LAPPEENRANTA UNIVERSITY OF TECHNOLOGY
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THE IMPACT OF ASPEN AND ALDER ON THE QUALITY OF NBHK

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ABSTRACT

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Master's thesis

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104 pages, 40 figures, 29 tables and 4 appendices

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Key words: hardwood, birch, aspen, alder, kraft pulp, mix, bleaching, refining, pulp properties, chemical composition, fibre properties, strength.

The purpose of this work was to study the effect of aspen and alder on birch cooking and the quality of the pulp produced. Three different birch kraft pulps were studied. As a reference, pure aspen and alder were included. The laboratory trials were done at the UPM Research Centre in Lappeenranta, Finland. The materials used were birch, aspen and alder mill chips that were collected around the area of South-Carelia in Finland. The chips used in the study were pulped using a standard kraft process. The pulps including birch fibres were ECF-bleached at laboratory scale to a target brightness of 85 %. The bleached pulps were beaten at low consistency by a laboratory Voith Sulzer refiner and tested for optical and physical properties.

The theoretical part is a study of hardwoods that takes into accounts the differences between birch, aspen and alder. Major sub-areas were fibre and paper-technical properties as well as chemical composition and their influence on the different properties. The pulp properties of birch, aspen and alder found in previous studies were reported. Russian hardwood forest resources were also investigated. The fundamentals of kraft pulping and bleaching were studied at the end of theoretical part.

The major effect of replacing birch with aspen and alder was the deterioration (lowering) of tensile and tear strengths. In other words, addition of aspen and alder to a birch furnish reduced strength properties. The reinforcement ability of the tested pulps was the following: 100 % birch > 80 % birch, 20 % aspen > 70 % birch, 20 % aspen, 10 % alder. The second thing noted was that blending of birch together with aspen and alder give better smoothness, optical properties and also formation. It can be concluded, that replacement of birch with alder during cooking by more than 10 % can negatively affect on the paper-technical properties of birch pulp. Mixing pure birch and aspen pulps would be more beneficial when producing printing paper made from chemical pulp.

ACKNOWLEDGEMENTS

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GLOSSARY OF SYMBOLS AND ACRONYMS

[aCL]	Active chlorine
μm	Micrometer (micron)
AA	Active alkali
BL	Black liquor
CED	Cupriethylenediamine solution
CI	Curl index
cm	Centimetre
CSF	Canadian standard freeness
CWT	Cell wall thickness
D	Chlorine dioxide treatment
DP	Degree of polymerisation
E	Alkali extraction
EA	Effective alkali
ECF	Elemental chlorine free
g	Gram
ha	Hectare
i.e.	For example
Kappa no.	Kappa number
kg	Kilogram
kJ	Kilo Joule
km	Kilometre
LC-refining	Low consistence refining
m	Meter
m	Mass
m^3	Cubic metre
MC	Moisture content
min	Minute
ml	Millilitre
mm	Millimetre
N	Newton
Na_2O	Sodium oxide

NaOH	Sodium hydroxide
o.d.	Oven dry
ºC	Degree Celsius
Pa	Pascal
PC	Post colour number
SEC	Specific refining energy
SR	Degree Shopper-Riegler
TA	Total alkali
TEA	Tensile energy absorption
TS	Total sulphur
WL	White liquor
WRV	Water retention value

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THEORETICAL PART

1 INTRODUCTION

With an increasing demand for printing grades, interest has grown in the use of hardwood pulps. Hardwood pulps are used in printing and writing papers where they contribute to improved printing ability, sheet bulk, opacity and surface smoothness. Applications are usually fine papers, printing papers and art papers.

Nowadays we have to increase utilization of new renewable resources. The impact of this trend on the forest product industry will include the introduction of more lignocellulose chemical products, and growing competition for existing forest resources.

Birch has been of interest as a papermaking raw material for many years. Typically birch wood is used as a raw material in hardwood pulping in Finland, Russia and other countries with similar climate. Birch is used primarily in kraft pulping and it is usually bleached. Birch is one of the longest and densest fibered hardwoods. Due to availability and price reasons also other alternatives are needed to produce an acceptable yield of fibers with acceptable papermaking properties. The objective is to make more efficient use of our resources.

Aspen is one of the world's most geographically widespread tree species. Due to its availability, aspen easy in processing and excellent in pulp quality. Alder also is wide spreading and fast regeneration wood.

The cubic growth of the alder and aspen is about equal to that of the birch. The aspen and alder growth fast at a young age but begin to slow down within 25-30 years. To avoid decay and natural losses, the rotation age should be 30-40 years, which is a half of the rotation age of the birch (60-70 years).

In the production of paper, wood fibres keep most of their original structure. The tree species determine the range of fibre structure and therefore the properties of the end paper product. The target of the study was to verify the possibility to utilise aspen and alder in the birch kraft cooking.

In pulping of hardwood, an important question arises as to whether two or more species could be treated together in the same process line and still produce pulps with satisfactory properties. That's makes the supply of raw material less restrictive.

The aim for this project was to study suitability of aspen and alder for a raw material of northern bleached hardwood pulp. In other words, how the birch fibres behave together with the other fibres and substances in the cooking and bleaching process. The focus of the master's thesis work was essential cooking properties of birch, aspen and alder chips. Also mixtures of birch/aspen and birch/aspen/alder were tested. All cooked pulps were ECF bleached and refined in order to clarify the paper technical properties of each pulp.

In the literature part, the review of reserves of birch, aspen and alder forests of Russian Federation are discussed. Birch, aspen and alder as wood species and their distribution are presented. Also the characteristics of fibres and their chemical composition are discussed. The kraft process and the possibilities to manufacture birch, aspen and alder are presented. In the experimental part, it was investigated how cooking and properties of pulp are changed when aspen and alder chips are added to birch chips. The possibility to use those pulps for fine paper production was studied as well.

2 REVIEW OF FOREST RESERVES OF BIRCH, ASPEN AND ALDER IN RUSSIAN FEDERATION

Russia has the largest stock of wood in the world. There is about 1/4 of all global wood resources [1]. The total area of the wood resources of the Russian Federation exceeds 1173.9 million ha (hectares) [2]. These resources comprise estimated 81.9 billion m^3 (cubic meters) (1998) of wood. This adds up to more than 22 % of the whole world's wood supply [3]. Approximately 78 % of all Russian forests located in the Siberia and the Far East, and 22 % is in European part [4]. Small-lived tree species such as birch, aspen, linden, poplar, willow, alder occupy 119.7 million hectares (16.7 %) [3].

Annual average increment of wood in forest is about 935 million hectares or 1.22 cubic meters per 1 hectares of forest land [2]. The forestation is the percentage of total country area (including all its water basins) is covered by forest. The forestation of Russian Federation is 44.7 %. The same figures for European and Asian parts of Russia are, according official statistic, 38.5 % and 46.7 %. [5] Species composition of Russian forest is multifarious. Table 1 shows the data of a species composition of Russian forests.

Table 1. Species composition of Russian forests [4].

Species	Millions ha	%	Billions m^3	%
Larch	263.3	41.3	22.9	32.0
Pine	114.3	17.9	14.6	20.4
Spruce	75.9	11.9	10.1	14.1
Cedar	39.8	6.2	7.6	10.6
Fir	14.4	2.3	2.4	3.3
Birch	96.1	15.0	9.25	12.9
Aspen	18.9	3.0	2.7	3.8
Oak	6.8	1.1	0.77	1.0
Lime	3.0	0.5	0.47	0.7
Alder	-	0.4	-	-

As can be seen from Table 1, 77 % of Russian forest is coniferous. The area of deciduous forest in Russia is about 130 millions hectares, that's almost 1/4 of all forest recourses of country (data for 1993) [4]. The biggest part of it (approximately 80%) occupies birch, aspen, lime (linden) and alder.

Forest resources in Russia are almost solely owned by state. According to economical, ecological and social role, all wood resources of Russia may be divided into 3 groups [7]:

1. Water-protective, soil-protective, reserves (national parks) and other woods where felling is forbidden, *i.e.*: forests belts, parks, health resort zones and suburb. Total area of first group forests is 268.7 million hectares or 22.9%.
2. Multi-purpose woods in forest-poor zones with limited exploitation of woodlands. Total area is 88.7 million hectares (7.6%).
3. Widely utilized woods of forest-rich zones where the most part of afforestations are reproduced with participants of man. Total area is 815.0 million hectares (69.5%).

Part of birch forest is about 1/2 of all deciduous forests of Russia and approximately 13% of all forest of Russian Federation (Figure 1).

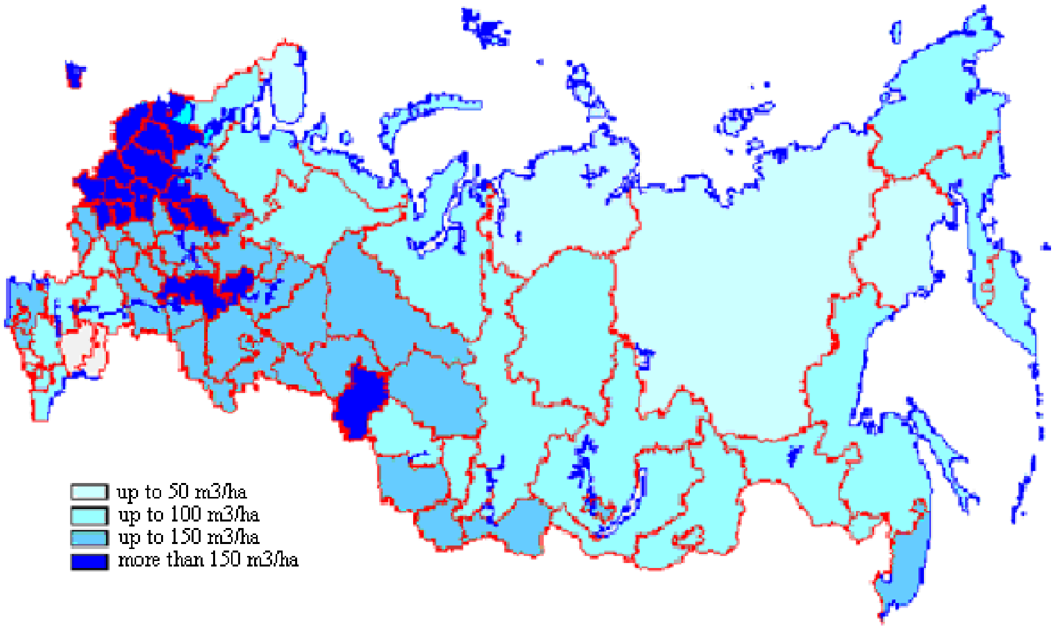


Figure 1. Reserve of birch wood, m^3/ha [7].

Area of birch forest is 95 millions hectares with total supply of wood around 9 billions m^3. Most of birch wood reserve located in European part of Russia. There are around 40 species of birch. Highly productive birch forests of European part of Russia give up to 350 m^3 wood/ha (data is for 50-years old trees). Figure 1 shows the birch wood supply of Russian Federation. [3]

Part of aspen forest is about 16% of Russian deciduous forests. Most of aspen forests are located in the south of European part of Russia and the south of Western Siberia. Total area of aspen forest is about 18.5 million hectares with wood supply up to 2.6 billion m^3. 50-years old aspen forest gives wood store about 420-500 m^3/ha. [4]

The alder forest extends in Kaliningrad and Bryansk regions, in the north of Russian plain (East European plain). Also, there is small amount of alder in Ural, Siberia, Far East and Caucasus mountains. Total area of alder forest is 1.6 million hectares with wood reserve more than 170 million m^3. In alder forest is more than 300 m^3 of alder wood per hectare. [6]

Table 2 and Table 3 are given basic statistical information about Russian forest resources of birch, aspen and alder. Data has been provided by the All-Russian Research and Information Centre for forest Resources (VNIITSLesresurs).

Figure 2 shows tree species composition of whole Russian Federation and Figure 3 shows the tree species composition of European part of Russia.

Table 2. Area and reserve of forest resources of birch, aspen and alder (data of Rosleskhoz).

Region	Total forestation area	Birch	Aspen	Alder
Archangelsk region				
area, thousand hectares	20184.6	3315.2	219.1	2.6
wood reserve, million m^3	2143.65	184.71	27.05	0.21
Vologda region				
area, thousand hectares	7178.1	2588.5	588.7	51.5
wood reserve, million m^3	989.82	353.92	93.1	6.03
Murmansk region				
area, thousand hectares	5026.5	1299.4	0.3	0
wood reserve, million m^3	198.08	27.51	0.02	0
Republic of Karelia				
area, thousand hectares	9267.4	939.8	58	21.8
wood reserve, million m^3	919.23	93.23	9.6	2.27
Leningrad region				
area, thousand hectares	3495.4	907.5	236.8	44.8
wood reserve, million m^3	641.27	160.1	59.2	6.43
Novgorod region				
area, thousand hectares	2199.4	873.7	246.1	132.1
wood reserve, million m^3	387.14	153.03	57.88	17.82
Pskov region				
area, thousand hectares	1090.2	335.8	84.5	60.4
wood reserve, million m^3	181.46	56.37	18.73	9.2
Bryansk region				
area, thousand hectares	733.4	188.2	72.1	42.4
wood reserve, million m^3	139.82	30.74	14.71	7.31
Vladimir region				
area, thousand hectares	969	294.5	52.7	20.4
wood reserve, million m^3	174.62	42.18	11	2.96
Ivanovo region				
area, thousand hectares	722.5	274.1	62.7	15.4
wood reserve, million m^3	129.67	44.91	14.16	1.98
Tver region				
area, thousand hectares	2116.8	740	197.2	66.6
wood reserve, million m^3	371.05	123.93	42.02	9.62

Table 3. Area and reserve of forest resources of birch, aspen and alder (data of Rosleskhoz) (continuation 2).

Region	Total forestation area	Birch	Aspen	Alder
Kaluga region				
area, thousand hectares	228.1	251	119.2	13.7
wood reserve, million m^3	39.86	47.93	29.26	2.63
Kostroma region				
area, thousand hectares	228.1	1417.6	342.7	18.4
wood reserve, million m^3	39.86	231.18	62.18	2.22
Moscow region				
area, thousand hectares	228.1	568.7	139.2	51
wood reserve, million m^3	39.86	108.13	32.29	7.06
Ryazan region				
area, thousand hectares	228.1	233.6	67.7	16.5
wood reserve, million m^3	39.86	32.42	12.56	3.01
Smolensk region				
area, thousand hectares	228.1	382	128.9	67.3
wood reserve, million m^3	39.86	72.65	29.94	12.01
Tula region				
area, thousand hectares	228.1	59.9	39.2	0.4
wood reserve, million m^3	39.86	11.3	8.46	0.06
Yaroslavl region				
area, thousand hectares	228.1	360	125.5	26
wood reserve, million m^3	39.86	60.29	27.5	2.97
Nizhny Novgorod region				
area, thousand hectares	228.1	1033.4	251.1	41.4
wood reserve, million m^3	39.86	147.82	46.6	4.43
Kirov region				
area, thousand hectares	228.1	1916.2	573.9	22.6
wood reserve, million m^3	39.86	238.33	78.28	2.52
Mari El republic				
area, thousand hectares	228.1	387.8	58.9	28.6
wood reserve, million m^3	39.86	55.89	10.98	3.34
Total in Russia				
area, thousand hectares	228.1	93006	19788	1728.9
wood reserve, million m^3	39.86	9229.9	2938.01	186.4

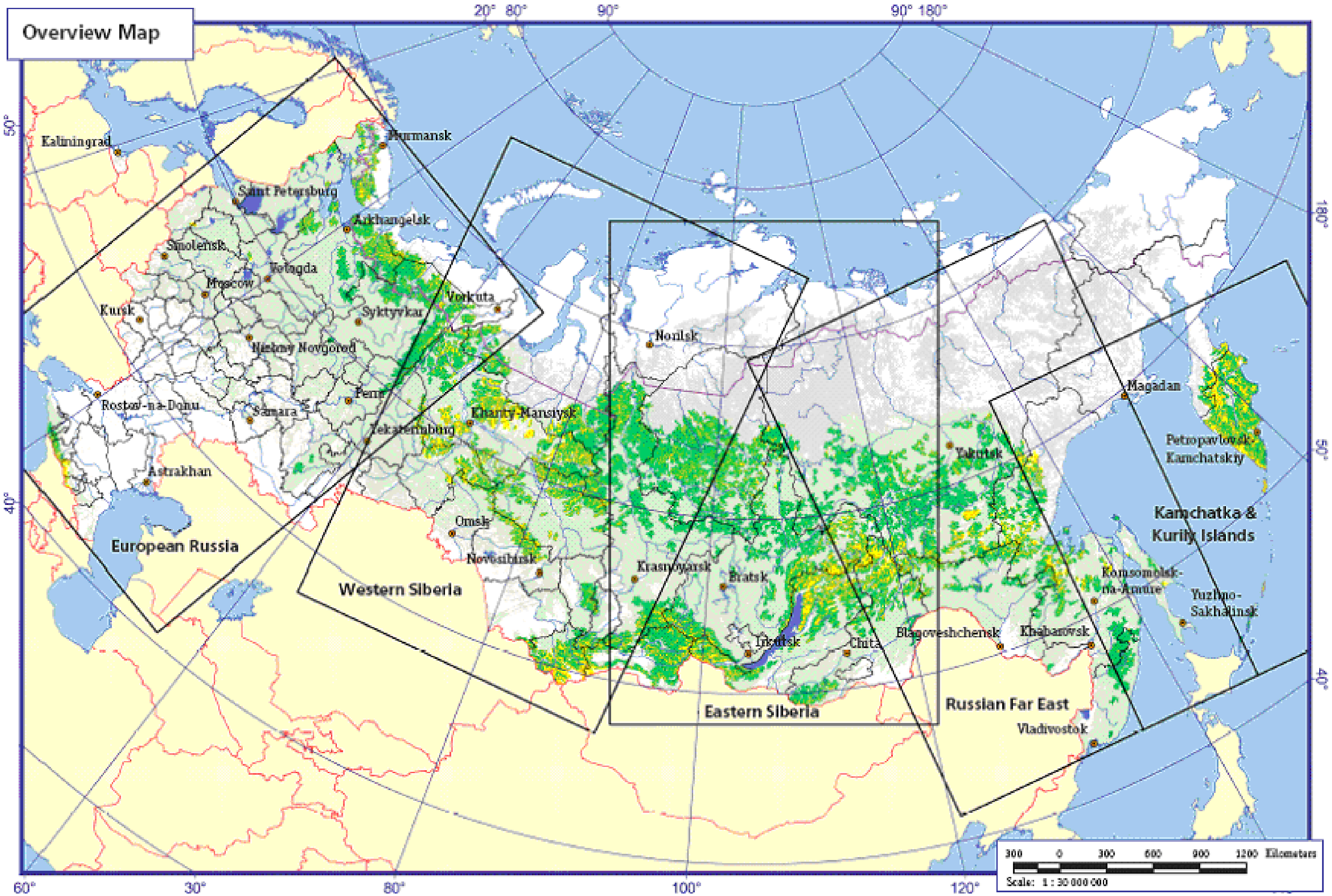


Figure 2. Tree species composition [8].

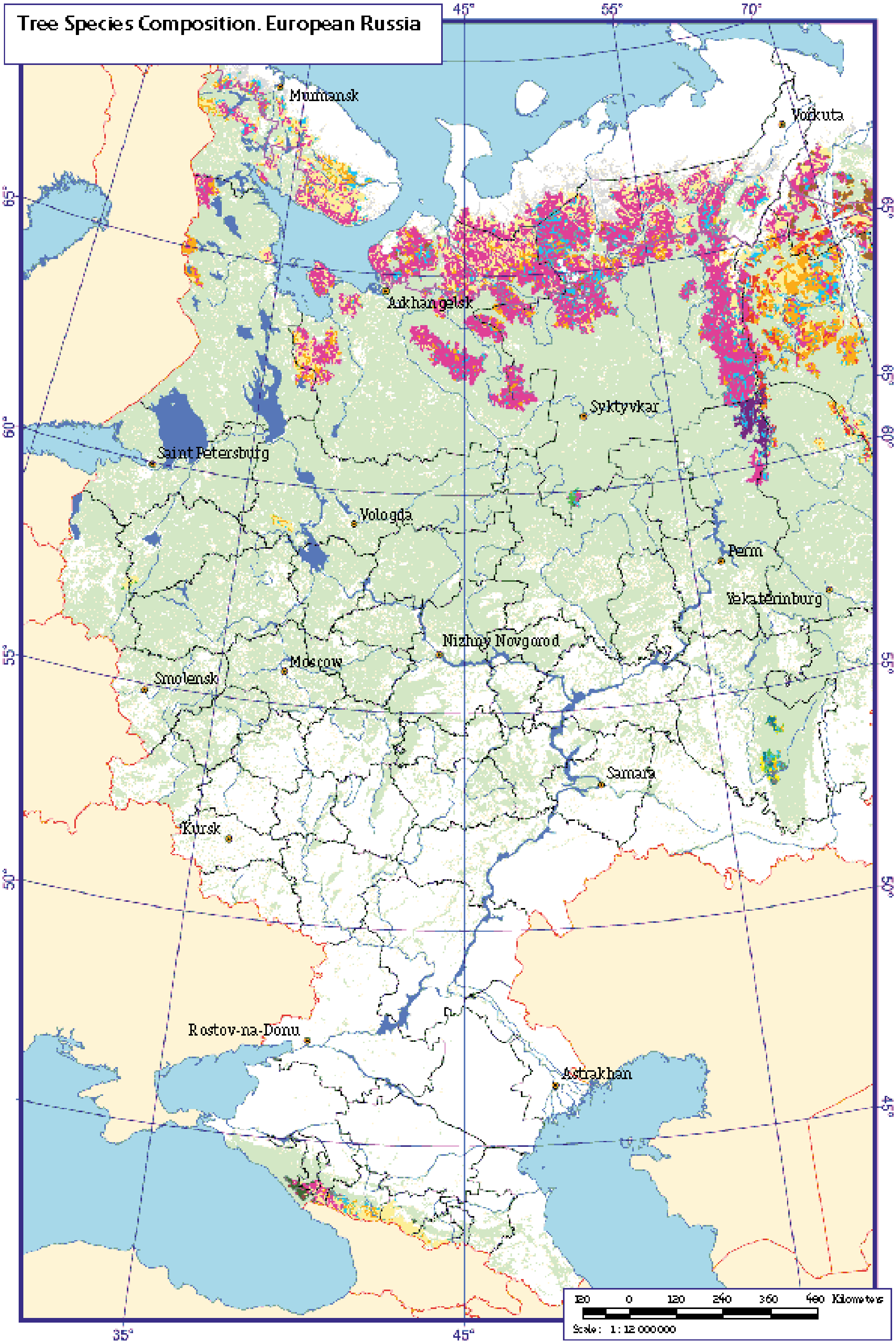
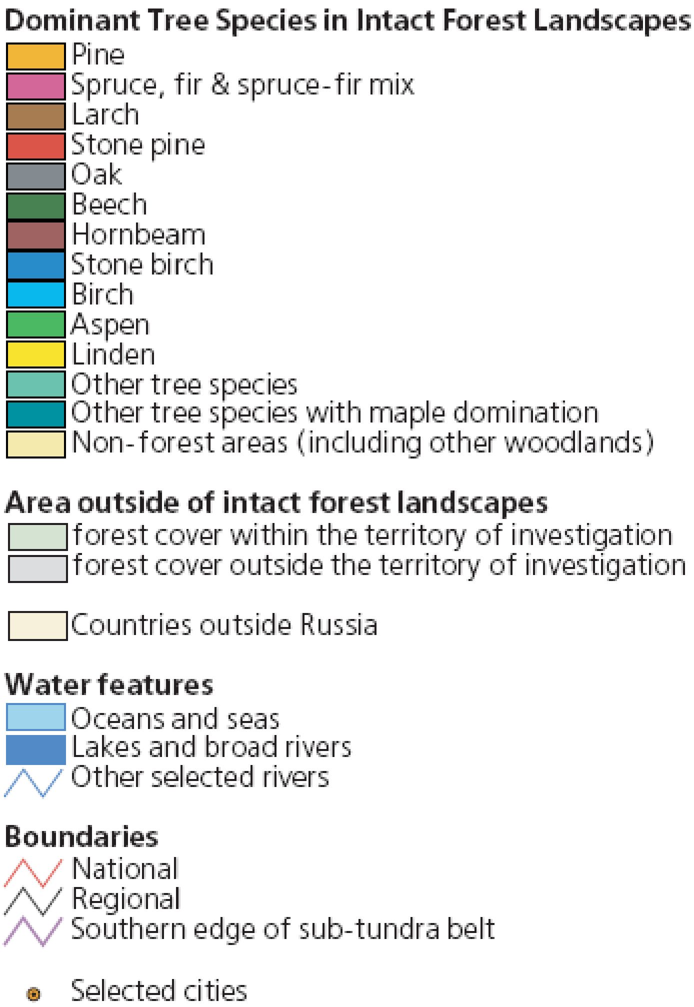


Figure 3. Tree species composition, European Russia [8].



3 Properties of birch, aspen and alder wood

3.1 Description of birch, aspen and alder

Birch

Birch is a deciduous tree of the genus *Betula* which is distributed over much of Russia, North America, in Asia south to the Himalaya, and in Europe. About 40 species are known. The birches comprise the family Betulacea (a small family of dicotyledonous plants in the order Fagales characterized by stipulate leaves, seeds without endosperm, and by being monoecious with female flowers mostly in catkins). [9]

Most important timber species in Europe and Russia are European silver birch (*Betula pendula*) and Downy birch (*Betula pubescens*). The wood varies slightly among species. Birch species are generally small to medium-size trees, mostly of temperate climates. [4]

Birch is typically reaching 15-25 m tall (exceptionally up to 39 m), with a slender trunk usually under 40 cm diameter (exceptionally to 1 m diameter), and a crown of arched branches with drooping branchlets. Birch is not a long-lived tree. Height growth ceases at about 60-70 years of age; few live longer than 140 to 200years. [10]

Aspen

Aspen is a deciduous tree native to northern hemisphere temperate climates. It is a member of the willow family and comprises a section of the poplar genus, *Populus*. There are six species in this section. Aspen has a very wide distribution, being found from Scandinavia to North Africa, and across most of Europe. Most common and important species is Trembling aspen (*Populus tremula*). [5]

Aspen typically grows in large clonal colonies derived from a single seedling, and spreading by means of root suckers. Each individual tree can live for 40–150 years (usually 80-90 year) above ground, but the root system of the colony is long-lived. Stems in the colony may appear at up to 30–40 meters with a diameter 1m from the parent tree. [10]

Aspen is one of the fastest growing tree species in Finland and Russia, even 40 years tree reach 20m and more. It is mature 35-40 years. It is short-lived, because it degrades with the medullary rot. The already growing profile of the aspen wood as a pulp supply in Canada is getting an additional boost as more and more pulp and paper companies realise its value. [11]

Alder

Alder is the common name of a genus of flowering plants (*Alnus*) belonging to the birch family (family *Betulacae*). The genus comprises about 30 species of monoecious trees and bushes, few reaching large size. [9]

Alder is mostly distributed in the Northern Hemisphere: across of Europe, into Russia; also the Caucasus, Turkey and Iran. It is typically found in wet areas and alongside streams and rivers, in wet woodland it is sometimes referred to as alder carr. Alder grows roughly the same areas as a birch. The largest species for European part of Russia and Europe are Black alder (*Alnus glutinosa*) and Specked alder (*Alnus incana*). [12]

Alder is a tall, broad-leaved deciduous tree of up to 35 m height and 1 m in diameter. More frequently it attains heights of 20-25 m. The alder is rapidly growing tree with long trunk and narrow crown. It grows quickly and it is short lived - grows up to 1/2 a metre a year, quickly reaching its height up to 20-25 m. Alder mature at about 40 years and rarely lives longer than 150 years. [10]

3.2 Structure of wood

There are two major fiber types as source for papermaking: long softwood fibers are used to give essential strength and short hardwood fibers are used in furnishes to provide good printability and stiffness to end product. The strength of hardwood fibers is not critical property for short fiber pulp; because paper can be strengthen by using long softwood fibers. But if hardwood will have good strength and drainage properties, the addition long softwood fibers can be reduced, or totally leaved out. [13]

In order to understand the behavior of the wood during pulping, and also the resulting pulping quality, it is indispensable to have a knowledge on the chemical composition and structure of birch, aspen and alder wood. [14]

3.2.1 Variability of wood

The physical properties of wood are unusually wide degree of variability, because of it is natural origin. These variations are in part the result of the growth conditions, such as climate, soils, water supply and available nutrients, *etc*. Also, all properties of wood are in part hereditary. The main structural and chemicals variation occurs between different hardwood species, between sapwood and heartwood, and according to the age of the tree. [13]

The properties of wood are further complicated by its complex internal structure, which gives rise to anisotropic behaviour. (It means physical properties diverge in different directions within the material).Wood is porous and heterogeneity material. Pore structure takes different forms pursuant to species. Heterogeneity refers to different properties from point to point in the material. [15]

The before mentioned sources of variability have introduced multiple difficulties in comparing of various kinds of wood and wood within the range one species.

Chemical and physical properties of wood (such as content of cellulose and extractives as well as wood density and fibre length, etc.) are important in determining the quality of wood for commercial use for chemical or thermomechanical pulps. [16]

3.2.2 Macrostructure of wood

Heartwood of birch is basically light yellow to white or grey to red brown. Sapwood colour is similar to heartwood colour. The growth-rings marked with a narrow line of darker colour. It is generally straight grained with a fine uniform texture. Birch wood is moderately heavy, hard and strong. It has very good wood bending properties with good crushing strength and shock resistance. Wood is light and elastic. It is not durable; durability heartwood fungus is 5 (it is non-resistant to heartwood decay). [10, 17]

The sapwood of aspen is white, sometimes tinted with light green and yellow. It is blending into the light brown heartwood. Sapwood colour is similar to heartwood colour, or distinct from heartwood. The wood of aspen has a uniform texture. It is straight grained, light and soft. Aspen wood has good dimensional stability and low to moderate shrinkage. The wood rated as slightly or nonresistant to heartwood decay. Advantage of aspen is it lasts well if it is kept dry. There is not much knots. The inherent high brightness and opacity make aspen very suitable for papermaking. [10, 18]

The wood of alder is white when first cut down, then becomes deep red on the surface, and eventually fades to reddish yellow of different shades. There are not differences between sapwood and heartwood. There are frequently flecks. The annual ring is not very distinct, but the medullary ray can be detected by its slight lustre, although nearly the same colour as the annual ring. The wood is diffuse-porous, moderately light and soft. It is tough and fairly strong, but is not very stiff. [10]

3.2.3 Microstructure of wood

Birch

Transversal, radial and tangential sections of birch wood are shown in Figure 4, Figure 5 and Figure 6 respectively.

Transversal section

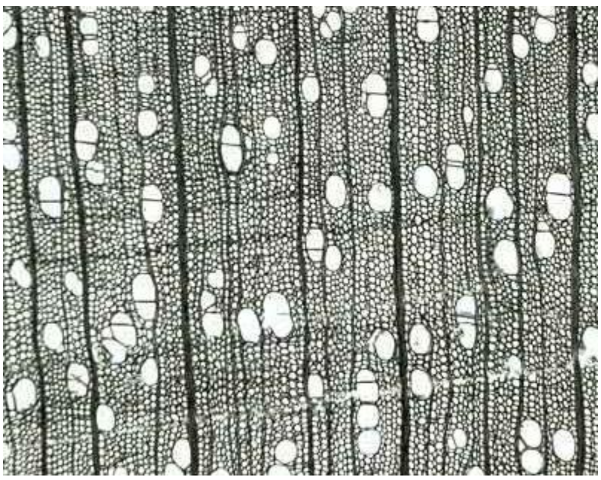


Figure 4. Birch, transversal section.

Birch is diffuse-porous wood. Growth ring boundaries are rather distinct; they are marked by 2 to 4 rows of radially cells. According to some growth conditions these boundaries can be rather indistinct. Pores are rather par apart scattered, in radial multiples of 2 to 4 pores and in clusters. Pore size varies highly from one growing site to the other. [19, 20]

Axial parenchyma bands marginal (or seemingly marginal) fine. There are up to three cells wide. Axial parenchyma is diffuse. Fibres are medium wall thickness. Average fibre length is 0.6-1.1-1.7 mm (millimetre) (the value in the middle is the average and the right and left values are the extremes). [21]

<u>Radial section</u>

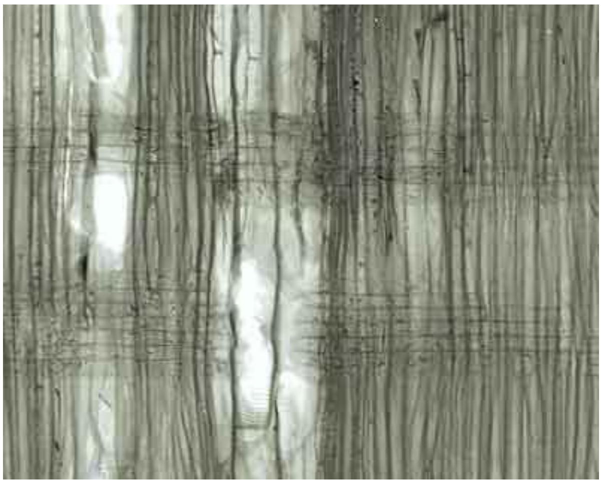


Figure 5. Birch, radial section.

Vessels elements are commonly short. There are around 2-3 vessels per radial rows. Average tangential vessel diameter is 30-90-130 μm (micrometer), and average number of them is 40-60 vessels/mm^2. Intervessel pits are alternate and extremely small, average diameter is 3-4 μm. Vessels-ray pits are with distinct borders and similar to inter vessel pits. [19]

Tangential section

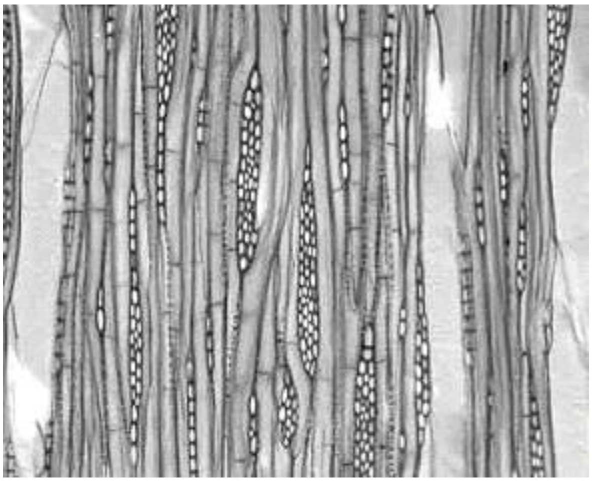


Figure 6. Birch, tangential section.

Rays are homogeneous, occasionally square marginal cells. Rays compose of a single cell type. There are 10-17-20 rays per tangential mm. [19]

Aspen

Three section (transversal, radial, tangential) of aspen wood are presented in Figure 7, Figure 8 and Figure 9.

Transversal section

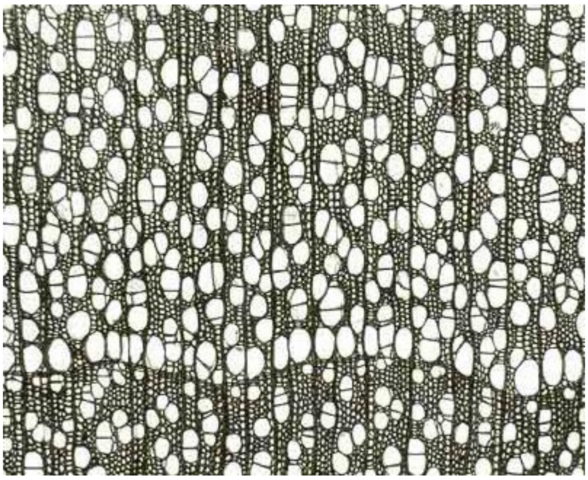


Figure 7. Aspen, transversal section.

Aspen is diffuse- to semi-ring-porous wood. Growth ring boundaries are more or less distinct; and it depends on pore size transition from earlywood to latewood. Pores are solitary or in radial groups of 2 to 3 multiples. Axial parenchyma is banded. Parenchyma bands are marginal, fine, up to three cells. Fibres are very thin-walled. Average fibre length is 0.4-1.0-1.6 mm. [19, 20]

Radial section

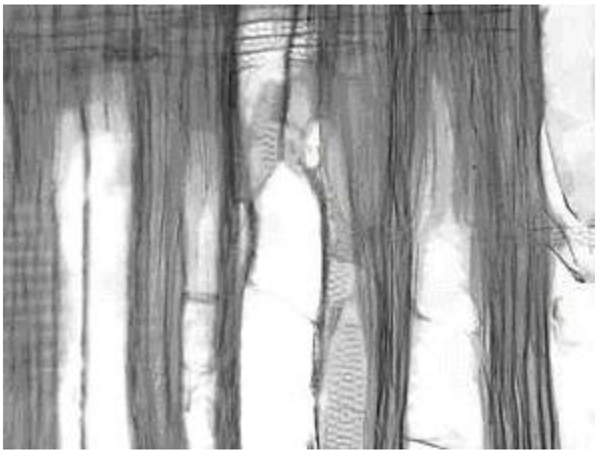


Figure 8. Aspen, radial section.

Vessels are in multiples. They are commonly short; usually there are 2-3 vessels per radial rows. Average tangential vessels diameter is 40-65-95 μm. Average number of vessels is 25-45-70 vessels/mm^2. Perforation plates are simple. Intervessels pits are alternate, average diameter of them is 10-11 μm. Vessel-ray pits are extremely large and simple. They are rounded or angular, restricted to marginal row. [19, 20]

Tangential section

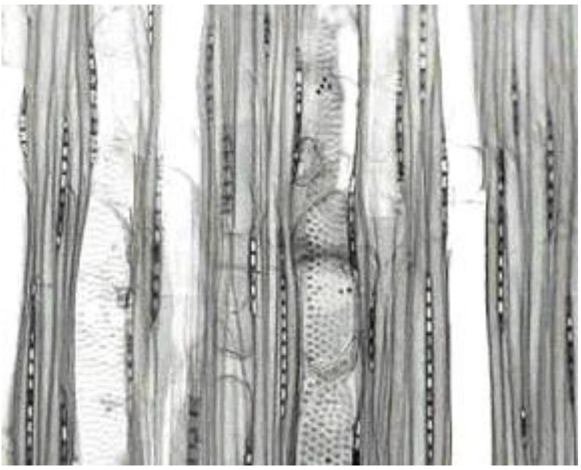


Figure 9. Aspen, tangential section.

Rays are homogeneous, rare with square marginal cells. There are 8-13 rays per tangential mm. Aggregate rays are absent.

Alder

Transversal, radial and tangential sections of alder wood are shown in Figure 10, Figure 11 and Figure 12 respectively.

Transversal section

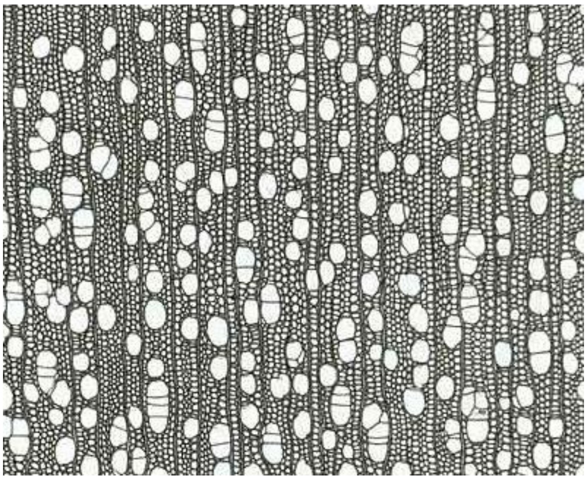


Figure 10. Alder, transversal section.

Alder, as well as aspen, is diffuse- and semi-ring-porous wood. Growth ring boundaries are distinct. Pores are more or less packed (with wide variability), in radial multiples and groups, often clustered in earlywood. Axial parenchyma is diffuse and diffuse-in-aggregates. Average number of cells per parenchyma strands is 4-8. Fibres are thin-walled. Average fibre length is 0.6-1.0-1.6 mm. [19]

Radial section

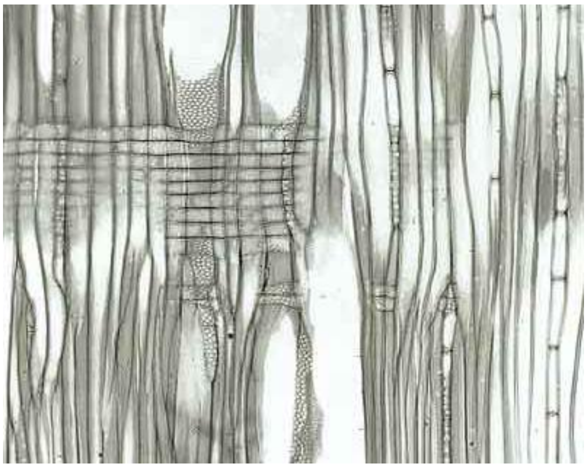


Figure 11. Alder, radial section.

Rays are homogeneous. Vessels arranged in no specific pattern. They are in multiples, commonly short; there are 2-3 vessels per radial rows. Vessels outline are angular. Average tangential vessels diameter is 40-60-90 μm [19]. Intervessel pits are opposite or alternate. Average diameter of them is 5-6 μm. Vessel-ray pits are relatively small, with distinct borders and similar to intervessel pits (but vessel-ray pits are smaller, around 3 μm). [20]

Tangential section

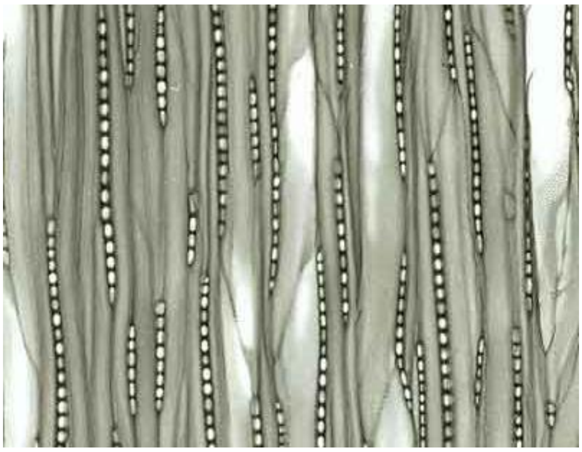


Figure 12. Alder, tangential section.

In proximity of aggregate rays growth ring boundaries are more ore less undulating. Aggregate rays generally present. There are 12-18 rays per tangential mm. [19]

3.3 Physical and mechanical properties

3.3.1 Density

Wood is anisotropic in nature. It is appearance and physical properties vary according to its sectioned plan. The value of density varies widely. Given the standard 12% moisture, all wood materials may be divided into three categories as follow [13]:

1. low density species, with density up to 510 kg per m^3
2. medium density species, with density varying within the limits from 550 to 740 kg per m^3
3. high density species, with density in excess of 750 kg per m^3

Birch is medium density tree. Average density of birch wood is 650 kg/m^3 and it can range from 490 kg/m^3 to 830 kg/m^3. The juvenile wood near the core is the lightest and the wood near the surface is heaviest. [22]

Aspen and alder consider low density species, density of aspen is 320-450-540 kg/m^3 and alder is 340-490-590 kg/m^3 [23, 24. 25, 26].

The wood of aspen and alder is light in weight compared with birch. Density indicates how large amount of the chip volume is solid wood. Low wood density means high wood consumption in the pulp industry. Density is considerable properties for papermaking because it is correlated with pulp yield. Birch has higher density than aspen and alder, therefore it is possible to get higher yield from $1m^3$ of digester. However, the smaller variation in density of aspen and alder should be noted –evenness of wood quality is always an advantage in industry. Also, density influence on impregnation of chips during pulping and affects on transferring of heat and cooking chemicals. [12, 27]

The physical properties of paper and compressibility are strongly correlated with wood density. High density woods, as birch produce bulkier stiffer and more porous sheets while low density woods produce smoother, less bulky sheets with higher tearing resistance and tensile strength. [22]

3.3.2 Moisture content

The water content of the wood determines the efficiency of impregnation prior to kraft pulping [28]. Moisture content (MC), formula 1, of wood is defined as the weight of water in wood expressed as a fraction of the weight of o.d. (oven dry) wood:

$$MC = \frac{m_{wc} - m_{dc}}{m_{dc}} \quad (1)$$

where,

m_{dc} - is the mass of dry chips

m_{wc} - is the mass of wet chips.

The moisture content in freshly green wood can vary within species, and can range from 30 % to more than 200 % [28]. The average moisture contents of a selection of hardwoods are listed in Table 4. These values are considered typical, but there is considerable variation within trees.

Table 4. Moisture content of green wood [29, 30, 31, 32].

Species	Moisture content of green wood, %	
	Heartwood	Sapwood
Birch	78-85-89	70-72
Aspen	73-86-113	82-113-142
Alder	84	97

Aspen has significantly higher moisture content of green wood in comparison with birch and alder. The objective is to use fresh wood in pulping process, which means relatively short storage. Therefore, the moisture content of green wood is important parameter for pulping. Moisture content of the chips should be controlled, because it affects the fluid-wood ratio and further chemicals addition and so process control during cooking. For example, uniform chips moisture is the key of good impregnation. [27]

Alder and aspen pulps are satisfactory qualitatively, but the density of aspen and alder wood is low compared to birch wood. Bark content of birch, aspen and alder represented in Table 5.

Table 5. Bark content of birch, aspen and alder [26, 33].

Species	Birch	Aspen	Alder
Bark content, %	10.3	8.9	8.6

As evident from Table 5, birch has slightly higher bark content. The wood consumption measured in cubic metres per ton of pulp is 40-45% greater with alder and aspen than with birch. Also this difference increase in practise, because greater wood losses for aspen and alder in drum barking (disadvantage of aspen and alder is a difficulty bark removal from logs). Thin and weak alder and aspen logs break among the larger-sized birch logs. In addition, when alder is mixed with birch it is impossible to adjust the pulping conditions to the best advantage of alder. The general aim in blend cooking is to avoid too high proportion of alder in the digester, usually not more than 10%. [12, 34]

3.3.3 Mechanical properties

Table 6 and Table 7 below show most important mechanical properties at 12% moisture of birch, aspen and alder.

Table 6. Most important mechanical properties [35].

Mechanical property	Birch	Aspen	Alder
Density, kg/m^3	650	450	490
Compressive strength, MPa	54	43.1	45
Bending strength, MPa	109.5	76.5	79
Tensile strength parallel to fibres, MPa	136.5	121	97
Impact strength, kJ/m^2	93	84	52
Modulus of elasticity, GPa	14.2	11.2	14.2

The mechanical properties of wood are its ability to resist applied or extarnal forces. As can be seen from Table 6 birch wood is more durable than aspen and alder. Elasticity of all woods is approximately the same.

Table 7. Shrinkage from green wood to oven dry moisture content [31].

Species	Shrinkage from green wood to oven dry moisture content, %		
	Radial	Tangential	Volumetric
Birch	6.3	9.1	16.8
Aspen	3.4	7.3	11.7
Alder	4.4	7.3	12.6

Table 7 presents average shrinkage values, from green to ovendry, for birch, aspen and alder woods. Shrinkage is the reduction in dimensions of timber due to the movement of moisture out of cell walls of the wood. Srinkage for birch wood is a bit higher than for two others.

3.4 Fiber morphology

The physical and chemical properties of hardwood fibres, particularly their dimensions, have a strong influence on papermaking potential of pulps, and most end-use properties of paper products. [36]

Hardwoods may contain four cell types: fibres, vessels, parenchyma and tracheids. Vessels elements, fibres and parenchyma constitute the main part of hardwood, and they are present in all species (Figure 13). [13]

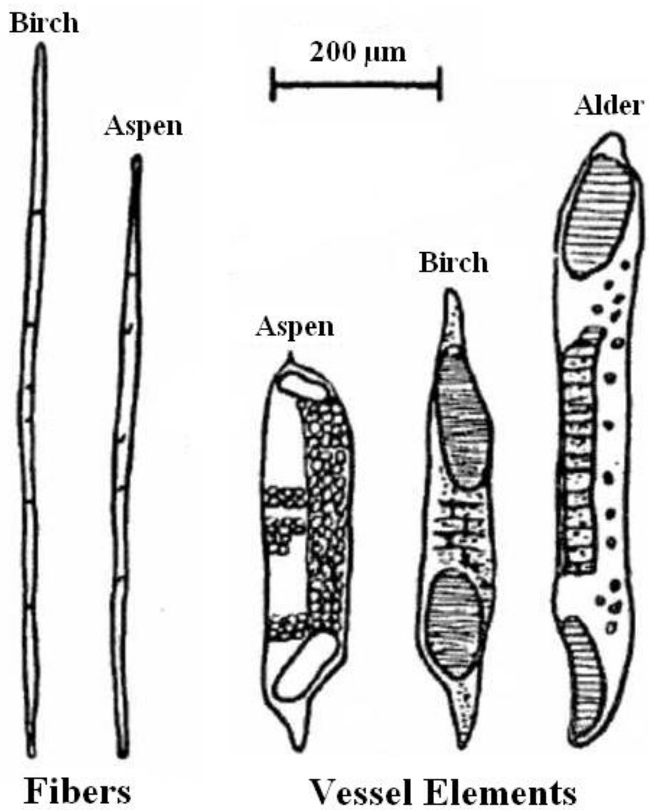


Figure 13. Cell types elements [13].

Table 8 indicates the proportion by volume of fibres, vessels and parenchyma cells in the stem wood of the 20-25 years old trees. Alder displays high fibre and low vessel and parenchyma cell quantities in comparison with aspen and birch.

Table 8. Proportions by volume of libriform (fibre), vessels and parenchyma cells in steam wood [4, 22, 26, 32].

Species	Fibre, %	Vessel, %	Parenchyma, %
Birch	60-68-76	12-23-30	5-7-12
Aspen	55-65-70	13-22-35	6-9-14
Alder	76	17	7

For papermaking, most important matter is the differences in fibre dimension (length, width) and stiffness. For hardwoods, however, the presence of vessels is also significant. Depending on the species of hardwood and the grade of paper being produced, vessel segments can cause negative effects as a print picking problems. [37] Fibre dimension of birch, aspen and alder are shown in Table 9.

Table 9. Average dimension of cells in steam wood [4, 16, 22, 38, 39].

Species	Birch	Aspen	Alder
Fibre length, mm	0.6-1.1-1.7	0.4-1.0-1.6	0.6-1.0 -1.6
Fibre width, µm	17-21-27	10-20-25	16-25-34
Cell wall thickness, µm	3.0-3.8-4.6	2.5-3.2-3.8	2.7-3.5-3.8
Cross-sectional area, μm^2	180	149	183
Length – thickness ratio	403	328	353
Fibre coarseness, µg/m	108-131	86	112
Vessels diameter, µm	30-90-130	40-60-95	40-60-90

The relationship between pulp fibre morphology and paper properties has been extensively studied earlier [40, 41]. Fibre length is one of the most important parameter for fibre uses in pulp industry. Tearing resistance of sheets made from hardwood fibres depend upon the fibre length. Also the stretch properties, bursting and tensile strength of paper to some extent depends on the fibre length. Birch wood has the longest fibres when compare to aspen and alder, therefore birch pulp shows better strength properties, than the other two. [42]

According to Table 9 aspen and alder are slightly shorter-fibred compared with birch. When the following figures are compared it should be remembered that aspen and alder species are generally not harvested until they are 50-100 years, and that average fibre length increase with age. [12]

Fibre width and thickness of the cell wall affect on fibre flexibility and their tendency to collapse in the paper production process, and in turn, paper properties. Thick walled fibres form bulky sheets with low tensile but high tearing strength. [36, 43]

On other hand, fibres with thin wall collapse more conformable. Conformable fibres bond better in a sheet structure and make denser stronger and smoother sheets. Indicator of cell wall thickness is basic density of the wood, has been used to assess the papermaking potential of wood species. [44]

According to [45] as the density of wood increased, paper structure became more porous and tensile strength decreased. This effect takes place because higher density wood has thicker cell walls which compress less. The pulp is therefore faster draining and bulky in structure and consequently porous. Thick walled fibres also require more energy in beating and provide weak fiber-to-fiber bonds leading to lower paper strength. [45]

As shown in the Table 9 birch fibres are slightly longer and they have thicker fibre walls than birch and aspen. Shorter fibres of aspen and alder can lead to lower surface strength. Thicker cell walls of birch have poorer flexibility and form sheets of high bulk in comparison with other two. Fibre wall thickness seems to have affected on bulk that persist even after bleaching and beating. Birch and alder fibres are similar in width, but they are slightly wider than aspen. The slight difference in width also leads to the difference in coarseness.

Important property of aspen and alder is a large number of fibres per unit weight. It indicates that higher opacity and less show through can be achieved by aspen and alder. [46]

According to [11] aspen boasts, small-diameter, thin-walled fibres which are ideal for producing high density sheet with a smooth surfaces.

Figure 14 shows the relationship of fibre properties and paper properties. As can be seen from Figure 14, that the main wood characteristics, that the affect the papermaking properties of short-fibre chemical pulp, are the morphological properties: the ratio of fiber width to cell wall thickness, fiber lenght, fiber coarseness and hemicellulose content. Short and thin-walled wood fibres with low coarseness give pulp with a high number if fibers per unit mass. Pulp that contains a high number of fibres per unit weight has excellent light-scattering property. Stiff, uncollapsed fibres give high bulk to paper. The smaller the length of fibres the better formation. Short fibres tend to have low surface strength. High hemicellulose content and low cell wall thickness guarantee a good bonding ability for the pulp.

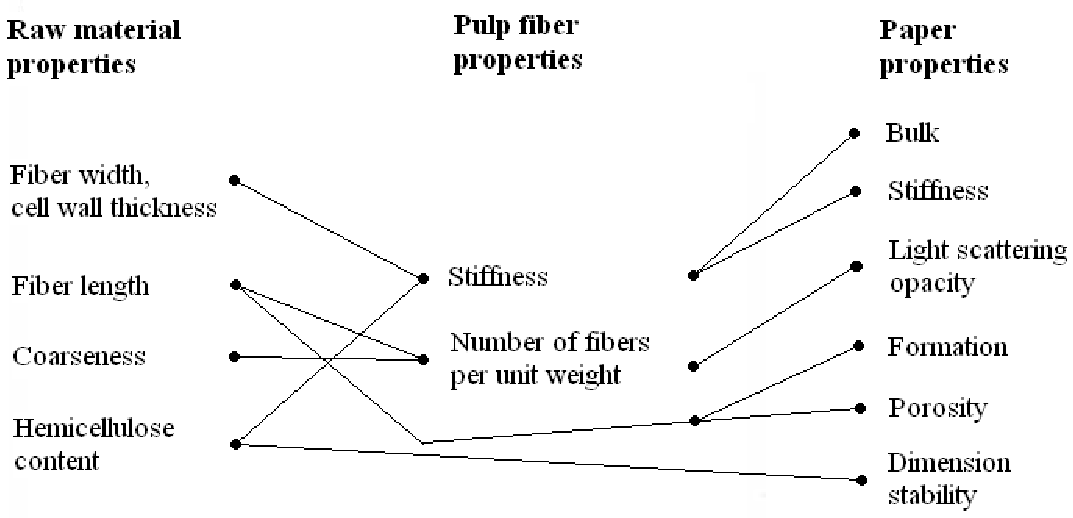


Figure 14. Influence of hardwood fibre properties on pulp fibre and paper properties [13].

3.5 Chemical composition

Table 10 contains details of the chemical composition of stem wood birch, aspen and alder. The cellulose content varies within species. Aspen displays high cellulose content and simultaneously low total lignin content, that is advantage from the standpoint of pulping.

Table 10. Distribution of major wood components in birch, aspen and alder [4, 14, 22, 26, 32, 33 ,35, 38, 39, 47].

	Birch	Aspen	Alder
Cellulose	41-46-56	44-51-53	41-45-50
Lignin	19-23-27	16-18-22	20-24-26
Extractives, hot water	2.0-2.6-2.8	1.8-2.0-2.5	2.4-2.8-3.2
Extractives, alcohol-benzene	2.6-3.1-3.3	2.4-2.5-3.1	4.3-4.6
Pentosans	23-27-35	18-21-31	20-23-31
Hexosans	4.5	4.8	-
Hemicellulose	22-25-27	24-22-30	24-25
Ash	0.25-0.4-0.5	0.3-0.38-0.50	0.25-0.35-0.45

Based on data from Table 10, birch and alder have higher lignin content than aspen. Compared to the birch, alder are similar in hemicellulose content. Aspen contains a little bit more hemicellulose than other hardwoods, but pentosan content for aspen is slightly lower compare to the two others species. In comparison with birch, alder wood is characterized by higher extractives content, while the lignin content is a bit higher.

The hemicelluloses are very important for papermaking. Strength of bond of fibres depends on the hemicellulose content. Also, fibres without hemicelluloses are difficult to refine. Aspen pulp has highest hemicellulose content and therefore better beatability than birch and alder. High hemicellulose content and low cell wall thickness give good bonding ability for the pulp. [48]

Total extractives content of the alder is clearly higher than that in birch and aspen. Many difficulties associated with pulping of aspen and alder wood has been attributed to extractives. [48]

As it evident from Table 10 ash content is higher for aspen wood.

3.6 Studies of pulp produced from birch, aspen and alder chips

3.6.1 Pulping response

Low in lignin and high in carbohydrates, aspen wood is a good raw material for chemical pulping [11, 49]. From point of view fibre morphology aspen has an excellent length-to-diameter ratio, and fibre wall thickness [50]. Pulping of aspen wood is noticeably faster than birch; therefore for achievement of the same degree of delignification of pulp, duration of cooking should be shorter [51]. On the other hand, the alder wood required stronger conditions of cooking than birch [25]. According to [46] after kraft cooking under the same conditions, birch pulp has higher kappa number, than aspen, and lower than alder respectively. Total yield after kraft cooking for all three species is fairly high. It should be noticed that the yield of the kraft pulp obtained from aspen wood is higher by 2-4 % than in case of birch wood. In turn, alder provides a lower yield by 3-5 % than birch. [11, 52]

But working with aspen does pose some potential headaches; the most serious are high extractives content in the wood and difficulty with removing of bark. The alder pulps contain even more extractives than aspen pulp. The higher content of extractives in alder and aspen pulp should be decreased by bleaching, by extraction, by fractionation. [11, 53]

Also, one of the most important factors accounting for low demand of the aspen and causing problems for efficient harvesting and utilization of this species, is the high extent of decay in the stem. [32, 49]

The decayed wood causes problems in debarking, pulping and bleaching, the pulp quality is inferior. Some of this decay can be removed in chipping and screening or with impregnation system with high compression plug screw feeders. [34]

3.6.2 Strength properties

Shorter fibres of aspen and alder have lower strength properties compared to birch [54]. Long birch fibres give the highest tear strength, provided that they bond to each other sufficiently. Burst index like breaking length, which depends to great extent on fibre bonding strength, is also improved by blending birch with aspen. [13]

In spite on the fact that birch has longer fibres both wood and pulp, when compared with aspen, pulp containing 100 % birch showed somewhat lower tear index, than aspen pulp. Partial replacement of aspen by birch could, however, improve the tear index of handsheet, indicating the importance of mixed refining in pulp production. [55]

Compared with birch, characteristics of alder pulps in sulphate cooking are short beating time and good tensile and bursting strength, but weaker tearing strength. The difference between tensile and bursting strength disappear when pulp is bleached, but alder pulps have a superior opacity and more lasting brightness after bleaching. [12, 56]

The physical properties of paper and compressibility are strongly correlated with wood density. High density woods, as birch produce bulkier stiffer and more porous sheets while low density woods produce smoother, less bulky sheets with higher tearing resistance and tensile strength. [45]

3.6.3 Bonding potential

Due to its inherent fibre properties, birch fibres produced a pulp with low interfiber bonding strength when compared with aspen. However, mixing birch 25-50 %, with aspen could produce some positive effect on tensile strength of the resulting sheet. [55]

3.6.4 Bleaching response

The choice of bleaching agents and the degree of bleaching have significant impact on both optical and mechanical properties of the resulting pulp. Bleaching should be applied taking into account of the possible influence down the process line. For example, substantial reduction in freeness may cause drainage problem on the paper machine. [55] The unbleached chemical aspen pulp processes high brightness pulp, and a high brightness level can be achieved by bleaching easily. Aspen wood is usually an exceptionally white colour (chips have ISO brightness of 61-62 %). As result, pulp made from aspen is relatively light in colour. [34] Unbleached birch pulp has lower brightness than the unbleached aspen and higher brightness than alder, which is believed to be accounted for by the inherent wood brightness. Brightness of unbleached pulp influence on chemical consumption for bleaching, thereby aspen wood is easily bleached or it can be bleached to the same level with lower chemicals cost. [11, 49]

Contrariwise, unbleached chemical alder pulp processes low brightness pulp, and a high brightness level achieved by bleaching heavier [52]. The brightness stability of the birch, aspen and alder pulps is in the order:

Aspen > Alder > Birch [25, 53]

3.6.5 Optical properties

Optical properties are more favourable for aspen and alder pulps. The opacity, smoothness and bulk of birch are poorer than those of the aspen and alder pulps. [54]

The important fibre properties of short-fibre pulp are stiffness and amount of fibres per unit weight. Short, thin-walled fibres give pulp with a high number of fibres per unit weight. Fibres of aspen are small-diameter and thin-walled which are ideal for producing a high density sheet with a smooth surface. [49]

Pulp which contains high number of fibres per unit mass has more air-fibre interface reflecting light. A higher amount of pulp per gram of pulp results of better formation and higher opacity, as in case of aspen and alder. [13]

Birch, which has low inherent wood brightness and high specific absorption coefficient for pulp, produced pulp with inferior brightness in comparison with aspen. However, substitution up to 75 % of birch didn't significantly affect on brightness of the resulting pulp, relative to pure aspen pulp. [55]

Pulp containing birch fibres has the lowest specific scattering coefficient when compared with pure aspen and alder, probably because birch wood has the thickest cell wall. [55]

3.6.6 Drainage

Drainage (dewatering) depends on the content of fines, the more fines the higher water retention value and air resistance. The aspen and alder pulps contain high amount of fines than the birch. Birch has lower SR number and WRV than aspen and alder. Practical experience shows that aspen and alder pulps have poorer drainage properties than birch pulps. Alder pulp has even much worse drainage than aspen. [25, 53]

3.6.7 Beatability

Aspen and alder required less specific refining energy; at a given level of SR number, when compared with birch [11, 54]. This characteristic could be accounted for by the high production of fines from aspen and alder. Adding aspen to birch furnish, from 25 % to 75 %, affected in significant reduction in refining energy consumption. [55]

3.6.8 Dimensional stability

Fibres have good dimensional stability if they have low tendency to swell (low hemicellulose content). Birch has better dimensional stability than aspen and alder pulps. [54]

3.6.9 Bulk

Birch, having stiffer fibres, produced handsheet with higher bulk value in comparison with aspen and alder which have thinner-walled fibres. The use of aspen, alder and birch furnish constitutes a disadvantage in products where high bulk is important requirement. [55]

4 Chemical pulping methods

Papermaking is a massive industrial branch with high capacities, complicated equipment and complex processes influenced by a great variation factors. Nowadays the main raw material used for papermaking is wood fibers. Both softwood and hardwood are used for production of fibrous material. All pulping processes are categorized either chemical or mechanical. The prevalent raw material for papermaking is chemical pulp.

The aim of all chemical pulping processes is fiber releasing through delignification, but the processes can be classified based on their different ways to attained this. Chemical pulping methods are based on the principle dissolving of lignin from the middle lamella while causing minimum damage to the cellulose and hemicelluloses, and to remove the resulting by-products from the pulp. Preservation of hemicelluloses is important, because they provide strength of paper sheet.

In pulp production for paper and paperboard, predominant processes are alkaline sulphate and various sulphite processes which can be alkaline, neutral and acidic [57]. Kraft process is a dominating chemical pulping process for manufacturing bleached and unbleached pulp all over the world (today the kraft pulps account for 89 % of the chemical pulps and for over 62 % of all virgin fibre material). [28]

The chemistry of the kraft process is extremely complex due to the many types and forms of organic material presented in wood. Chemical reactions with wood components are heterogeneous-phase border reaction. Polysaccharides react simultaneously during delignification, but these reactions are important for the pulp properties. Reactions with extractives are also important. [57] The advantage of the kraft technology is recovering and reusing the chemicals and extracting the available energy into the process.

4.1 Kraft pulping process

4.1.1 General description of the kraft cooking process

Kraft pulping is a process of dissolution of lignin by white liquor at high temperature and pressure. Kraft process was patented in 1884. The process was soon applied for wood and in 1885 the first kraft paper was produced. The name kraft, which means strength in German, characterizes the stronger pulp produced when sodium sulfide is included in the cooking liquor, in comparison with the pulp obtained if sodium hydroxide alone is used as in the soda process. [58]

The major reasons for the success of the kraft pulping are [59]:

1. An efficient and economical recovery process for pulping chemicals
2. All commercially availably woods and non-wood raw materials can be pulped by the process
3. Using of chlorine dioxide very efficiently in the bleaching of kraft pulps
4. Kraft pulps produce paper and board products with generally superior strength properties compared to products from other pulps.

Industrial kraft cooking realize batchwise or continuously. In the batch process, the chips are cooked in individual digester with loading, cooking and dumping done in sequence. In the continuous process, the chips and cooking liquor are fed at a constant rate in the top of the digester and the chips move down for discharge from the bottom. The total cooking time is determined by the rate of the rate of downward movement of the chips column. [58]

The basic processes in industrial kraft pulping are:

- Feeding the chips and cooking liquor
- Digesting
- Discharge of pulp
- Washing and screening

The wood logs are debarked and chipped in a special way, and chips screened. The chips are fed to digester together with warm (temperature is about 80-100 ºC) cooking liquor. The cooking liquor is the mixture of white liquor spent black liquor from a previous cook. [27]

Wood chips are impregnating with the cooking liquor at liquor-to-wood ratio of about 3.5-4 [60]. The digester contents are heated to 150-180 ºC, by direct steam or by indirect heating in a steam/liquor heat exchanger. The cooking temperature is kept until the desirable degree of delignification is obtained, after that the digester contents go to a blow tank by digester pressure. [60, 57] After pulping, the chips are soft and can be fiberized by little mechanical force. Usually, in the batch system method "blow the digester" by steam pressure is used [60]. The mechanical action of ejection breaks up the wood chips into individual fibres. [58]

The black liquor is removed from the pulp by pressuring or counter flow washing and sent to the chemical recovery section. The liquors are evaporated and burned to provide fuel and to release the inorganic ions for reuse. Released heat is recovered in a blow heat recovery system. Volatile compounds generated during heating and cooking are clarified from the digester to control cooking pressure. The gases go to condenser system for recovery of volatile wood compounds (*e.g.* turpentine). [60]

Then, the pulp from blow tank is washed and screened. Used liquor is recovered in a counter-current washing system, applying minimum of dilution water (it makes the highest possible degree of pulp purification). Deficient delignified remains of wood (reject) are separated from the fiber suspension in screening operations. Knots and undefibrated chips are usually separated out from the suspension in knotters before pulp washing, and they reintroduce to cooking for redelignification. Other contaminating impurities (bark, shives *etc.*) are removed in screening and cleaning systems. [60]

The unbleached pulp is stored at elevated consistency for further processing. It could be bleached or used for manufacturing of unbleached paper and board. Unbleached kraft pulp has a brown color in consequence of the residual lignin in the pulp. Requirement for fine paper is to get bright pulp; therefore the rest of the lignin has to be removed by selective chemicals. [57]

The spent liquor is concentrated in a multistage vacuum evaporator chain (generation of heavy black liquor). The heavy black liquor is combusted in a recovery boiler. The recovery boiler has two main functions [57]:

- Burn the dissolved organic material to carbon dioxide and water and produce an inorganic smelt of sodium carbonate and sodium sulfide
- Recover of the heat in the hot flue gases as high pressure steam for power generation.

The inorganic smelt flowing off the bottom of the recovery boiler is dissolved on weak wash filtrate recirculated back from the recausticizing plant. The produced green liquor is purified in sedimentation or filtering arrangement, and then brought in contact with reburnt lime (CaO) which has been slaked into calcium hydroxide. Dissolved sodium hydroxide and calcium carbonate sediment is formed by reaction of calcium hydroxide with sodium carbonate. The recovered calcium carbonate is reburnt in a lime klin to calcium oxide and reused in recausticizing. White liquor is the purified liquor containing sodium hydroxide and sodium sulfite; it is used as cooking liquor. [57]

The kraft process is based on efficient reuse and recirculation of chemicals. This property is very important nowadays, when ecological demands are very high.

4.1.2 Kraft cooking liquors

The kraft cooking liquor is a blend of white liquor, water in chips, condensed steam and weak black liquor used to control the liquor-to-wood ratio. The white liquor is heavily alkaline solution; in which main active compounds are the OH^- and HS^- ions, which are present in the kraft cooking liquor as solution of sodium hydroxide and sodium sulfide. The hydrosulfide ion plays an important role in the kraft pulping by accelerating delignification and making nonselective soda cooking into selective delignifying process. There are also other sodium salts presents in smaller amounts include carbonate, sulfate, thiosulfate, polysulfide, sulfite and silicate. [57]

Sodium hydroxide and sodium sulphate reactions in cooking liquor (formula 2 and formula 3):

$$NaOH + H_2O \leftrightarrow Na^+ + OH^- \qquad (2)$$

$$Na_2S + H_2O \leftrightarrow 2Na^+ + OH^- + HS^- \text{ [27]} \qquad (3)$$

The concentration of white liquor is 140-170 g/l active alkali as NaOH. The amount of chemicals is calculated as equivalents of sodium hydroxide or sodium oxide and can be recalculated to other equivalents; practice is based on sodium contents of the compounds. Conversion factor from NaOH to Na_2O is 1.29 and 0.775 in inversely.
The composition of a main components for a typical white liquor present in Table 11. [28]

Table 11. Composition of typical white liquor [28].

Compounds	Concentration [g/l]	
	as NaOH	as compound
NaOH	90.0	90.0
Na_2S	40.0	39.0
Na_2CO_3	19.8	26.2
Na_2SO_4	4.5	8.0
$Na_2S_2O_3$	2.0	4.0
Na_2SO_3	0.6	0.9
Other compounds		2.5
Total alkali (TA)	159.6	170.6
Total sulphur (TS)	47.1	19.7
Effective alkali (EA)	110.0	
Active alkali (AA)	130.0	

Composition of kraft cooking liquors and concentration of active chemicals in white liquor are characterized as [61]:

Total alkali (TA) is the sum of all sodium compounds.

Active alkali indicates amount of HS^- and OH^- ions (formula 4).

$$\text{Active alkali: } (AA) = NaOH + Na_2S \qquad (4)$$

Effective alkali shows OH^- ion concentration (formula 5).

$$\text{Effective alkali: } (EA) = NaOH + 1/2Na_2S \qquad (5)$$

Sulfidity include whole sodium sulfide concentration and shows ratio of HS^- and OH^- ions (formula 6). Usually in modern mills sulfidity is 35-45%. Higher proportion of sulfide is advantage in extending pulping to lower lignin contents [60].

$$\text{Sulfidity: } (S) = \frac{Na_2S}{NaOH + Na_2S} \times 100\% \qquad (6)$$

Causticity is characterized by efficiency of white liquor production (caustisizing reaction). It shows how much Na_2CO_3 has been transformed to NaOH (formula 7).

$$Causticity = \frac{NaOH}{NaOH + Na_2CO_3} \times 100\% \qquad (7)$$

Reduction indicates how entirely sodium sulfate has been reduced to sodium sulfide (formula 8). Causticity and reduction values are used to express the efficiency of the chemical recovery. [61]

$$Reduction = \frac{Na_2S}{Na_2S + Na_2SO_4} \times 100\% \qquad (8)$$

Figure 15 shows dependence of the main components in white liquor. Figure 15 is schematic diagramm relating the terminology used in desribing the composition of kraft cooking liquor. [57]

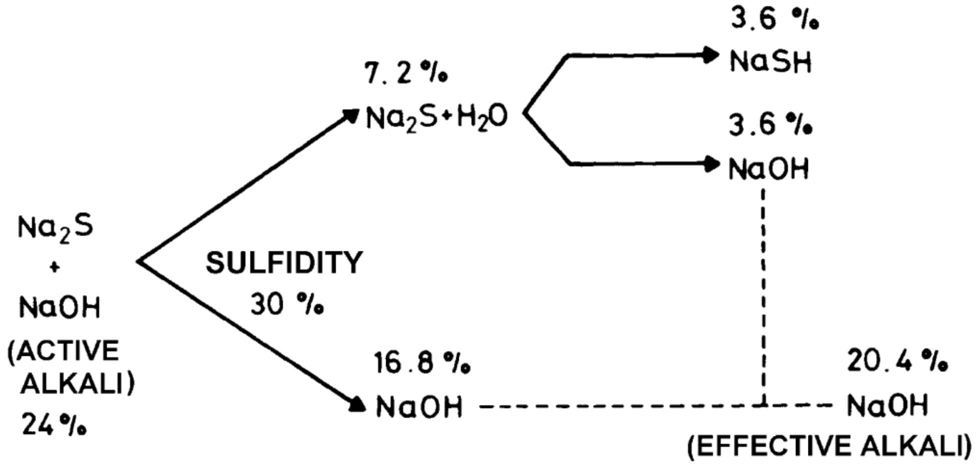


Figure 15. Schematic diagram of active and effective alkali dependence [27].

4.1.3 Three phases of a kraft cooking

Unfortunately, the kraft pulping is not totally selective for the lignin, some of the wood components, typically low molecular weight polysaccharides, dissolve in the cooking liquor. Other wood components, such as lignin, are largely insoluble in their original form, but are degraded by the cooking liquor to small soluble fragments. For example, in kraft pulping with 50 % yield, approximately 20 % of the original wood is lost due to loss of polysaccharides, mostly hemicelluloses. The cellulose is more steadfast to attack by alkali than the other wood components, although its degree of polymerisation is reduced. About 5 % of the wood is lost due to loss of cellulose. [59]

The dissolution of lignin and carbohydrates during kraft cooking can be divided into three distinct stages:

- initial delignification (fast)
- bulk delignification (slower)
- residual delignification (very slow)

In order to keep up high yield and to conserve sufficiently high quality of the pulp, delignification is limited to a certain degree of delignification, objective kappa numbers of about 15-20 for hardwood kraft pulps. [28]

The three distinct phases are shown in the Figure 16. H-factor expresses the cooking time and temperature as one single variable.

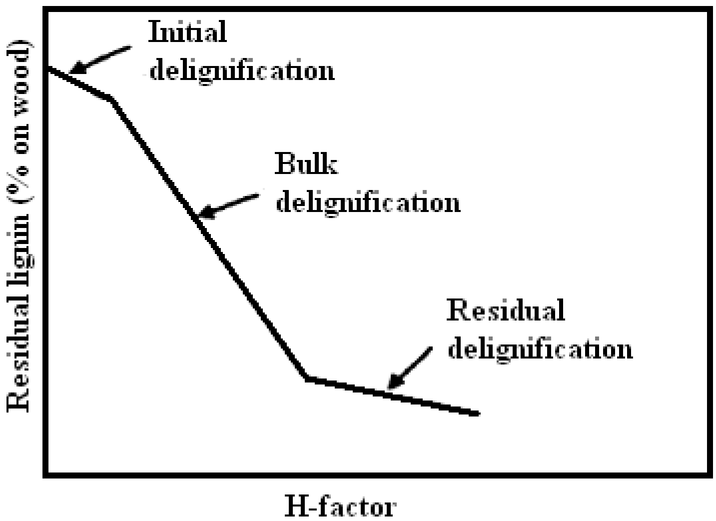


Figure 16. Removal of lignin in kraft pulping as a function of the H-factor [59].

The initial phase is characterized by very fast dissolving of small amount of lignin; about 60 % of the alkali is consumed. At the same time the largest amount of hemicellulose is removed from the wood material together with lignin. Bulk delignification phase is long; most of the lignin is dissolved during this phase. The carbohydrate yield and the alkali concentration of the pulping liquor decrease only slightly in this stage. Kraft cooks are typically completed at lignin content about 3 % for hardwoods, well within bulk delignification phase. The third and last, residual delignification phase characterized by very low delignification rate. In that phase the carbohydrates yield and alkali concentration starts to decrease rapidly. The reactions of destruction of cellulose occur and develop with time. The conversion between the initial and bulk delignification phases is generally determined by two criteria – the rate of alkali consumption with lignin removal, and the ratio of carbohydrates to lignin removal. [28]

In pulping it is unsuitable to complete the end of delignification to residual delignification phase. Usually, the reaction is stopped in the end of bulk delignification phase, where removal of lignin can continue with effective cellulose conserving by oxygen delignification. But even if the residual delignification has not started, degradation of cellulose exist in the course of reaction.

There are several types of the reactions of carbohydrates that take place during kraft pulping. Two of them that damage cellulose to a great extent are alkaline hydrolysis of β-glycosidic bonds and peeling reaction (removing of end units from the macromolecules of cellulose). [28]

4.1.4 The basic variables affecting the kraft cooking process

As was mentioned earlier, wood has a high degree of variability in both physical and chemical structure. Pulping time, temperature, charge and concentration of effective alkali, sulfidity, may be changed to produce pulps of any desirable yield. The kraft process conditions combined with the chemical and physical nature of the species of wood which is pulped, determine the chemical composition and mechanical properties of the obtained pulp. Mechanical treatment of fibres during the fibre line processes has also influence on pulp strength properties (for example pressure and heat shocks, mechanical strain and especially their combinations). [58]

Variables associated with the wood:

- Fiber dimension

The fibre length has an important bearing on the properties of the paper. Pulps from long-fibred softwood generally have greater strength than pulp from hardwoods, but they are obtained in somewhat lower yield. The properties of birch, aspen and alder wood are given in Table 9 page 34. [27]

- Chemical composition

The variation in pulp yield between tree species is the result of the difference in the lignin, cellulose, hemicelluloses and extractives content. From the point of view of the kraft pulping operation, the chemical distinction is of more importance. The chemical composition of birch, aspen and alder wood is shown in Table 10 page 37. Aspen wood is a typically in containing much more glucan than the two other species studied. This is reflected in its higher cellulose and lower lignin content. Birch generally possesses a lower lignin content and higher percentage of xylan, a considerable amount of which is retained during pulping. Aspen delignify faster than birch and alder. Dybcyn and his associates compared the rate of pulping of aspen and birch in sodium hydroxide liquor of the same strength (14% Na_2O based on o.d. wood). The data showed that time of cooking at the maximum temperature should be approximately twice lower, than for birch. At the same time, the yield of pulp and its carbohydrate content were higher with aspen. [51]

- Density

Wood density is extremely important economic factor in pulping technology. Denser woods, as birch, pack more dry weight into a green volume. It is preferred in pulping, because a greater weight can be packed into a given digester volume. It is more economical to cook the greatest possible weight in of wood for each digester cycle in batch pulping or for each unit of residence time in continuous digester. [27]

- Moisture content

The moisture variation in the wood will vary the chemical concentration and have direct effect on pulping rate. [58]

- Chips size

Chips size is affected on chemicals impregnation and packaging density in the digester. Especially thickness is important, because it is most essential parameter for cooking chemicals impregnation. [27]

Variables associated with the pulping operation:

- Effective alkali charge

The amount of effective alkali required depends on other factors, such as the wood species, chips dimensions, but it is of the order of 12 % (as Na_2O on o.d. wood) for hardwood species. In practise, with hardwoods less alkali is required for adequate pulping when compare to softwoods. Higher charge gives a greater degree of delignification. The alkali-to-wood ratio may be adapted in two ways: by keeping the liquor concentration constant and changing the liquor-to-wood ratio; and by the keeping the liquor-to-wood ratio constant and changing the chemical concentration of the liquor. Also, increasing of the EA charge increases the brightness of the pulp, both before and after bleaching. [58]

- Effective alkali concentration

Alkali concentration in cooking liquor depends also on liquor-to-wood ratio (the higher the liquor-to-wood ratio, the lower the alkali concentration). Alkali concentration should be low in the beginning of cooking and steadfast during it. [27] Also, too low an initial alkali concentration consumption can cause the pH to dropp too low in order to keep dissolved lignin in solution. High EA concentration at the beginning accelerates delignification and the degradation of carbohydrates. This results in a radical reduction in length of time necessary to reach given degree of delignification or yield. On other hand, it reduces the pulp yield at a given kappa number. An additional effect of increasing chemical concentration is a requirement lower evaporation of the black liquor and thus saving the steam. [58,61]

- Sulfidity

The increase of sulfidity fastens delignification. Also, consumption of alkali is less. The presence of sodium sulphide increase selectivity of the process, whereby the rate of lignin removal increase without increase in rate of cellulose degradation. The increasing in sulfidity has disadvantages like increased amount of odorous gas and risk of corrosion of equipment. In practise, new modern design mills have advanced to the point that odorous gas are burned either in the lime kiln or in the recovery boiler. Corrosion can be controlled by material selections and by the use of electrical protection. [58]

- Impregnation

Two mechanisms exist for transport of the chemicals in the impregnation stage: penetration of the chemicals through the pores of the wood and diffusion of the ions of the cooking liquor through liquid present in the wood. In hardwoods, penetration occur fast through the vessels, but penetration is almost nonexistent in a transverse section because pits membrane are non-porous and don't allow liquid pass into cells. [58]

- Time/temperature of the digestion, including heat-up profile

Chips have to be impregnated as well as possible before the start of the cooking phase. There is no optimal value for temperature heat-up time. It depends on impregnation conditions. [27]

There is correlation between cooking time and temperature. A higher cooking temperature requires shorter cooking time and conversely. The effect of cooking temperature and time has been combined to one factor, named H-factor. Cooking temperature with hardwood can vary between 155 -170 °C. Temperature increase to over about 170 °C increases yield losses. Also, typically a higher temperature means less uniform cooking, when surface parts of chips is cooked more than inner. [27]

4.1.5 Modified kraft pulping

Selectivity may be defined as the relative reaction rates of delignification and cleavage of polysaccharides chain. For optimal selectivity the temperature should be low at the beginning and the end of pulping, the alkali concentration should remain constant, the concentration of hydrogen sulphide should be as high as possible. These principles have been applied to the industry to obtain pulp with high strength properties and significantly lower lignin content. This procedure is termed "extended delignification". [60]

Even the kraft process is highly developed and efficient, it has some inappropriate attributes. The yield from wood is low because carbohydrates are dissolved as well as lignin during cooking. Extended pulping methods may affect in additional yield loss. Many modification of kraft pulping have been proposed, but only two have been commercialised: polysulfide and antraquinone. Interestingly, the chemically modified kraft processes were re-evaluated, when interest has developed in extended pulping. [60]

5 Bleaching

5.1 General description of bleaching

Bleaching is a chemical process applied to the pulp in order to increase its brightness. Brightness is the reflectance of visible light from fibres formed into sheets. Bleaching increases the visual quality. The capability of a paper to show printed text and images thus improves. In addition, it means purifying the pulp, thereby expanding its application, increasing its stability, and improvement of some of its properties. [60]

There are mainly three reasons for bleaching pulp [58]:

1. The first is to make the paper whiteness higher to increase the contrast between ink and paper in printing
2. The second reason is that pulp contains impurities which in other words are dots in the paper

3. The third reason is to reduce the effects of aging because paper has a tendency to become yellow and fragile with time, mainly due to lignin.

The absorbance of visible light by fibres is caused mainly by the presence of lignin. Native lignin is colored slightly, and residual lignin after kraft pulping is highly colored. Also, lignin darkens with age. [61]

In chemical pulp bleaching, the process can be done by two ways:

- By degrading and dissolving the lignin (lignin-removing bleaching)
- By modification of the lignin structures that decolorize the lignin (lignin-retaining bleaching).

Lignin-removing bleaching not only enhances the brightness, but the brightness stability of the product as well. Another objective of the bleaching of kraft pulps is to dissolve extractives and decolorize or remove unwanted particles that contaminate pulp fibres (for example shives).

5.2 Bleaching chemicals

Efficiency of different bleaching chemicals depends on wood species and process conditions. It is important that bleaching chemicals are selective, in other words, they have to react with lignin and extractives in significant preference to reacting with carbohydrate components in the pulp. In the bleaching system there are competing reactions which lead to generation of the unwanted by-products and do not produce higher brightness. For example, the bleaching chemicals can react with lignin already dissolved. [60]

The bleaching chemicals are mixed with the pulp suspension and the mixture is retained at established pH, temperature and concentration conditions for a defined time. The bleaching reactions are highly complex, due to the complexity of lignin and the wide variety of the bleaching chemicals. The effectiveness of the bleaching reactions are verified by measurement of brightness, lignin content of pulp, and residual chemicals. The bleaching chemicals are often applied sequentially with washing between stages, because it is not possible to achieve adequate removal or decolourisation of lignin by one single treatment. Reaction time of bleaching chemicals varies from few minutes to several hours. [60]

There are two types of chemicals commonly used for the bleaching of kraft pulps:

- Oxidants (e.g. chlorine, chlorine dioxide, oxygen, ozone, hydrogen peroxide)
- Alkali (namely, sodium hydroxide)

Table 12 summarizes the chemicals used in the pulp bleaching, their function, advantages and disadvantages. Chlorine dioxide is commonly used for industrial bleaching nowadays. However, mainly for environmental reasons, bleaching totally without chlorine chemicals is applied too.

Table 12. Bleaching chemicals [60].

	Function	Advantages	Disadvantages
Oxidants			
Chlorine	Oxidize and chlorine lignin	Effective, economical delignification; good particles removal	Organochlorine formation; highly corrosive
Hypochlorite	Oxidize, decolorize, and solubilize lignin	Easy to make and use; low cost	Can cause loss of pulp strength; chloroform formation
Chlorine dioxide	1) Oxidize, decolorize, and solubilize lignin 2) In small amounts with Cl_2, protects against cellulose degradation	Achieve high brightness without loss of pulp strength; good particle bleaching	Must be made on-site; cost; some organochlorine formation; highly corrosive
Oxygen	Oxidize and solubilize lignin	Low chemical cost; provides chloride-free effluent for recovery	Requires significant capital equipment when used in large amounts; potential loss of pulp strength
Hydrogen peroxide	Oxidize and decolorize lignin	Easy to use; low capital cost	High chemical cost; poor particle bleaching; can cause loss of pulp strength
Ozone	Oxidize, decolorize, and solubilize lignin	Effective; provides chloride-free effluent for recovery	Must be made on-site; cost; poor particle bleaching and pulp strength
Alkali			
Sodium hydroxide	Hydrolyze chlorolignin and solubilize lignin	Effective and economical	Darkens pulp

Oxidants are utterly important bleaching chemicals. They oxidatively degrade lignin hereby decreasing its molecular size. During this process carboxyl acids groups are formed which increase water and alkaline solubility of the lignin fragments. Alkali, called sodium hydroxide, is an important chemical in the bleaching sequences. It is degrades lignin by hydrolysis and ionizes acidic and phenolic groups, contributing the dissolution of lignin from the pulp. [61]

Single application of chemicals has a limited effect on brightness improvement and delignification of the pulp. Multistage bleaching can provide much greater benefits. The washing used between stages removes dissolved impurities, is partially responsible for improvement of the efficiency of the bleaching. Also, multistage sequences take advantage of the different action of each chemical and provide synergy in bleaching or delignification. [60]

EXPERIMENTAL PART

6 Objective of the study

The objective of this study was to evaluate the effect of replacing birch chips with aspen, or mixed aspen and alder chips in kraft cooking. The bleached pure birch kraft pulp was compared to the bleached (80 % birch, 20 % aspen) pulp and the bleached (70 % birch, 20 % aspen, 10 % alder) pulp, in order to evaluate the effects of initial wood species composition on the resulting pulp properties. The properties of unbleached pulps were also compared.

The focus of the experimental part was on comparing kraft pulping of birch aspen and alder pulps, and impact of replacing birch by aspen and alder on the properties of the pulp. Furthermore the effect of bleaching and refining was tested. The target for all pulps was to reach brightness level 85 %.

Pulping trials and measurements were done at Lappeenranta UPM Research Centre, Finland. The pilot scale process is shown on Figure 17. As evident from Table 17, collected chips of birch, aspen and alder were kraft cooked, ECF bleached and refinded by Voith Sulzer refining. Properties of unbleached and bleached pulps were determine. Properties of black liquor was analysed too. After that handsheet was made and optical anf physical properties were tested.

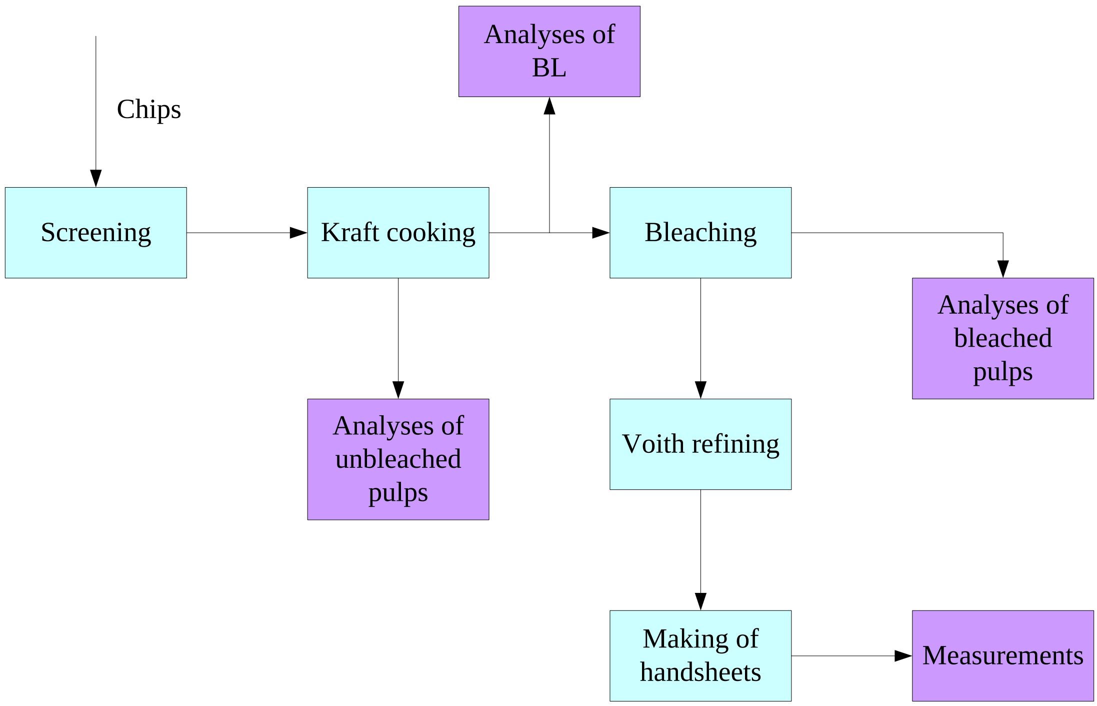


Figure 17. Pilot scale trial process.

7 Materials and methods

7.1 Mill sampling

The hardwood chips included birch, aspen and alder were of industrial grade. The raw material used in this study was the same as used at the mill. All of them were obtained in the form of chips. The chips were transported to UPM Research Centre and screened. For the trials fresh chips were used. The white liquor samples were taken from the production line.

7.2 Screening of chips samples

Birch, aspen and alder chips were screened. The screening was carried out in standardized screening equipment.

The samples were handled as follows:

1. Approximately 10 kg of chips was taken per one screening.
2. All free pieces of inner and outer bark were picked out. Chips with remaining bark were peeled out from bark.

3. Chips with loose rot were picked out.
4. The remaining part of the sample was places evenly on the top element of the screen. Screening was carried out during 10 minutes.
5. After the screening had been finished each fraction was weighted. The weight of each fraction expressed in percentage of the total weight of the sample was calculated.
6. All screened samples were stored up in closed plastic bags.

Table 13. Size distribution of screening chips.

		Birch	Aspen	Alder
over 45 mm	oversized	0.8	0.0	0.0
slots 8 mm – 45 mm	overthick	5.6	2.1	3.7
slots 8 mm - 13 mm	accepted	65.4	75.6	69.8
13 - 7 mm	accepted	22.9	19.5	23.7
7 - 3 mm	undersized	5.1	2.7	2.6
under 3 mm	fines	0.2	0.1	0.2

Results of the screening are shown in Table 13. The chips quality was good. Birch chips contained slightly lower percentage of accepted fractions. Aspen chips contained less overthick and undersized chips. For cooking accepted fraction was taken. Total amount accepted chips for birch, aspen and alder was 88.3 %; 95.1 % and 93.5 % respectively.

7.3 Determination of dry matter content in samples of chips

The green weight of the samples was established immediately after selection. Drying of the samples was carried out continuously during 22 - 24 hours of time in a drying oven at the temperature of 105 ± 2 ºC. New samples were not added to the oven during the drying period.

After the drying is finished the samples were cooling in an exsiccator 10 -15 minutes, and the dry weight of the samples were established immediately after cooling. Dry matter content for each species is shown in Table 14.

Table 14. Dry matter content.

wood species	dry matter content, [%]
Birch	55.9
Aspen	51.4
Alder	40.8

After screening accepted chips were kept in a cold room and then conditioned at room temperature in order to simulate real industrial conditions.

7.4 Cooking

Chips with determined dry matter content were weighted and loaded into the digester. Then an amount of water, calculated considering the amount of water in the loaded chips, was also weighted and loaded to the digester together with white liquor. The digester then was tightly closed and switch on and rotation was started.

Kraft cooking was carried out in cooking laboratory. In each experiment, 1750 g of oven-dried chips were cooked in an 18-litres rotating laboratory digester with electrical heating.

When the process was completed the digester was switch off and cooled down instantly. Odorous gases were released. When the digester was cooled down, black liquor was separated from the chips and analysed for residual EA.

7.4.1 Cooking conditions

Following cooks were done (the abbreviations used for the sample point are listed in Table 15):

1. 100% birch
2. 100% aspen
3. 100% alder
4. 80% birch + 20% aspen
5. 70% birch + 20% aspen + 10% alder

Table 15. The abbreviations used for the pulp samples.

Sample	Abbreviation
100% birch	B
100% aspen	As
100% alder	Al
80% birch + 20% aspen	BAs
70% birch + 20% aspen + 10% alder	BAsAl

Effective alkali charged was 20% as NaOH. White liquor that was used had the following properties (Table 16):

Table 16. Properties of white liquor.

Properties	Value
Effective alkali, g/l	112
Active alkali, g/l	140
Total alkali, g/l	157
Sulphidity, %	40

Total, active and effective alkali were determined according to SCAN standard – [SCAN-N 30:85]. The principle of the method lies in the titration of the white liquor with hydrochloric acid of known concentration.

Sulphidity (fromula 9) was calculated according to SCAN-N 30:85:

$$Sulphidity = \frac{2(a-2b+c)}{2a-2b+c} = \frac{2(5.911-2*6.556+8.603)}{2*5.911-2*6.556+8.603} = 0.4 = 40\% \quad (9)$$

where:

a, *b* and *c* are volumes of acid consumed for titration

a = 5.991 ml – volume consumed at the first inflexion point

b = 6.556 ml – total volume consumed at the second inflexion point

c = 8.603 ml – total volume consumed at the third inflexion point

The volume for white (formula 10) cooking liquor can be calculated:

$$V_{WL} = \frac{m_{oven\,dried\,chips} \times EA_{charge}}{EA_{concentraton}} \times 1000 = \frac{m_{oven\,dried\,chips} \times 0,2}{112} \times 1000 \qquad (10)$$

The amount of water that is necessary to maintain liquid-to-wood ratio 4:1 was calculated with consideration of the amount of water in chips and the amount of white liquor.

Pulping conditions are shown in Table 17. Cooks with "100% birch", "80% birch + 20% aspen" and "70% birch + 20% aspen + 10% alder" were repeated in order to obtain enough pulp for refining.

Table 17. Conditions of the cooking.

	100% birch, 100% aspen, 100% alder	80% birch + 20% aspen	70% birch + 20% aspen + 10% alder
Effective alkali, g NaOH/l	112	112	112
Cooking liquor charge (as NaOH), %	20	20	20
Sulfidity, %	40	40	40
Liquor-to-wood ratio	4:1	4:1	4:1
Maximum temperature, °C	160	160	160
Heat-up time to top temperature, min	60	60	60
Cooking time, min	130	120	135
H-factor	914	848	947

After the process was stopped black liquor was extracted and cooled down with a cooler. The chips were then taken out, defibrated, then screened and washed.

Laboratory kraft cook is not followed by sudden pressure release, which causes defibration of cooked chips and it widely used in industry. For separation of fibres, a laboratory defibrator was used.

After the cooking the pulps were screened with a Somerville screen with 0.15-mm slots size, washing was done during this stage. It should be mentioned, that washing efficiency is very high in laboratory trial washing due to long treatment and sufficient amount of water. The reject ratio was calculated by measuring the volumes of the screened accept and reject pulps and determining their consistencies.

Screen accepts were centrifuged in order to remove excess of water, fluffed and homogenized for 10 min in a special device. After that pulp was measured for total weight, consistency and oven-dried weight. Screen rejects were oven-dried and weighted. The screened pulp was kept in the cold room for further analysis and processing.

7.5 Black liquor analyses

The analysis of black liquor in this study is the measuring of residual alkali content and calorific value in the black liquor after kraft cooking. Residual alkali was determined by titration of diluted black liquor with hydrochloric acid according to standard [SCAN-N 33:94]. Analysis calorific value of black liquor was made under [ISO 1928] standard. At first black liquor was evaporated and then it was burned in high-pressure oxygen in a bomb calorimeter under specific conditions.

7.6 Analysis of unbleached pulp

7.6.1 Dry matter content

Dry matter content of all unbleached pulps was determined according to [ISO 638:1978 (E)].

7.6.2 Determination of residual lignin content

The Kappa number is an indication of the residual lignin content of the pulp. For determination of the kappa number [SCAN-C 1:00] method was used. Lignin in pulp can be easily oxidised by potassium permanganate. This method measures the amount of potassium permanganate consumed by roughly 1 g of oven-dried pulp in the period of time 10 minutes. The Kappa number is proportional to Klasson lignin content (formula 11):

$$Kappa\ number * 0.15 = Klasson\ lignin, \quad \% \qquad (11)$$

7.6.3 Determination of viscosity

Analyses of viscosity of the pulps were made according to [ISO 5351–2004 (E)]. The principle of the method is dissolving of the sample in 1M cupriethylenediamine solution (CED) and determination of the viscosities of the sample solution in capillary viscometers by measuring the drainage time and specified amount of liquid.

7.6.4 Determination of brownstock brightness

After cooking, washing and screening was determined brightness of pulps. Determination was carried out in accordance with modified [ISO 2470:1999 (E)]. Brightness of pulp is diffuse blue reflectance factor of an opaque pile of brightness cakes made of pulp, measured at 457 nm effective wavelength.

7.6.5 Water retention value (WRV)

Water retention value is the amount of water that remains after centrifugation of a wet pulp sample in special conditions, expressed as grams of water per grams of oven-dry pulp. WRV provides an indication of fibres ability to take up water and swell. The WRV is highly correlated to the bonding ability of fibres.

The water retention value (WRV) was measured according to the [ISO 638:1978 (E)]. Water retention value is an empirical measurement that describes the water retention capacity of a sample cake formed of fibres. The rinciple of the test based on centrifugation of cake, which is prepared by draining water on a wire/glass fibre filter, with a certain centrifugal force for a definite period of time, after which it is weighed, dried and weighed again.

The water retention value was calculated according to the formula 12:

$$WRV = (m1/m2)-1 \qquad (12)$$

where,

m1 – weight of centrifuged wet sample cake (g),

m2 – weight of oven-dry sample

7.6.6 Definition of fibre properties with FiberLab

All samples were analyzed with FiberLab (Metso Automation). The FiberLab analyser automatically measures, classifies and reports on the dimensional properties of fibre samples.

The equipment consists of an analyser and a sample unit. Two CCD cameras capture fibre images. The direct measured results are the fibre length, fibre width and fibre wall thickness. The calculated values by program are the curl index, coarseness, cross-sectional area and volume index. [62]

7.7 Bleaching

Following samples were ECF-bleached to target brightness 85% ($D_0ED_1D_2$):

1. 100% birch
2. 80% birch + 20% aspen
3. 70% birch + 20% aspen + 10% alder

All the pulps were bleached under the same conditions. The amount of pulp in the bleaching was 850 g calculated as oven dried. Two bleaching were performed for each pulp. The bleaching was made according to the scheme in the Figure 18 below:

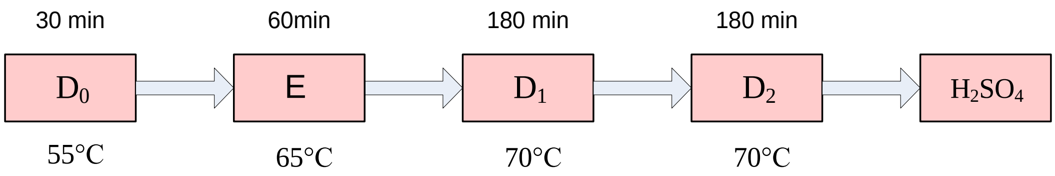


Figure 18. The sequence of bleaching.

The chlorine dioxide dosage in the D_0-stage, expressed as % Active chlorine [aCl] on pulp/kappa number was calculated according to formula 13:

$$[aCl] = Kappa\ no. \times Kappa\ \ factor \qquad (13)$$

where,

Kappa no. - Kappa number of pulp entering bleaching.

Bleaching conditions for pure birch pulp, (80% birch + 20% aspen) pulp and (70% birch + 20% aspen + 10% alder) pulp are shown in Table 18, Table 19 and Table 20 respectively. After each bleaching stage, the pulp was washed with water. After all bleaching stages acid treatment by sulphuric acid was realized.

Table 18. The conditions of bleaching for pure birch pulp.

Stage	Chemicals	Consistency, %	Chemical charge, %	Time, min	Temperature, ºC	Final pH
D_0	ClO_2	7.5	4.30	30	55	2.4 – 2.5
E	NaOH	10	1.40	60	65	11.1
D_1	ClO_2	10	2.87	180	70	2.2
D_2	ClO_2	10	1.43	180	70	2.8 – 2.9

Table 19. The conditions of bleaching for (80% birch + 20% aspen) pulp.

Stage	Chemicals	Consistency, %	Chemical charge, %	Time, min	Temperature, ºC	Final pH
D_0	ClO_2	7.5	3.95	30	55	2.1
E	NaOH	10	1.40	60	65	11.1 – 11.2
D_1	ClO_2	10	2.63	180	70	2.6
D_2	ClO_2	10	1.32	180	70	2.8

Table 20. The conditions of bleaching for (70% birch + 20% aspen + 10% alder) pulp.

Stage	Chemicals	Consistency, %	Chemical charge, %	Time, min	Temperature, ºC	Final pH
D_0	ClO_2	7.5	4.15	30	55	2.8 – 2.9
E	NaOH	10	1.40	60	65	11.2
D_1	ClO_2	10	2.77	180	70	2.4
D_2	ClO_2	10	1.38	180	70	2.9

7.7.1 Brightness and brightness reversion

Brightness is one of the most significant and frequently used tests in bleaching. Brightness is a test of the reflectance of a light from pulp sheets. Brightness is the reflectivity of the sample compared to a specific standard surface using blue light with a peak wavelength at 457 nm.

Post colour (PC) number is used to indicate the extent of brightness reversion. Post colour number was calculated according to formula 14:

$$PC = [(100 - R_2)^2 / 2 \times R_2] - [(100 - R_1)^2 / 2 \times R_1] \qquad (14)$$

where,
R_1 - brightness before aging
R_2 – brightness after aging

7.8 Beating (LC-refining)

The following bleached pulps were refined by laboratory Voith Sulzer refiner:

- 100% birch
- 80% birch + 20% aspen
- 70% birch + 20% aspen + 10% alder

The advantage of Voith Sulzer LR1 refiner is that the operating conditions can be adjusted to simulate mill scale refiners so that realistic refining results, including the energy consumption, are obtained.

The refiner was equipped with conical fillings. The stock concentration was 4% and specific edge load of 0.5 J/m was used with refining energies of 0, 25, 50, 75, 100 kWh/t. Drainability or beating degree of pulp can be determined using Schopper-Riegler [ISO 5267–2:2001 ISO] or Canadian freeness [5276–1:1999] methods.

7.9 Analyses of bleached pulp

At all refining level the pulps were analyzed for:

- Fiber properties using FiberLab (Metso Automation) analyzer
- Brightness
- Freeness
- Shopper-Riegler
- WRV
- Extractive content
- Carbohydrate content

- Ash content
- Microscopy pictures were taken also.

7.10 Sheet preparation

Laboratory handsheets were made in a standard laboratory sheet former without white water recycling according to the modified [ISO 5269-1:2005] standard. A square sheet was prepared on furnish under suction. After formation the sheet was separated from the wire and pressed twice with dry blotter on one side of a sheet and a smooth metal plate on the other with pressure of 410 kPa for totally 7 minutes. After pressing the sheets was dried and conditioned at the same time in the conditioning room at temperature t = 23ºC and relative humidity RH=50%. The target basis weight of the sheets was as air-dry 60 $g/m^2 \pm 2$ g/m^2.

It should be mentioned that industrial papermaking process has short circulation of white water which reused for dilution of pulp suspension, as a result of fibre balance is maintained and fines are delivered back. That provides better structure of the web. Laboratory scale system does not have it, in laboratory sheet forming system the fines, which go through the wire are lost with water.

7.11 Physical and mechanical properties of the handsheets

A number of standard tests were carried out on the prepared sheets (Appendix I):

- Basic weight (grammage)
- Scott bond
- Tearing strength
- Burst strength
- Burst index
- Bulking thickness
- Bulking density
- Bulk
- Roughness, Bendsten
- Tensile strength

- Tensile index
- Tensile energy absorption
- TEA index
- Tensile stiffness
- Tensile stiffness index
- Stretch
- Y-value, (C/2º)
- Opacity
- Light scattering coefficient
- Absorption coefficient
- Brightness reversion, PC-number
- Air-resistance, Gurley

8 Results and discussion

8.1 Results from kraft cooks

As noted earlier with the kraft cooking process, the cooking conditions have a distinct impact on the resulting kraft pulp properties. The concentration of chemicals, liquid-to-wood ratio, cooking time and temperature applied in this study of the mixed wood are the optimum kraft cooking conditions found previously for birch and aspen. [53]

According to literature aspen wood cooks easily and faster in comparison with birch while alder *vice versa* requires longer cooking than birch. Therefore, was decided to decrease time by 10 minutes of cooking for BAs; and increase time of cooking by 5 minutes for BAsAl.

Data listed in Table 21 show distinctions in properties of kraft pulps depending on the species of wood. However, the differences were rather smoothed out, for blends birch, aspen and alder wood.

Table 21. Analyses of unbleached pulp.

Pulp	Dry matter content, %	Yield, %	Kappa number
100% birch	29.73	53.92	18.3
100% birch	30.11	54.88	17.4
100% aspen	31.19	56.84	10.8
100% alder	24.68	50.29	19.8
80% birch + 20% aspen	30.58	54.61	16
80% birch + 20% aspen	30.30	53.83	16.9
70% birch + 20% aspen + 10% alder	30.72	53.5	16.3
70% birch + 20% aspen + 10% alder	30.28	55.09	18.5

The variation of pulp yield of pure pulps and birch pulp with addition of aspen and alder is illustrated in Table 21. Yield indicates the loss of the wood during delignification process. Results clearly indicate that pure aspen has the highest yield. That’s also affect on the yield of pulp when replacing birch with aspen. The yield of the kraft pulp obtained from the alder wood is lower by 4-5 % than in case of birch wood. Interestingly, when birch, aspen and alder were blended; alder didn't influence negatively upon yield of pulp.

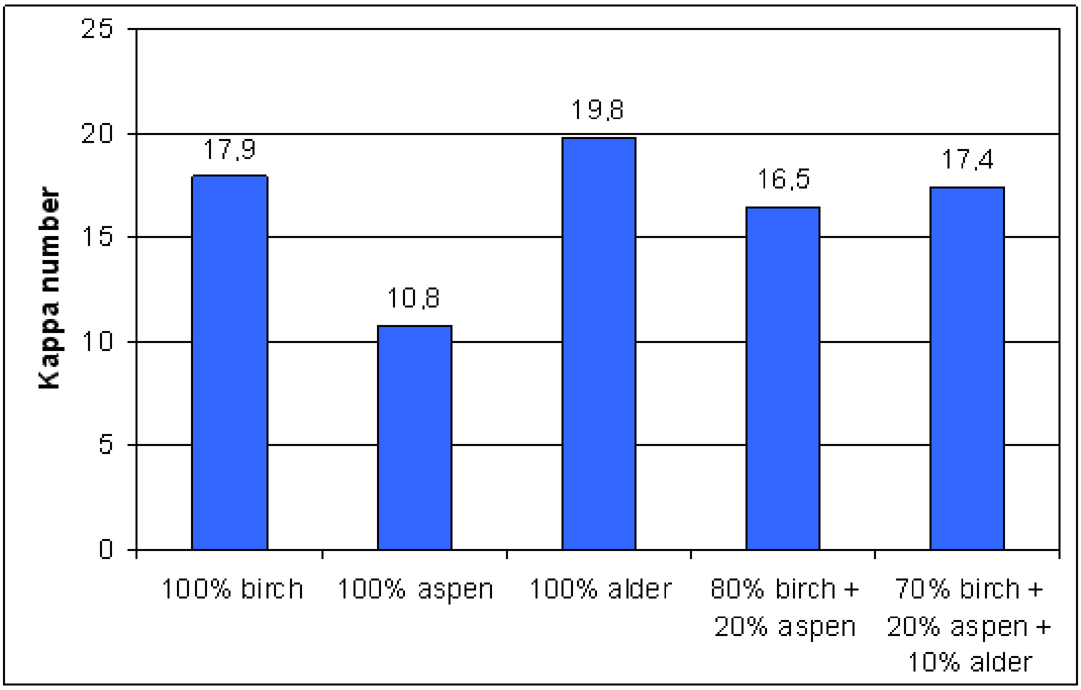


Figure 19. The kappa numbers of the pulps.

As it is evident from Figure 19 the kappa no. is lowest for pure aspen pulp and highest for alder pulp. Even if time of cooking decreases when replaces birch with aspen, kappa no. increases. The addition of alder to birch and aspen mixture has detrimental effect on kappa number, but it is still slightly lower than for pure birch.

Table 22. Analyses of unbleached pulp.

Pulp	Viscosity	Brownstock brightness	Water retention value	Residual alkali
100% birch	1115	28.28	1.83	8.14
100% birch	1100	28.62	1.82	5.63
100% aspen	1020	38.25	1.74	8.04
100% alder	1130	24.49	2.06	7.19
80% birch + 20% aspen	1143	29.48	1.80	6.58
80% birch + 20% aspen	1090	31.12	1.80	9.24
70% birch + 20% aspen + 10% alder	920	28.97	1.76	6.68
70% birch + 20% aspen + 10% alder	940	27.51	1.76	5.83

Lower residual alkali (Table 22) for the mixed birch, aspen and alder chips means higher consumption of alkali. Brownstock brightness of pure aspen pulp was significantly higher than the other species. It can be concluded a high brightness level of aspen can be achieved by bleaching easily. There was positive effect on brownstock brightness when birch was replaced with aspen.

However, aspen is not necessarily an economical choice (production/digester volume) because the density of aspen is smaller than birch's and wood is bought to the mill by its volume not weight.

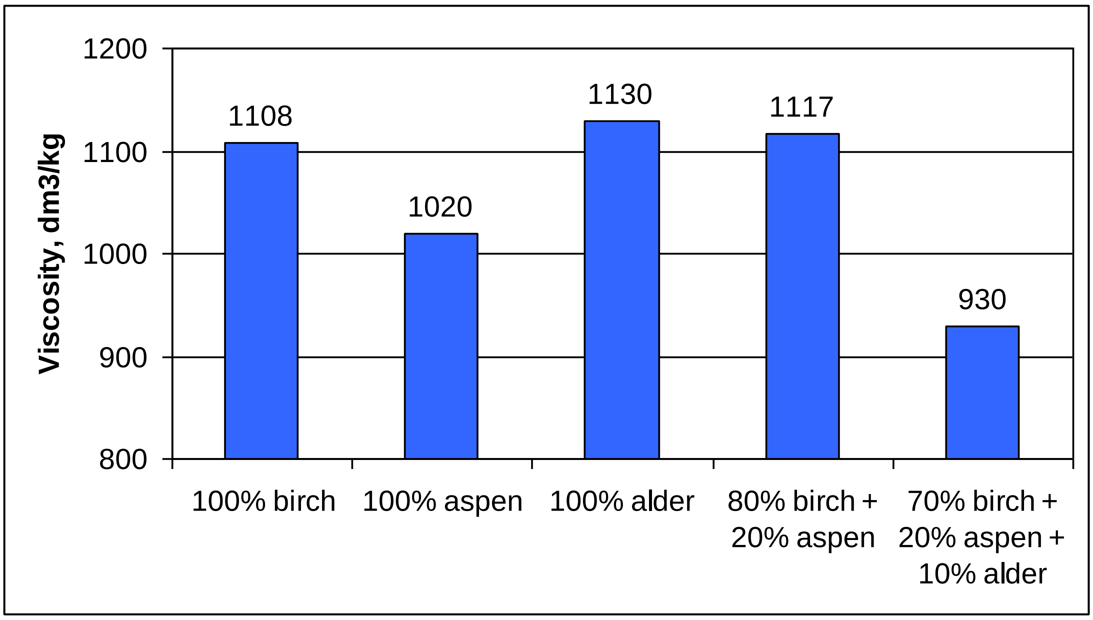


Figure 20. Viscosity of the pulps.

Viscosity of a pulp gives an estimation of the average degree of polymerisation of the cellulose fibre. So the viscosity indicates the relative degradation of cellulose fibre during pulping/bleaching process. According to data from Figure 19 and Figure 20 viscosity depends more on time of cooking and residual lignin content than tree species. In Figure 20 it can be seen that aspen has the lowest and alder the highest viscosity when pure pulps are compared.

Interestingly, mixed birch, aspen and alder pulp shows the lowest viscosity when all pulps are compared. Longer cooking time for that pulp probably is the reason for decrease in viscosity, which means bigger damage of carbohydrates and decrease of the degree of polymerization (molecular weight of the macromolecules). Also error in experiment could exist.

It should be mentioned that amount of hemicellulose influence the average molecular weight of pulp. As hemicelluloses are polysaccharides with much lower degree of polymerisation than that in cellulose, it can influence the average degree of polymerisation and viscosity.

8.2 Fiber properties

Table 23 and Table 24 show the fibre characteristics of all unbleached pulps. The average values between the pure pulps are slightly different and mixed pulps are rather similar.

Table 23. FiberLab results of unbleached pulps.

Pulp	Fiber length, [mm]	Fiber width, [μm]	Fines, [%]	Vessels, [1/1000 fibres]	Curl, [%]
B	0.98	19.9	1.27	22.24	14.8
As	0.93	20.8	4.66	31.76	12.1
Al	0.78	21.2	2.01	24.79	12.2
BAs	0.98	20.1	1.81	27.22	14.6
BAsAl	0.96	19.9	1.91	25.1	14.0

As can be seen from Table 23, there was a rather small difference between fibre properties of the pulp samples. The birch had the longest fibres and alder shortest, which was contrary to literature data. Replacement with aspen and alder in blended pulps didn't affect negatively on fibre length. Difference in cell wall thickness between samples was also small.

The frequently reported greater coarseness of birch and aspen fibres is due to larger perimeters of those fibres, not due to cell wall thickness, because the cross/sectional area is larger too.

The thick cell walls in aspen pulp fibres are expected to give high tear strength. The thicker cell wall is very favourable to porosity and opacity development, because the fibres are not readily collapsible. The fibres of the alder pulp are short, which helps in improving the paper formation.

The correlation between coarseness and cell wall thickness (Table 24) was quite good, since the aspen pulp had the thickest cell wall and highest coarseness, when comparing pure species. Differences in fibre widths were small as well. The values of fibre curl are of the same magnitude for all the pulps.

Table 24. FiberLab result of unbleached pulps.

Pulp	Coarseness, [mg/m]	Cell Wall Thickness, [μm]	Cross sectional area, [μm2]	Fibrillation, [%]	Kink index [1/m]
B	0.089	5.9	227.8	2.94	868.83
As	0.090	6.2	242.3	2.98	715.52
Al	0.066	5.0	200.7	2.72	859.14
BAs	0.092	6	232.7	2.91	895.4
BAsAl	0.090	5.9	225.9	2.93	822.01

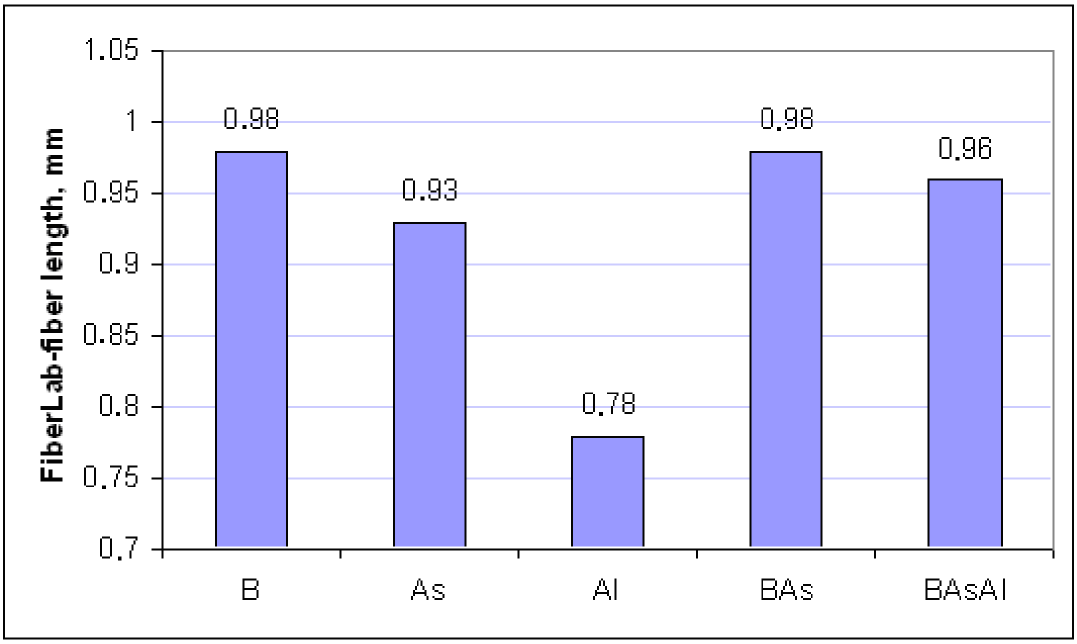


Figure 21. The fiber length of the unbleached pulps.

Fiber length is pulps are shown in Figure 21. Birch fibres have a greater length when compare with aspen and alder. Longer fibres tend to have higher tear and surface strength. Thick-walled narrow aspen and birch fibres are especially stiff. Short, thin-walled alder fibres, with low coarseness, on the other hand, give pulp with a high number of fibres per unit mass. A bigger amount of fibres per unit pulp typically results in better formation and higher opacity. The content of fines in aspen pulp was higher than in the birch and alder. [13]

8.3 Analysis of black liquors

The black liquor dry solids content after laboratory kraft cooking for B, BAs and BAsAl pulps was 16.7 %, 16.3 % and 17.9 % respectively. The liquors were evaporated to 77.03 %; 78.03 % and 69.05% dry solids content. After that, gross calorific value of black liquors was determined.

The heating value or caloric value is the amount of heat released during the combustion. Gross heating value accounts for water in the exhaust leaving as a vapour, and includes liquid water in the black liquor prior to combustion.

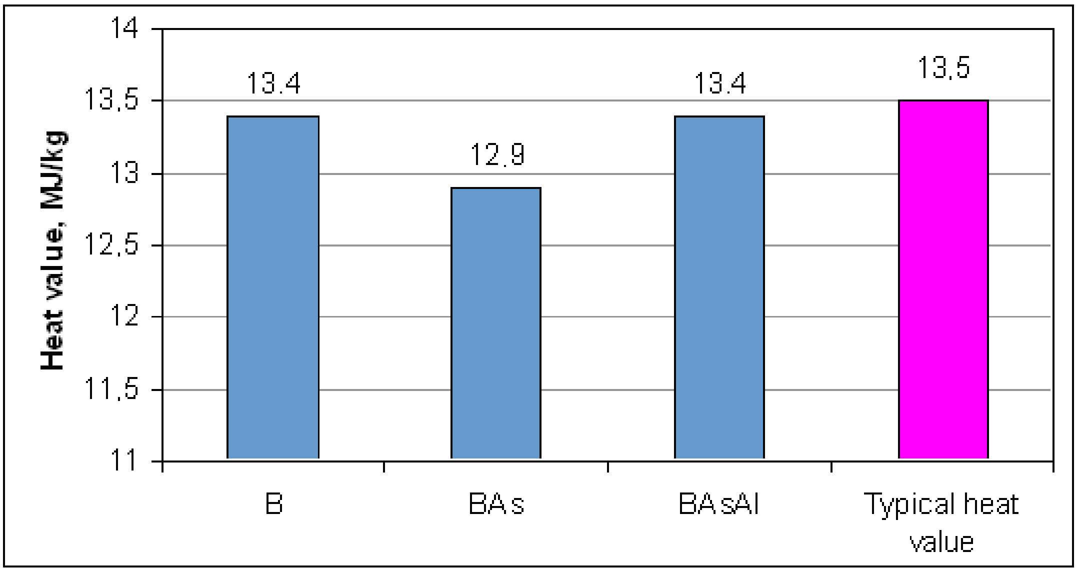


Figure 22. Caloric value of BL.

Caloric values for B, BAs and BAsAl pulps are given in Figure 22. Heat values of BL for laboratory pulps are shown by blue colour, and typical heat value of BL for hardwood pulp is shown by pink colour. According to Figure 22, it can be concluded that there is not much differences between the pulps. Replacing birch with aspen hovewer, seems to reduce the BL heat value a little bit.

8.4 Bleaching

The intention of the final bleaching was not to create differences between raw materials. It was only used to remove residual lignin as selectively as possible, by using DEDD sequence before Voith refining. The [aCl] charge was defined as kappa factors based on earlier experience. The final brightness of the pulps varied between 85.8-86.8 %. The data presented in Table 25.

Table 25. Analyses of bleached pulps.

Pulp	Cooking kappa no.	Brightness, %	Viscosity, dm3/kg	Brightness reversion
100% birch	17.2	85.8	875	78.1
80% birch + 20% aspen	15.8	86.8	815	80.3
70% birch + 20% aspen + 10% alder	16.6	85.4	810	79.9

There is positive effect when birch replaced with aspen (Table 25). The bleachability was shown to be affected by differences in amount of lignin in unbleached pulp, the easiest to bleach being aspen (lowest initial kappa no.). Brightness values of the bleached unrefined pulps were the same, whereas the BAs had the highest initial brightness of unbleached pulp and good brightness stability of bleached pulp, Figure 23. Also, (80% birch + 20% aspen) pulp had the best brightness stability (Figure 23).

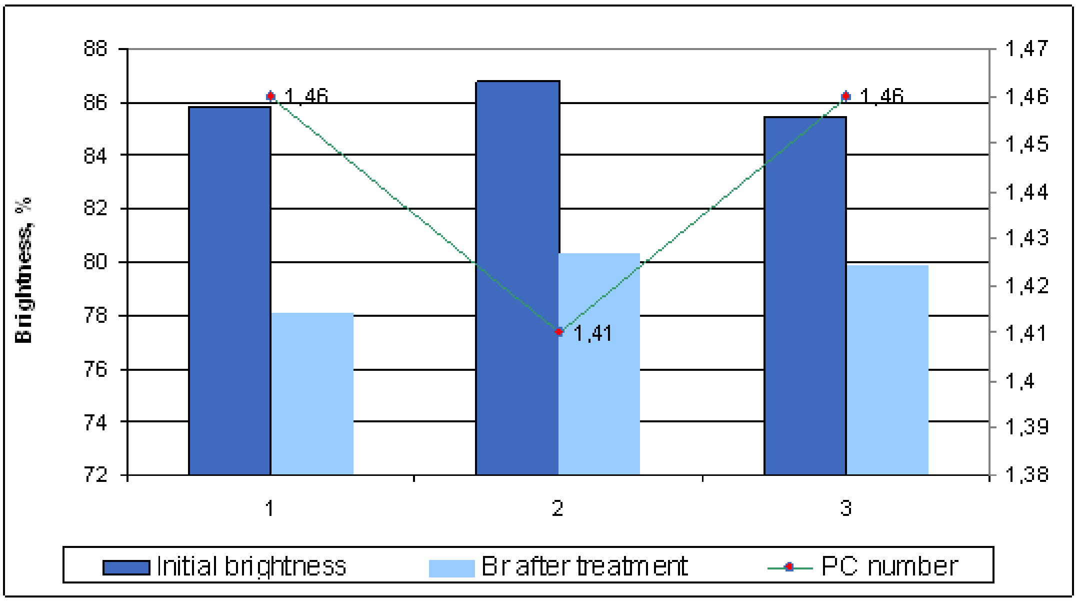


Figure 23. Brightness before and after treatment.

8.5 Microscopy analyses

8.5.1 Microscopy pictures of fibres

From unbleached and bleached fibres microscopy picture were taken. They were colored by Graff-C. Pictures were taken with 100 and 400 fold magnification. All the results are shown in Appendix III.

The figures displays fibres and vessels. The same thing was shown in tables of fibres properties (FiberLab), can be seen in the figures. All fibres look resembling. The vessels elements of birch, aspen and alder are approximately the same. According to the literature studty, they have similar fibres and vessels morphology.

8.5.2 Microscopy pictures of paper surface (ESEM)

Microscopy picture were taken frm the bleached pulps.Pictures were taken at 100 and 400 fold magnifications. All the results are presented in Appendix III. There were not signaficant differences.

8.6 Chemical analysis of bleached pulp

The chemical compositions of the pulps show only small differences in content of extractives and carbohydrates composition.

8.6.1 Carbohydrate composition

The analysis of carbohydrates composition of the bleached pulps was carried out by internal method of UPM RC. The principle is that carbohydrate chains are cleaved into monosaccharides in the presence of hydrochloric acid, heat and pressure, and analysed by gas chromatography. The results are presented in Table 26.

Table 26. Carbohydrate composition.

	100 % birch	80 % birch + 20 % aspen	70 % birch + 20 % aspen + 10 % alder
Galactose, [mg/g]	<1	<1	<1
Glucose, [mg/g]	32	31.9	32.2
Mannose, [mg/g]	1.1	1	1
Arabinose, [mg/g]	<1	<1	<1
Xylose, [mg/g]	177	165	159
Glucuronic acid, [mg/g]	<1	<1	<1
Galacturonic acid, [mg/g]	<1	<1	<1
Carbohydrates, total, [mg/g]	212	200	196

The most important results are the amounts of glucose and xylose. Table 26 are presented that the pure birch pulp had higher content of xylose than the other pulps. The data shows that 100% birch pulp has higher amount of carbohydrates per unit of weight of the pulp. This is caused by higher xylose content in the pure birch pulp. The data for other carbohydrates does not display any particular differences. The comparison of (80% birch, 20% aspen) pulp and (70% birch, 20% aspen, 10% alder) pulp shows that both pulp have similar composition.

8.6.2 Extractives content

The extractives content were analyzed, because some of the components are more harmful than others, when thinking on the process and end-products. For instance, betulinol is deriving only from bark, and it is often the main component in precipitations or stickies found at both pulp and paper mills. [63] The compositions of extractive components are shown in Figure 24 and Table 27.

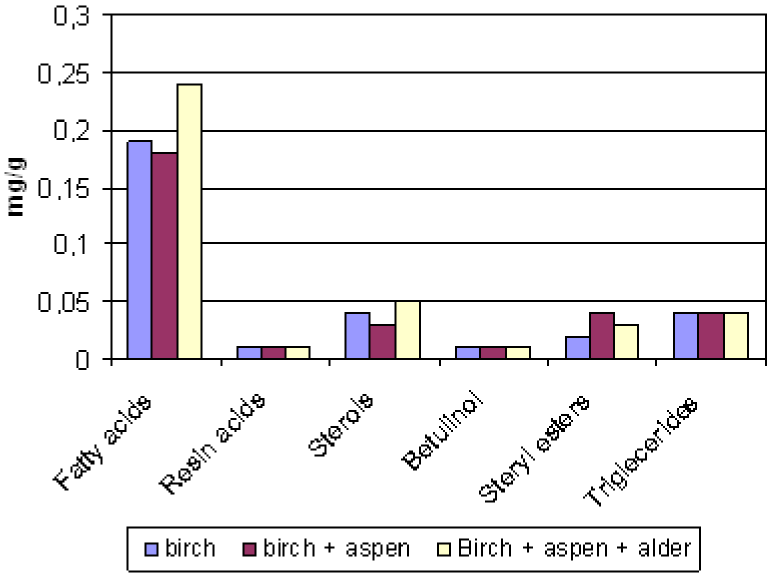


Figure 24. Extractives composition.

Table 27. Extractives components.

	100 % birch	80 % birch + 20 % aspen	70 % birch + 20 % aspen + 10 % alder
Acetone extractive, %	0.59	0.48	0.33
Fatty acids, mg/g	0.19	0.18	0.24
Resin acids, mg/g	0.01	0.01	0.01
Sterols, mg/g	0.04	0.03	0.05
Betulinol, mg/g	< 0.01	< 0.01	< 0.01
Steryl esters, mg/g	0.02	0.04	0.03
Triglycerides, mg/g	0.04	0.04	0.04
Extractive total, mg/g	0.30	0.30	0.37

Extractives derive mostly from bark (betulinol) and from the parenchyma cells connected with the vessels. According to Figure 24 and Table 27, BAsAl pulp has higher content of fatty acids, whereas birch pulp has higher amounts of extractives by acetone. Reason for this phenomenon could be dissolution in acetone other components of pulp, for example hemicellulose. Also process variables like washing and bleaching affect the composition of extractives. The content of betulinol is low in all cases, which means efficient debarking and washing.

Sterols are saturated and stable. Also, they can be oxidized and the result of it is bad smell. Sterols are found in stickies although they are not sticky themselves [64]. The fatty acids are oxidized too, which can result in taste and odor problems, which can be cause for allergic reactions. Particularly the unsaturated fatty acids are easily oxidized leading to volatile bad smelling matters. Moreover they are sticky. All these substances generate disturbances in wet end chemistry of a papermaking. Resin and fatty acids soaps affect on foaming. Fatty acids, steryl esters form deposits in kraft mills. Triglycerides and fatty acids could decrease sheet strength. [63]

8.6.3 Ash content

The amount of ash in B, BAs and BAsAl was 0.11%; 0.09 % and 0.09 % respectively.

8.7 Beating

Three bleached pulps were used for further testing (all beating results are presented as charts in Appendix II):

- 100% birch pulp
- 80% birch and 20% aspen pulp
- 70% birch + 20% aspen + 10% alder

8.7.1 Beatability

Refining or beating is a mechanical process causing microfibrillation of the pulp fibres. During the refining process fibres undergo several different processes. The most important of them are fibrillation, shortening and generation of fines. Fibrillation is desired if high paper strength should be maintained, it increases, interfiber bonding, surface of fibres and their flexibility. Refining energy consumption, freeness and Shopper-Riegler degree are shown in Table 28.

Table 28. Beatability of the bleached pulps.

Beating degree	SEC, kWh/t				
	0	25	50	75	100
	°SR				
100% birch	13.5	15.0	18.0	20.0	23.5
80% birch + 20% aspen	14.5	15.5	18.0	20.5	23.0
70% birch + 20% aspen + 10% alder	15.0	16.0	18.5	21.0	24.5
	CSF, ml				
100% birch	680	650	570	540	465
80% birch + 20% aspen	670	650	590	535	480
70% birch + 20% aspen + 10% alder	660	610	580	520	465

The response of the beating on pulps is shown by the beating curves in Figure 25 Figure 26.

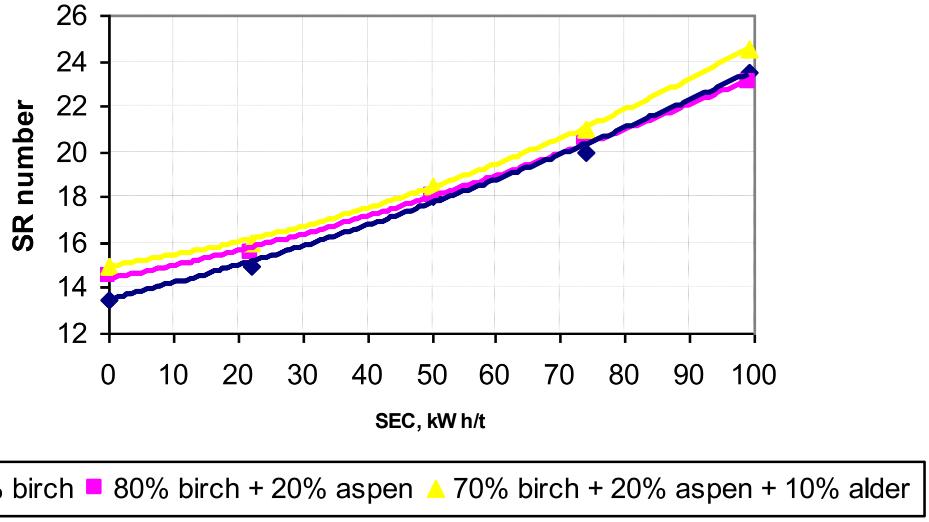


Figure 25. Need of refining energy.

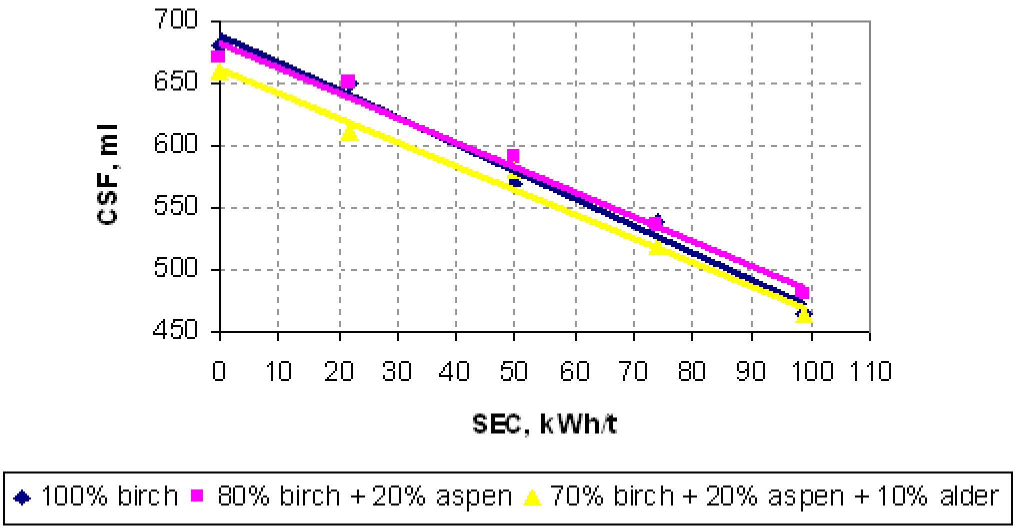


Figure 26. Canadian standart freeness vs. specific refining energy.

Pulp, produced from the mixed chips requires less specific energy consumption (Figure 25, 26), at a given level of freeness/Shopper-Riegler degree, when compare with pure birch. SR numbers of pure birch pulp were about the same as that (80% birch, 20% aspen) pulp, and those of the (70% birch, 20% aspen, 10% alder) pulp were slightly lower. According to the literature it is the consequence of basic density. Aspen and alder have lower basic density than birch, so they are easier to refine. Birch has higher hemicellulose content than aspen and alder, but that did not affect refining energy consumption.

The development of SR-number was basically the same for all pulps. The development at low beating levels was slowest for 100% birch pulp. At the end of the beating the difference of pure birch pulp to (80% birch, 20% aspen) pulp disappeared.

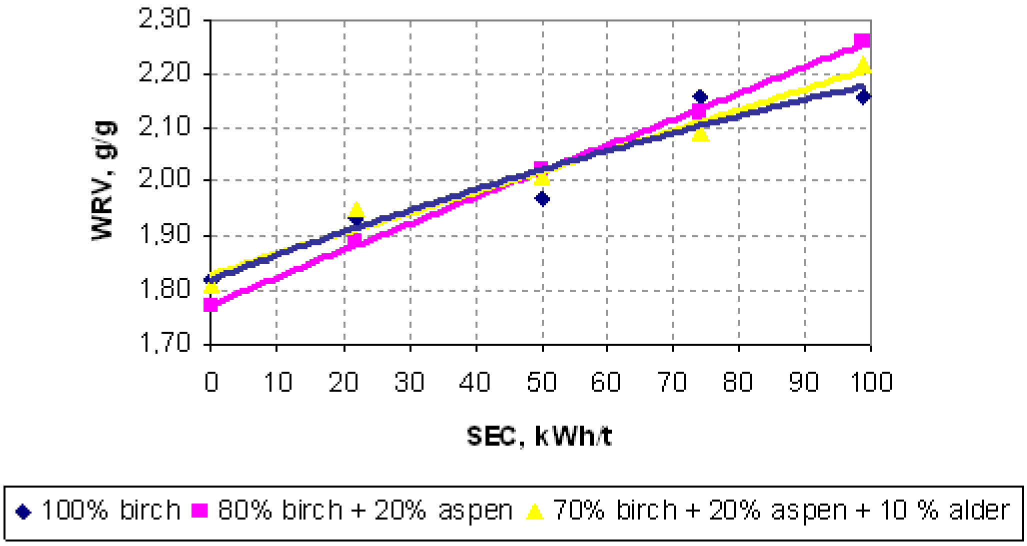


Figure 27. WRV vs. specific refining energy.

Pulp drewatering was alsdo examined with WRV. Figure 27 shows development of water retention values as a function of specific refining energy. For all pulps WRV values are approximately the same.

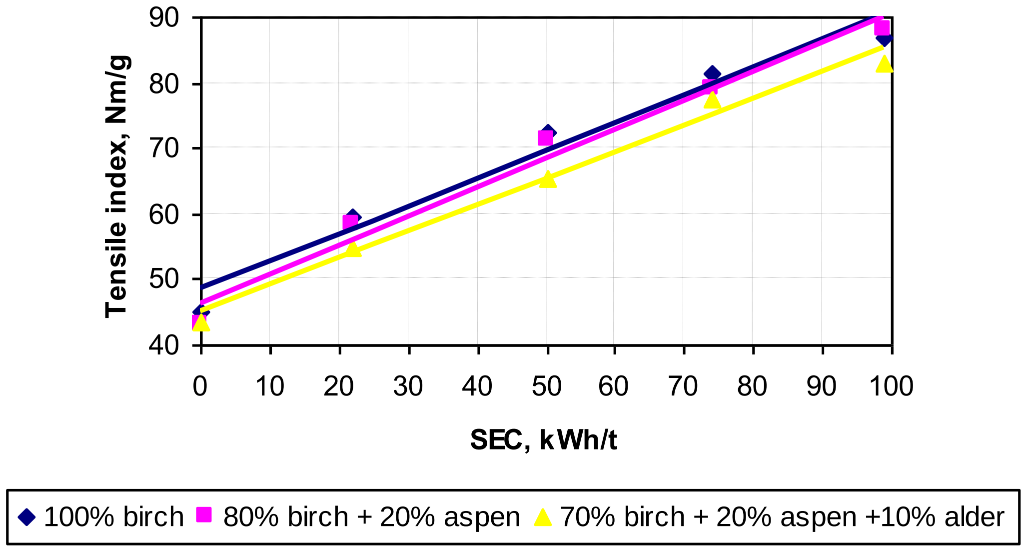


Figure 28. Tensile index vs. specific refining energy.

The specific refining energy vs. tensile index is shown in Figure 28. Tensile index of the handsheets decreased when the proportion of the birch pulp in the blended pulp was decreased.

Tensile index of 100% birch, (80% birch, 20% aspen) pulp and (70% birch, 20% aspen, 10% alder) pulp as unrefined were 45.0 Nm/g, 43.0 Nm/g, 43.5 Nm/g. Figure 28 shows that the (70% birch, 20% aspen, 10% alder) pulp needed more refining energy to target tensile index than the pure birch pulp or (80% birch, 20% aspen) pulp. For example, the specific refining energy consumption of the 100% birch pulp was 45 kWh/t, and that of (80% birch, 20% aspen) pulp was 48 kWh/t, whereas that of the (70% birch, 20% aspen, 10% alder) pulp was 59 kWh/t.

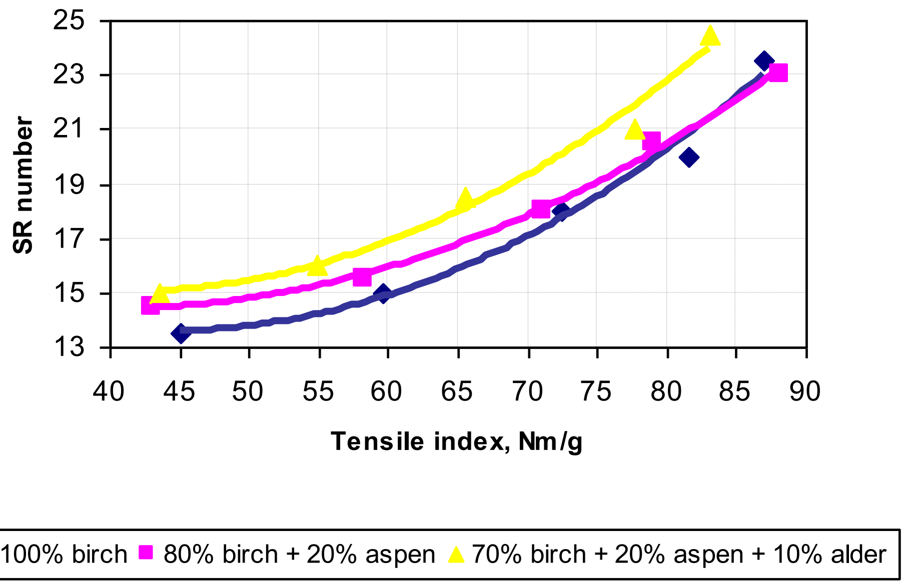


Figure 29. SR vs. tensile index.

In case of (70% birch, 20% aspen, 10% alder) pulp, SR number (Figure 29) and WRV at a given tensile index (Figure 30) are slightly higher. There is also small difference at low refining level between the pure birch and (80% birch, 20% aspen). This indicates that 100% birch pulp would have better water removal both in wire section (lower SR) and also in the wet pressing and drying (lower WRV) at a given tensile index.

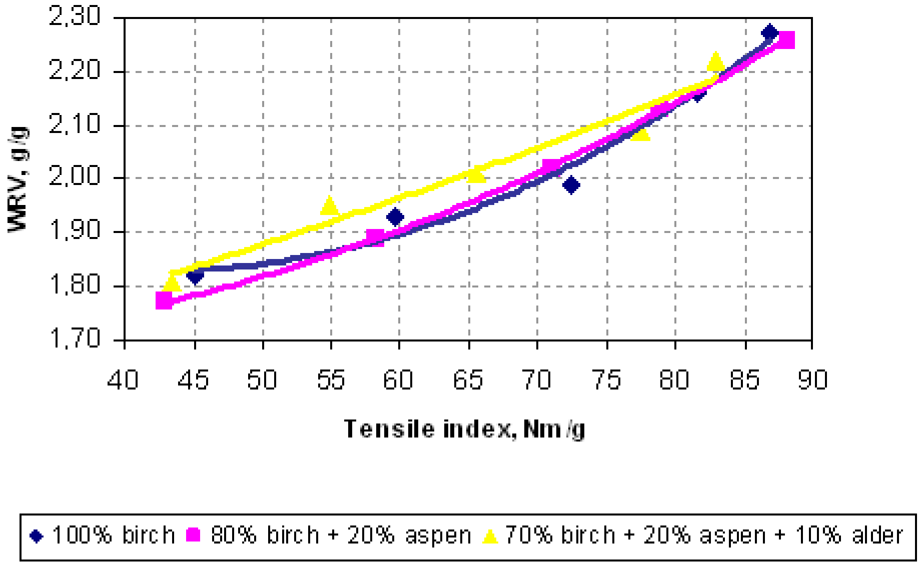


Figure 30. WRV vs. tensile index.

Tensile index of 100% birch pulp at a given WRV (Figure 30)was at the same level as (80% birch, 20% aspen) pulp. Tensile index for (70% birch, 20% aspen, 10% alder) pulp was slightly lower, in comparison to others.

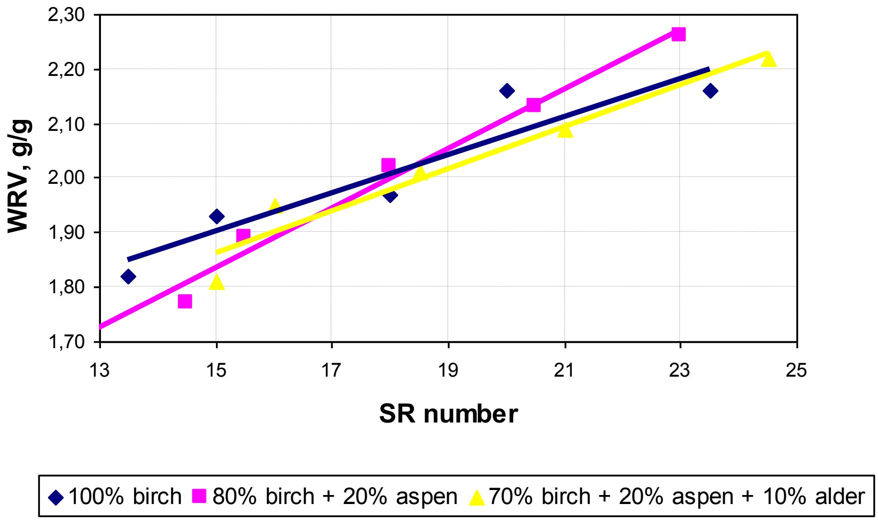


Figure 31. WRV at given SR number.

Water retention value is an indicator of the bonding ability of the pulp. It is also supposed to indicate the dewatering properties during wet pressing and drying. SR number depends on external fibrillation and the fines content, WRV more is more influenced by the internal fibrillation and swelling capacity of the fibre walls. Figure 31 shows WRV values at a given SR number.

8.7.2 Strength properties

There are a number of factors affecting the strength of paper sheets. The morphological properties of fibres in wood are important (especially length), as is the extent of mechanical damage that occurs during chipping, blowing and refining. The length of cellulose chain (or DP) is also contributes to the strength properties. Chemical damage, i.e. shortening of cellulose chains takes place during pulping and bleaching. Refining is also greatly affected on the strength of paper sheet. [58]

One of the most important properties for copy paper is runnability in copy machine. Paper also should have good surface strength, and also sufficient bending stiffness. For coated fine papers important strength properties are good tensile strength, high tear strength and breaking stiffness and also high bending stiffness.

Only small differences in the tensile stiffness values were found, mainly in favour of the mixed pulps, Figure 32 and Figure 33.

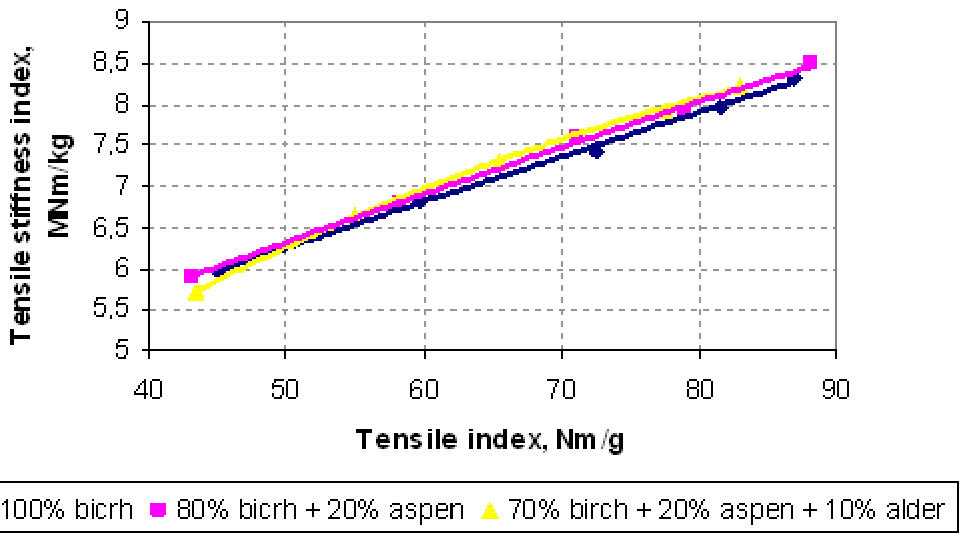


Figure 32. Tensile stiffness index as a function of tensile index.

Bending stiffness is dependent on the modulus of elasticity and the thickness of paper sheet. One way to increase the bending stiffness is to increase tensile stiffness (elastic modulus). [65]

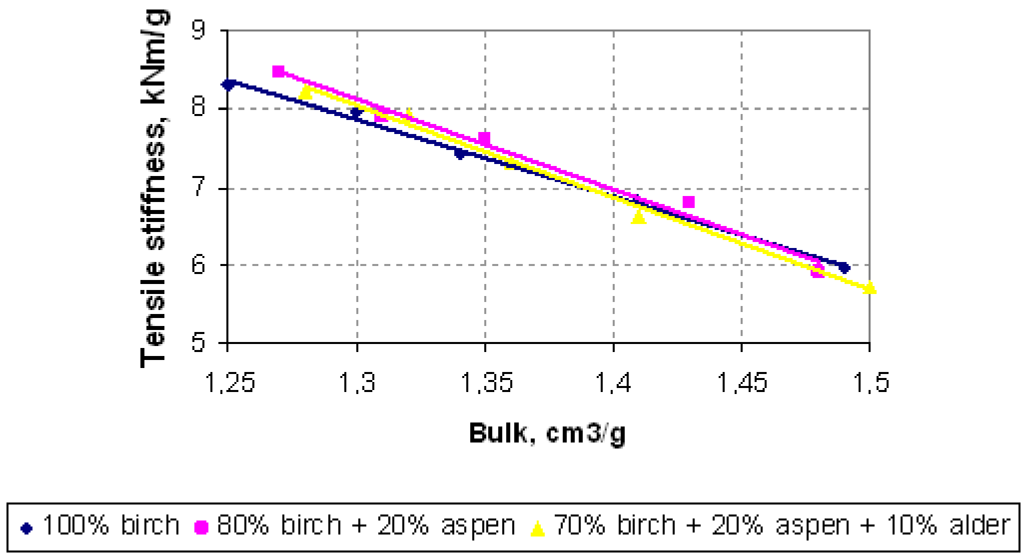


Figure 33. Tensile stiffness index vs. bulk.

Figure 33 shows that tensile stiffness at a given bulk. The differences are marginal.

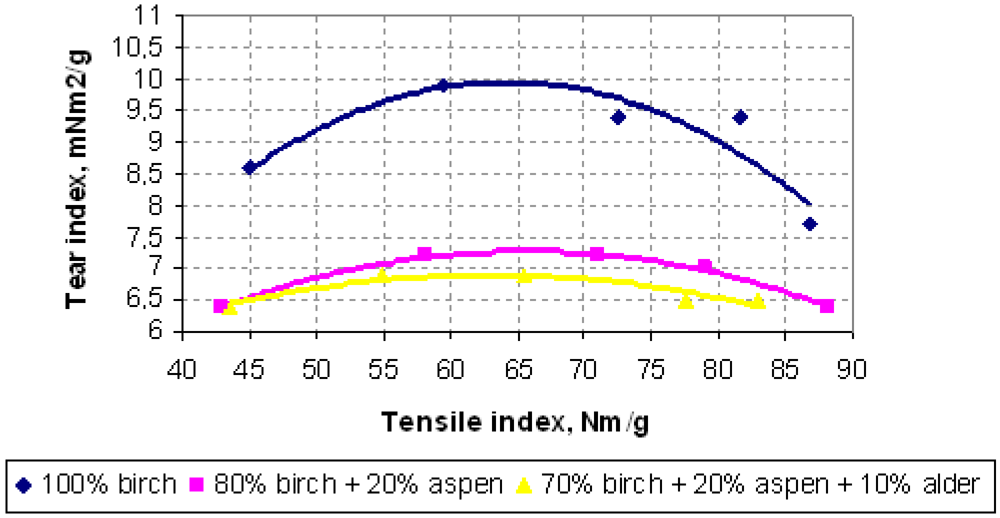


Figure 34. Tear index vs. tensile index.

The pure birch pulp had clearly higher tear index at a given tensile index than the other pulps (Figure 34). Tear index of (80% birch, 20% aspen) pulp and (70% birch, 20% aspen, 10% alder) pulp was the same. This is main benefit of pure birch pulp.

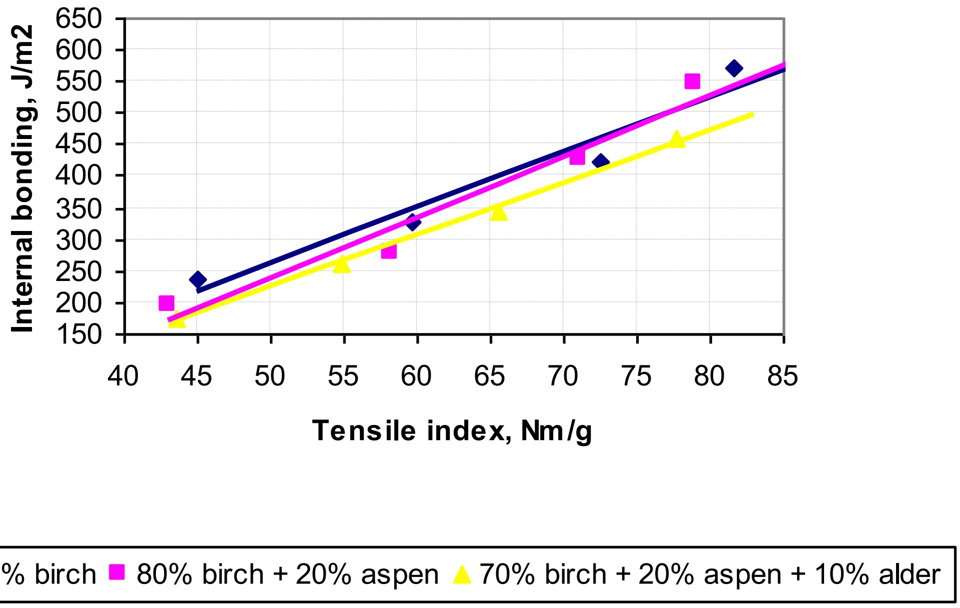


Figure 35. Internal bonding as a function of tensile index.

All pulps had approximately the same internal bonding values at a given tensile index (Figure 35). If the internal bonding are compared at a certain bulk or porosity (air resistance value), there was no differences between the various pulps.

8.7.3 Structural properties

The effects of replacement birch with aspen and alder on sheet density and air resistance were only minor if any. The same applies to roughness, Figure 38.

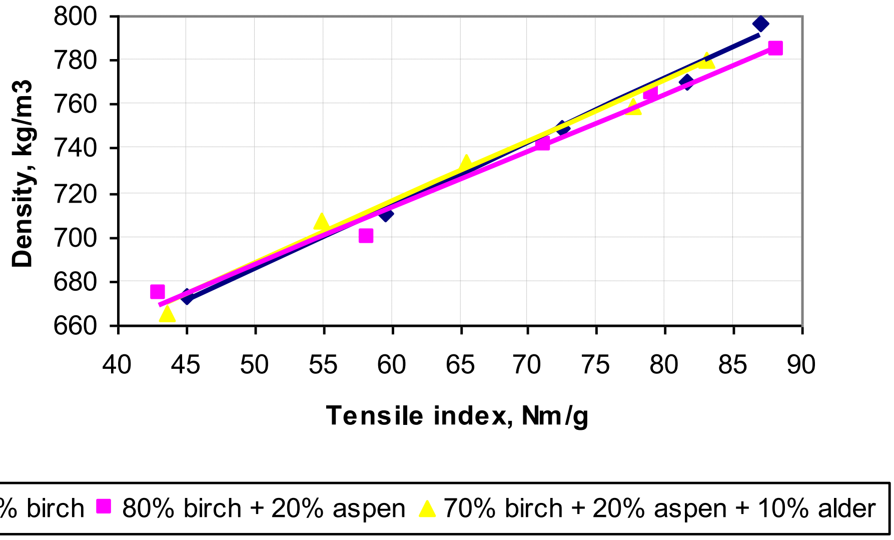


Figure 36. Density vs. tensile index.

Density or bulk is important properties when considering the suitability of a pulp for a fine paper. Several paper properties are affected by density and in many grades high bulk or low density is desired. There were no differences in density values at a given tensile index Figure 36.

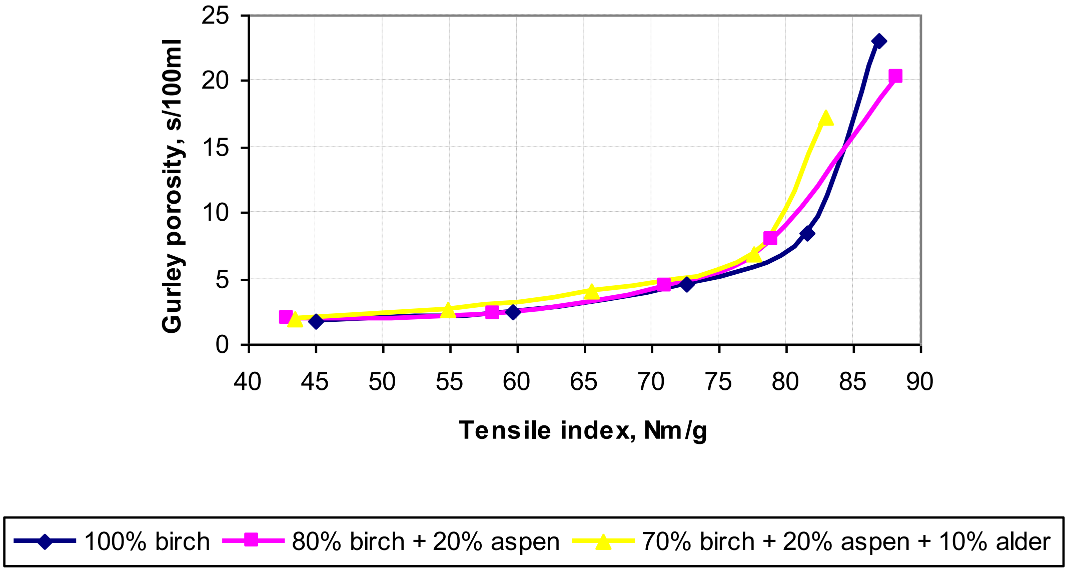


Figure 37. Air resistance as a function of tensile index.

In the drying of paper in the paper machines the water vapour should get out easily, so high enough porosity is needed [63] . There was a minor affect on porosity at high refining level when alder was added, (70% birch, 20% aspen, 10% alder) had slightly lower porosity at a given tensile index , than the other pulps (Figure 37). The pure birch pulp and (80% birch, 20% aspen) pulp had similar air resistance values at a given tensile index.

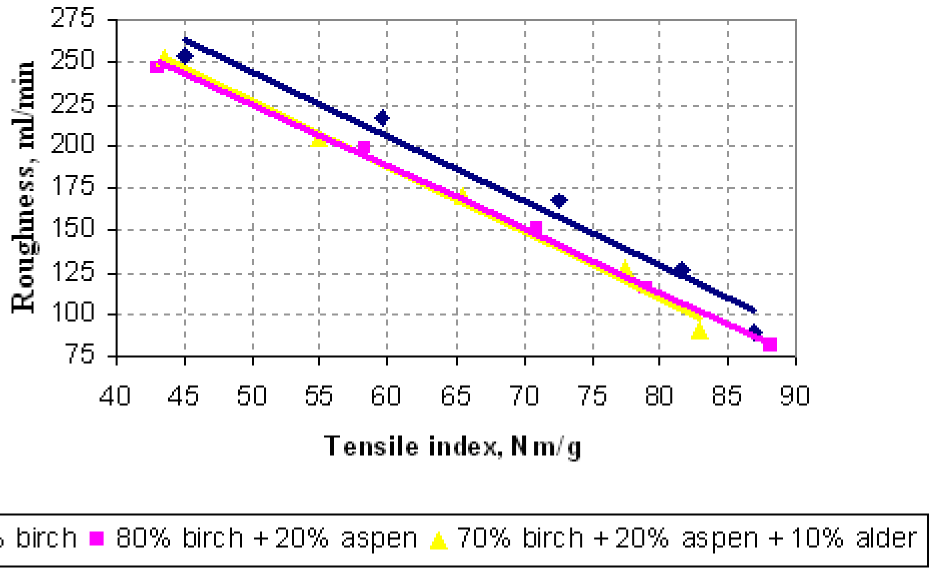


Figure 38. Roughness vs. tensile index.

The pure birch pulp had the highest surface roughness at a given tensile index (Figure 38). The mixed pulps had about the same smoothness.

8.7.4 Optical properties

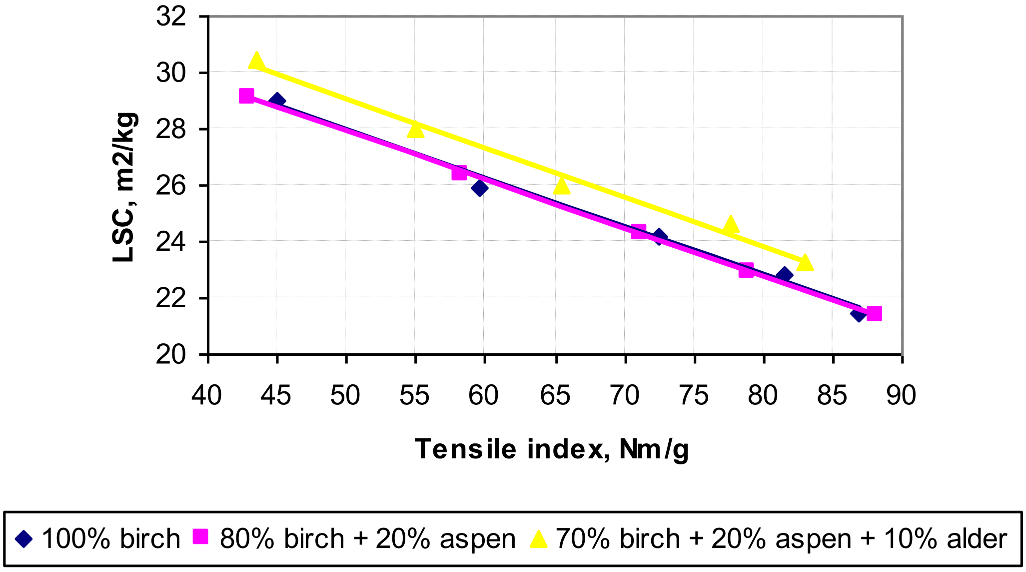


Figure 39. Light scattering coefficient vs. tensile index.

Addition of alder to birch pulp increased light scattering coefficient compared to the pure birch pulp at the same tensile index, Figure 39. Light scattering coefficient was clearly higher for (70% birch, 20% aspen, 10% alder) pulp than the other pulps.

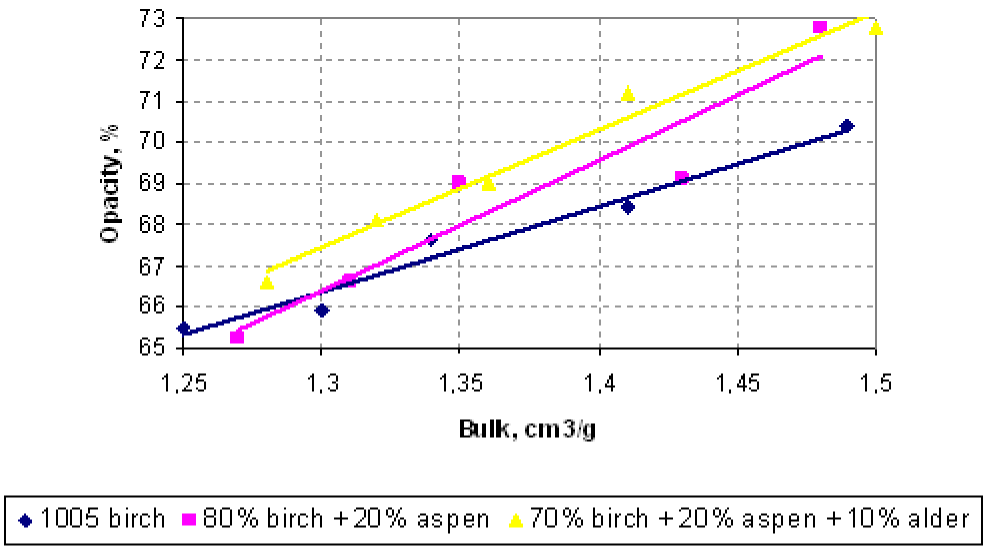


Figure 40. Opacity vs. bulk.

One of the critical property pairs of the fine paper and of the top layer of the paper board is opacity-bulk relationship [63]. Figure 40 shows the opacity values of the pulps plotted against bulk. Mixed pulp contained alder had higher opacity at a given bulk level than the (80% birch, 20% aspen) pulp or pure birch pulp.

9 Summary

In Table 29 presented properties of investigated pulps and their suitability for fine paper.

Table 29. Suitability for fine paper.

	100% birch	80% birch, 20% aspen	70% birch, 20% aspen, 10% alder
Pulping			
Cooking time	0	-	+
Yield	0	0	0
Rejects	0	0	0
Viscosity	0	0	-
Extractives	0	0	+
Fibre length	0	0	0
Fines	0	+	0
Bleaching			
Bleachability	0	+	-
Brightness stability	0	+	+
Runnability			
Drainage (SR number)	0	0	+
Beatability	0	0	±
Tear strength	0	--	--
Structural properties			
Bulk	0	0	0
Stiffness	0	0	0
Printability			
Opacity	0	0	+
Smoothness	0	+	+
Porosity	0	0	0

- Positive effect

- Negative effect

Pulping

Aspen was the easiest wood to cook, probably because morphological properties of wood, such as low lignin and high carbohydrate composition, bright colour of wood, *etc.* Cooking of alder was the most difficult and succeeded the worst. However, the differences were rather smoothed out, for blends of birch, aspen and alder wood.

Morphological properties

Many properties of pulp and handsheets can be explained by fibre morphology. Morphological properties of all the pulps were in the same magnitude. Exception was in the fines content. By replacement birch with aspen and alder difference were found in the content of fines. When 20% of aspen was added to birch pulp fines content was increased.

Bleaching

Brightness of mixed bleached pulps was slightly higher than that for pure birch pulp. Also, (80 % birch, 20 % aspen) pulp consumed less amount of chlorine dioxide than the two others.

Brightness stability was also investigated. Pure birch pulp had the lowest brightness stability and blended pulps had similar stability, when the effect of moisture and heat were tested.

Chemical composition

Residual lignin content was slightly lower for the mixed pulps, especially for the (80 % birch, 20 % aspen) pulp. Extractives content of pure birch pulp and (80 % birch, 20 % aspen) pulp was the same, and alder increase content of extractives. When alder was added the pulp contained slightly more fatty acids than the other pulps. There was also a difference in carbohydrates composition. Content of xylose were higher by 10% in the pure birch pulp compared to the other pulps.

Refinability and papermaking properties

There were not significant differences in energy consumption. Refining energy to achieve a certain SR level was slightly lower for the (70 % birch, 20 % aspen, 10 % alder) pulp. On other hand, the (70 % birch, 20 % aspen, 10 % alder) pulp requires somewhat more specific energy consumption, at a given tensile index than the 100% birch and (80 % birch, 20 % aspen) pulps.

Water retention values/drainability were slightly higher for the (70% birch, 20% aspen, 10% alder) pulp at a given tensile index. WRV values were approximately the same for all pulps when compared at a given SR number.

Strength properties were the best for pure birch pulp and the worst for (70 % birch, 20 % aspen, 10 % alder) pulp. Pure birch pulp has the best bonding strength. Compared at the same SR level, the tensile index of birch was superior; i.e. at SR 20 was pure birch 79 Nm/g, (80 % birch, 20 % aspen) blend 78 Nm/g, and (70 % birch, 20 % aspen, 10 % alder) pulp 72 Nm/g. The tensile stiffness at given bulk was approximately the same for all pulps. Compared at the same tensile index, the tear index of both mixed pulps was clearly lower. Internal bonding was the same for the pure birch and (80 % birch, 20 % aspen) pulps, and slightly lower for (70 % birch, 20 % aspen, 10 % alder) pulp up to tensile index level 70 Nm/g.

The mixed pulps had better optical properties than pure birch. Both blended pulps had smoother surface than pure birch pulp. Opacity was the highest for the (70 % birch, 20 % aspen, 10 % alder) pulp. Compared at high bulk, the opacity was higher for (80 % birch, 20 % aspen) pulp; at low bulk no difference occurred between the pulps.

Hardwood pulps are usually not used to provide strength but to provide better formation and optical properties to the paper. Both blended pulps have better optical properties. Blended pulps were brighter and easier to bleach than pure birch. Brightness stability was almost the same pulps, but for (80 % birch, 20 % aspen) pulp it was slightly higher.

10 Conclusions

The main purpose of the thesis was to study the behaviour of NHBK when small addition of aspen and alder are attended. Also, suitability of mixed pulp for production of fine paper was studied.

The samples do not necessarily give a right picture from the average properties of raw material because samples were chosen accidental from the mill chips; also just two parallel cooking was done. But achieving the main objective succeeded well. The general effect of replacement birch with aspen and alder were found.

The main conclusion of this thesis is that replacement of birch with aspen and alder decreases strength properties. The pure birch pulp had high strength properties and less extractive content (better tensile index and tear index than the blended pulps).

If the aspen and alder could replace the birch pulp in the mixture, better smoothness, optical properties and also formation would be achieved

However, advantages and disadvantages of the blended pulp could be smoothed out when fillers and binders will be added

Alder pulp would be difficult to use as a co-pulp in fine papers. Replacement of birch with alder by more than 10 % could negatively affect on properties of birch pulp. Still, small addition (5-10 %) of alder may be utilised for production of fine paper, as a new forest resource. However, depending on which paper properties are important the amount of alder, that can be torelated in cooking might vary to some extent.

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Appendices

Methods and standards

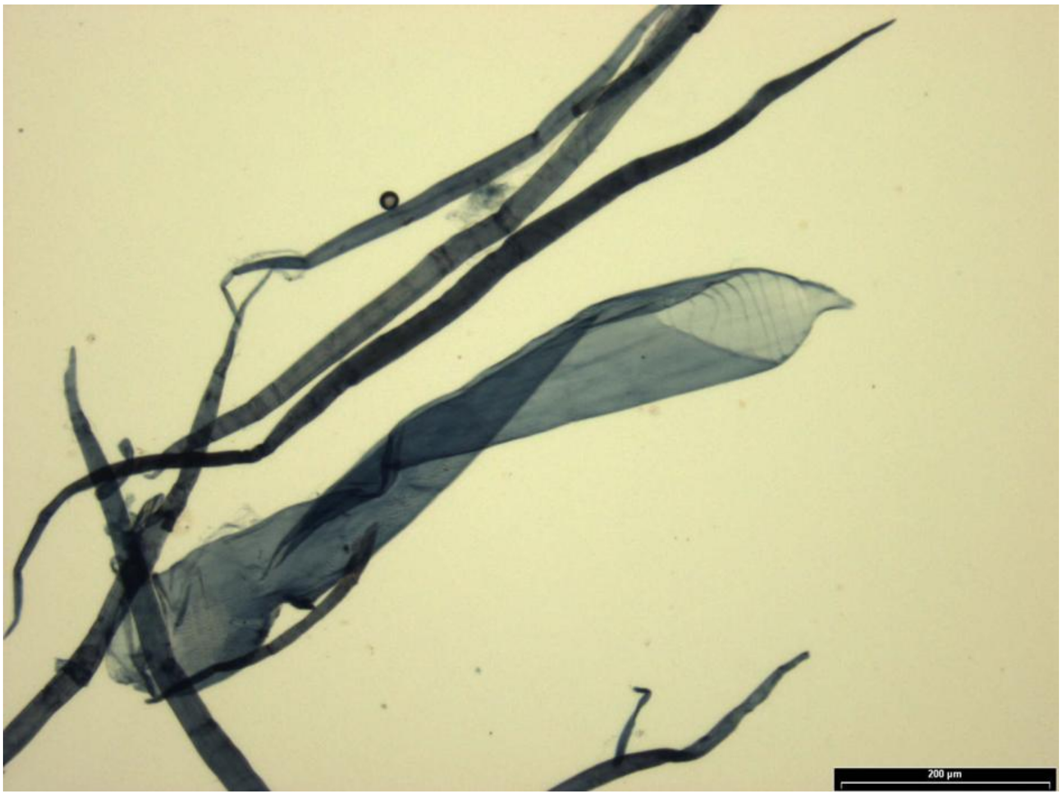
Pulps	
Screening	internal method
Wet disintegration	ISO 5263:1995 (E)
Dry matter content	ISO 638:1978 (E)
Viscosity	ISO 5351–2004 (E)
Kappa number	ISO 302:2004 (E), SCAN-C 1:00
Consistency	ISO 4119:1995 (E)
Brightness	ISO 2470:1999 (E), modified
Drainability, CSF,	ISO 5267–2:2001
Drainability, SR number	ISO 5276–1:1999
Fiber length	ISO 16065–1:2001
Coarseness	ISO 23713:2005
WRV	ISO 638:1978 (E)
Extractive content	SCAN-CM 49:03
Ash content	ISO 1762:2001 (E)
Carbohydrate	internal method
Microscopy imagine (fibre furnish analysis)	ISO 9184-4
Liquors	
Total, active and effective alkali of WL	SCAN-N 30:85
Residual alkali of BL	SCAN-N 33:94
Calorific value of BL	ISO 1928:1995 (E)
Handsheets	
Preparation of laboratory sheets	ISO 5269–1:2005(E), ISO 5270:1998(E)
Basic weight (grammage)	ISO 5270:1998 (E)
Scott bond	internal method
Tearing strength	ISO 1974:1990 (E)

Tear index	ISO 5270:1998 (E)
Burst strength	ISO 2758:2001(E)
Burst index	ISO 5270:1998 (E)
Bulking thickness	ISO 5270:1998 (E)
Bulking density	ISO 5270:1998 (E)
Bulk	ISO 5270:1998 (E)
Bendsten roughness	ISO 8791–2:1990 (E)
Tensile strength	ISO 5270,1924-2
Tensile index	ISO 5270,1924-2
Tensile energy absorption	ISO 5270,1924-2
TEA index	ISO 5270,1924-2
Tensile stiffness	ISO 5270,1924-2
Tensile stiffness index	ISO 5270,1924-2
Stretch	ISO 5270,1924-2
Y-value, (C/2º)	ISO 5631:2000 (E)
Opacity	ISO 2471:1998 (E)
Light scattering coefficient	ISO 9416:1998 (E)
Absorption coefficient	ISO 9416:1998 (E)
Brightness reversion, PC-number	Tappi T260 om-91
Air-resistance, Gurley	ISO 5636-5

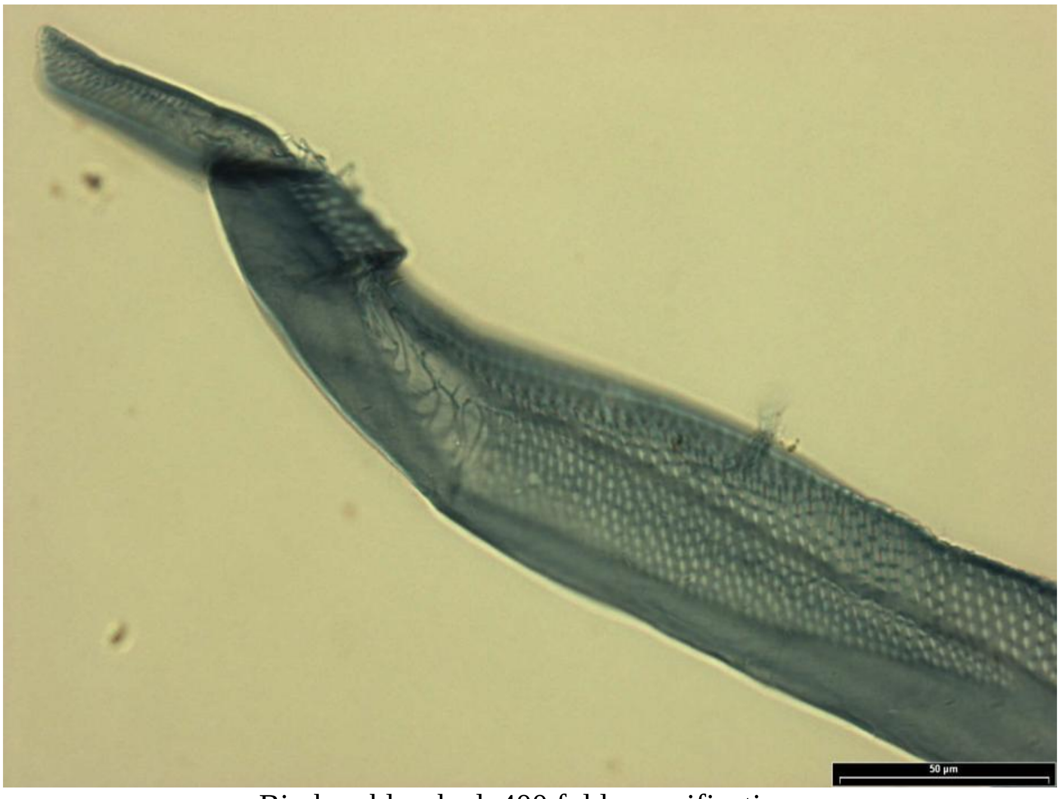
Description	Unit	100 % birch				
SEC	kWh/t	0	22	50	74	99
Schopper-Riegler	°SR	15.0	16.0	18.5	21.0	24.5
CSF	ml	660	610	580	520	465
Water retention value, WRV	g/g	1.81	1.94	2.01	2.09	2.27
Bulking thickness	µm	83	81	79	76	76
Apparent bulk density	kg/m³	673	711	749	770	797
Bulk	cm3/g	1.49	1.41	1.34	1.3	1.25
Tensile index	Nm/g	45	59.6	72.5	81.6	86.9
Stretch at break	%	2.62	3.05	3.5	3.7	3.65
TEA index	J/kg	-	-	-	-	-
Tensile stiffness index	MNm/kg	5.96	6.83	7.43	7.97	8.31
Breaking length	m	4588	6081	7395	8327	8859
Tearing resistance	mN	482	569	557	549	469
Tear index	mNm²/g	8.6	9.9	9.4	9.4	7.7
Burst index	kPam²/g	2.2	3.4	4	5.4	5.7
Bonding strength SB Low	J/m²	236	329	423	570	-
Brightness	%	81	80.5	80.1	79.4	79.3
Opacity	%	70.4	68.4	67.6	65.9	65.5
Light scattering coefficient	m²/kg	29	25.9	24.2	22.8	21.5
Absorption coefficient	m²/kg	0.29	0.28	0.27	0.28	0.27
Air resistance Gurley	s/100ml	1.8	2.4	4.6	8.5	23
Roughness Bendtsen 150/1	ml/min	246	198	150	115	81

Description	Unit	80% birch + 20% aspen				
SEC	kWh/t	0	22	50	74	99
Schopper-Riegler	°SR	14.5	15.5	18.0	20.5	23.0
CSF	ml	670	650	590	535	480
Water retention value, WRV	g/g	1.77	1.89	2.02	2.13	2.26
Bulking thickness	µm	94	84	85	79	77
Apparent bulk density	kg/m^3	674	700	742	765	785
Bulk	cm^3/g	1.48	1.43	1.35	1.31	1.27
Tensile index	Nm/g	43	58.3	71.1	79	88.2
Stretch at break	%	2.4	3.1	3.4	3.4	3.7
TEA index	J/kg	779	1312	1692	1862	2266
Tensile stiffness index	MNm/kg	5.91	6.8	7.61	7.91	8.48
Breaking length	m	4385	5951	7252	8054	8994
Tearing resistance	mN	408	426	457	421	389
Tear index	mNm^2/g	6.4	7.2	7.2	7	6.4
Burst index	$kPam^2/g$	2.2	3.1	4.2	4.7	5.2
Bonding strength SB Low	J/m^2	194	280	425	545	-
Brightness	%	82.8	82	81.3	80.6	79.9
Opacity	%	72.8	69.1	69	66.6	65.2
Light scattering coefficient	m^2/kg	29.1	26.4	24.3	22.9	21.4
Absorption coefficient	m^2/kg	0.23	0.25	0.24	0.26	0.27
Air resistance Gurley	s/100ml	1.92	2.29	4.38	7.98	20.3
Roughness Bendtsen 150/1	ml/min	253	217	167	126	89

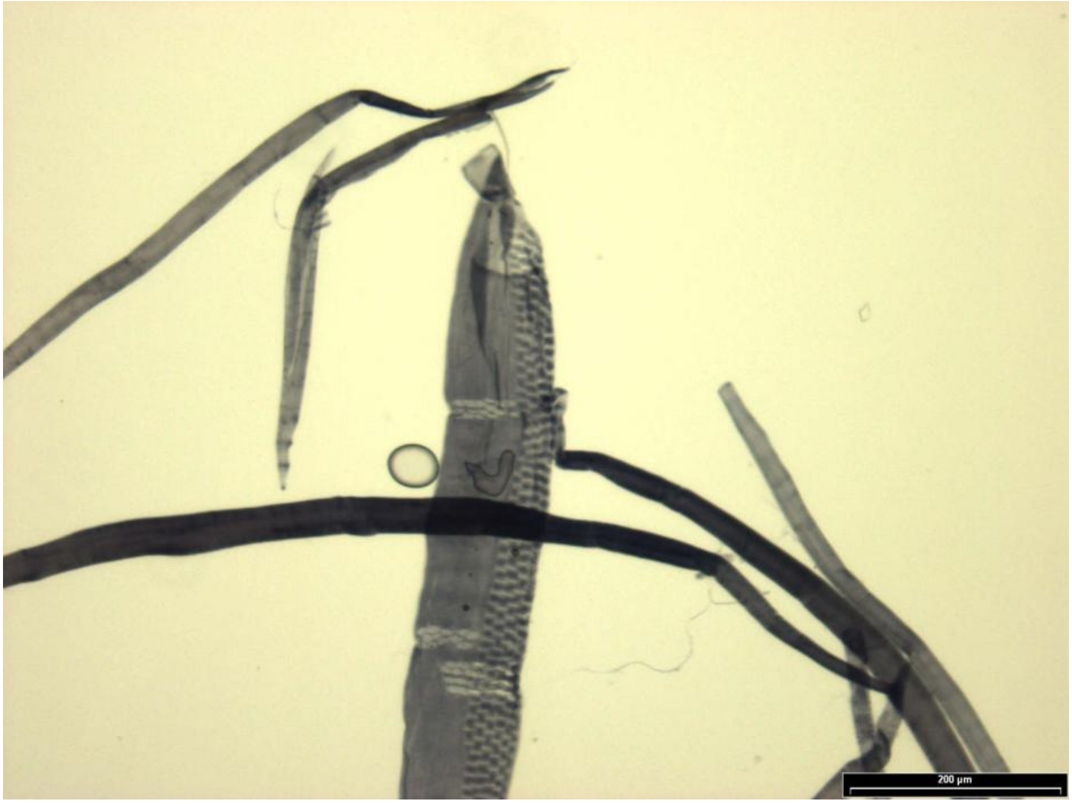
Description	Unit	70% birch + 20% aspen + 10% alder				
SEC	kWh/t	0	22	50	74	99
Schopper-Riegler	°SR	15.0	16.0	18.5	21.0	24.5
CSF	ml	660	610	580	520	465
Water retention value, WRV	g/g	1.81	1.94	2.01	2.09	2,22
Bulking thickness	µm	91	86	81	79	75
Apparent bulk density	kg/m^3	666	707	734	759	780
Bulk	cm^3/g	1.5	1.41	1.36	1.32	1.28
Tensile index	Nm/g	43.5	54.9	65.5	77.6	83
Stretch at break	%	2.5	2.7	3.1	3.3	3.5
TEA index	J/kg	794	1075	1460	1811	2020
Tensile stiffness index	MNm/kg	5.73	6.64	7.31	7.92	8.23
Breaking length	m	4435	5602	6685	7913	8466
Tearing resistance	mN	388	420	409	388	381
Tear index	mNm^2/g	6.4	6.9	6.9	6.5	6.5
Burst index	$kPam^2/g$	2.3	3.2	4	4.5	5.2
Bonding strength SB Low	J/m^2	175	260	345	459	-
Brightness	%	82.2	81.6	81.0	80.5	80.0
Opacity	%	72.8	71.2	69	68.1	66.6
Light scattering coefficient	m^2/kg	30.5	28	26	24.6	23.3
Absorption coefficient	m^2/kg	0.25	0.25	0.27	0.27	0.28
Air resistance Gurley	s/100ml	1.93	2.65	4.05	6.87	17.2
Roughness Bendtsen 150/1	ml/min	252	204	170	127	90



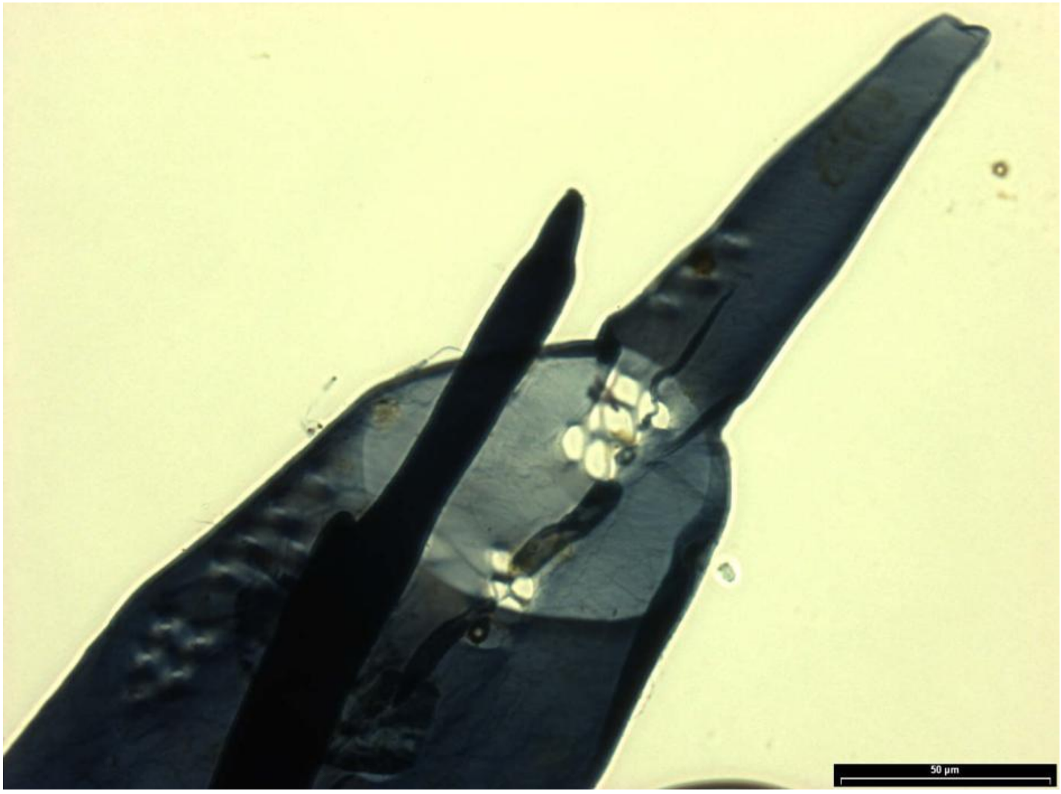
Birch unbleached, 100 fold magnification.



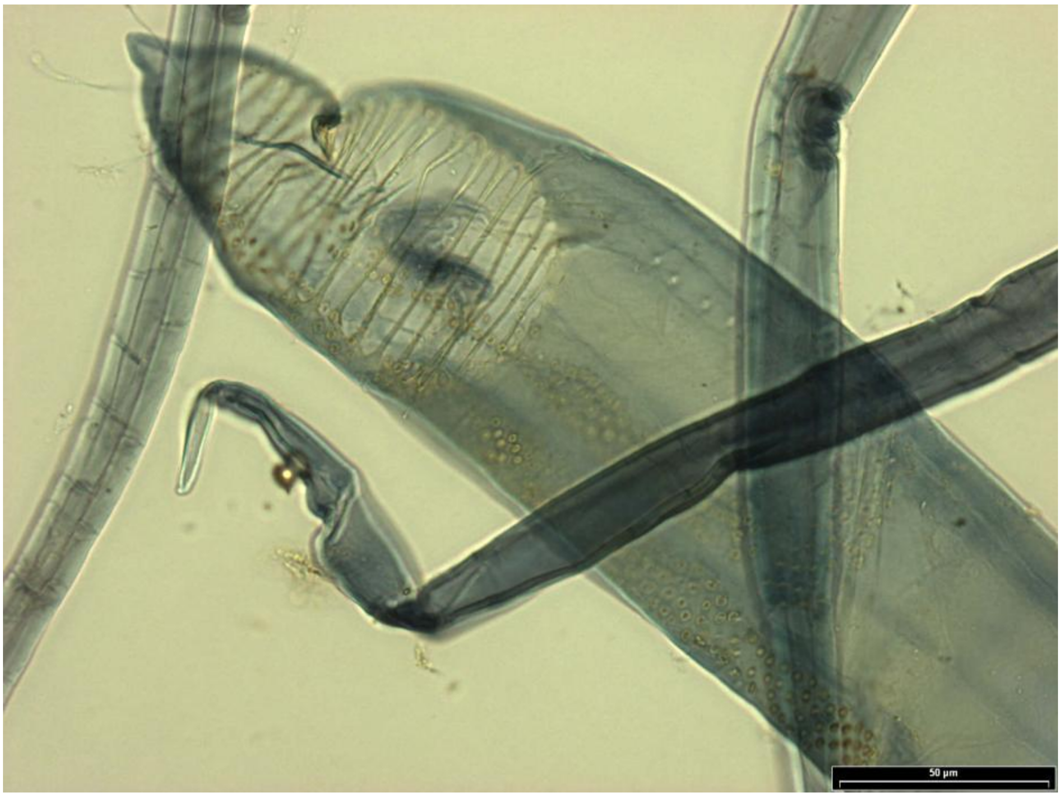
Birch unbleached, 400 fold magnification.



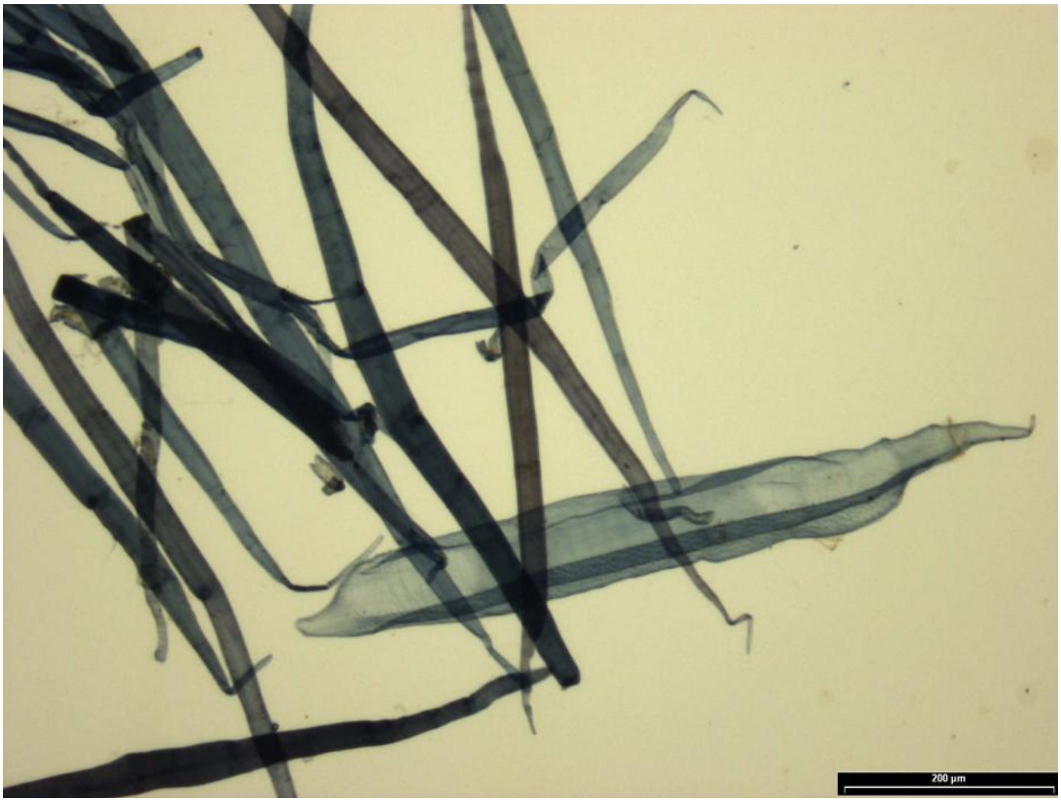
Aspen unbleached, 100 fold magnification.



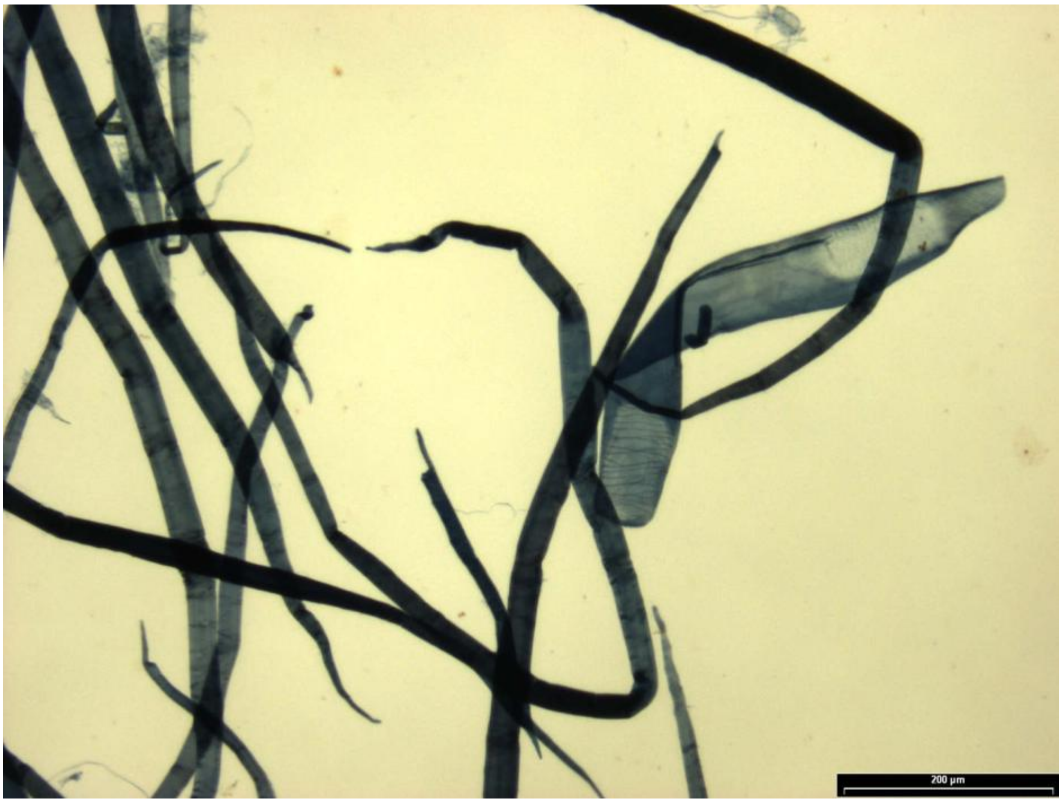
Aspen unbleached, 400 fold magnification.



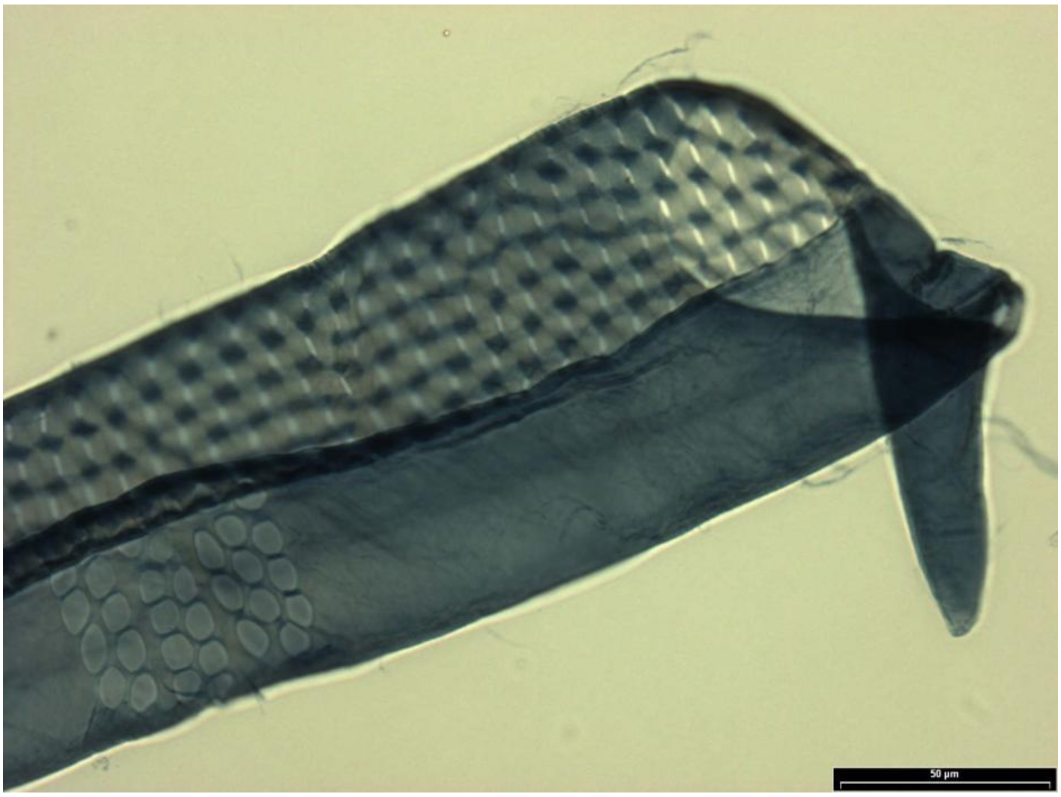
Alder unbleached, 100 fold magnification.



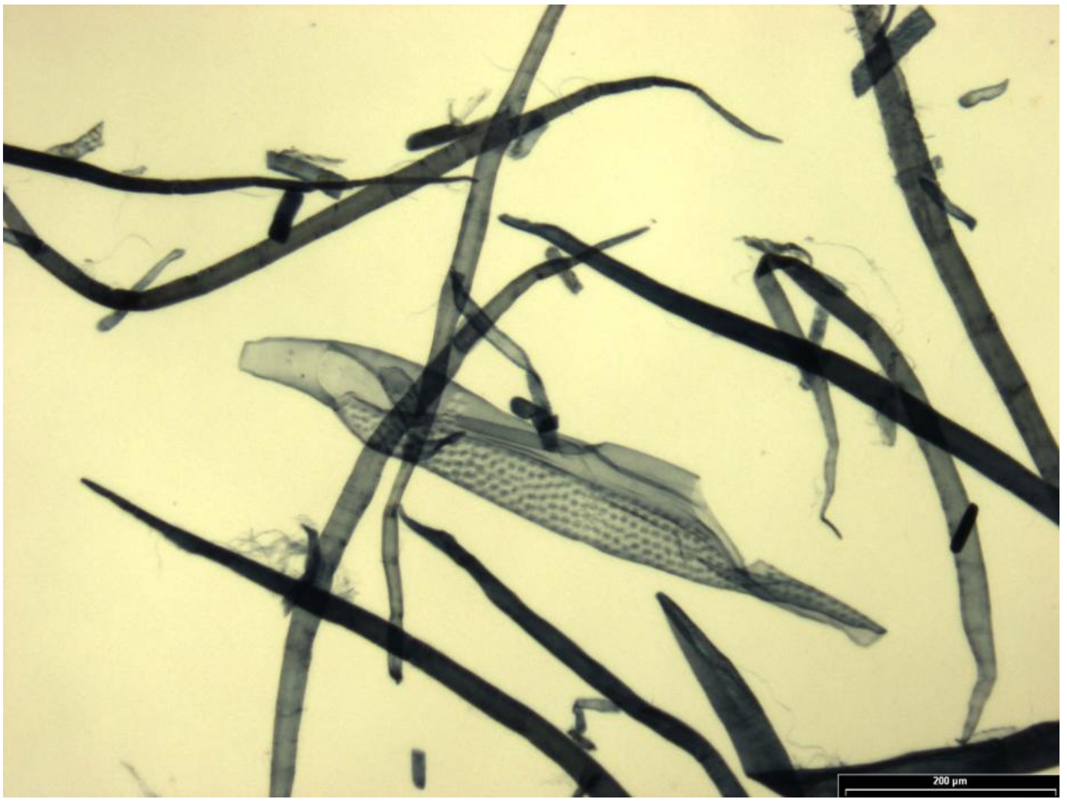
Alder unbleached, 400 fold magnification.



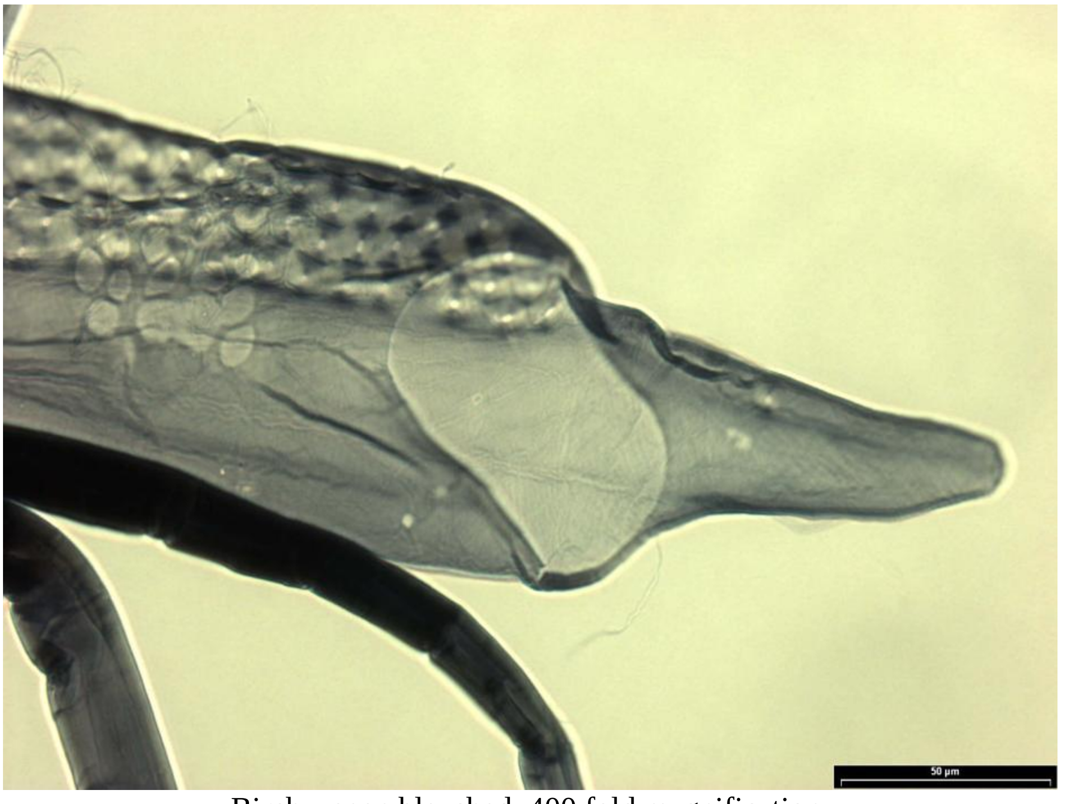
Birch bleached, 100 fold magnification.



Birch bleached, 400 fold magnification.

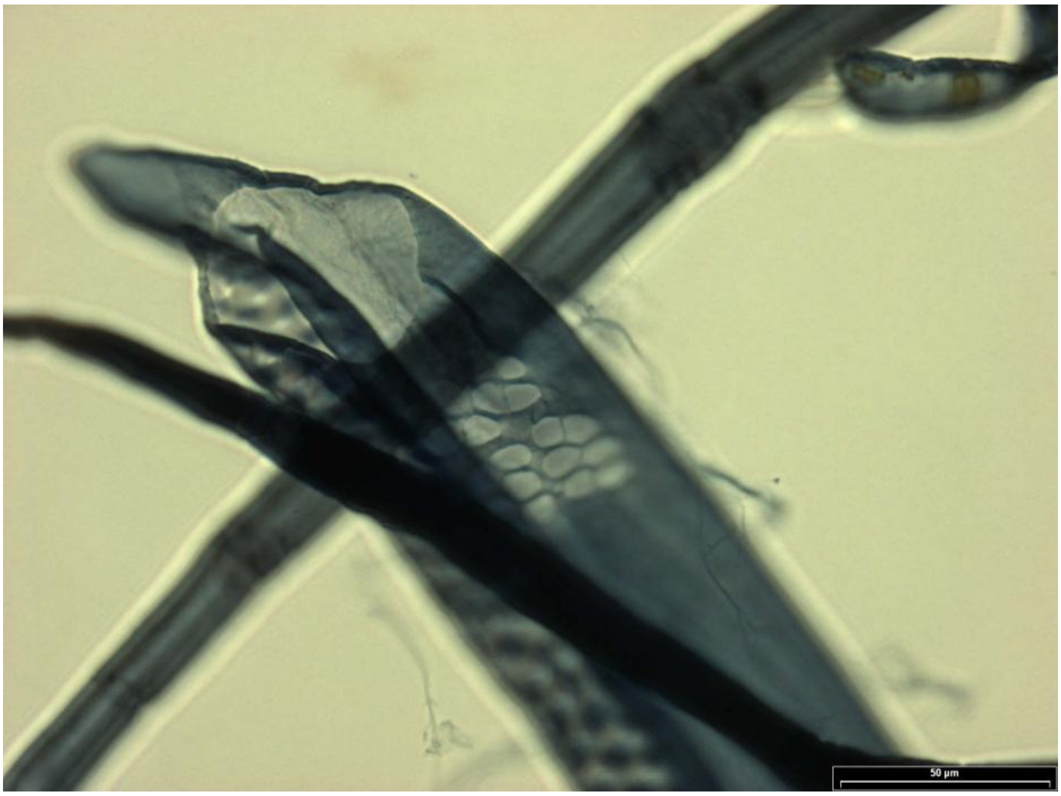


Birch, aspen bleached, 100 fold magnification.

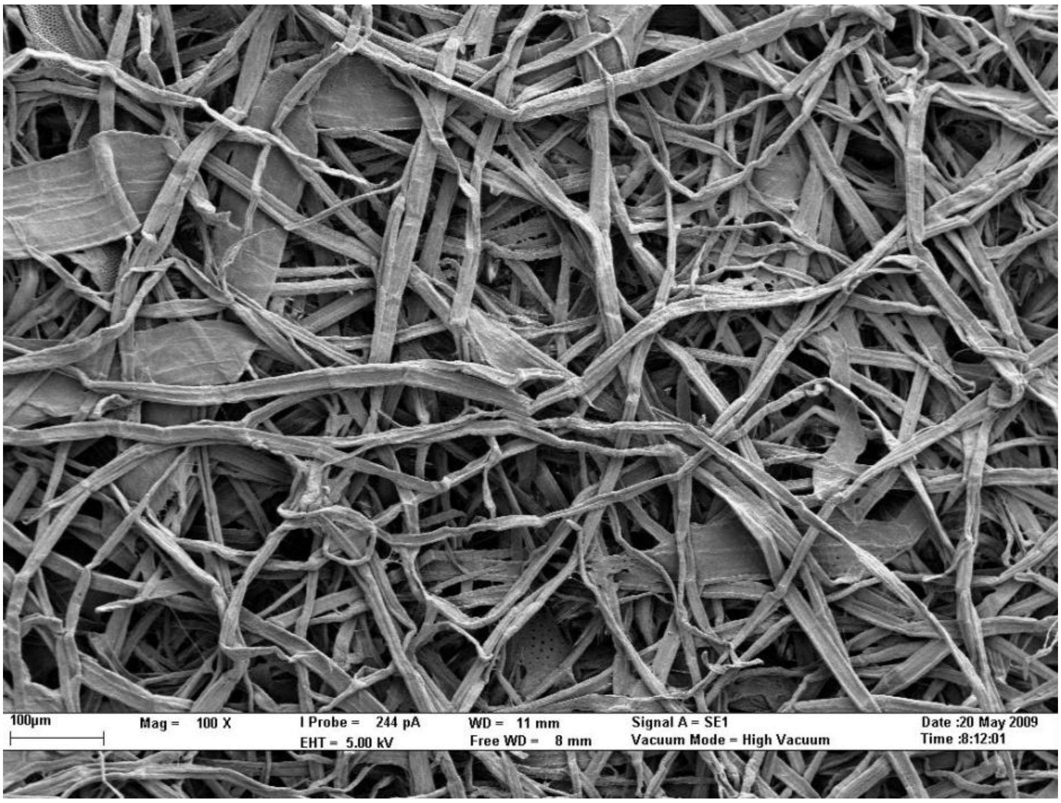


Birch, aspen bleached, 400 fold magnification.

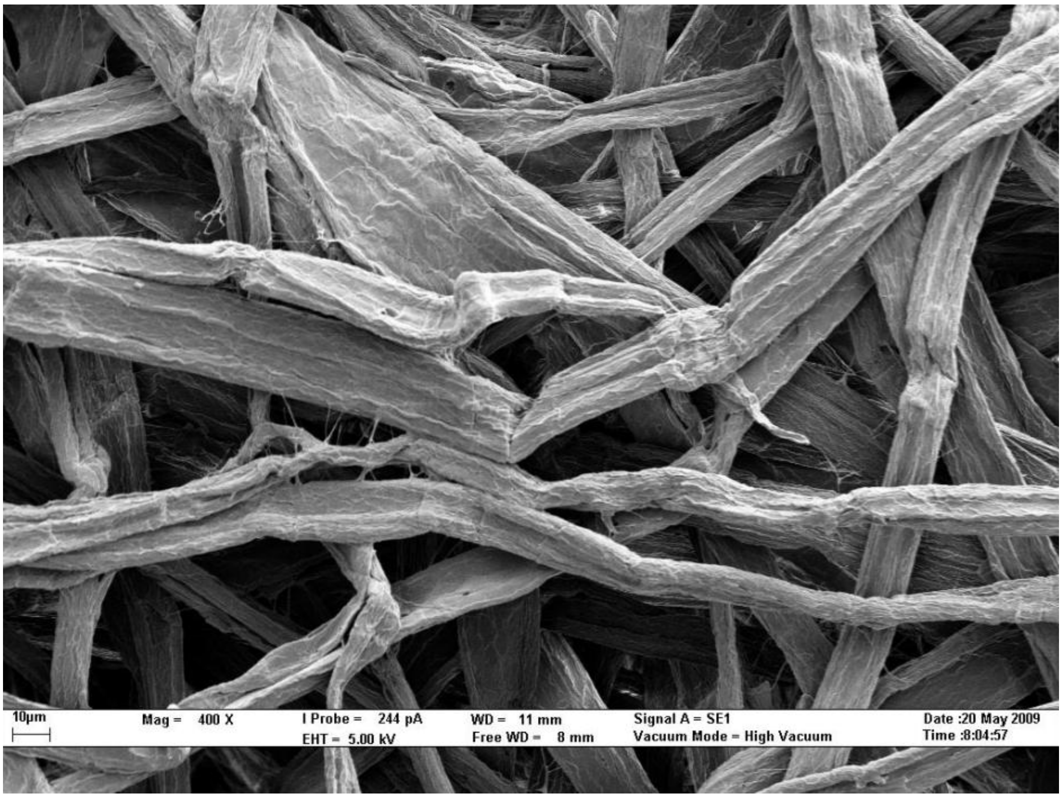
Birch, aspen, alder bleached, 100 fold magnification.



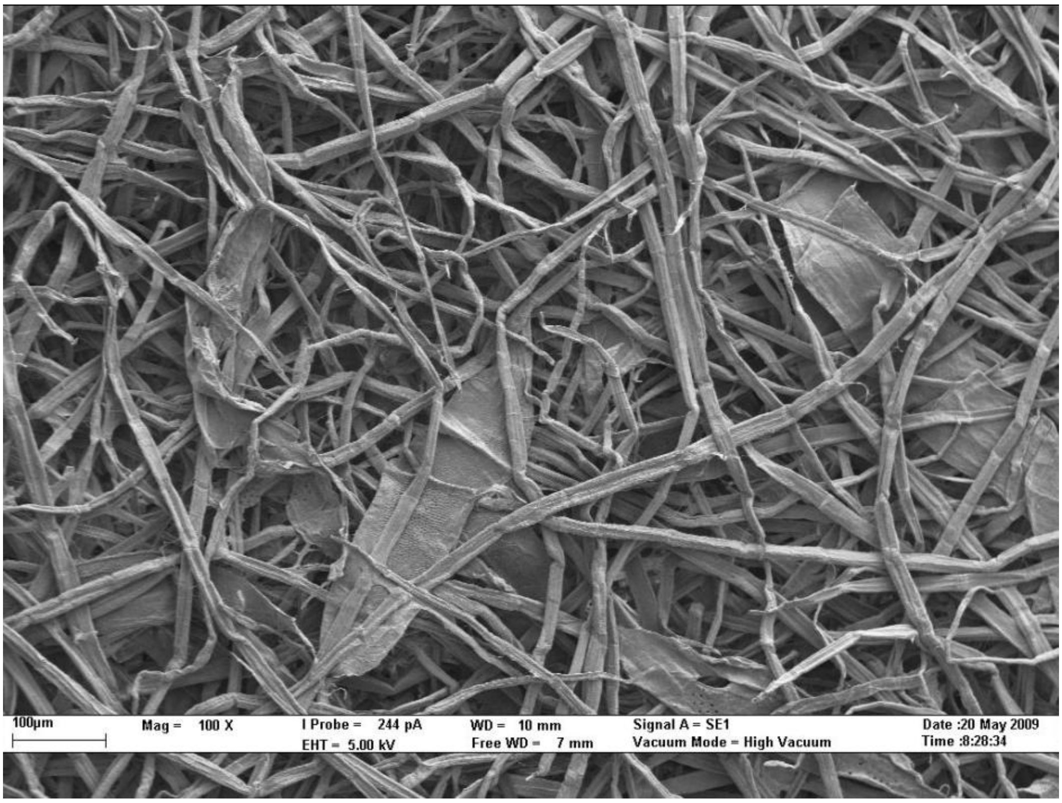
Birch, aspen, alder bleached, 400 fold magnification.



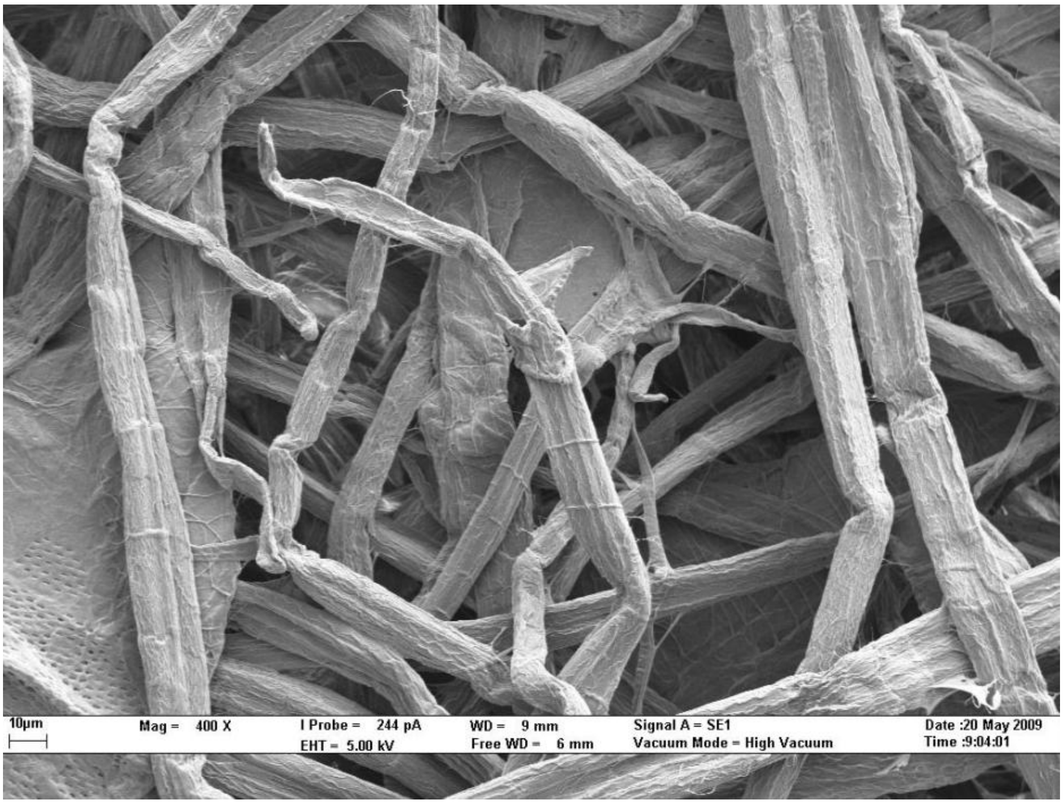
ESEM picture of 100 fold magnification of birch bleached pulp.



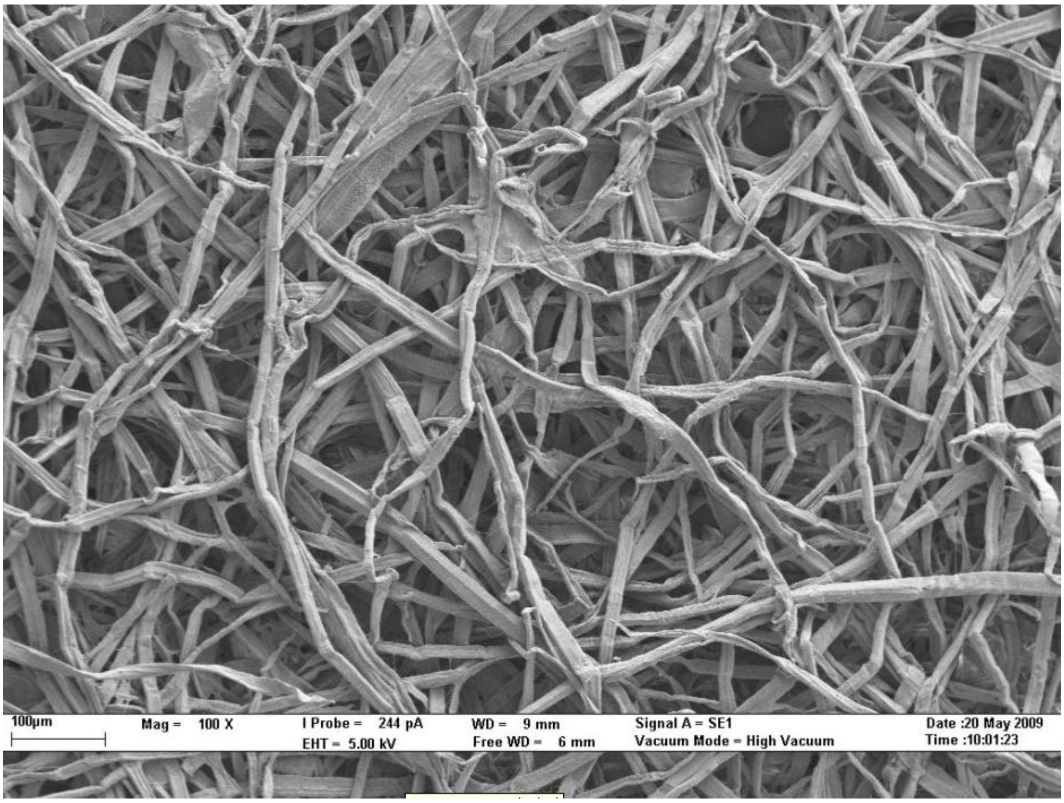
ESEM picture of 400 fold magnification of birch bleached pulp.



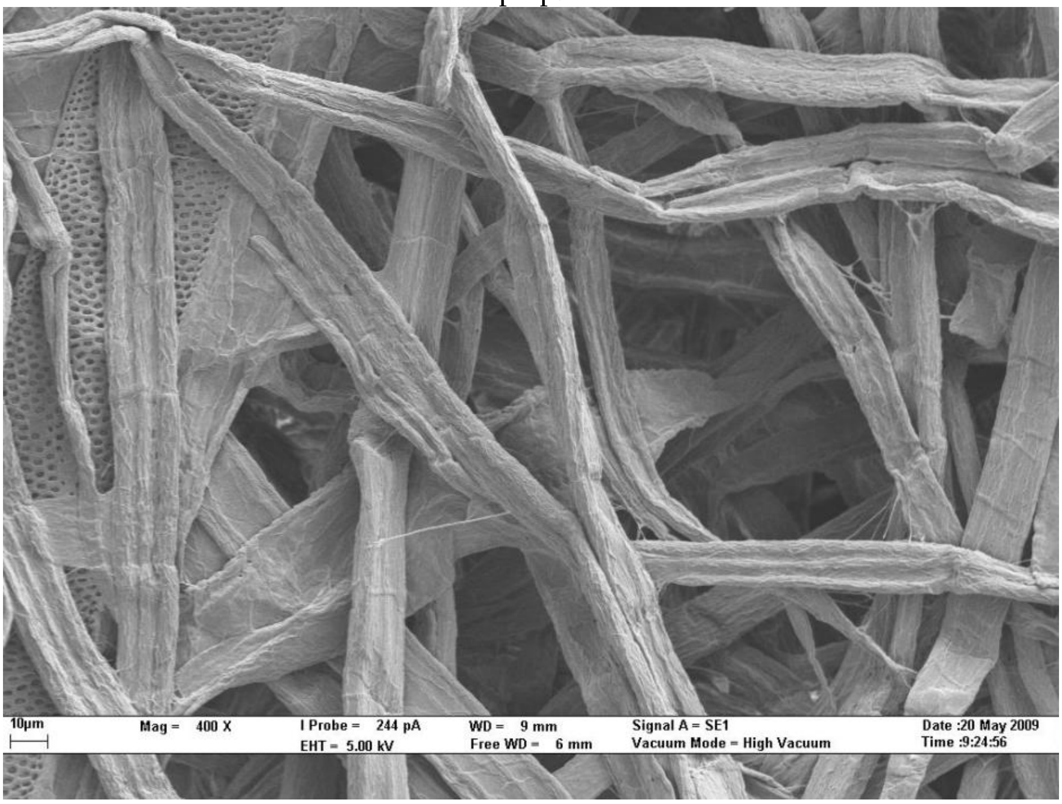
ESEM picture of 100 fold magnification of mixed birch and aspen bleached pulp.



ESEM picture of 400 fold magnification of mixed birch and aspen bleached pulp.



ESEM picture of 100 fold magnification of mixed birch, aspen and alder bleached pulp.



ESEM picture of 400 fold magnification of mixed birch, aspen and alder bleached pulp.

FiberLab results (unbleached pulp)

Pulp	Fiber length, [mm]	Fiber width, [µm]	Fines, [%]	Coarsensess, [mg/m]	Cell Wall Tchickness, [µm]	Vessels, [1/1000 fibers]	Curl, [%]	Cross sectional area, [µm2]	Fibrillation, [%]	Kink index [1/m]
Birch	0.98	19.9	1.27	0.089	5.9	22.24	14.8	227.8	2.94	868.83
Aspen	0.93	20.8	4.66	0.090	6.2	31.76	12.1	242.3	2.98	715.52
Alder	0.78	21.2	2.01	0.066	5.0	24.79	12.2	200.7	2.72	859.14
Birch, aspen	0.98	20.1	1.81	0.092	6	27.22	14.6	232.7	2.91	895.4
Birch, aspen, alder	0.96	19.9	1.91	0.090	5.9	25.1	14.0	225.9	2.93	822.01

FiberLab results (bleached pulps)

Pulp	Refining energy, [KWh/t]	Fiber length, [mm]	Fiber width, [µm]	Fines, [%]	Coarsensess, [mg/m]	Cell Wall Thickness, [µm]	Vessels, [1/1000 fibers]	Curl, [%]	Cross sectional area, [µm2]	Fibrillation, [%]	Kink index [1/m]
Birch	0	0.95	20.0	1.47	0.100	5.8	38.63	19.5	229.6	3.19	1014.91
	25	0.95	19.6	1.66	0.097	6.0	22.01	18.0	226.8	3.05	889.67
	50	0.97	19.9	1.71	0.096	6.0	23.21	17.6	235.0	3.27	769.35
	75	0.97	19.8	1.75	0.094	6.1	26.02	17.8	234.6	3.49	773.37
	100	0.96	20.1	1.96	0.098	6.1	26.81	17.9	234.9	3.61	720.29
Birch, aspen	0	0.93	19.8	2.17	0.088	5.9	29.59	19.1	228.1	3.27	955.58
	25	0.95	20.0	2.32	0.096	5.9	27.60	18.0	229.0	3.35	839.48
	50	0.95	19.7	2.26	0.090	5.9	25.64	17.2	226.0	3.46	750.10
	75	0.95	19.9	2.37	0.091	6.0	25.59	17.3	231.9	3.57	713.09
	100	0.96	19.9	2.36	0.092	6.0	27.73	17.6	232.4	3.83	679.52
Birch, aspen, alder	0	0.91	19.7	2.43	0.094	5.7	28.46	18.1	217.8	3.39	956.58
	25	0.93	19.6	2.36	0.088	5.8	26.71	17.3	214.2	3.34	824.41
	50	0.93	19.7	2.52	0.094	5.8	26.29	16.9	218.2	3.52	725.64
	75	0.94	19.7	2.50	0.082	5.9	23.84	16.7	219.7	3.63	703.63
	100	0.93	19.7	2.55	0.088	5.9	16.3	16.3	225.2	3.74	694.49