

pulps extracted with 2% NaOH (*Figure 4*) is an effect of the increase in fiber flexibility. The substantial extraction of hemicelluloses that occurs at higher alkali concentrations reduces the tensile strength index of the sheets, due to the removal of acidic groups.

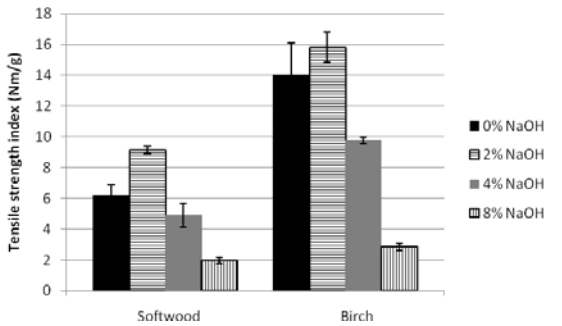

FIGURE 4. Tensile strength index of sheets at different alkali treatments. Error bars indicate standard deviation of measurements.

Fiber properties were analysed with a Kajaani FS300. Fibers from the pulp sheets and fibers from dry defibrated pulp sheets were analysed. In the analysis procedure, the fibers were suspended in a water solution. Consequently, the results relate to the fiber properties in a rewetted state. The results in *Table V* clearly demonstrate a much higher curl index for softwood pulps. There is also a clear tendency for the alkali treatment to induce curl formation. Approximately the same curl indices were obtained before and after dry defibration. An increase in the curl index when fibers are treated with swelling agents has been noted previously. [35-36] It is not clear, however, whether the swelling agents induce curl or simply retain it by means of stress relaxation in the fibrils. The fiber lengths were not notably affected by the dry defibration procedure. There was, however, a slight decrease in fiber length recorded for the pulps extracted with 8% NaOH, but this effect was observed even prior to dry defibration. It is possible that the decrease in fiber length is due to error in the measurements, related to the increased curl of the fibers. If the fibers are curled in the line of measurement, the apparent fiber length may be shorter than it actually is. [37]

The dry defibrated pulps were subjected to knot content analysis. Results for the birch pulps are shown in *Figure 5*. No reliable results regarding the knot content of the softwood pulp could be obtained with the current method, because there was a high tendency for liberated fibers to form low density flocs inside the test tube.

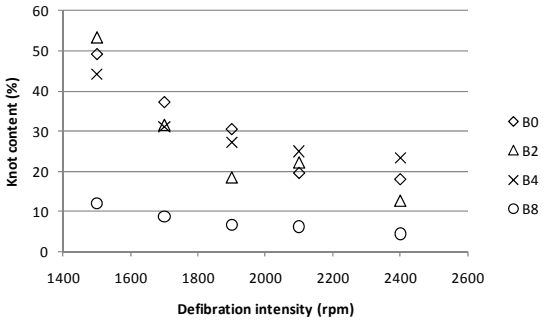

FIGURE 5. Knot content plotted against defibration intensity of birch pulp. The pooled standard deviation for the knot content was 3.0%.

The reference birch pulp and the birch pulps extracted with 2% and 4% alkali, displayed a high amount of knots when disintegrated with low energy input, *Figure 5*. As expected, the knot content decreased as the defibration intensity increased. The knot content was relatively low for all pulps at the highest defibration intensity (2400 rpm). The birch pulp treated with 8% alkali was much easier to defibrate and very low amounts of knots were obtained even at low defibration intensities. It was also noted that some of the fibers of the birch pulps treated with 8% alkali, denoted as knots in the method used, were fibers that had formed low density flocs. Consequently, the content of dense knots in these pulps was lower than shown in *Figure 5*. The substantially lower tensile strength index of the birch pulp treated with 8% NaOH was also reflected in the knot content analysis; an indication of the importance of the bond strength in the pulp sheet on ease of defibration.

Network Strength

After dry defibration, fiber network pads were dry-formed in the test piece former and tested for their network strength. In an absorption product, a fluff pulp will experience forces. High network strength of a fluff pulp means that greater forces are needed to disrupt the network.

The generally accepted view is that the network strength for fiber networks of equal density is largely dependent on fiber length and on the content of knots in the dry defibrated pulp. [7-8] Long fibers provide more fiber-fiber contact points per fiber, which enhances network strength. At low intensity in the dry defibration, the content of knots is high and the

network strength tends to be rather low, due to a low number of free fibers per volume element. At high intensities, the number of knots is low, but there is greater likelihood of fiber cutting.

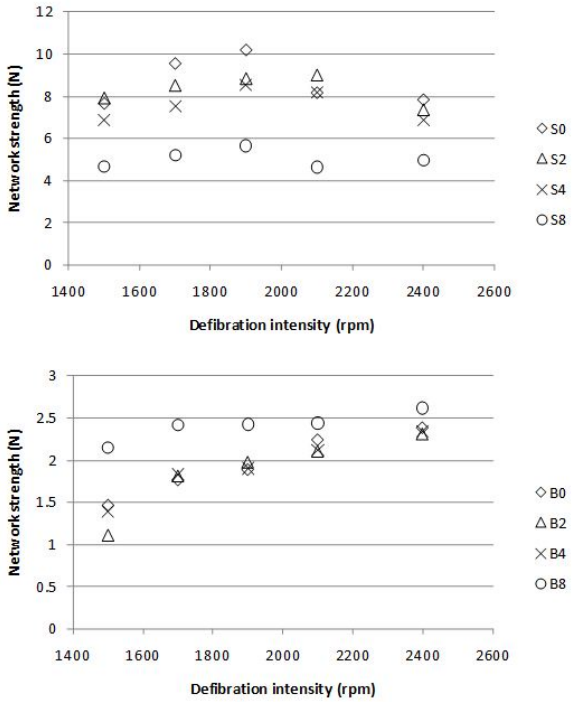

FIGURE 6. Network strength plotted against the defibration intensity of (a) the softwood kraft pulps and (b) the birch kraft pulps. No clear fractured zone could be seen in the test pads of the softwood kraft pulp extracted with 8% NaOH (S8) after the test. The pooled standard deviation for the network strength was 0.89 N for the softwood kraft pulps and 0.18 N for the birch kraft pulps.

The network strength of the softwood kraft pulp pads is shown in *Figure 6 (a)*. For the pulps extracted with 0%, 2% and 4% NaOH there was a tendency for the network strength to increase as the defibration intensity increased from 1500 rpm to 1900-2100 rpm. The network strength of the pulp extracted with 8% NaOH was significantly lower, and no clear effect of the defibration intensity on the resulting network strength could be seen. The average fiber length of that pulp was measured to be around 0.2-0.3 mm shorter than the other pulps, cf. *Table V*. However, it seems unlikely that this small decrease in fiber length could have such a major effect on network strength. Another explanation could be the large increase in the curl of these fibers. The network strength tester used in this investigation was designed to report the highest force recorded during the test and to stop when the force decreased. It is possible that the force recorded is the force needed to straighten the fibers and not to rupture the network. Askling et al. [8] investigated the material properties of low-density dry-formed networks with Dynamic Mechanical Analysis. It was noted that an increase in the curl of the fibers gave an increase in the critical strain (where the critical strain is the strain at which the network ruptures). Their explanation was that when the network starts to deform, curled fibers begin to straighten before any slippage between them takes place, cf. *Figure 7*. The observation that after the network strength test the test pads with the most curled fibers (i.e. after extraction with 8% NaOH), had no clear fractured zone in them supports the idea that the same mechanism was in effect in this investigation. For the test pads with more straight fibers (0%, 2% and 4% alkali), a clear fracture in the pad was always observed. These results suggest that a more flexible dry-formed network is formed when more curled fibers are present.

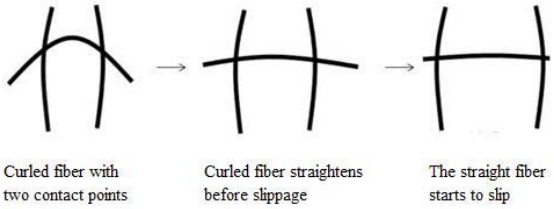

FIGURE 7. Illustration of a curled fiber with two contact points that straightens before starting to slip. Adapted from Askling et al.[8]

The network strengths of the birch pulps were on a considerably lower level than the softwood pulps see *Figure 6 (b).* This is because the birch kraft pulp has a much shorter fiber length than the softwood kraft pulp (<1 mm in birch in comparison to more than 2.5 mm in softwood). The network strength for the birch kraft pulps extracted with 0%, 2% and 4% NaOH increased as the defibration intensity increased. The network strength was high for all the defibration intensities of birch kraft pulp extracted with 8% NaOH. These results are consistent with the knot content results shown in *Figure 5*, since the fibers have to be liberated in order to contribute to network strength.

Differences in network density were not considered in the evaluation of network strength properties. The density of the softwood fiber networks was on a considerably lower level than that of the birch fiber

networks. The density of the softwood test pad networks was between 0.055-0.064 g/cm³ and the density of the birch test pad networks was between 0.069-0.084 g/cm³. However, no systematic influence of density on network strength could be seen.

Wet Compression Test

The same type of test pads as in the network strength analysis were used for the wet compression test, but the pads were pressed at 0.37 MPa for 9 seconds before they were subjected to the wet compression testing procedure. The results of this investigation can be seen in *Figure 8*.

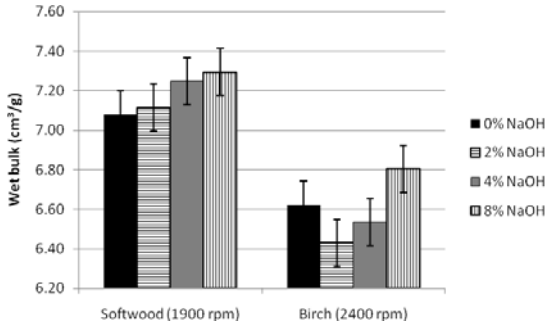

FIGURE 8. Wet bulk at 6 kPa for softwood kraft fibers at different concentrations of NaOH. Softwood was defibrated at 1900 rpm and birch defibrated at 2400 rpm. Error bars indicate standard deviation of measurements estimated from 5 measurements of reference softwood pulp (0% NaOH).

Fiber networks that have a high resistance to pressure in the wet state will retain more porosity when put under pressure. Consequently, the wet bulk under pressure of fiber networks is of importance in fluff pulp applications. The wet bulk of softwood kraft pulp networks are higher than the wet bulk of birch kraft pulp networks. These differences can be explained by the longer fiber length of the softwood pulp. The effect of alkali extraction on the wet bulk of softwood kraft pulps is minor, although the wet bulk tends to increase with increasing concentration of NaOH in the extraction. The birch kraft pulps show a different trend with a decrease at 2% alkali and then an increase with increasing alkali concentration. The differences are, however, minor, and for the most part within the experimental error. Nevertheless, it seems likely that the trend seen for the softwood kraft pulps is due to increased hornification, cf. *Table IV*. It can also be noted that alkali extraction of birch pulp with 8% NaOH yielded the highest wet bulk value. One consequence of hornification is a decrease in wet fiber flexibility [e.g. Paavilainen, [21] Zhang et al., [22] Köhnke et al. [38]]. The trends seen in the results may thus be explained by hornification, since the ability of fiber networks to resist pressure in the wet state is largely determined by the wet fiber flexibility of individual fibers. [11]

CONCLUSIONS

Extraction of kraft pulp fibers with NaOH decreased the amount of hemicelluloses, especially xylan, and the charged group content of the fibers. The reduced amount of hemicelluloses and charged groups increased the extent of hornification of the fibers. Analysis of pulp sheets showed that treatment with a low concentration of NaOH (2%) gave an increase in the tensile strength index, possibly due to an increase in the flexibility of the fibers due to the swelling action of the alkali. Higher concentrations of NaOH gave a decrease in the tensile strength index, most likely due to a reduction in the specific bond strength between fibers. Alkali extraction induced curl formation at the two highest alkali levels. The knot content of the birch pulp was very low for the birch pulp extracted with 8% NaOH. Results also suggest that air-laid fiber networks of alkali treated softwood pulp (8% NaOH) tend to be more flexible than networks of untreated softwood pulp and birch pulps. In the water absorption tests, fiber networks of softwood pulp retained more water than the birch pulps. The influence of alkali extraction was relatively minor. Even so, the trend for the softwood kraft pulp was that higher concentrations of NaOH in the extraction gave a somewhat higher wet bulk when compressed.

The results presented in this study indicate that extensive alkali extraction may be beneficial for the performance of fluff pulp: (*i*) Pulp sheets are easy to defibrate, (*ii*) low density fiber networks that resist breakage better (more flexible networks) were obtained from softwood pulp, and (*iii*) there is a tendency for high absorption capacity under load (high wet bulk).

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