

Lappeenranta University of Technology
The Faculty of Technology
Mechanical Engineering
New Packaging Solutions

Ulla Lainio

**NATURAL AND SYNTHETIC FIBRES IMPROVING TENSILE
STRENGTH AND ELONGATION OF PAPER PRODUCTS**

Master's thesis

Examiners:

PhD Henry Lindell, professor of packaging technology at
Lappeenranta University of Technology

PhD Pedro Fardim, professor of fibre and cellulose technology at Abo
Akademi Turku

ABSTRACT

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Natural and synthetic fibres improving tensile strength and elongation of paper products

Master's Thesis
2009

84 pages, 36 figures, 17 tables and 2 appendices.

Examiners: PhD Henry Lindell, professor of packaging technology, Lappeenranta University of Technology and
PhD Pedro Fardim, professor of fibre and cellulose technology, Abo Akademi
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Keywords: Natural fibre, synthetic fibre, tensile strength, elongation, stretch, fibre matrix, fibre bond, speciality paper, viscose, polyester, nylon, polyethylene, polypropylene and bicomponent fibres.

The theory part of the Master's thesis introduces fibres with high tensile strength and elongation used in the production of paper or board. Strong speciality papers are made of bleached softwood long fibre pulp. The aim of the thesis is to find new fibres suitable for paper making to increase either tensile strength, elongation or both properties. The study introduces how fibres bond and what kind of fibres give the strongest bonds into fibre matrix.

The fibres that are used in the manufacturing of non-wovens are long and elastic. They are longer than softwood cellulose fibres. The end applications of non-wovens and speciality papers are often the same, for instance, wet napkins or filter media. The study finds out which fibres are used in non-wovens and whether the same fibres could be added to cellulose pulp as armature fibres, what it would require for these fibres to be blended in cellulose, how they would bind with cellulose and whether some binding agents or thermal bonding, such as hot calendaring would be necessary. The following fibres are presented: viscose, polyester, nylon, polyethylene, polypropylene and bicomponent fibres.

In the empiric part of the study the most suitable new fibres are selected for making hand sheets in laboratory. Test fibres are blended with long fibre cellulose. The test fibres are viscose (Tencel), polypropylene and polyethylene. Based on the technical values measured in the sheets, the study proposes how to continue trials on paper machine with viscose, polyester, bicomponent and polypropylene fibres.

TIIVISTELMÄ

Lappeenrannan teknillinen yliopisto
Teknillinen tiedekunta
Konetekniikan laitos
New Packaging Solutions

Ulla Lainio

Paperituotteiden vetolujuutta ja venymää parantavat luonnon- ja synteettiset kuidut

Diplomityö
2009

84 sivua, 36 kuvaa, 17 taulukkoa ja 2 liitettä.

Tarkastajat: FT, professori Henry Lindell, pakkaustekniikka, Lappeenrannan teknillinen yliopisto
PhD, professori Pedro Fardim, kuitu- ja selluloosatekniikka, Abo Akademi Turku

Hakusanat: luonnonkuitu, synteettinen kuitu, vetolujuus, venymä, kuitumatriisi, kuitusidos, erikoispaperi, viskoosi, polyesteri, nylon, polyeteeni, polypropeeni ja bi-komponenttikuidut.

Diplomityön teoreettinen osa selvittää, mitä kuituja voidaan käyttää, kun tavoitteena on valmistaa mahdollisimman lujaa ja venyvää paperia tai kartonkia. Lujissa erikoispapereissa käytetään perinteisesti valkaistua pitkäkuitusellua. Työn tarkoituksena on etsiä uusia kuituja, jotka soveltuisivat paperin valmistukseen ja lisäisivät joko vetolujuutta, venymää tai molempia. Työssä selvitetään, miten kuitusidokset syntyvät ja minkälaisilla kuiduilla saadaan lujimmat sidokset kuitumatriisiin.

Kuitukankaissa käytettävät synteettiset kuidut ovat pitkiä ja joustavia. Kuidut ovat pidempiä kuin havusellun kuidut. Kuitukankaiden ja erikoispaperien loppukäyttösovellutukset ovat usein samat, esimerkiksi kosteuspyyhkeet tai suodatinmateriaalit. Tutkimuksessa selvitetään, mitä kuituja kuitukankaissa käytetään ja voisiko samoja kuituja lisätä selluun lujitteeksi. Tutkimuksessa tarkastellaan, mitä uusien kuitujen käyttö sellun seassa edellyttäisi, kuinka ne sitoutuisivat sellukuituihin ja pitäisikö kuitujen sitomiseksi käyttää sideaineita tai lämpökäsittelyä, kuten kalanteria. Työssä esitellään viskoosi, polyesteri, nylon, polyeteeni, polypropeeni ja bi-komponenttikuidut.

Työn empiirisessä osassa valitaan sopivimmat uudet kuidut, joista valmistetaan laboratorioarkkeja. Koekuituja sekoitetaan pitkäkuituselluloosaan. Koekuidut ovat viskoosi (Tencel), polypropeeni ja polyeteeni. Koearkkien teknisten arvojen perusteella ehdotetaan jatkotutkimusta paperikoneella viskoosi-, polyesteri-, bikomponentti- ja polypropeenikuiduilla.

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Turku, December 10 2009

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ABBREVIATIONS

cN/tex	centnewton/tex, a strength value
Co-PES	co-polyethersulfone
g/cm ³	grams per cubic centimetre
g/den, g/d	grams per denier
g/m ²	grams per square metre
denier	1 denier = 0,111 mg/m
DSC	differential scanning calorimeter
dtex	decitex. Unit of the linear density of a continuous filament or yarn, equal to 1/10th of a tex or 9/10th of a denier
EVA	ethylene vinyl acetate
HDPE	high density polyethylene
HWM	high wet modulus (rayon)
H415 865	Tencel fibre grade
IR	infra red
J/kg	joule per kilogram
kN/m	kilonewton per meter
LDPE	low density polyethylene
L&W	Lorentzen & Wettre
mm	millimetre
mN	micronewton
Nm	nanometer
N/m	newton per meter
N/tex	newton/tex, a strength value
Mm	micrometer
OH group	hydroxyl group
PE	polyethylene
PET	polyethylene terephthalate
POY	partially oriented polyester yarn
PP	polypropylene
PSNSD	fiber grade produced by DuPontSA
RBA	relative bonded area
RWSD	fiber grade produced by DuPontSA
SEM	scanning electron microscope
SR	Schopper-Riegler pulp consistency
TGA	thermogravimetric analyzer
tex	1 tex = 1 mg/m (milligrams per meter)
UV	ultra violet

1 INTRODUCTION

The purpose of this study “Natural and synthetic fibres improving tensile strength and elongation at break of paper products” is to introduce alternative fibres for the production of wood free uncoated paper or board. The alternative fibres should improve tensile strength and elongation at break. Among the other important properties, superior tensile strength and elongation (stretch) are crucial considering the end use of speciality papers, such as masking tape and wet wipe applications. In addition to speciality papers, the new fibres could be used in moulding papers used for pressed thermo formed trays.

This study presents the key fibre raw materials, softwood and hardwood cellulose pulp, currently used in the production of speciality papers with focus on fibre dimensions and fibre properties. As the tensile strength is largely dependent on bonding ability of fibres, the fibre bonding methodology is presented. Concepts “tensile strength” and “elongation at break” and factors affecting these properties are also considered. The study illustrates which cellulose based fibres give the best strength.

The purpose of this study is to introduce new fibres which are not used today in the manufacturing of speciality papers or board. Non-woven materials, produced of man-made fibres or of a mixture of man-made and natural fibres, often have superior strength compared to cellulose pulp based speciality paper. The fibres used in the production of non-woven materials, are longer and give elevated strength to the end product compared to cellulose pulp fibres. The end-use of a non-woven product can be identical to a paper product, for example a wet wipe. Consequently, the study represents the most common natural and man-made fibres and their properties used in the production of non-woven materials. These are: rayon (viscose), polyester, polypropylene, polyethylene, bicomponent fibres and nylon.

Based on the literature and internet sources used in this study, there is a lot of information available concerning tensile strength of fibres. Tensile strength is a subject which has been largely studied. Elongation at break, instead, appears to be an area which has been studied in a lesser extend. The limited availability of studies regarding the elongation at break affects the content of this study, being more focused on tensile strength.

The empiric part of this study presents practical trials. Test hand sheets with new fibres were made at Abo Akademi fibre and cellulose technology laboratory. The new fibres were mixed with softwood long fibre cellulose pulp. The hand sheets were measured with the focus on tensile strength and elongation. Based on the results, the findings and further recommendations are presented at the end of the study.

2 THEORY PART OF THE STUDY

2.1 Definition of tensile strength and elongation at break

This study introduces fibres with high tensile strength and fibres with high elongation.

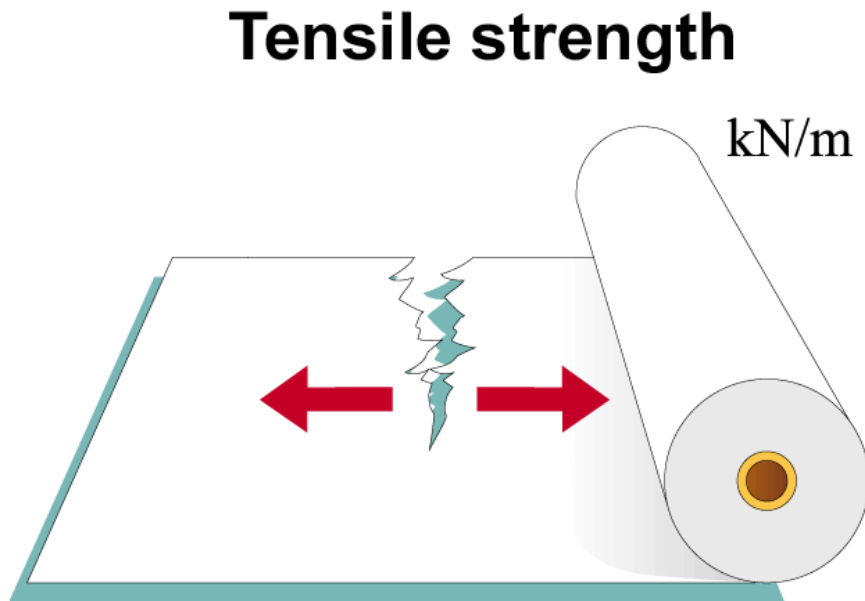


Figure 1. Illustration of tensile strength (Knowpap, 2004)

Tensile strength is the highest loading rate a paper or board sample sheet can withstand without breaking, when being stretched in the surface direction. Tensile strength is the final point of the stress-strain curve. Measuring unit is N/m or kN/m . Tensile strength is measured in machine and in cross direction.

(<http://users.evtek.fi/~penttiv/mater/papomin.pdf>)

Paper and board are required to have a sufficient general level of strength. For example, creped masking tape base papers must be strong enough not to break during the converting process.

Testing is done with stretch tests, in which the strain placed on the sample is recorded either mechanically or electronically. In addition to maximum load, the change in length of the initial test sample break, or breaking strain, is also recorded. Breaking energy as an integral of the force-strain curve can also be defined in stretch tests. The comparison of tensile strengths in samples with different basis weights is calculated as a tensile index, which is tensile strength divided by basis weight multiplied by 1000. Correspondingly, the breaking index is

calculated by dividing the breaking energy with the basis weight and multiplying by 1000, after which the breaking index becomes mJ/g. (Knowpap, 2004)

Because some paper products such as towels, wet wipes and filter paper are subjected to wetting by water in their normal use, wet tensile testing has become important. This test is essentially the same as that for dry tensile strength, except that the specimen is wetted. Paper that has not been specifically treated to produce wet strength possesses from about 4 to about 8 percent of its dry strength when completely wetted. By treating paper, wet strength can be about 40 % of the dry strength.

(<http://www.indiapapermarket.com/history2.asp#strength>)

Elongation at break is the elongation the paper sample has right before it breaks. Measuring unit is %. Elongation at break is measured in machine and in cross direction. (<http://users.evtek.fi/~penttiv/mater/papomin.pdf>)

2.2 Cellulose pulps in speciality paper production

Strong speciality paper is usually produced of softwood and hardwood fibres. Chemical pulp fibres are used because they give paper a high network strength due to good fibre bond strength. Mechanical pulp is not used. For instance, speciality crepe paper is produced 100 % of softwood cellulose pulp. Softwood pulp is used due to its ultimate strength compared to hardwood. A mixture of softwood and hardwood pulp can also be used but softwood is the dominant raw material in strong speciality paper grades.

The motivation to this study is the question “How the tensile strength and elongation of speciality paper could be optimised by selecting the right fibres?” This chapter presents the chemical pulp types currently used in the production of speciality paper.

2.3 Softwood pulp

Key Finnish softwoods used for paper production are pine and spruce. In North America, Douglas-fir, hemlock, ponderosa pine, white and black pine, and balsam fir are used as pulpwood. In the southern United States, Southern pine varieties are used. In South America and New Zealand, radiata pine is used. The various softwood varieties do not significantly differ from one another in terms of chemical composition.

The dimensions of softwood fibres used in pulp production do not vary largely. Pine from the southern United States and North America differ the most from Finnish softwood varieties. These varieties have long and thick-walled fibres, which affects the pulp properties to some extent.

Softwood is comprised of two types of cells: tracheids (90-95 %) and ray cells (5-10 %). Softwood fibres are wood tracheids. Tracheids give the softwood mechanical strength (particularly thick-walled summerwood tracheids) and transport water, which occurs primarily via tracheids in thin-walled and large cavity springwood.

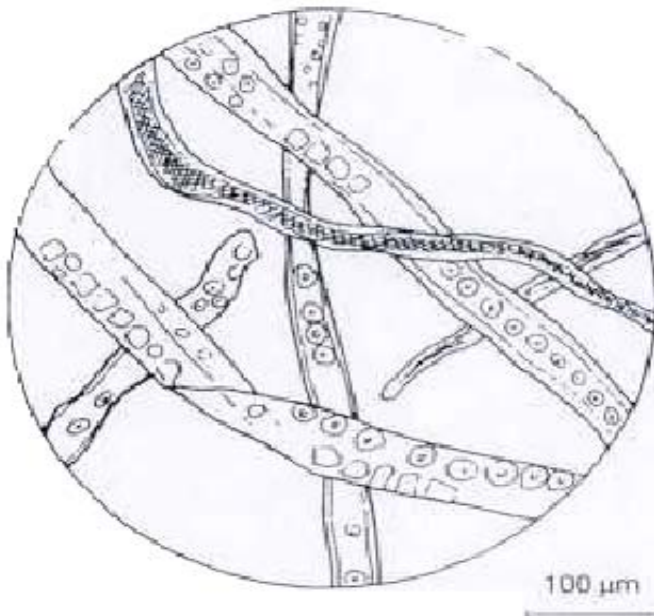


Figure 2. Pine fibres. (Isotalo, 1996, p. 121-124).

Softwood fibres are closed at both ends. The length of Nordic pine and spruce fibres is usually 2-4 mm and the median thickness is 1/100 of the length. Springwood fibres have thin walls, large cavities and an almost square cross-section. Summerwood fibres have thick walls, small cavities and a rectangular cross-section. Due to their long fibres, softwood pulps are called long fibre pulps.

The key properties of softwood sulphate pulp, whose primary function is to give strength to the network, are those affecting bonding capacity. The fibre must possess sufficient length and strength. The technical properties of paper can be predicted by the coarseness of sulphate pulp, in that fibre cell wall thickness accounts the sheet properties of pulp from different raw materials. (Knowpap, 2004)

Softwood pulp (microscopic image - enlarged 145x)



Figure 3. Softwood pulp (microscopic image enlarged 145x). (Knowpap, 2004)

2.4 Hardwood pulp

Nordic birch is one of the most important hardwoods used in paper production. It is one of the longest and densest fibered hardwoods. Birch is used primarily in sulphate pulps and it is usually bleached.

In central and southern Europe beech, white beech and oak are used in pulp production, in North America aspen, beech, basswood and oak. One of the key competitors of Finnish birch pulp in the world market is eucalyptus pulp.

There are greater differences in chemical composition between various hardwood varieties than between softwood varieties. Eucalyptus has a very high cellulose content and low hemicellulose content, while in birch it is the opposite. The fibre dimensions of hardwood species also differ greatly from one another. As eucalyptus fibres are smaller than birch fibres, their number per unit of weight is higher. This gives papers made with eucalyptus pulps better formation and a higher degree of opacity than papers made with birch pulps.

Hardwood species can be differentiated by the wide variety of specialized cell types. Wood fibres are comprised of support cells, vascular bundles and ray parenchyma formed of large cavity vascular cells, and longitudinal storage parenchyma. Hardwood also contains a certain number of other intermediate cell types, such as tracheids. The term fibres refers to all cells functioning as support cells. The number of fibres in birch is 65-70 % of all cells.

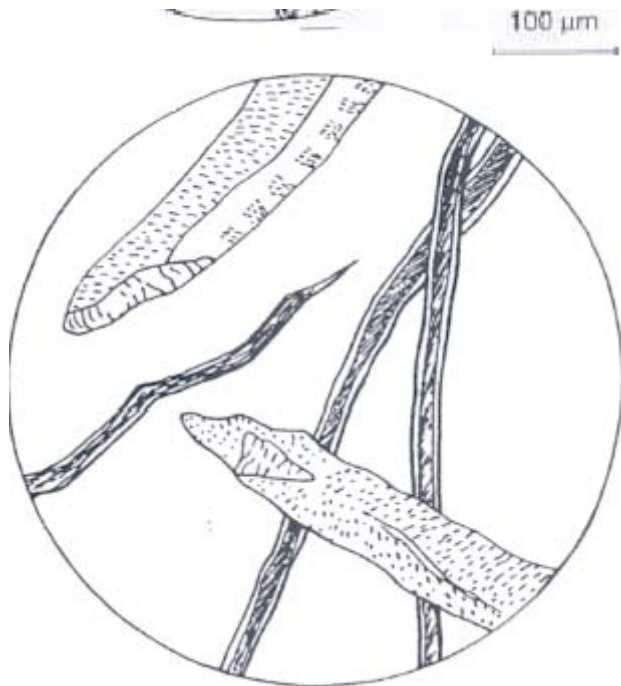


Figure 4. Birch fibres. (Isotalo, 1996, p. 121-124)

Hardwood fibres have thicker walls and are shorter and thinner in size than softwood fibres. Hardwood fibres have an average length of 1-2 mm and thickness of approx. 0.025 mm. They contain fewer pores than softwood fibres. Due to their smaller size, hardwood fibres are significantly lighter than softwood fibres. There are approximately 6-7 times the number of fibres in a ton of hardwood pulp as there are in the same amount of softwood pulp.

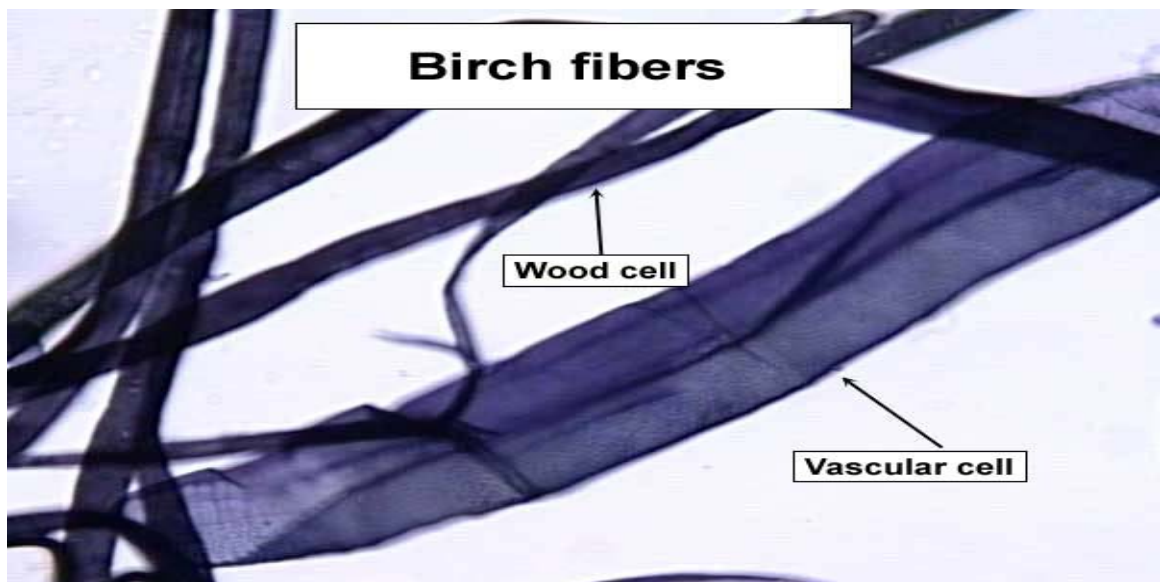


Figure 5. Hardwood fibre. (Knowpap, 2004)

Due to its low flocculation point, hardwood pulps are used in fine papers to improve the printability of the end product. Fibre strength is not one of the most critical properties of hardwood pulps.

The technical potential of paper of various hardwood fibres differs significantly from one another. Birch is a highly competitive material in papers requiring good strength properties with minimal refining. Birch has superior strength properties, but a higher density and lower light scattering coefficient than other hardwood pulps. (Knowpap, 2004)

Unrefined hardwood pulp (microscope picture, enlargement 75 x)



Figure 6. Unrefined hardwood pulp (Knowpap, 2004)

3 DIMENSIONS AND PROPERTIES OF HARDWOOD AND SOFTWOOD FIBRES

Fibre dimensions have a more important impact on the differences between softwood and hardwood pulps than their chemical composition. The most important fibre dimensions in paper making are fibre length, width, fibre wall thickness and linear density. *Fibre length* affects the strength properties of the pulp and the paper made of it. *Fibre width* and *fibre wall thickness*, affect fibre *flexibility* and *tendency to collapse* in the paper production process and, in turn, the paper properties. *Fibre size* also has an impact on the number of fibres per unit of weight, which has an effect on, for example, paper formation. (Knowpap, 2004; Isotalo, 1996, p. 24-25; p. 121-124)

The median *fibre length* of Finnish pine and spruce is approx. 3 mm. Spruce fibres are slightly longer and can be used to produce a slightly stronger chemical pulp than pine. In Finland the majority of spruce raw material is used in the production of mechanical pulps.

Hardwood fibres are shorter and have more size variation than softwood fibres. The largest wood fibres are only about one-third the length of softwood tracheids. Finnish birch wood fibres are in average 1.1-1.2 mm long. (Knowpap, 2004)

The diameter of softwood fibres is in average larger than that of hardwood fibres. This applies especially to the springwood fibres of softwood. There are also clear differences in wall thickness. The wide springwood fibres of softwood have even thinner walls than found in birch, while summerwood fibres have far thicker walls. (Knowpap, 2004)

Summerwood fibres with thick walls provide very different paper technical properties compared to springwood fibres with thin walls. Summerwood fibres are stiff, they retain their shape relatively well during refining and provide a porous, absorbent sheet with good tear strength. Springwood fibres are fast to refine, they collapse easily and they form a dense sheet with good tensile and burst strength. (Isotalo, 1996, p. 24)

Table 1. Dimensions of hardwood and softwood fibres.

**Dimensions of hardwood
and softwood fibers**

	Birch	Euca-lyptus	Pine (spring)	Pine (summer)	Spruce (spring)	Spruce (summer)
Fiber length, mm	1.1	1.0	2.9	2.9	2.9	2.9
Fiber width, μm	22	16	35	20	33	19
Fiber wall thickness, μm	3	3	2.1	5.5	2.3	4.5

(Knowpap, 2004)

Kuva 9. Eräiden puukuitujen keskimääräisiä kuitumittoja

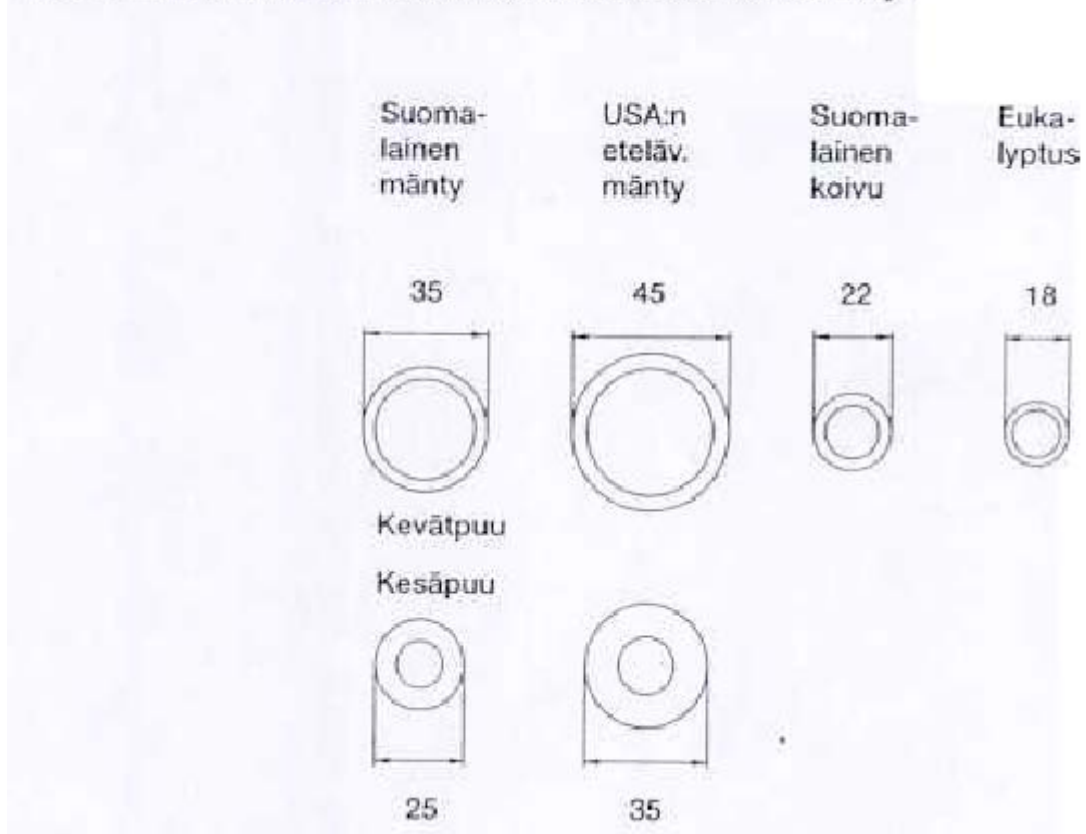


Figure 7. Average thicknesses (μm) of some wood fibres. From the left top: Springwood fibres of Finnish pine, Southern U.S. pine, Finnish birch, Eucalyptus. In the bottom: Summerwood fibres. (Isotalo, 1996, p. 25)

3.1 Effect of fibre dimensions on tensile strength

Fibre dimensions have a significant impact on paper technical properties. A stronger pulp can be produced of long fibre softwood pulp than of short fibre pulp. Fibre length is, however, optimal, i.e. after certain average length (2-3 mm) paper strength is generally not increased, but the strength is determined by the strength of individual fibres. Also, fibres that are too long will not produce an even sheet structure (formation) and paper strength might even be compromised. Fibres that are too short may produce an even sheet structure, but their strength properties will no longer be useful and run ability will be compromised.

The greatest advantages offered by hardwood fibres are based on their smaller size and lower linear density. The smaller fibres in hardwood pulp papers provide a better formation. (Knowpap, 2004)

3.2 Effect of fibre properties on tensile strength

The following table shows a list of basic fibre properties and their effect on paper properties.

Key fiber properties

Fiber property	Effect on fiber bonding
- Fiber strength	- determines the maximum tensile strength
- Linear density	- strength of one fiber, specific area and adaptability
- Fiber length	- amount of bonds in one fiber
- Fiber circumference	- maximum area and specific area of a bond
- RBA (relative bonded area)	- amount of bonded area
- Specific bonding strength	- strength of a bond per bonded area unit

Figure 8. Key fibre properties. (Knowpap, 2004)

The properties listed in the previous chart provide an understanding how tensile strength changes when fibre properties are changing. Certain models can be used to characterize how fibre length, fibre circumference (2 x fibre width when the fibre is completely collapsed) and specific bond strength affect paper tensile strength. At a certain RBA (Relative Bonded Area), the doubling of any of the above-mentioned fibre properties will effectively double the tensile strength at the beginning of the curve. Linear density has the opposite effect. Doubling it will halve the tensile strength at a certain RBA. The effect of fibre strength is based on the fact that it determines the maximum tensile strength of the fibre network. (Knowpap, 2004)

The flexibility of a cellulose fibre is the most important property controlling tensile strength. (Paavilainen, 1993, p. 4-11)

Fibre's tendency to collapse has a favourable effect on tensile strength. The following factors improve the collapsing of fibres:

- Fibres with thin walls compared to their thickness. For example pine spring wood cells and birch and acacia fibres. Softwood summerwood fibres and eucalyptus fibres instead, are fibres with thick walls compared to their diameter. They build a bulky and less bonded sheet.
- Fibres with low lignin content i.e. highly processed and bleached pulps.
- Beating of cellulose fibres increases the swelling of the fibre. Beating results as internal fibrillation, decreases the resistance to collapse and reduces the stiffness of the fibre.
- Heavy wet pressing or calendaring when paper has high moisture content promote the collapsing of fibre. (Hägglom-Ahnger et al, 2000, 90-98)

Cell wall thickness explains over 80 % of the paper strength variations. The paper technical potential of soft wood fibres is mainly based on fibre wall thickness and not on fibre length. Tensile strength increases with the decrease of cell wall thickness, i.e. with the increase of fibre conformability (especially flexibility). Excellent reinforcement pulp with high tensile strength can be produced from young round wood raw material having low cell wall thickness.

Fibre's external fibrillation and build up of fines have a favourable effect on tensile strength.

The number of fibres has an influence on the relative bonded area (RBA) only if the fibres are so flexible that they can build inter fibre bonds.

Fibre length affects paper properties. But although the reduction of fibre length reduces tensile strength, tensile strength is mainly controlled by bonding ability of fibres. (Paavilainen, 1993, p. 9-11)

Practical paper technical potential of softwood sulphate pulps can be predicted with help of coarseness, which is determined by cell wall thickness, fibre width and cell wall density. Over 80 % of the total variation in tensile and tear strength can be explained by the coarseness.

Fibre properties depend on each other in different stages of the process from raw material to paper.

The following factors have the strongest impact on the final properties of paper:

- Fibre wall thickness in wood fibre
- Fibre flexibility in pulp
- Bonded area and structure of matrix in fibre matrix.

(Paavilainen, 1993, p. 10; Rantala, 1995, p. 16-18)

3.3 Fibre bonds

Fibre bonds hold the paper together. Fibre bonds are the condition of strong paper. The fibres form a matrix held together by fibre bonds at contact points between fibres.

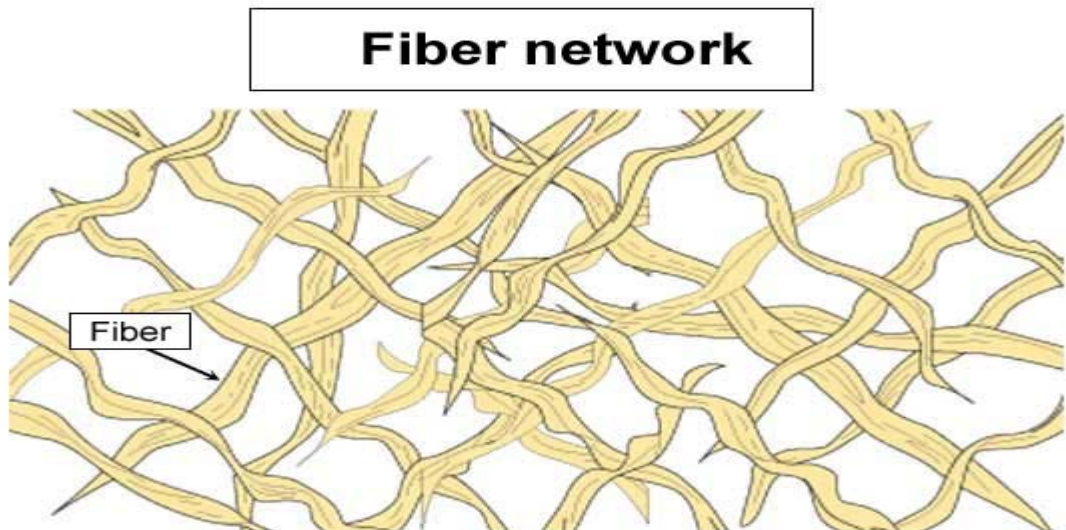


Figure 9. Fibre network. (Knowpap, 2004)

Papers and pulps are heterogenic. Fibres differ from one another in dimensions, chemical composition, and degree of fibrillation, the number of collapses, kinks, bends, pores and damages. Many properties can vary from one point to another within a single fibre. The properties of a fibre can vary longitudinally and laterally. The structural properties of fibres and paper are also always affected by a random function and its distribution. The tensile strength of fibres and paper is determined according to the weakest point.

The median strength of fibre bonds in chemical pulp is 4-20 mN. Typically, fibres in fine paper have bonded from either end over their entire length. A 60 g/m² paper sheet made of chemical softwood pulp contains approximately 450,000 fibre bonds per square centimetre. Therefore, the bonded surface area is approximately 9 cm², which equals a specific surface of 0.15 m²/g.

Interfiber bonding (microscopic image, enlarged 600x)

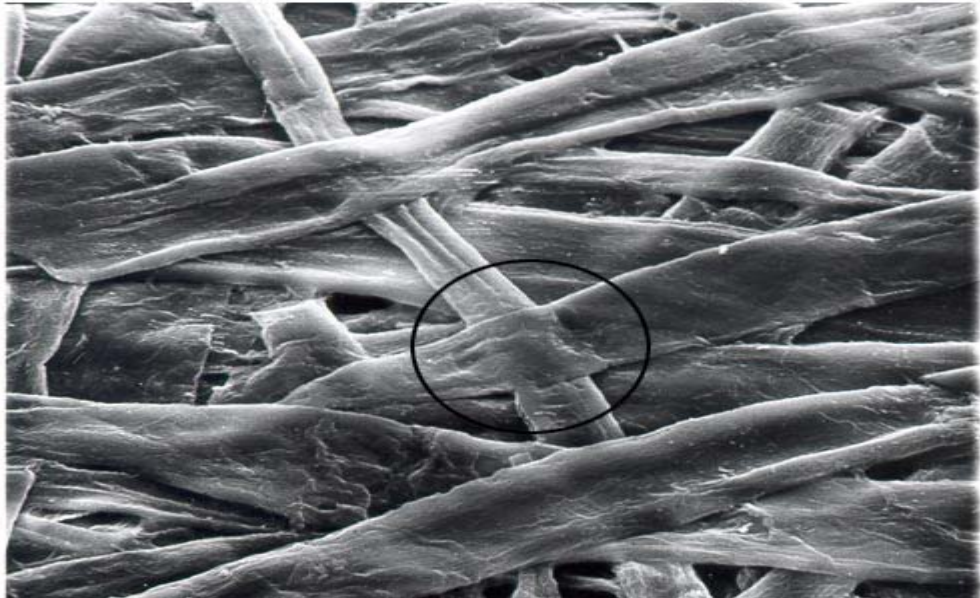


Figure 10. Interfiber bonding. (Knowpap, 2004)

The adhesion between fibres is based on hydrogen bonds. The hydrogen atom is capable of forming a weak bond with a more negatively charged atom, such as oxygen. There are no free hydroxyl groups found in paper, as they are all bonded. Some of the fibres' hydroxyl groups are bonded with water molecules.

Bond strength varies due to several factors. In most applications it would be economical to have as high bond strength as possible. Specific bond strength can be influenced most by altering the chemical composition of the bonding interfaces, but structural factors of bonds and fibre bonding can also have an impact. (Knowpap, 2004)

3.4 Effect of fibre bonds on tensile strength and elongation

When the number of inter fibre bonds increases, tensile strength of paper increases as well.

The first hydrogen bonds between fibres are formed at the end of press section. Most of the hydrogen bonds are built during drying where the last drops of water are removed and the hydrogen bonds between fibre and water are replaced by the hydrogen bonds between fibres. Tensile strength of paper increases continuously during drying. Anyhow, if the moisture content of the paper is 2-3 %, the run ability is inferior to the paper with higher moisture content. This is because many run ability parameters of the paper start to suffer already when paper moisture decreases below 20 %. These properties are for instance elongation, tear and burst strength. (Hägglom-Ahnger et al, 2000, p. 90-93; Knowpap, 2004)

The number of inter fibre bonds can still be influenced after drying. Their amount can be increased or decreased for example by calendaring. When dry paper is calendared with hard nip, the inter fibre bonds open clearly and tensile strength decreases. By calendaring with soft nip with sufficient moisture, the number of inter fibre bonds and tensile strength increase.

-> When the amount of inter fibre bonds increases: then the tensile strength increases. (Hägglom-Ahnger et al, 2000, p. 90-93)

3.5 Fines in bonding

The fines released from fibres have an ability to increase the amount of inter fibre bonds. The specific surface of fines is several times that of fibres. The chemical composition, size and shape of fines determine their bonding capacity. The finer-grained the fines are, the more effective they are in bonding. During the removal of water from fibre network, the last water film is attached to the surface of fibres. Due to surface tension, the last water drops gather to intersection of fibres. Fines originated from fibres follow the water to the same points and act as adhesive there. (Hägglom-Ahnger et al, 2000, p. 90-93; Knowpap, 2004)

4 THE MEANS TO AFFECT TENSILE STRENGTH AND ELONGATION

In a nutshell, the strength of paper is determined by the following factors in combination: (1) the strength of the individual fibres of the stock, (2) the average length of the fibre, (3) the inter fibre bonding ability of the fibre, which is enhanced by the beating and refining action, (4) the structure and formation of the sheet and (5) bonding between different plies, in multilayer sheets. The following chapter will present these, and some additional factors by which tensile strength can be improved. (<http://users.evtek.fi/penttiv/mater/papomin.pdf>)

In addition to the sufficient number of inter fibre bonds, presented in the previous chapter, tensile strength can be optimised by the following means: the right selection of fibres, pulping method, refining, additives, type of head box and wire section, wet pressing, drying, surface sizing, coating and calendaring.

4.1 Selection of fibres

In addition to increasing the number of inter fibre bonds presented in the previous chapter, tensile strength can be increased by the following means related to individual fibres:

- With strong, long fibres possessing good bonding properties. The strength of an individual fibre determines the maximum level of strength. Long fibres are

capable of forming more fibre bonds, which increases the level of fibre matrix bonding and, in turn, its strength.

- The fibre is strong when its linear density is high. As the fibres should collapse in order to build inter fibre bonds, high linear density should be obtained by using thick fibres instead of fibres with thick cell walls. The linear density of the fibre affects its strength, specific surface area and formability. If the fibre has an especially thin wall, its strength will remain low. The specific surface area of a fibre with a high linear density will most likely be greater than a fibre with a low linear density. In regards to the tensile strength of a fibre matrix, the linear density of an individual fibre should not be too high, either, because this will reduce the formability of the fibre. (Hägglom-Ahnger et al, 2000, p. 97; Knowpap, 2004)

4.2 Cellulose pulp

The pulp bonding capacity of mechanical pulps is poorer than that of chemical pulps, due to the lignin remaining on the fibre surface. Lignin does not possess hydroxyl groups. Chemical pulp fibres are more intact and they tend to be longer than mechanical pulp fibres. Mechanical pulp production also causes structural damage in the fibres, which compromises their strength. In other words, cellulose pulp has the best bonding capacity. (Hägglom-Ahnger et al, 2000, p. 97; Knowpap, 2004)

4.3 Refining

During refining, the bonding capacity of fibres is increased by increasing the formability and specific surface area of the fibres. However, fibres must not be over refined, as this will reduce the strength potential of fibres. (Knowpap, 2004)

New surfaces and fines are created in refining (example pine pulp)

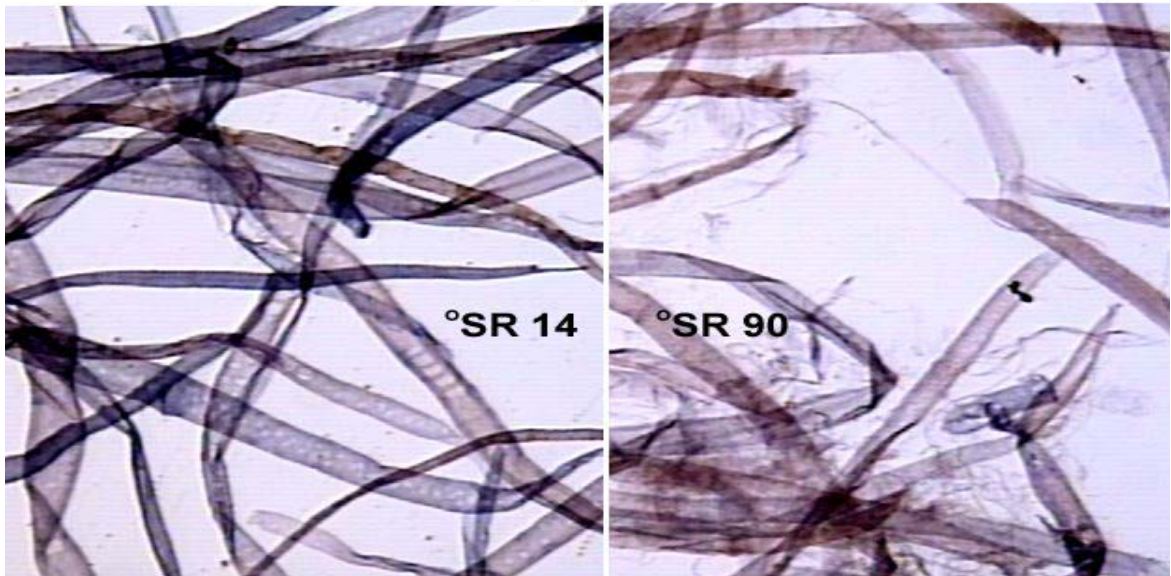


Figure 11. Pine pulp before and after refining. (Knowpap, 2004)

4.4 Process technical means

When the pulp consistency in the head box is too high, the fibres bond to one another forming floccules. In this case formation of the web in the paper machine wire section will be poor. This results in web sections with low fibre counts. When tensile strength is measured, breakage is initiated at the weakest point of the sample. If formation is poor, tensile strength is poor.

In addition to formation, fibre orientation is determined in the paper machine wire section. Paper tensile strength in the direction of measurement is greater the more strongly the fibres are oriented in the direction of measurement.

Wet pressing draws fibres closer to one another, thus increasing fibre bonding. An increase in wet pressing reduces the risk of web breaks.

Hydrogen bonds between fibres form when the web solids content is 50-60 %, i.e. in the paper machine drying section. The degree to which the web is permitted to shrink during drying has a significant impact on tensile strength. If the web is allowed to air dry, the fibres will shrink while drying, thus shrinking the fibres bonded to them and resulting in 'bent' fibres in the dried fibre matrix. When measuring tensile strength, the bends are corrected, and individual fibres and fibre bonds are left to bear the load, thus considerably increasing the breaking strain but compromising tensile strength. If drying shrinkage is prevented by stretching the

web mechanically, the fibres contained in the paper will be straighter. When this type of sample is measured for tensile strength, more fibres and fibre bonds will bear the load simultaneously, thus resulting in a lower breaking strain but higher tensile strength than found in air-dried paper. If the web is stretched excessively during drying, fibre bonding will be prevented and tensile strength compromised. (Hägglom-Ahnger et al, 2000, p. 90-97; Knowpap, 2004)

4.5 Surface sizing, coating and calendaring

Paper is produced using different additives, which can give the paper properties that cannot be achieved with the fibre material alone. Dry-strength sizes increase bonding strength. Surface sizing enhances paper properties by increasing the number of fibre bonds with water-soluble binding agents, usually starch. Sizing is based on the starch glucose units that contain OH groups, which are capable of forming hydrogen bonds, thus 'gluing' the fibres together.

In coating the optical properties of the paper are improved by applying a layer of coating to the paper surface. Because the strength of the coating layer is weaker than that of the base paper, the tensile strength of uncoated papers with the same basis weight will be higher.

If calendaring is done with sufficient moisture using a soft roll, the fibres will bond and the bonding capacity will increase. Examples of these types of papers are glassine and release papers. (Knowpap, 2004)

4.6 Paper Properties

The following paper properties have the most significant impact on tensile strength.

Table 2. Paper properties that impact tensile strength. (Knowpap, 2004)

➤ Basis weight
➤ Moisture
➤ Fibre orientation
➤ Ash content
➤ Formation

Good paper formation increases tensile strength. Paper breaks at its weakest points, i.e. between the floccules where the basis weight is the lowest. Thus, if the formation is poor, tensile strength will decrease. Unfortunately, the long fibres which give good strength have the greatest tendency to flocculate. Consequently, when optimal tensile strength is required good formation should be obtained by process technical measures rather than by using shorter fibres. (Hägglom et al, 2000, p. 97)

4.7 Means to affect elongation at break

Drying method has an effect on tensile strength and on elongation at break. Tensile strength and elongation depend partly on each other. It is often the case that when tensile strength increases, elongation decreases.

Paper moisture has an impact on both tensile strength and elongation. Paper with lower moisture content has lower elongation and burst strength than paper with higher moisture content. Only the tensile strength will increase when paper is over dried. (Hägglom-Ahnger et al, 2000, p. 90-97)

4.8 Conclusions on cellulose pulp fibres

Based on the previous chapters, tensile strength can be optimized by selecting the following types of cellulose fibres.

Table 3. Cellulose fibres that give the optimal tensile strength

➤ Chemical pulp
➤ Softwood pulp
➤ Long fibres
➤ Strong fibres
➤ Flexible fibres
➤ Springwood fibres with thin walls
➤ Easily collapsing fibres
➤ Good bonding capability
➤ Externally fibrillated fibres
➤ Fibres with good ability to build up fines

Tensile strength and elongation depend partly on each other. There is no simple model to increase both properties simultaneously when using cellulose pulp. When tensile strength is increased, elongation at break will easily suffer. Drying method and paper moisture have an impact on tensile strength and elongation. Wet pressing, surface sizing and pulp consistency have an impact on tensile strength.

When cellulose pulps don't provide the needed strength and elongation, there are other reinforcement fibres available. The following chapters contain information about man-made fibres used in the non-woven industry. These fibres can also be used in paper making.

5 SYNTHETIC FIBRES IN PAPERS AND NON-WOVENS

The development and use of a variety of man-made fibres have created a revolution in the textile industry in recent decades. It has been predicted that similar widespread use of synthetic fibres may eventually occur in the paper industry. Active interest has been evident in recent years, both on the part of fibre producers and of paper manufacturers. Many specialty paper products are currently made of synthetic fibres.

(<http://www.indiapapermarket.com/history.asp#synthetic>)

5.1 Advantages of synthetic fibres in papermaking

The advantages of synthetic or man-made fibres in papermaking can be summarized as follows:

Natural cellulose fibres vary considerably in size and shape, whereas synthetic fibres can be made uniform and of selected length and diameter. Long fibres are necessary in producing strong papers. There are limitations, however, to the length of synthetic fibres that may be formed from suspension in water because of their tendency to tangle and to rope together. Even so, papers have been made experimentally with fibres several times longer than those typical of wood pulp; these papers have improved strength and softness properties.

Natural cellulose fibres have limited resistance to chemical attack and exposure to heat. Because synthetic fibre papers can be made resistant to strong acids, they are useful for chemical filtration. Paper can even be made from glass fibre, and such paper has great resistance to both heat and chemicals.

The natural cellulose fibres of ordinary paper are hygroscopic; i.e., they absorb water from the air and reach an equilibrium depending upon the relative humidity. The moisture content of paper, therefore, changes with atmospheric conditions. These changes cause swelling and shrinkage of fibres, accounting for the

puckering and curling of papers. Synthetic fibres not subject to these changes can be used to produce dimensionally stable papers.

(<http://www.indiapapermarket.com/history.asp#synthetic>)

5.2 Cost of synthetic fibres

The cheapest man-made fibre, rayon viscose, costs from three to six times as much as an equivalent amount of wood pulp, whereas most of the true synthetics, such as the polyamides (nylon), polyesters (Dacron, Dynel), acrylics (Orlon, Creslan, Acrilan), and glass, cost from 10 to 20 times as much. This difference in cost does not preclude the use of existing synthetics, but it limits their use to special items in which the extra qualities will justify the additional cost. The cost factor is increased by the absence in most synthetic fibres of the bonding property of natural cellulose fibres. When beaten in water, natural fibres swell and cement together as they dry. Paper made from synthetics must be bonded by the addition of an adhesive, requiring an additional manufacturing step.

(<http://www.indiapapermarket.com/history.asp#synthetic>)

5.3 Similarity of synthetic fibre papers and non-wovens

There is a distinct similarity between synthetic fibre "papers" and non-wovens. As a step in the manufacture of yarn, staple fibres are carded (i.e., separated and combed) to form a uniform, lightweight, and fragile web. Subsequently, this web is gathered together to form a strand or sliver, which is drawn and spun into yarn. If several of these flat webs, however, are laminated together and bonded with adhesive, a nonwoven fabric that has properties resembling both paper and cloth results. In this area it is difficult to draw a clear distinction between what is paper and what is cloth. Processes are now available to form sheet material both by the dry forming method and by the water forming or paper system. When textile-type fibres are formed into webs by either of these processes, the resulting products have properties that enable them to compete in some fields traditionally served by textiles. (<http://www.indiapapermarket.com/history.asp#synthetic>)

5.4 Fibres in non-wovens

This study has a focus on cellulose pulp, rayon, polyester, nylon, polyethylene and polypropylene. All these fibres are used in the non-woven industry.

In comparison to traditional paper, non-woven products are made using modified "papermaker" equipment which allows the manufacturer to process blends with pulp and fibres which deliver higher strength.

Speciality paper is traditionally produced of cellulose pulp fibres. When the use of alternative wood pulp fibres and process-technical and other modifications listed in chapter 4 are excluded, higher tensile strength and elongation could be obtained by using some of the fibres used in the non-woven industry. Non-woven materials are known for superior tensile properties versus speciality paper. Non-woven industry is widely using synthetic fibres, and also cellulose based fibres. The following chapters will generally present the fibres used in the non-woven industry. The emphasis will be on rayon viscose and on polyester fibres. Rayon and polyester were selected because they are most commonly used in the non-woven industry in the production of, for instance, wet wipes.

Polypropylene, polyethylene, nylon and bicomponent fibres are also briefly presented. Rayon viscose will be presented first as it is a regenerated cellulose fibre. All the other fibres are man synthetic and they will be presented after rayon viscose. The following fibres are the most commonly used in the non-woven industry.

Table 4. Fibres in the non-woven industry

TRADITIONAL TEXTILE FIBRES
PET
Polyolefin (PP/PE)
Nylon
Cotton
Rayon
Wool
Lyocell
HI-TECH FIBRES
Aramid (Nomex/Kevlar)
Conductive Nylon
Bi-component (side by side, sheath core)
Melamine (heat & flame resistant)
Superabsorbent
Hollow fibres
Spandex fibres
Fusible co-PET fibre, Glass fibre

Fibres are the basic element of non-wovens. These include traditional textile fibres as well as recently developed hi-tech fibres. Wood pulp, which is far shorter in length than textile fibres, is the only natural fibre which is used in very large amounts due to bulk, water absorbency and low cost. Cotton has excellent inherent properties for non-wovens fabrication. Viscose rayon has been widely used in non-wovens fabrication in the area of disposable and sanitary products. Rayon fibres can be easily made to webs and readily bonded into non-woven fabrics. All these cellulosic such as cotton, rayon and acetate are absorbent, act as carriers of microbial agents, and give strength and biodegradability. Among the synthetic fibres, polypropylene (PP) is widely used. PP is inexpensive and has good rheological characteristics to form fine fibres. PP fibres are hydrophobic,

voluminous and thermoplastic. Polyethylene terephthalate is used where strength and mechanical properties are of prime importance. Nylon fibres are used for their excellent (resiliency) recovery properties.

Although a large number of fibres are available, the commercially important are limited into few types. The dominant fibres are polyolefins, polyester and rayon. Rayon was the major fibre used in non-wovens production until 1985. Today, the cost of polypropylene and polyethylene is comparable to rayon and they provide superior strength. Non-wovens made of rayon are mainly found in medical, surgical, sanitary and wipes products. Nylon, which is more expensive than the other fibres is used in lesser extend. The other “special fibres” listed in the table above, have only a limited market share, maximum about 15 %, of the whole non-wovens' materials market.

(http://www.apparesearch.com/education_research_nonwoven_fibers_and_fiber_consumption_nonwovens.htm)

6 VISCOSE

6.1 Definition of viscose

Viscose Rayon is the oldest commercial manmade fibre, defined as “manmade textile fibres and filaments composed of regenerated cellulose”. The process of making viscose is either continuous or a batch process. The batch process is flexible producing a wide variety of rayons. There are three main types of Rayon: viscose Rayon, cup ammonium Rayon and saponified cellulose acetate. (http://www.apparesearch.com/education_research_nonwoven_rayon_fibers.htm)

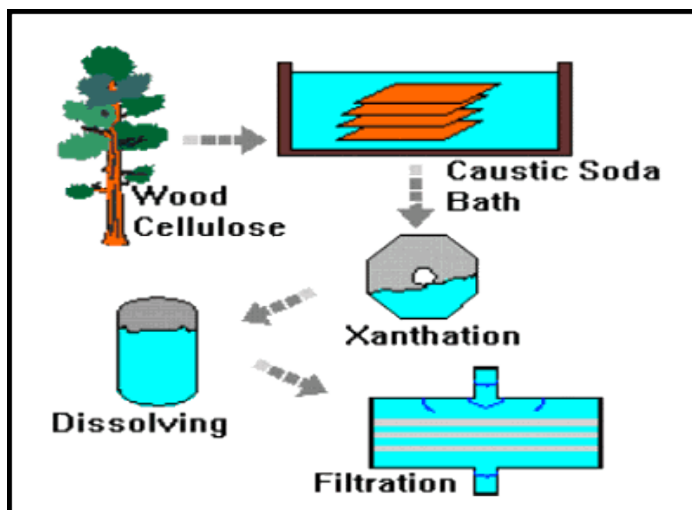


Figure 12. Production process of Rayon viscose. (http://www.e4s.org.uk/textilesonline/content/6library/report1/textile_fibers/viscose.htm)

6.2 Rayon viscose fibres product range

Some of the important Rayon fibre types are:

- Polynosic Rayon (in chapter 6.6).
- High wet modulus Rayon (HWM) (in chapter 6.6).
- Speciality Rayons such as flame retardant rayons.
- Super absorbent Rayons with high water retention.
- Micro denier fibres. These fibres are used in fabrics to improve strength and absorbency.
- Cross section modified fibres suitable for non-wovens. They have enhanced absorbency, bulk, cover and wet rigidity.
- Tencel.
- Lyocel which has all the advantages of Rayon and in many aspects is superior. It has high strength in both dry and wet, high absorbency and can fibrillate.

(http://www.e4s.org.uk/textilesonline/content/6library/report1/textile_fibres/viscose.htm)

6.3 Properties of rayon viscose

The key properties of Rayon fibres are listed below.

Table 5. Key properties of Rayon viscose.

➤ Fibres with thickness of 1,7 – 5,0 dtex are the most common.
➤ Wet strength.
➤ Elongation at break varies between 10-30 % dry and 15-40 % wet. Elongation decreases with an increase of degree of crystallinity and orientation of rayon.
➤ Chemical properties: hot dilute acids attack Rayon. Prolonged exposure to sunlight causes loss of strength because of degradation of cellulose chains.
➤ Abrasion resistance is fair and rayon resists pill formation. Rayon has both poor grease recovery and grease retention.
➤ Highly absorbent.
➤ Soft and comfortable.
➤ Easy to dye.

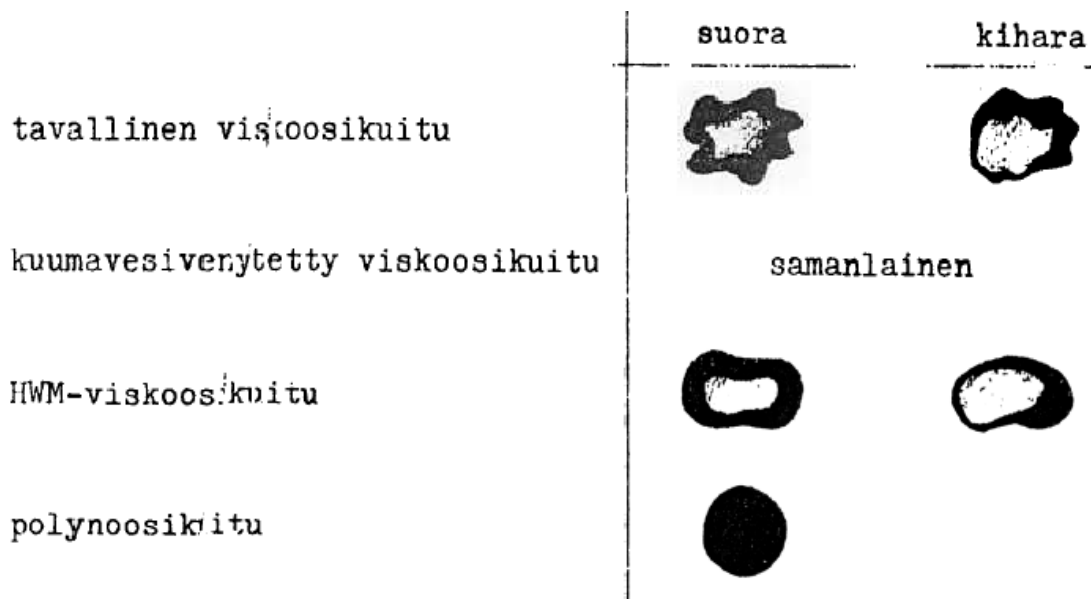
6.4 Rayon viscose fibre types and their structure

Viscose fibres are largely used in the production of non-woven materials. Viscose fibres can be categorised in four groups:

1. Standard viscose fibres
2. Hot stretched viscose fibres
3. HWM viscose fibres (High wet modulus)
4. Polynosic fibres

Figure 13. below illustrates the cross-sections of viscose fibres. The fibres in the figure are presented from 1. To 4.

HWM viscose fibres and polynosic fibres are commonly called modal fibres. Viscose fibres are available, depending on the end use, either in staple form or in filaments, straight or curly. Staple fibres with length of less than 60 mm are called cotton type fibres. Staple fibres with length of more than 60 mm are called wool type fibres. (Viskoosikuidut, 1979, p. 40)



Kuva 1. Viskoosikuitutyyppien poikkileikkausmuoto suoralle ja kiharalle kuidulle.

Figure 13. Cross-sections of straight and curly viscose fibres. (Viskoosikuidut, 1979, p. 40)

6.5 Properties of standard and hot stretched viscose fibres

Standard-type viscose fibres have moderate strength and they are relatively stiff. Their strength is reduced in wet conditions.

Hot stretched viscose fibres have slightly superior properties compared to standard viscose fibres. Viscose fibres have sufficient dry strength for many applications but wet strength is poor, about 50 % of dry strength. Cotton type standard viscose fibres have a dry strength of 2,2-2,8 cN/tex and wool type of 1,7-2,4 cN/tex. Viscose filaments have lower strength than staple fibres, less than 2 cN/tex in dry. Standard cotton type viscose fibres have an elongation of 18-28 % and wool type of 25-40 %.

All viscose fibres have good water absorption capacity. Viscose is the most absorbent fibre in common use. When wet, the standard viscose fibres swell and loose length. When they get dry they don't regain their original shape. Shrinkage can be prevented with finishing treatments.

Cotton type viscose fibres have a thickness between 1,3-33 dtex. Wool type viscose fibres have a thickness between 4,2-50 dtex. The length of cotton type fibres is 28-60 mm. The length of wool type fibres is 60-150 mm. The length of staple fibres is 6-12 mm.

Viscose fibres are not thermoplastic. They don't change shape in heat and they can not be shaped with help of heat the same way the most of the synthetic fibres can be shaped. The fibres start to loose strength at about 150 °C and they decompose at 185-205 °C. In the following chart the above mentioned properties are summarised (values are based on fibre research of Säteri).

Table 6. The properties of standard viscose fibres

Property	Cotton type	Wool type
Thickness, dtex	1,3-33	4,2-50
Length, mm	28-60	60-150
Dry strength, cN/dtex	2,2-2,8	1,7-2,4
Wet strength, cN/dtex	1,1-1,4	0,9-1,2
Elongation dry, %	18-28	25-40

(Viskoosikuidut, 1979, p. 43)

6.6 Properties of polynosic and HWM viscose fibres

The typical characteristic of polynosic and HWM viscose fibres – strong modal fibres - is high dry and wet strength. The drawing process applied in spinning may be used to produce fibres with extra strength and reduced elongation. Such fibres are designated as high tenacity rayons, which have about twice the strength and

two-third of the stretch of regular Rayon. Polynosic Rayon has a high degree of orientation, achieved as a result of very high stretching (up to 300 %) during processing. Fibres have a unique fibrillar structure, high dry and wet strength, low elongation (8-11 %), relatively low water retention and very high wet modulus. Polynosic Rayon is somewhat less absorbent than standard viscose.

(http://www.e4s.org.uk/textilesonline/content/6library/report1/textile_fibres/viscose.htm)

Modal fibres have a wet tensile strength of minimum 2,2 cN/dtex and a dry strength of 3,4-3,9 cN/dtex . Elongation of dry HWM fibres is 10-20 %. Elongation of polynosic fibres is 8-11%. Thickness of modal fibres is 1,4-4,4 dtex. Length of modal fibres is 32-60 mm. When the fibres absorb moisture, they swell just slightly, thus their dimensional stability is good. Also the high wet modulus and elastic recovery have a positive effect on dimensional stability. Below there is a summary of the above mentioned properties. (Viskoosikuidut, 1979, p. 40-49)

Table 7. The properties of modal fibres

Property	Modal fibre
Thickness, dtex	1,4-4,4
Length, mm	32-60
Dry strength, cN/dtex	3,4-3,9
Wet strength, cN/dtex	above 2,2
Elongation dry, %	HWM:10-20, polynosic max. 11
Elongation wet, %	max. 15

In the following chart there are the physical properties of standard viscose fibres, HWM fibres and polynosic fibres. Hot stretched viscose fibres have slightly superior properties compared to standard viscose fibres. (The values in the chart are from a different source than the values of the studies of Säteri presented previously. They deviate slightly from the previous values.)

Table 8. Strength and elongation of standard viscose, HWM and polynosic fibres

Property	Standard viscose fibre	HWM fibre	Polynosic fibre
Dry strength, cN/dtex	1,6-3,1	3,8-5,5	3,9-5,5
Wet strength, cN/dtex	0,8-1,7	3,3-4,1	2,7-4,4
Elongation dry, %	15-30	12-17	7-11
Elongation wet, %	20-35	14-20	8-15

(Viskoosikuidut, 1979, p. 48)

6.7 Applications of viscose fibres

Viscose fibres are used in nearly all the sectors of textile industry. Mostly the viscose fibres are used in blends with other fibres, like cotton, wool and synthetic fibres. Viscose fibres can also be used alone. (Viskoosikuidut, 1979, p. 40-49) End uses of rayon include for example industrial products, medical surgical products, nonwovens, tire cord, apparel: clothes, home furnishings and hygiene products. (http://www.e4s.org.uk/textilesonline/content/6library/report1/textile_fibres/viscose.htm)

The greatest advantage of the viscose fibres in the non-woven industry is the diversity of properties, which can be modified according to the end use. The other advantages are fast and high water absorption and disposability. (Viskoosikuidut, 1979, p.132-133)

3M company has developed a Micropore Surgical Tape. It looks like thin paper; it is gently sticky on one side with a web of non-woven rayon fibres on the other side. (<http://www.3m.com.sg/Micropore.html>)

6.8 Viscose fibres in paper production

Japanese paper making companies use rayon-cellulose pulp mixtures.

Kazagumo papers produce opaque papers of 100 % wood pulp, embedded with long shimmering rayon fibres. Ajisai papers are created with the use of shiny (rayon or mitsumata) fibres placed on the top of the paper. End-uses are a pasted-down layer on book or an invitation. "Momi" papers are used in book covers or photo background. They have a polished surface which makes them fairly hard-wearing, though made of wood pulp. The Momi Hyakusen papers are additionally creped.

(http://www.japanesepaperplace.com/opaque/opaque_patterned_papers.htm)



Momi Hyakusen Green



Momi Hyakusen Blue

Figure 14. The Japanese Momi Hyakusen crepe papers.

Japanese Shoji paper is using cellulose pulp 66 % mixed with rayon 30 % and vinyl 4 %. The end-use of the product is sliding doors covered with paper. (http://www.japanesepaperplace.com/shoji_papers.htm)

6.9 Viscose fibres for speciality paper production

The viscose fibres are longer than cellulose pulp fibres which are currently used in speciality paper production. Long viscose fibres could provide a stronger paper sheet. Viscose fibres have the capability to build hydrogen bonds. Thus there should be the possibility to utilise them in paper production without major obstacles compared to cellulose pulp.

When a paper with higher tensile strength is desirable, modal fibres, i.e. the strong high wet modulus (HWM) viscose fibres or polynosic fibres could be tested in mixture with cellulose pulp. It is possible that elongation can not be improved simultaneously with the increased strength because modal fibres have inferior elongation compared to standard viscose fibres. In addition to modal fibres, Lyocel, which possesses high dry and wet strength and fibrillation capability, could also be tested (for high tensile strength).

When the improvement of elongation is desirable, standard viscose fibres could be tested. They possess higher elongation but lower strength compared to modal fibres.

7 POLYESTER

7.1 Definition of polyester

DuPont Company produced the first U.S. commercial polyester fibre in 1953. The most common polyester for fibre purposes is poly (ethylene terephthalate), PET. This is also the polymer used for soft drink bottles. The raw material for the production of polyester is oil.

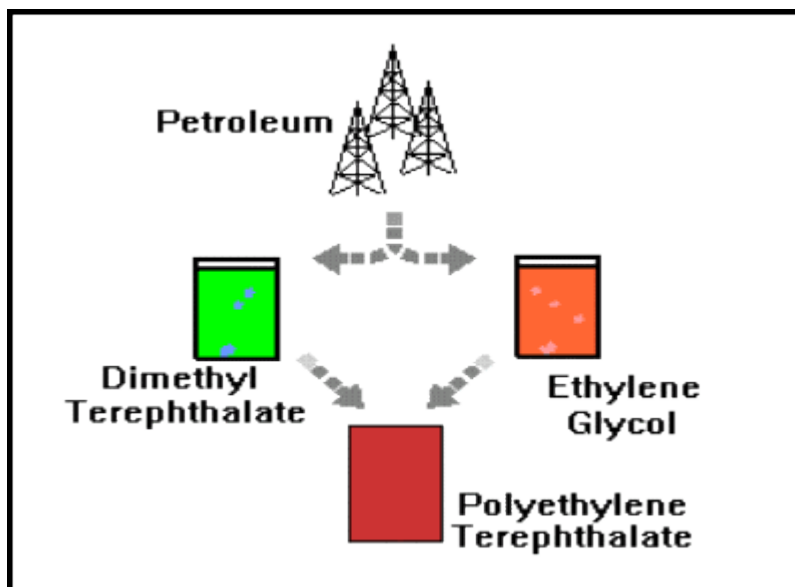


Figure 15. Basic Principles of Polyester Fibre Production (www.fibersource.com/f-tutor/polyester.htm)

Polyester fibre is a "manufactured fibre in which the fibre forming substance is any long chain synthetic polymer composed at least 85 % by weight of an ester of a dihydric alcohol and terephthalic acid".

(www.fibersource.com/f-tutor/polyester.htm; Cook, 1968, p. 358-361)

7.2 Polyester fibres product range

Polyester fibres are produced either with standard strength or with high strength. Filament fibres are used for the production of the finest micro fibres. There are also modified speciality fibres, such as extra strong, curly, shrinking, anti-static, profiled, flame-retardant, hollow and micro fibres. Polyester is used alone or mixed with other fibre types in order to improve the properties of natural fibres or prevent the shrinkage and wrinkling of cellulose fibres.

(www.finatex.fi/html/kuitu/teko/pes.htm)

Generally, polyester fibres are produced with a round cross-section. Polyester fibres are also produced with star-shaped, H-shaped and hollow cross-sections.

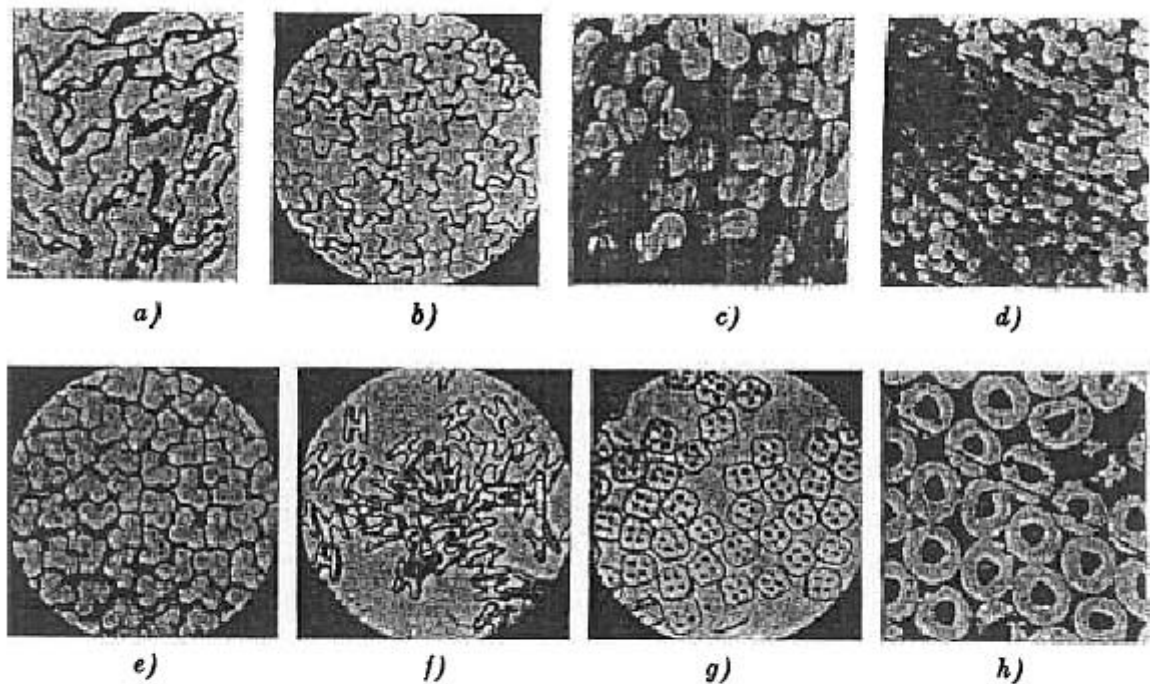


Figure 11.1. Fibre cross-sections.

(a), (b) Profiled fibres; (c)–(e) adhesive profiled fibres; (f) H-profiled fibre; (g), (h) adhesive profiled hollow fibres.

Figure 16. Polyester fibre cross sections (Ludewig, 1964, p. 368)

A profiled cross-section imparts a corresponding corrugation to the usually smooth cylindrical fibre surface which has a favourable effect on the adhesion of the yarn and fabric structure of synthetic fibres. As a consequence of the air ducts in the hollow fibres, there is in addition greater heat retention, and also a lowering of the density. As filament yarn, polyester fibres have a smooth longitudinal appearance. (Ludewig, 1964, p. 368)

7.3 Polyester fibre formation

The sequences for production of PET fibres and yarns depend on the different ways of polymerization (continuous, batch-wise, and solid-phase) and spinning (low or high windup speed) processes.

Polyester is produced by spinning, drawing or melt-blown processes.

Spinning process: The degree of polymerization of PET is controlled, depending on its end-uses. PET for industrial fibres has a higher degree of polymerization, higher molecular weight and higher viscosity.

Drawing process: To produce uniform PET, the drawing process is done at temperature above the glass transition temperature (80-90 °C). The drawing process gives additional orientation to products. The draw ratios (3:1-6:1) vary

according to the final end-uses. For higher tenacities, the higher draw ratios are required.

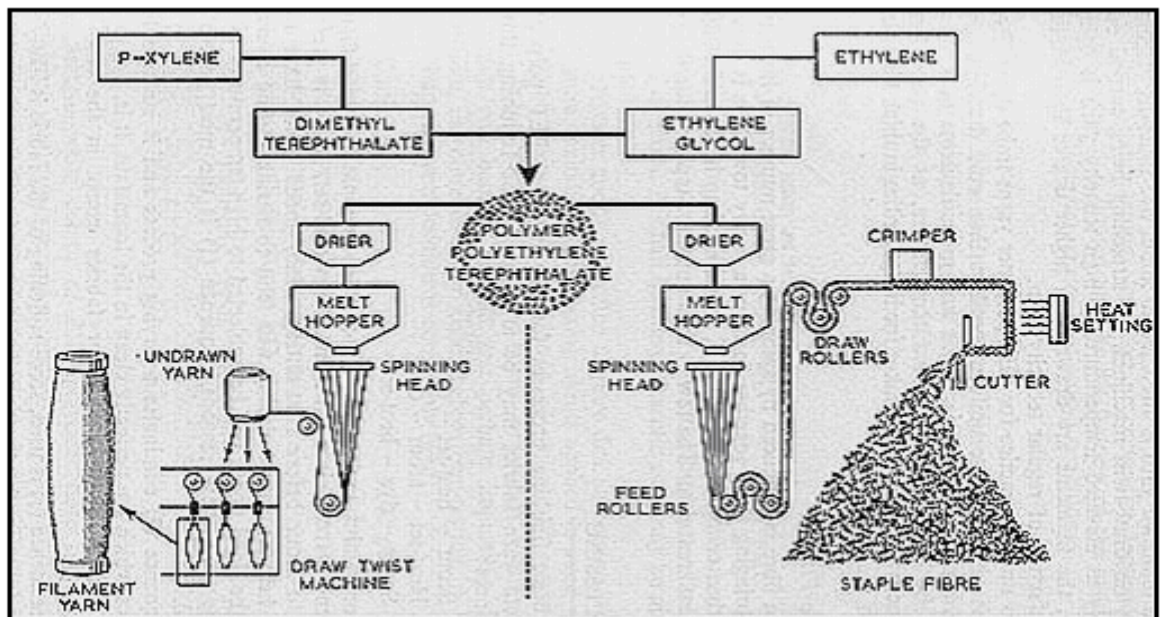


Figure 17. Polyester fibre flow chart.

Melt-blown process: The intrinsic viscosity and crystallinity levels of the melt-blown polyester determine how the finished product will perform. A higher viscosity leads to an increased level of crystallinity, which improves the barrier properties. However, it reduces modulus, toughness and elongation.

(http://www.e4s.org.uk/textilesonline/content/6library/report1/textile_fibres/polyester.htm; Cook, 1968, p. 358-361)

7.4 Properties of polyester

Polyester is a strong fibre. It is stronger than rayon. Polyester is similar to nylon in many respects (nylon will be presented in chapter 8). Both of them are strong with high abrasion resistance and low moisture absorption. They are also resistant to rot and chemicals and can be set into shapes by the application of heat. Polyester has become probably the most important synthetic fibre. Polyester is the most widely used polymer in the non-woven industry since 1995. The next most popular is polypropylene. There are slight but important differences in properties of polyester compared with those of other synthetics. Polyester has also lower production costs than rayon and nylon.

(<http://www.engr.utk.edu/mse/pages/Textiles/Polyester%20fiber.htm>;
[http://www.e4s.org.uk/textilesonline/content/6library/report1/textile_fibres/polyester](http://www.e4s.org.uk/textilesonline/content/6library/report1/textile_fibres/polyester;);
 Harrison, 1997, p. 32-39)

One of the most important properties of polyester fibre is its resistance to stretching. The fibres have resistance to small extensions and bending. The modulus of polyester is about double that of nylon, which gives fabrics containing polyester a crisper handle and good dimensional stability. Because of its high melting point polyester has good thermal stability. It softens at about 200 °C and will not easily burn. Unless supported in a fabric by another fibre it will melt away from heat rather than burst into flame. At a temperature of 150 °C it retains about 50 % of its strength and has good long term resistance to heat in the absence of strong chemicals.

(<http://www.e4s.org.uk/textilesonline/content/6library/report1/textilefibres/polyester>)

Polyester is both hydrophobic and oleophilic. The hydrophobic nature means water repellence and rapid drying. But because of the oleophilic property, removal of oil stains is difficult. Under normal conditions, polyester fibres have a low moisture absorption of around 0.4 % (compared with 4 % of nylon and 7 % of cotton), which contributes to good electrical insulating properties even at high temperatures. The tensile properties of the wet fibre are similar to those of dry fibre. Its strength is little affected when wet and it dries quickly. Hydrophobic characteristic is desirable for lightweight facing fabrics used in the disposable industry. They provide a dry feel on the facing, even when the inner absorbent media is saturated.

(<http://www.engr.utk.edu/mse/pages/Textiles/Polyester%20fiber.htm>;

http://www.e4s.org.uk/textilesonline/content/6library/report1/textile_fibres/polyester)

Polyester fibres have good resistance to weak mineral acids, even at boiling temperature, and to most strong acids at room temperature. Hydrolysis is highly dependent on temperature. Conventional polyester fibres soaked in water at 70 °C for several weeks do not show a measurable loss in strength, but after one week at 100 °C, the strength is reduced by approximately 20 %.

Polyester has optical characteristics of many thermoplastics, providing bright, shiny effects desirable for some end uses, such as silk-like apparel. Because of its rigid structure, polyester absorbs very little dye in conventional dye systems.

Polyester fibres have good resistance to sunlight but ultraviolet radiation causes long-term degradation.

(<http://www.e4s.org.uk/textilesonline/6library/report1/textilefibres/polyester>;
Fukuhara 1993 p. 91, 387)

Table 9. Summary of polyester fibre's key properties:

Polyester fibre's key properties
➤ Strong
➤ Resistant to stretching and shrinking
➤ Resistant to most chemicals
➤ Quick drying
➤ Crisp and resilient when wet or dry
➤ Wrinkle resistant
➤ Abrasion resistant

Properties of polyester fibres are strongly affected by fibre structure. The fibre structure, which has an influence on the applicability of the fibre, depends on the process parameters of fibre formation such as spinning speed (threadlike stress), hot drawing (stretching), stress relaxation and heat setting (stabilization) speed.

As the stress in the spinning threadlike is increased by higher wind-up speed, the PET molecules are extended, resulting in better as-spun uniformity, **lower elongation and higher strength**, greater orientation and high crystalline. Hot drawing accomplishes the same effect and allows even higher degrees of orientation and crystalline. Relaxation is the releasing of strains and stresses of the extended molecules, which results in reduced shrinkage in drawn fibres. Heat stabilization is the treatment to "set" the molecular structure, enabling the fibres to resist further dimensional changes. Final fibre structure depends considerably on the temperature, rate of stretching; draw ratio (degree of stretch), relaxation ratio and heat setting condition. The crystalline and non-crystalline orientation and the percentage of crystalline can be adjusted significantly in response to these process parameters.

Table 10. Physical properties of polyester.

Property	Filament yarn		Staple & tow	
	Regular tenacity	High tenacity	Regular tenacity	High tenacity
Breaking tenacity, N/tex	0.35-0.5	0.62-0.85	0.35-0.47	0.48-0.61
Breaking elongation	24-50	10-20	35-60	17-40
Elastic recovery at 5% elongation, %	88-93	90	75-85	75-85
Initial modulus, N/tex	6.6-8.8	10.2-10.6	2.2-3.5	4.0-4.9
Specific gravity	1.38	1.39	1.38	1.38
Moisture regain, %	0.4	0.4	0.4	0.4
Melting temperature, °C	258-263	258-263	258-263	258-263

(http://www.e4s.org.uk/textilesonline/content/6library/report1/textile_fibres/polyester;
<http://www.engr.utk.edu/mse/pages/Textiles/Polyester%20fiber.htm>;
<http://www.fibersource.com/f-tutor/polyester.htm>)

7.5 Tensile strength and elongation of polyester

Tensile strength and elongation at break can be varied a lot in accordance with the degree of drawing. Continuous polyester filaments are produced as high-tenacity types with low elongation at break, as well as the standard type with average tenacity and elongation. The strength of staple fibres is lower and the extensibility higher than with continuous filaments.

As the degree of fibre stretch is increased (yielding higher crystalline and molecular orientation), so is tensile strength. At the same time elongation is usually reduced. An increase of molecular weight further increases the tensile properties, modulus, and elongation. Typical physical and mechanical properties of PET fibres are given in the following figure: Typical stress strain curve for PET fibres.

Fig.2. Typical stress strain curves for PET fibers
 A: high tenacity filament, B: high tenacity staple
 C: regular tenacity filament, D: regular tenacity staple
 E: POY filament
 To convert N/tex to g/den multiply by 11.33

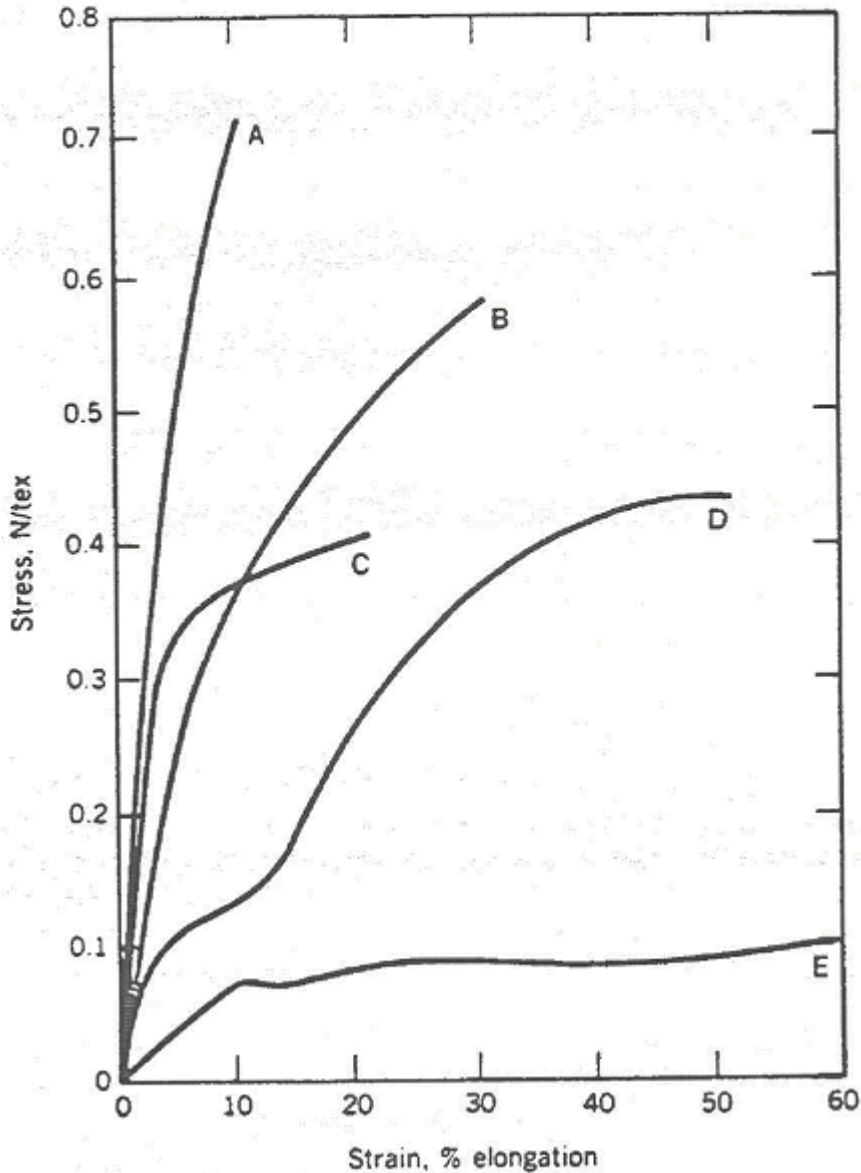


Figure 18. Stress – strain curve for polyester fibres. (Ludewig, 1964, p. 369)

The filament, represented by curve C, has a much higher initial modulus than the regular tenacity staple shown in curve D. But D has a greater tenacity and elongation. High tenacity filament and staple (curve A and B) have very high breaking strengths and module, but relatively low elongations. Partially oriented

yarn (POY) and spun filament yarns have low strength but very high elongation (curve E).

Because of the high modulus of elasticity, fine continuous polyester filaments have a very good elastic recovery. Test carried out with fibres subjected to rapid loading and equally rapid relaxation showed the following elastic recovery of the fibres within the first minute of removal of the load:

At 2 % extension = 97 % elastic recovery

At 4 % extension = 90 % elastic recovery

At 8 % extension = 80 % elastic recovery.

The capability to recover rapidly is the cause of several textile properties which distinguish continuous polyester filaments from other synthetic fibres. These properties are very good bulkiness and grease resistance and general and dimensional stabilities.

Continuous polyester filaments, in comparison with other synthetic filaments, have the advantage that their wet strength is almost 100 % of their dry strength. (Ludwig, 1964, p. 369)

Based on the stress-strain curves presented in Figure 20, we can make the following conclusions:

A: High tenacity filament has very high breaking strength and low elongation.

B: High tenacity staple has very high breaking strength and low elongation.

C: Regular tenacity filament.

D: Regular tenacity staple has high tenacity and elongation.

E: Partially oriented yarn has low strength and very high elongation

Regular tenacity filaments (curve C) and regular tenacity staples (curve D) are used in blends with cellulose. Regular tenacity staple fibres (curve D) have higher tenacity and elongation than regular tenacity filament (curve C).

7.6 Polyester fibres for speciality paper production

Based on the previously presented facts and provided that fibre bonds with cellulose fibres can be made, the following polyester fibres could be tested for speciality paper production trial, mixed with cellulose pulp:

- Regular tenacity staple (curve D), could be tested. The use of regular tenacity staple fibres could bring higher strength and elongation to the finished product.

- Partially oriented yarn (curve E), is a fibre with very high elongation. It could be tested in paper production for high elongation paper, provided fibre bonds with cellulose fibres can be obtained.
- High tenacity staple fibres (curve B), could be tested when high strength is targeted.

7.7 Polyester fibres in paper production

DuPont SA supplies fibres to non-woven industry. DuPont SA produces polyester fibres which are also suitable for paper production:

A range of special engineered short cut uncrimp fibres are available in different cut lengths from 6-30 mm and 1.7-13 dtex for reinforcement of special paper grades and end uses e.g. for wallpaper, filtration, car, abrasives, medical, laminates and food packaging. For example: Binder Co-PES (low melting core sheet) 2.2 dtex 6 mm and Crimped 1.7/6 mm T342 for fluff pulp blends and speciality papers with higher bulk.

Dacron® (it is a polyester fibre trade mark) materials can be embossed or printed on, fixed for coating or laminating. They are dimensionally stable and do not shrink. They are used for wallpaper production.

For comparison, spun lace hydro entangled non-woven can be produced of the following fibres of DuPontSA: Dacron 158 1.6 dtex/38 mm or PSNSD 1.7 dtex/38 mm or RWSD 1.3 dtex, 1.7 dtex and 3.3 dtex in different cut lengths.

(http://www.dupontsa.com/fibres/non_woven.html)

7.8 Other application areas of polyester

Polyester fibres are used for example in the following areas: clothing, surgeon's gowns, mattress pad facing, home furnishings: carpets, curtains, draperies, sheets and pillowcases, wall coverings and upholstery. Other Uses: Hoses, power belting, ropes and nets, thread, tire cord, auto upholstery, sails, floppy disk liners, and fibrefill for various products including pillows and furniture, filtration media, apparel interlining, carpet backing, furniture and bedding, automotive seats and agricultural crop covers.

Polyester is flexible and has a feel of a tissue.

One of the important applications of polyester is in the form of bicomponent fibres. Polyester is used to increase the strength of the non-woven fabric. Dry and wet laid non-wovens made from a range of synthetic and inorganic fibres are used in various insulation and industrial applications. Non-woven polyester fibre mats are used in flexible electrical insulation laminates and electrical tape backing

applications. Composites made of 100 % polyester fibres are widely used as filtration media. Its layered structure gives excellent tear strength, a smooth, fibre free surface and edge stability. The main advantage of these products is that they have no short fibres to be carried downstream and contaminate the filtrate.

(<http://www.engr.utk.edu/mse/pages/Textiles/Polyester%20fiber.htm>)

8 NYLON

8.1 Definition of nylon

Nylon was the first synthetic fibre to be commercialized (1939). It is a polyamide fibre, derived from a diamine and dicarboxylic acid. There are several commercial nylon products. The most common nylon fibres in textile industry are nylon 66 (polyhexamethylene adipamide) and nylon 6 (polycaprolactam, a cyclic nylon intermediate). Raw materials for these are variable and sources are benzene (from oil refining or coke production), furfural (from oat hulls or corn cobs) or 1,4 butadiene (from oil refining). Nylon is produced by melt spinning and is available in staple, tow, monofilament and multi-filament form.

(http://www.apparesearch.com/education_research_nonwoven_nylon_fiber.htm)

8.2 Properties of nylon

Nylon fibre has outstanding durability and excellent physical properties. Nylons are semi-crystalline polymers. The amide group provides hydrogen bonding between polyamide chains giving nylon high strength at elevated temperatures and toughness at low temperatures. Nylon possesses stiffness, wear and abrasion resistance, low friction coefficient and good chemical resistance. These properties have made nylon the strongest of all man made fibres in use. Nylon's outstanding property in the textile industry is its versatility. It can be made strong, fine for sheer or light. Nylon is used alone or in blends with other fibres, where its main contributions are strength and abrasion resistance.

(http://www.apparesearch.com/education_research_nonwoven_nylon_fiber.htm)

Table 11. The key properties of nylon 66

Nylon 66
➤ Tenacity-elongation at break ranges from 0,78 N/tex (8,8 g/d) -18 % to 0,38 N/tex (4,3 g/d) - 45 %. Its tensile strength is higher than of rayon.
➤ 100 % elastic under 8 % of extension.
➤ Melting point is 263 °C. It means good temperature performance.
➤ Chemically stable.
➤ No mildew or bacterial effects.
➤ 4 - 4.5 % of moisture regains.
➤ Degraded by light as natural fibres.
➤ Permanent set by heat and steam.
➤ Abrasion resistant.
➤ Has the lustre of silk.
➤ Excellent durability and physical properties.

(http://www.apparesearch.com/education_research_nonwoven_nylon_fiber.htm)

8.3 Nylon in the non-woven and paper industry

Because of its high cost, nylon has a limited use in non-woven products. It is used as a blending fibre because it provides excellent tear strength. It is more costly than polyester, polypropylene or rayon. Nylon is used for example in the following applications: clothes, wipes where it gives strength, heat insulations, battery separators and speciality papers.

(http://www.apparesearch.com/education_research_nonwoven_nylon_fiber.htm)

9 POLYPROPYLENE AND POLYETHYLENE

9.1 Definition of olefin, polypropylene and polyethylene

Olefin fibre is a manufactured fibre. Olefins are the product of polymerization of propylene and ethylene gases. Polypropylene (PP) and polyethylene (PE) are the two most common members of the family. Polypropylene is extremely versatile as fibre forming material. It is a highly crystalline thermoplastic resin.

(<http://www.britannica.com/eb/article?tocId=76436>)

9.2 Polypropylene product range

Polypropylene can be used in a wide range of fibrous forms. Fibrous forms of polypropylene include staple, bicomponent staple, monofilament, multifilament, slit film yarns, slit-fibrillated film yarns, spun bonds, melt blown non-wovens, synthetic pulps and extruded nettings. It can be made to rope and cordage, geotextiles, carpet backing, filtration materials, disposable diapers, hospital/medical care products and protective clothing.

The melting point of polypropylene (160-170 °C) is an advantage in many non-wovens' processing steps. PP fibre can be softened sufficiently to bond to one another without destroying the fibre properties.

Because of its performance characteristics and relatively low cost, polypropylene is extensively used in non-wovens industry. PP dominates in many non-woven markets. PP is used, for example, on the top sheet of absorbent diapers.

(http://www.apparesearch.com/education_research_nonwoven_Olefin_Fiber.htm)

9.3 Properties of polypropylene

Polypropylene fibres are produced in a variety of types with different tenacities designed for different end uses. Fibres for general textile use have the tenacity in the range of 4.5-6 g/den but special filaments even up to 13 g/den can be made.

The degree of orientation achieved by drawing influences the mechanical properties of Polypropylene filaments. The higher the degree of stretch, the higher the tensile strength and the lower the elongation. Commercial polypropylene monofilaments have the elongation at break of at the range of 12-25 %. Multifilament and staple fibres are in the range of 20-30 % and 20-35 %, respectively.

Thermal properties of polypropylene are the following: Polypropylene fibres have a softening point in the region of 150 °C and a melting point at 160-170 °C.

Other properties: Polypropylene has excellent resistance to alkalis and acids, high abrasion resistance and resistance to insects and pests. Polypropylene fibre is easy to process and inexpensive compared to other synthetic fibres. Its low moisture absorption helps aid the quick transport of moisture. Disadvantages of polypropylene are, for instance: hard to be dyed after manufacturing, poor UV and thermal stability, poor adhesion to glues and latexes. PP is flammable.

(http://www.apparesearch.com/education_research_nonwoven_Olefin_Fiber.htm)

9.4 Properties of polyethylene

Polyethylene (PE) fibre is one of the world's strongest and lightest fibres. It floats and resists chemicals and water. Polyethylene is created through polymerization of ethylene. It is a thermoplastic used in consumer goods, such as in shopping bags. Polyethylene is a polymer. It consists of long chains of the monomer ethylene. Polyethylene contains carbon and hydrogen. Depending on the crystalline and molecular weight, there are different melting points of PE. The melting point is typically between 120 and 130 °C. Low density polyethylene (LDPE) has a lower melting point of 105-115 °C. Polyethylene is available in a wide range of flexibilities depending on production process, with high density polyethylene (HDPE) being the most rigid. (www.ides.com; www.fibersource.com)

9.5 Summary of tensile strength and elongation values of viscose, polyester, polypropylene and nylon

The following table summarizes the tensile strength and elongation values of Rayon viscose, polyester, polypropylene and nylon fibres. All the values that were available in the literature used in this study are listed below.

Table 12. Tensile strength and elongation values of some fibres.

Property	Viscose standard fibre	Viscose HWM fibre	Viscose polynosic fibre	Polyester filament regular tenacity	Polyester filament high tenacity	Polyester staple or tow regular tenacity	Polyester staple or tow high tenacity	Polypropylene	Polypropylene monofilament	Polypropylene multifilament or staple	Nylon 66
Dry strength N/dex	0,16-0,31	0,38-0,55	0,39-0,55	0,35-0,50	0,62-0,85	0,35-0,47	0,48-0,61	0,40-1,15			0,38-0,78
Elongation dry, %	15-30	12-17'	7-11'	24-50	10-20'	35-60	17-40		12-25'	20-35	

10 BICOMPONENT STAPLE FIBERS

Bicomponent fibres are very advanced multifunctional fibres.

Bicomponent fibres are manufactured from two different polymers that interact with each other.

The sheath material (typically polyethylene) has an excellent softness and a low bonding temperature and can thus be used as binder material in fibre blends or to other kinds of materials. This makes it interesting to test bicomponent fibres for speciality paper production. It should be tested whether bicomponent fibres can be bonded to cellulose fibres without binding agents with the help of heat in the drying section of the paper machine.

The core material (polypropylene or polyester) is used to ensure the integrity of the product. The core does not melt during bonding and it forms a three-dimensional network in the product, giving strength to the product.

Bicomponent fibres allow the producers to manufacture nonwoven materials without using chemical binding agents. Bicomponent fibres can be heat sealable, they can be laminated to plastics without any binders and they are heat mouldable.

There are, for instance, the following bicomponent fibres in the market:
Fibres with different cross sections: concentric, eccentric, side-by-side and splittable.

Sheath materials may be: high density PE, low density PE, linear low density PE, Co-polypropylene and EVA.

Core materials may be: polypropylene, polyester or polyethylene.

Finishes: hydrophilic, durable hydrophilic, hydrophobic, wet lay.

Crimp types are: zigzag, eccentric, spiral (for maximum bulk).

Fibre lengths: short cut 3-24 mm. Staple fibre: 38-128 mm.

It is possible to add additives on the fibres, to improve antibacterial properties, softness, temperature, UV protection and flame retardancy.

Using the thermoplastic properties of the chosen polymers, the manufacturer has the possibility of creating fibres with several key properties, thereby making them more valuable than traditional fibres.

In the following picture there are some bicomponent fibre types.



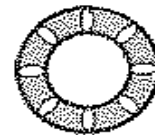
Side by Side



Eccentric Sheath - Core



Concentric Sheath - Core



Hollow Splittable



Zigzag Type

Conventional Two Dimensional Crimp



Wavy Type

Lofty Two Dimensional Crimp



Spiral Type

Highly Lofty Three Dimensional Crimp

Figure 19. Pictures of different bicomponent fibre types. (www.fibervisions.com)

11 CONCLUSIONS OF THE THEORY PART OF THE STUDY

The cellulose pulp fibres providing the highest strength potential to speciality paper are the strong chemical softwood long fibre pulps. The fibres with the best strength potential are springwood fibres with thin walls and good tendency to collapse. The fibres should have the ability to build up fines, fibrillate and thus possess good bonding ability.

The theory part of the study presented the following new fibres for a paper maker: viscose, polyester, polypropylene, polyethylene, nylon and bicomponent fibres. Among these, nylon and polyester are very strong fibres. Rayon viscose fibres are capable of building hydrogen bonds. The capability of a fibre to build hydrogen bonds is an important factor that should be considered when proceeding further to the experimental part of this study on paper machine. Polyester and polypropylene don't have the ability to build hydrogen bonds, thus they must be bonded to cellulose fibres with binders or with heat. It can be expected that mixing these fibres with cellulose pulp, superior strength properties of the ready paper sheet should be achieved.

There are fibres that could provide enhanced elongation to the speciality paper sheet. Simultaneous improvement of elongation and tensile strength with the same new fibres appears to be challenging, although there are fibres that could be tested to fulfil both tasks.

For the improvement of tensile strength, the following new fibres could be tested mixed with cellulose pulp:

- Viscose fibres: strong high wet modulus (HWM) viscose fibres, lyocel or polynosic fibres. These modal fibres have higher strength but inferior elongation compared to standard viscose fibres.
- Polyester fibres: high tenacity staple fibres.

For the improvement of elongation, the following fibres could be tested:

- Standard viscose fibres. They have high elongation but lower strength compared to modal fibres.
- Polyester: partially oriented yarn.

For the simultaneous improvement of elongation and tensile strength, the following fibres could be tested:

- Polyester: regular tenacity staple fibres.

The fibres that are currently in use in speciality paper production, for instance Dacron, a polyester fibre, could be safe to start with.

- Nylon and polypropylene could be tested later. Nylon could provide strength but it is an expensive fibre. Consequently it is not extensively used in paper or non-woven industries today.

For the moulding papers used for thermo pressed trays it could be worth testing the fibres improving the elongation of paper because the paper used for moulded trays should be somewhat elastic, although it is not a creped or clupak paper. Thus the following new fibres could be tested:

- Standard viscose fibres. They have high elongation but lower strength compared to modal fibres.
- Polyester: partially oriented yarn.
- Nylon.

When moulding trays, it is important that the paper resists temperature.

Nylon and polyester fibres can be set into shapes by the application of heat. Polyester has a high melting point and good thermal stability. It softens at about 200 °C and will not burn easily.

Nylon is the strongest of all man made fibres. It resists very high temperature. The melting point of Nylon is 263 °C thus it has an excellent temperature performance.

As a summary of the theory part of the study it can be said that there are new and interesting fibres in the market for speciality paper and board producers. Synthetic fibres added to soft and hardwood cellulose in the right proportion could bring elevated elongation or tensile strength to the paper sheet. High elongation and tensile strength are important properties for speciality crepe paper which is often under stress during its application as masking tape, wet wipe or coffee filter. In addition to the stress, the paper is often wet when it is further processed or used as a ready product. When paper is wet, it loses a lot of strength. The addition of synthetic fibres that don't lose strength when wet could add strength to the paper.

Polyester has lower cost and superior strength versus viscose rayon. Viscose rayon is capable of building hydrogen bonds. Polyester, polypropylene and nylon are not able to build hydrogen bonds. They must be bonded by other means. All these fibres are stronger and longer than cellulose fibres. Thus it can be expected that by using these fibres mixed with cellulose pulp in the production of paper, superior strength properties should be achieved.

12 EXPERIMENTAL PART OF THE STUDY

The experimental part of the fibre study contains the processing, measurements, analysis and conclusions of fibres and paper sheets made in fibre laboratory.

The target was to produce paper sheets with superior elongation or tensile strength or both, compared to paper sheets made of bleached chemical softwood pulp. The improved properties should be reached by adding armature fibres to cellulose pulp.

The armature fibres were selected based on their availability for the laboratory scale test. Consequently, the following armature fibres were received from their manufacturers and used in tests: Polyethylene (PE), Polypropylene (PP+) and Viscose Tencel (viscose).

The fibres and hand sheets were analysed at Stora Enso Imatra experimental laboratory. The PP and PE fibres were analysed by thermal analysis differential scanning calorimeter (DSC) and viscose fibres by thermogravimetric analyzer (TGA). The hand sheets were studied by scanning electron microscope (SEM). The target was to study fibre bonds and the position of fibre in matrix. Contact angle measurements were made in order to evaluate natural hydrophobic characteristics.

12.1 Test fibres

Some European producers of synthetic fibres were contacted in order to receive sample deliveries of fibres for the trials and to get more information on the performance of the synthetic fibres in papermaking.

Comments and samples were received from two companies: Lenzing Fibres Limited, U.K. and Asota GES.M.B.H, Austria.

12.2 Recommendations on Polyethylene and Polypropylene fibres

According to Asota, the paper should be calendared with hot calander so that the fibres can bond.

PP and PE fibres are slippery, they have a low friction. If they are not bonded to cellulose with the help of heat, they will not likely bond. It is probable that the desired properties will not be reached. Binding agents are not added to paper in this case.

Fibres should be added to cellulose pulp at the latest possible stage in the paper machine. They should not be heavily mixed with the cellulose pulp. They should be mixed extremely gently.

It is known that some Chinese paper manufacturers successfully add PP and PE fibres in paper when producing heat sealable tea bag paper. In that case, the polyolefin act as sealing layer. It is also known that some paper makers use nylon in speciality papers.



Figure 20. PP test fibres.



Figure 21. PE test fibres.

12.3 Recommendations on Viscose Tencel fibres

Lenzing Fibres Limited produces short cut staple grades of Tencel cellulosic fibre for paper making applications. Lenzing viscose staple fibre grades are supplied in cut lengths no shorter than 25 mm and so are not suitable for paper processing.

Tencel short cut grades are supplied in cut lengths ranging from 3 mm to 20 mm. The most popular cut length for papermaking is 4 mm. Tencel is a 100 % cellulosic fibre which can be refined, like wood pulp, to generate sub-micron diameter fibrils. The degree of fibrillation can be used to tailor sheet properties such as tensile strength, tear strength, opacity and porosity. The technical bulleting in paragraph 12.7 contains further information.

Lenzing provided a sample of 1.7dtex, 4 mm, dull lustre Tencel for the hand sheet trials from their U.K. factory. The product code is H415 865. Fibre dtex values are not particularly easy to compare with pulp fibres. Tencel has a circular cross section and 1.7dtex corresponds to a fibre diameter of 11 microns.

Refining to high SR values (e.g. 70) will maximise sheet strength provided that the fibre length is not shortened excessively, so gentle refining conditions are recommended.



Figure 22. Viscose Tencel test fibres.

12.4 Test fibre characteristics

The test fibres used were:

1. Polyethylene (PE) Asota E 4803 2,8 dtex, 6 mm. Melting point ~130-135 °C. Supplied by Asota.
2. Polypropylene (PP+) Asota W/E 4219 2,2 dtex, 6 mm. Melting point ~155-170 °C. Supplied by Asota.
3. Viscose Tencel 1.7 dtx dull uncrimped Lyocell fibre. Product code H415865 (Viscose). Supplied by Lenzing.

12.5 Polyethylene

Technical information on Polyethylene (PE) Asota E 4803 2,8 dtex:

Asota E 4803 is a melt spun polyolefin (PE) staple fibre and a special type of a melt-bonding fibre. It has been developed specially for technical products or papers. Asota E 4803 is made for wet laid process with thermal bonding or thermal fusion finish. Asota E 4803 is supplied as short cut fibre. Titre (dtex) 2,8 is equal to staple length 6 mm. The fibre can be used in food contact.

Table 13. Polyethylene fibre characteristics

		Titre 2,8 dtex
Fibre cross section / diameter	round	20 micron
Tear strength	cN/tex	>20
Elongation at break	in %	>50
Thermal shrinkage	110 °C / 10	<10 %
Melting point	°C	~ 130
Specific gravity	g/cm ³	~ 0,95

12.6 Polypropylene

(PP+) Asota W/E 4219 2,2 dtex is a melt-spun polyolefin staple fibre modified with MSA grafted polypropylene (for better adhesion to cellulose). This fibre-type is specially developed for papers which are thermally sealed or welded. The wide melting range from 155 °C to 165 °C promotes the melt-bonding process. The fibre can be used in food contact. Asota E 4219 is supplied as short cut fibre.

Table 14. Polypropylene fibre characteristics

		Titre 2,2 dtex
Fibre cross section / diameter	round	17,5 micron
Tear strength	cN/tex	>40
Elongation at break	in %	>40
Thermal shrinkage	120 °C / 10	<15 %
Melting range	°C	~ 155-165
Specific density	g/cm ³	~ 0,90

12.7 Viscose Tencel

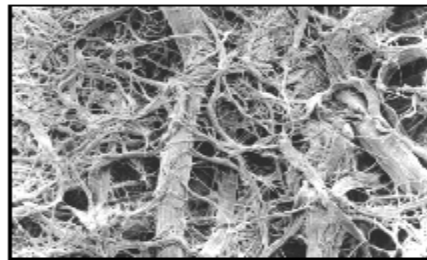
Technical data sheet of Viscose Tencel 1.7 dtx dull uncrimped Lyocell fibre describes the tested fibres.

TENCEL® FOR SPECIALITY PAPERS

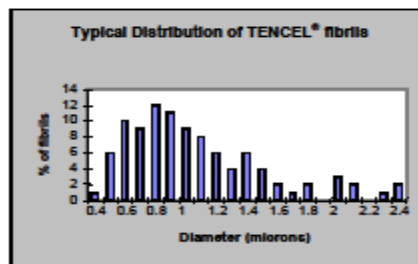
The use of TENCEL® in speciality papers is well established. Refining TENCEL® to generate fine, circular cross-section fibrils enables optimisation of sheet tear strength, opacity and permeability. TENCEL® can be used to produce 100% binder-free papers and it is also ideal for use in blend with woodpulp or microglass fibers.

Fibrillated TENCEL® fibers are used in the production of a wide range of special purpose papers. The fibrillation can be achieved using normal papermaking equipment such as beaters or refiners or by vigorous mixing in a hydropulper or high shear mixer.

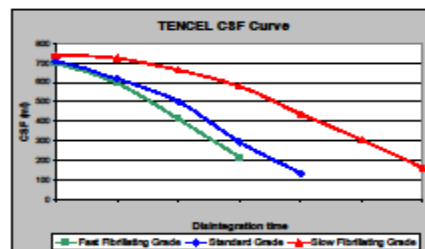
TENCEL® - Fibrillated



Wet fibrillation of TENCEL® yields a distribution of fibril diameters down to sub-micron levels:



TENCEL® fiber is available in a number of different grades and in cut lengths down to 2mm, to suit different processing conditions. Grade selection can also be utilized to enable the control of fibrillation rate, as indicated by the Canadian Standard Freeness test:



Incorporation of TENCEL® gives enhanced sheet thickness and a smooth paper surface. In combination with glass fiber, TENCEL® imparts improved paper strength and integrity in a binder-free composition.

	Tensile Index (Nm/g)	Tear Index (mN.m ² /g)	Bulk (cc/g)
Microglass	5.1	5.5	7.7
Woodpulp	14.8	4.7	2.2
TENCEL®	10.7	16.0	4.0

Blending low levels of TENCEL® with pulp gives very similar improvements in tensile and tear strength to those obtained with short cut polyester, together with the additional advantage of maintaining a furnish of 100% biodegradable and flushable cellulose.

Examples of specific applications for TENCEL® papers include electrical insulation papers, battery separator papers, automotive filters (fuel & oil), HEPA and ULPA filters, medical filters, cooking oil, food and beverage filters.

TENCEL® fibers comprise exceptionally low levels of residual metal ions and TENCEL® papers satisfy the requirements for FDA food contact approval (CFR 21 Sections 176.170 and 176.180) as well as German BgVV (36/1) approval for use in food contact applications.

Figure 23. Technical data sheet of Viscose Tencel.

12.8 Production of test hand sheets

The production of hand sheets and laboratory analysis are described in this chapter.

The target for making the hand sheets was to find the optimal furnish mixture that would improve tensile strength and elongation of paper.

The hand sheets were made and measured at Abo Akademi fibre and cellulose technology laboratory in Turku, Finland.

The pulp used for the comparative sheets was 100 % bleached chemical softwood pulp from Kaskinen pulp mill, later called "Cellulose". The Cellulose was tested in combination with test fibres. This Cellulose is normally used for the production of strong speciality papers when the targeted paper properties include good tensile strength and high elongation.

It was decided not to try to use binders when producing the hand sheets.

- 1.) First step: Reference hand sheets of 100 % Cellulose fibres were produced and measured.
- 2.) Second step: Reference hand sheets containing 10 % of test fibres and 90 % Cellulose fibres were made and measured.

Before making the hand sheets it was important to measure the dryness of pulp and the test fibres. The dryness figures of the fibres used in the sheets are listed in the following chart.

Table 15. Dryness % of test fibres

Cellulose	95 %
Viscose	93 %
PE	100 %
PP +	100 %

Cellulose pulp had dryness of 95 % and Viscose fibres 93 % because they absorb moisture from the atmosphere. PE and PP+ were totally dry.

The hand sheets were made according to ISO 5269/1. 32,67 g of mass was added into 40 litres of water.

Disintegrator for chemical pulp testing (according to SCAN-C 18:65) was used to disintegrate the cellulose.

The water from the sheets was removed by using the press according to SCAN CM 64:00.

The sheets dried overnight in an air conditioned laboratory.

The sheets were measured the following day when properly dried.

The following properties were measured:

- Basis weight (g/m²)
- Thickness (micron)
- Tensile strength (kNm/kg)
- Stretch (%)
- Work (J/kg)
- Density (kg/m³)

Prior to measuring tensile strength and elongation, paper sheets were cut to proper sizes. Irregular sheet edges were cut off with a cutting press.

Thickness was measured at 5 control points with L&W micrometer.

Basis weight was measured by weighing the sheets.

Tensile strength and elongation were measured with L&W tensile strength tester.

Test pieces were cut to narrow stripes of 15 mm wide and 100 mm length.

Hand sheets containing 10 % PE and 10 % PP were treated in three alternative ways:

- 1.) Sheets were calendared in a nip with temperature of 100 °C.
- 2.) Sheets were dried with IR light for 5-7 seconds.
- 3.) Sheets were neither calendared nor IR dried.

Hand sheets with 10 % PE were dried with IR light for 5 seconds. Hand sheets with 10 % PP were dried for 7 seconds. Different drying durations were selected due to different melting points of fibres. PE fibres have a melting point of 135 °C and PP fibres 155 °C.

Calendaring and drying were tested to evaluate the impact of heat treatment on measured paper technical values. The fibre producer Asota had recommended using heat to bind PE and PP fibres to fibre matrix, as no additional binding agents were used.

Hand sheets made of softwood cellulose and cellulose + 10 % viscose were neither calendared nor dried with IR light. These fibres don't require heat treatment for binding the fibres in the fibre matrix. Cellulose and viscose fibres bind with hydrogen bonds.

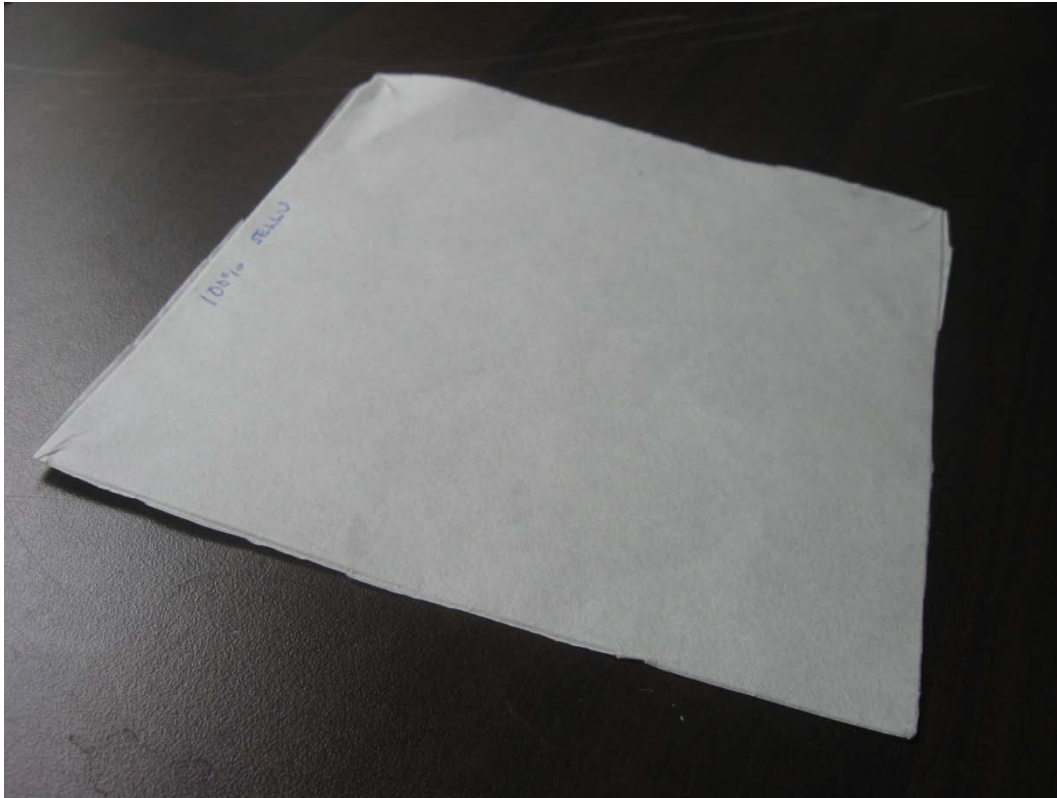


Figure 24. Hand sheet containing 100 % cellulose.

13 RESULTS

13.1 Presentation of the results

This chapter will present the paper technical values of the hand sheets. The measurements were made on 2-8 samples. Table 16 on next page includes the measured values of each individual test piece. The average values of strength, stretch and work (x) are stated after the values of the test pieces.

The abbreviations used in Table 16 have the following meanings:

- 1.) SW pulp = Softwood Cellulose pulp 100 %
- 2.) Viscose 10% = Softwood Cellulose pulp 90 % + Viscose 10 %
- 3.) PE 10 Cal. = Softwood Cellulose pulp 90 % + PE 10 % calendared
- 4.) PE 10 IR = Softwood Cellulose pulp 90 % + PE 10 % IR dried for 5 seconds
- 5.) PE 10 = Softwood Cellulose pulp 90 % + PE 10 %
- 6.) PP 10 Cal. = Softwood Cellulose pulp 90 % + PP 10 % calendared
- 7.) PP 10 IR = Softwood Cellulose pulp 90 % + PP 10 % IR dried for 7 seconds
- 8.) PP 10 = Softwood Cellulose pulp 90 % + PP 10 %

Results	SW Pulp 100%	Viscose 10%	PE 10% Cal	PE 10% IR	PE 10%	PP 10% Cal	PP 10% IR	PP 10%
Test piece No 1								
Fmax	18,17 N	19,34 N	15,14 N	15,58 N	13,24 N	16,65 N	18,27 N	15,82 N
Strength	22,10 kNm/kg	21,24 kNm/kg	16,43 kNm/kg	16,90 kNm/kg	14,36 kNm/kg	18,22 kNm/kg	19,98 kNm/kg	17,39 kNm/kg
Stretch	1,93 %	2,30 %	2,06 %	1,64 %	1,45 %	1,93 %	2,03 %	1,74 %
Work	309,2 J/kg	352,7 J/kg	225,6 J/kg	192,5 J/kg	140,6 J/kg	231,0 J/kg	298,0 J/kg	211,0 J/kg
Test piece No 2								
Fmax	18,95 N	19,19 N	15,92 N	15,14 N	10,65 N	16,51 N	17,19 N	15,09 N
Strength	23,05 kNm/kg	21,08 kNm/kg	17,27 kNm/kg	16,43 kNm/kg	11,55 kNm/kg	18,06 kNm/kg	18,80 kNm/kg	16,59 kNm/kg
Stretch	2,27 %	1,90 %	1,56 %	1,69 %	1,62 %	1,82 %	1,74 %	1,50 %
Work	381,2 J/kg	297,6 J/kg	187,1 J/kg	191,9 J/kg	130,4 J/kg	218,9 J/kg	231,1 J/kg	170,7 J/kg
Test piece No 3								
Fmax	17,34 N	16,61 N	15,38 N		14,65 N	14,55 N	15,19 N	15,58 N
Strength	21,09 kNm/kg	18,24 kNm/kg	16,69 kNm/kg		15,90 kNm/kg	15,92 kNm/kg	16,61 kNm/kg	17,13 kNm/kg
Stretch	1,99 %	1,80 %	2,32 %		1,75 %	2,23 %	1,92 %	1,51 %
Work	308,0 J/kg	241,5 J/kg	280,8 J/kg		199,3 J/kg	241,6 J/kg	213,4 J/kg	174,8 J/kg
Test piece No 4								
Fmax	20,12 N	17,39 N			13,19 N			17,19 N
Strength	24,48 kNm/kg	19,10 kNm/kg			14,31 kNm/kg			18,90 kNm/kg
Stretch	1,96 %	1,78 %			1,23 %			1,94 %
Work	357,7 J/kg	251,6 J/kg			121,0 J/kg			258,9 J/kg
Test piece No 5								
Fmax	18,80 N	18,51 N						
Strength	22,88 kNm/kg	20,33 kNm/kg						
Stretch	1,68 %	1,47 %						
Work	280,3 J/kg	218,9 J/kg						
Test piece No 6								
Fmax	20,81 N	17,14 N						
Strength	25,31 kNm/kg	18,83 kNm/kg						
Stretch	2,17 %	1,17 %						
Work	402,7 J/kg	153,1 J/kg						
Test piece No 7								
Fmax	17,83 N	18,61 N						
Strength	21,69 kNm/kg	20,44 kNm/kg						
Stretch	1,77 %	1,51 %						
Work	284,4 J/kg	221,5 J/kg						
Test piece No 8								
Fmax	19,54 N	15,09 N						
Strength	23,77 kNm/kg	16,58 kNm/kg						
Stretch	2,35 %	2,77 %						
Work	421,8 J/kg	336,7 J/kg						
Approved samples	8	8	3	2	4	3	3	4
Strength								
x	23,05 kNm/kg	19,48 kNm/kg	16,80 kNm/kg	16,66 kNm/kg	14,03 kNm/kg	17,40 kNm/kg	18,47 kNm/kg	17,50 kNm/kg
s	1,429 kNm/kg	1,597 kNm/kg	433,7 kNm/kg	337,1 kNm/kg	1,808 kNm/kg	1,282 kNm/kg	1,708 kNm/kg	989,0 kNm/kg
v	6,20 %	8,20 %	2,58 %	2,02 %	12,89 %	7,37 %	9,25 %	5,65 %
Stretch								
x	2,02 %	1,84 %	1,98 %	1,66 %	1,51 %	1,99 %	1,90 %	1,67 %
s	0,23 %	0,50 %	0,39 %	0,04 %	0,22 %	0,21 %	0,15 %	0,21 %
v	11,59 %	27,30 %	19,44 %	2,13 %	14,85 %	10,41 %	7,64 %	12,61 %
Work								
x	343,2 J/kg	259,2 J/kg	231,2 J/kg	192,2 J/kg	147,8 J/kg	230,5 J/kg	247,5 J/kg	203,9 J/kg
s	55,01 J/kg	66,44 J/kg	47,11 J/kg	441,9 mJ/kg	35,22 J/kg	11,39 J/kg	44,62 J/kg	40,95 J/kg
v	16,03 %	25,63 %	20,38 %	0,23 %	23,83 %	4,94 %	18,03 %	20,09 %
Rupturelevel	9.8 %	9.8 %	9.8 %	9.8 %	9.8 %	9.8 %	9.8 %	9.8 %
Time	20.0 s	20.0 s	20.0 s	20.0 s	20.0 s	20.0 s	20.0 s	20.0 s
Velocity	12 mm / min	12 mm / min	12 mm / min	12 mm / min	12 mm / min	12 mm / min	12 mm / min	12 mm / min
Load cell	200 N	200 N	200 N	200 N	200 N	200 N	200 N	200 N
Test span	100 mm	100 mm	100 mm	100 mm	100 mm	100 mm	100 mm	100 mm
Strip width	15,00 mm	15,00 mm	15,00 mm	15,00 mm	15,00 mm	15,00 mm	15,00 mm	15,00 mm
Grammage	54,80 g/m2	60,70 g/m2	61,45 g/m2	61,45 g/m2	61,45 g/m2	60,95 g/m2	60,95 g/m2	60,95 g/m2
Thickness	99 micron	123 micron	131,5 micron	131,5 micron	131,5 micron	145,5 micron	145,5 micron	145,5 micron
Density	553,5 kg/m3	493,5 kg/m3	467,3 kg/m3	467,3 kg/m3	467,3 kg/m3	418,9 kg/m3	418,9 kg/m3	416,8 kg/m3

13.2 Analysis of the results

The average basis weight of the hand sheets made of Cellulose 100 % was 55 g/m². All the other samples had a basis weight of 61 g/m².

It was not possible to reach improved strength or elongation with the tested fibres (PE, PP and Viscose). The Hand sheets made of 100 % Cellulose had the best average strength (23,05 kNm/kg), stretch (2,02 %) and work (343,2 J/kg) values compared to the other pulp mixtures. The second highest strength and work values were obtained with Viscose (19,48 kNm/kg) and the third highest with PP 10 % dried with IR (18,47 kNm/kg). The lowest strength values were measured on PE 10 % without heat treatments (14,03 kNm/kg).

It can be stated that the results correspond to the expected values. It could be expected that PP and PE would not provide improved strength as it was not possible to add binders or thermal bond the fibres in high enough temperature. It could be clearly seen that heat treatment by calendaring and with IR improved strength and work. For PP fibres, IR was more efficient in strength improvement than hot calander. For PE fibres there was no difference, hot calander and IR had an equal impact on strength.

A longer heating time with IR could have brought higher strength. It was not tested how IR and calendaring applied on the same sample would affect strength, stretch and work.

Viscose fibres with a higher dtex figure than the tested 1.7 dtex could have given different results, eventually a higher strength. PE and PP fibres had higher dtex figures. PE 2,8 dtex and PP 2,2 dtex. Fibres with a higher length than the tested ones should be trialled later on.

Calendaring improved stretch more efficiently than IR on both PE and PP fibres. It was clear that heat treatment had a positive impact on stretch on both PE and PP. Hand sheets made of 100 % Cellulose had the best average stretch value (2,02 %), but the values of PE 10 % calendared (1,98 %) and PP 10 % calendared (1,99 %) were nearly the same as of Cellulose 100 %.

PE fibres had a higher initial elongation at break than PP fibres but the final stretch is at the same level.

The hand sheets containing PE and PP fibres have higher softness than the sheets made of Cellulose 100 % or of Cellulose 90 % + Viscose 10 %. The improved softness can be seen as an advantage in manual applications as soft paper is comfortable to handle.

The hand sheets containing PE and PP fibres have a glossier appearance than the sheets of Cellulose 100 % or of Cellulose 90 % + Viscose 10 %. It is due to the glossy look of PE and PP fibres.

When preparing the water-cellulose- test fibre mixture, PP and PE fibres wanted to float on the surface of water. It could be seen that PE and PP float and resist water.

13.3 Analysis of PE and PP fibres

Differential scanning calorimetry (DSC) was used to determine the melting point of PP and PE fibres.

DSC is a thermoanalytical technique in which the difference in the amount of heat required to increase the temperature of a sample is measured as a function of temperature. (http://en.wikipedia.org/wiki/Differential_scanning_calorimetry)

On next pages, Figure 25. illustrates the DSC measurement of PE fibres and Figure 26. the DSC measurement of PP fibres.

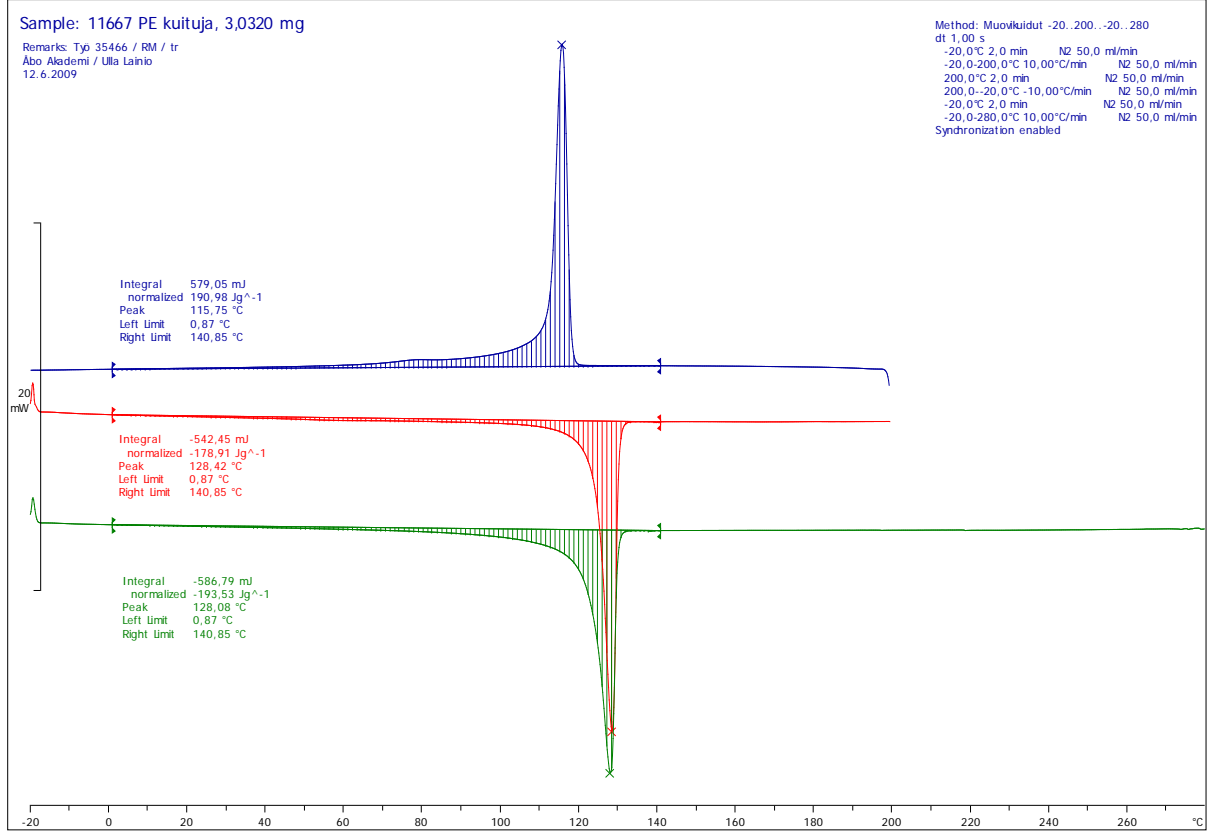
The curves can be interpreted as follows:

Red curve means heating.
Blue curve means cooling.
Green curve means the second heating.

During the first heating the purpose was to melt the fibres on the bottom of the cup and reach complete contact and relaxation of the polymer. The second heating shows the real melting point and range. The melting point of PE was 128 °C. The melting point of PP was 158 °C

Melting is indicated by the downward curve and crystallisation by the upward curve.

Y axis is the required amount of energy and x axis is the temperature.



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Figure 25. Melting point of PE.

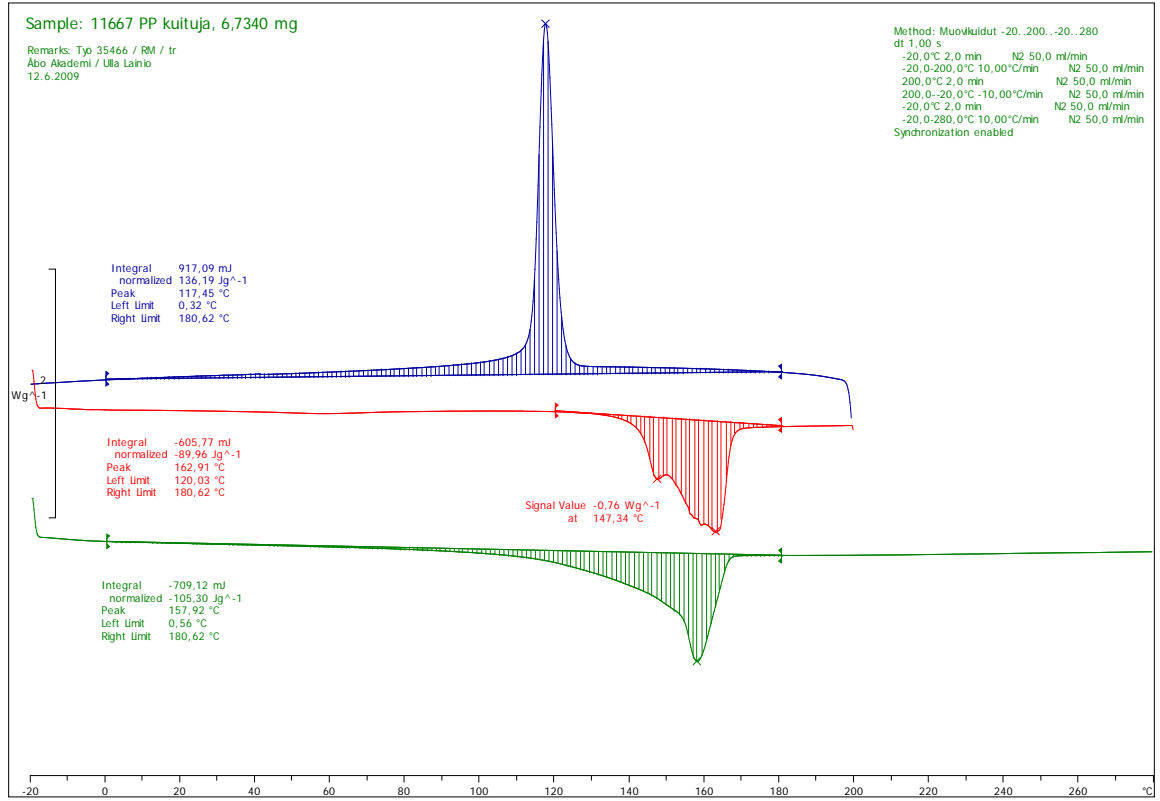


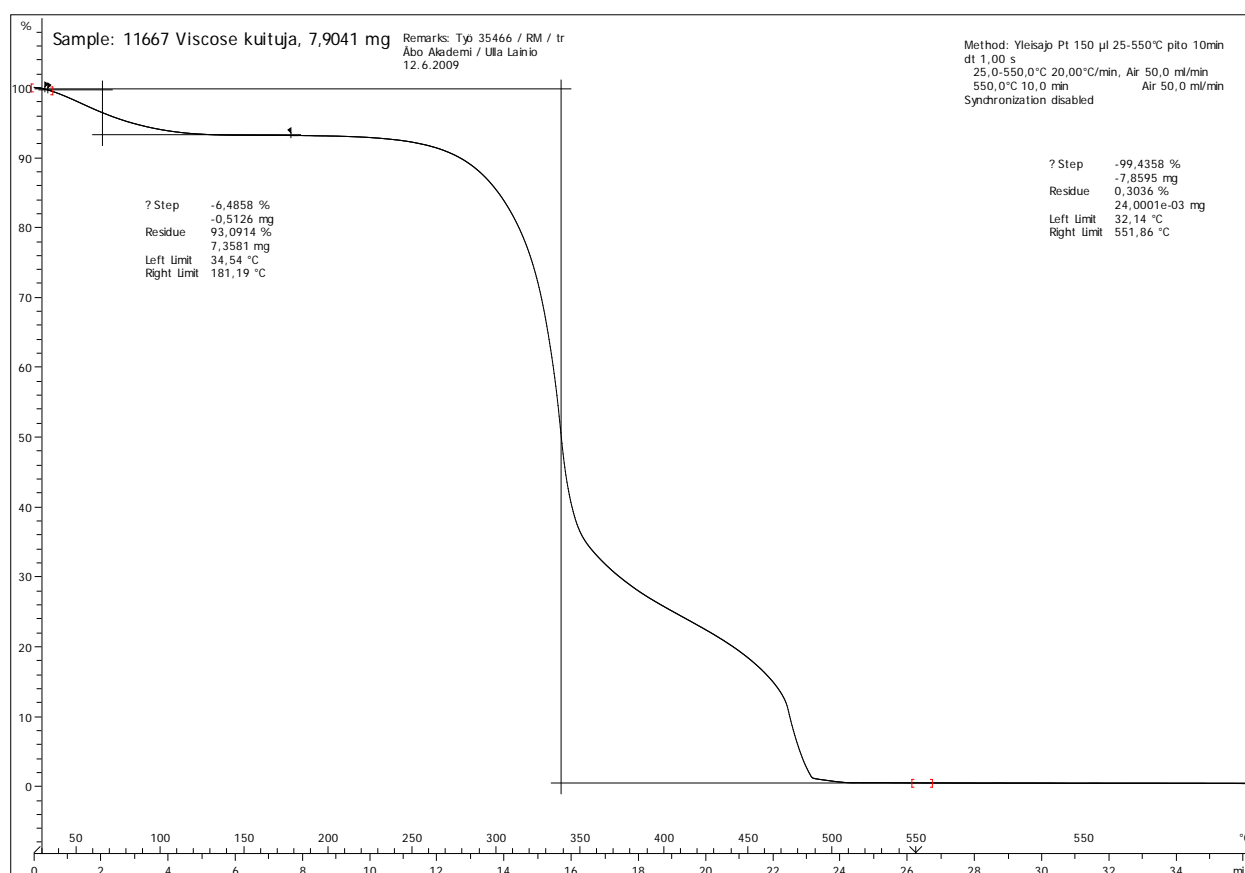
Figure 26. Melting point of PP.

13.4 Analysis of viscose fibres

Viscose fibres were analysed by thermogravimetric analysis (TGA). TGA testing is used to determine changes in weight in relation to change in temperature. There are three measurements: weight, temperature and temperature change. TGA is used to determine the characteristics of materials such as polymers, to determine degradation temperatures, absorbed moisture content of materials and the level of inorganic and organic components in materials.

(http://en.wikipedia.org/wiki/Thermogravimetric_analysis)

The curves below can be interpreted as follows: The first loss of weight (-6.4858 %) indicates the escape of moisture. The second loss of weight means break down of carbon hydrates (-99,4358 %). The third weight loss means break down of all other organic material. The temperature range during testing was from 32,14 °C to 551,86 °C. The duration of measurement was 10 minutes. The measurement was carried out with air as the combustion gas.



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Figure 27. TGA analyse of viscose fibres.

13.5 Contact angle measurements

All the hand sheets were measured in order to define the contact angle. Contact angle indicates how hydrophobic or hydrophilic the paper is. We wanted to check whether the hand sheets composed of cellulose 100 % and cellulose 90 % + 10 % viscose would be more hydrophilic than the hands heets containing PE and PP. When water was dropped on the sheets, there were no significant tendencies in the hydrophobic nature of the hand sheets.

When treated with di-iodine methane and measured for 0,02 seconds, cellulose 100 % and cellulose 90 + 10 % viscose hand sheets had higher contact angle average values than the hand sheets containing PE and PP. It means that cellulose 100 % and cellulose 90 + 10 % viscose hand sheets were in fact more hydrophobic than the sheets containing PE and PP.

Table 17. Contact angle measurements

		Contact angle								
	time (sec.)	0,02	0,12	0,22	0,32	0,42	0,02	0,12	0,22	0,32
Di-iodine methane							water			
Cellulose	measurement 1	46,6	28,5	21,5			43,5	20,8		
	measurement 2	36,0								
100% cellulose	measurement 1	37,0	31,3	27,3	26,0	24,0	26,2			
	measurement 2	35,2	24,4	23,4	23,4		31,3			
	measurement 3	35,3	17,0				30,4			
	measurement 4	35,5	21,7				31,1			
	measurement 5	35,4	25,7				27,7			
PE	measurement 1	28,0					34,9	17,6	14,6	
	measurement 2	34,9	27,6	25,8	24,1		21,5			
	measurement 3	27,1					24,4			
	measurement 4	33,7	20,3				36,9			
	measurement 5	28,2					32,0			
PP	measurement 1	30,2					32,2			
	measurement 2	27,2					28,1			
	measurement 3	27,7					24,4			
	measurement 4	30,3					22,9			
	measurement 5	31,5					23,2			
Viscose	measurement 1	30,8					25,6			
	measurement 2	31,1	22,1				23,2			
	measurement 3	38,6					25,2			
	measurement 4	35,4	23,7				23,9			
	measurement 5	30,7					26,8			

drops were dropped on all sampes on matt side

13. 6 Scanning electron microscope pictures

The hand sheets were studied with SEM technique. The target was to study fibre bonds and the position of fibres in the matrix. PE and PP fibres are straight, not fibrillated. They have not changed their shape. They are not well bond with cellulose fibres. In some pictures they are on the top of the sheet. PE fibres are better blended with cellulose fibres than PP fibres. PP fibres tend to be grouped together rather than evenly mixed with cellulose. The following photos represent cellulose + PE fibres, cellulose + PP fibres and cellulose + viscose fibres.

SEM pictures of cellulose + PE fibres

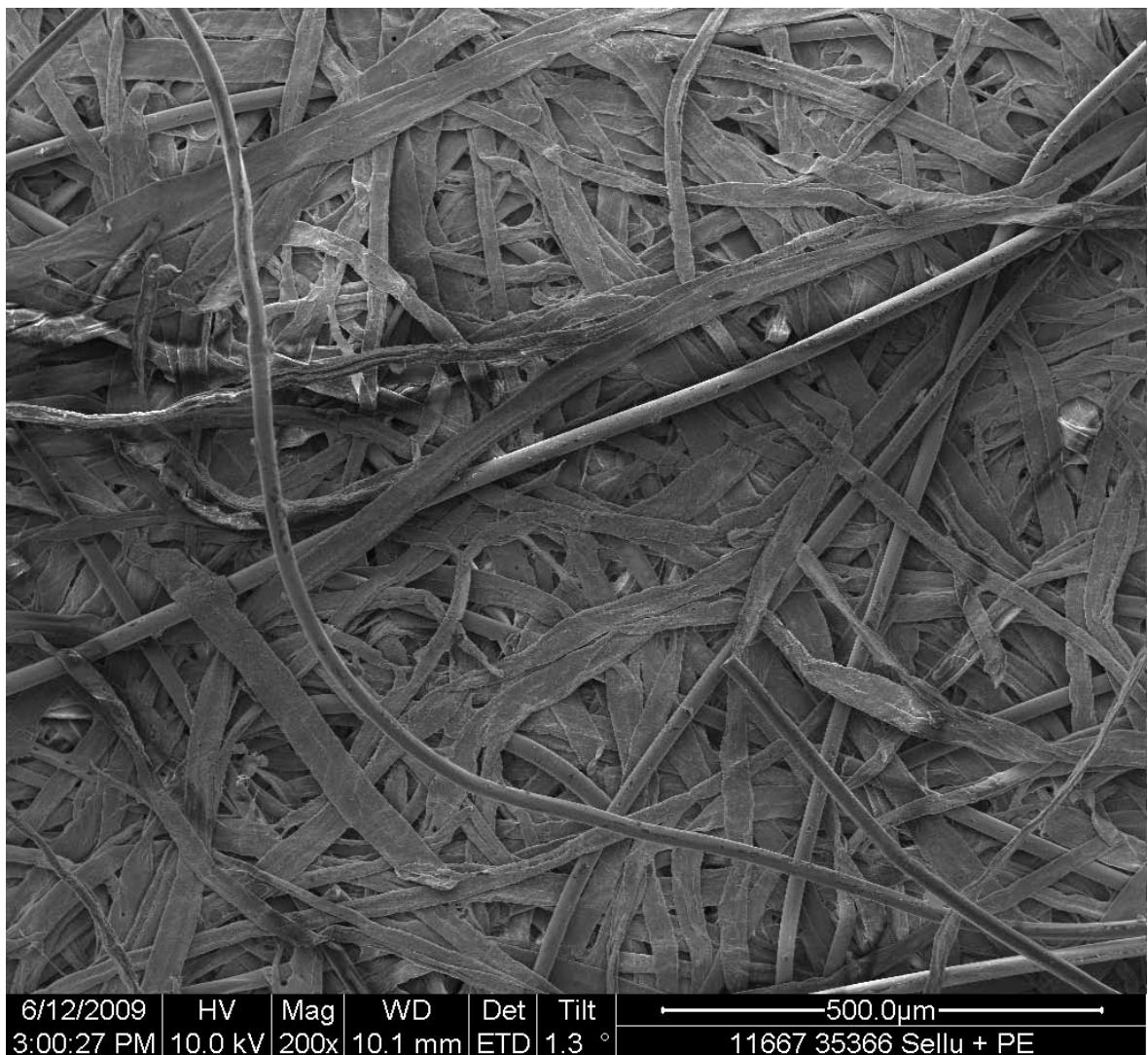


Figure 28. Cellulose + PE fibres.

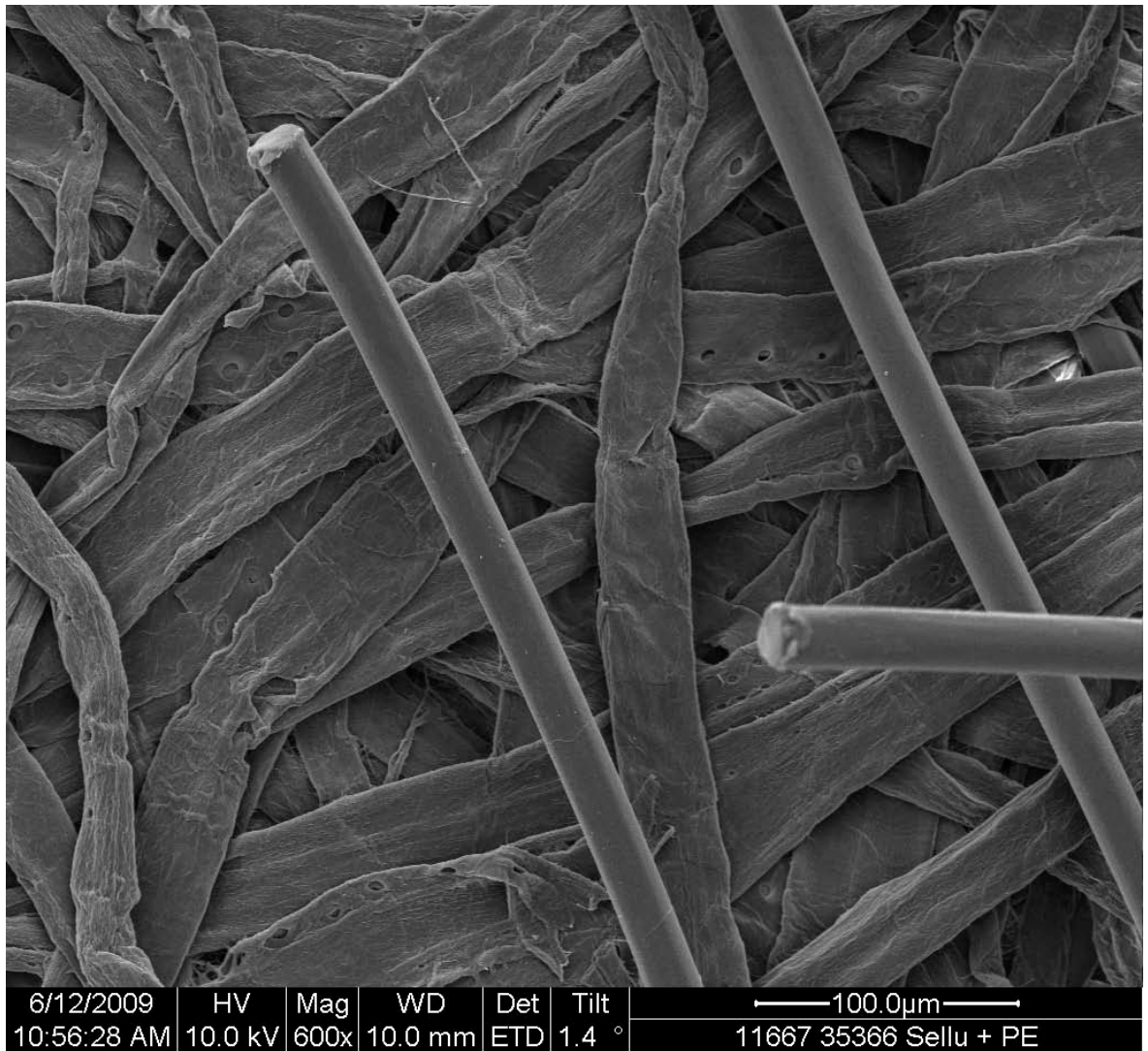


Figure 29. Cellulose + PE fibres. PE fibres don't bond with cellulose.

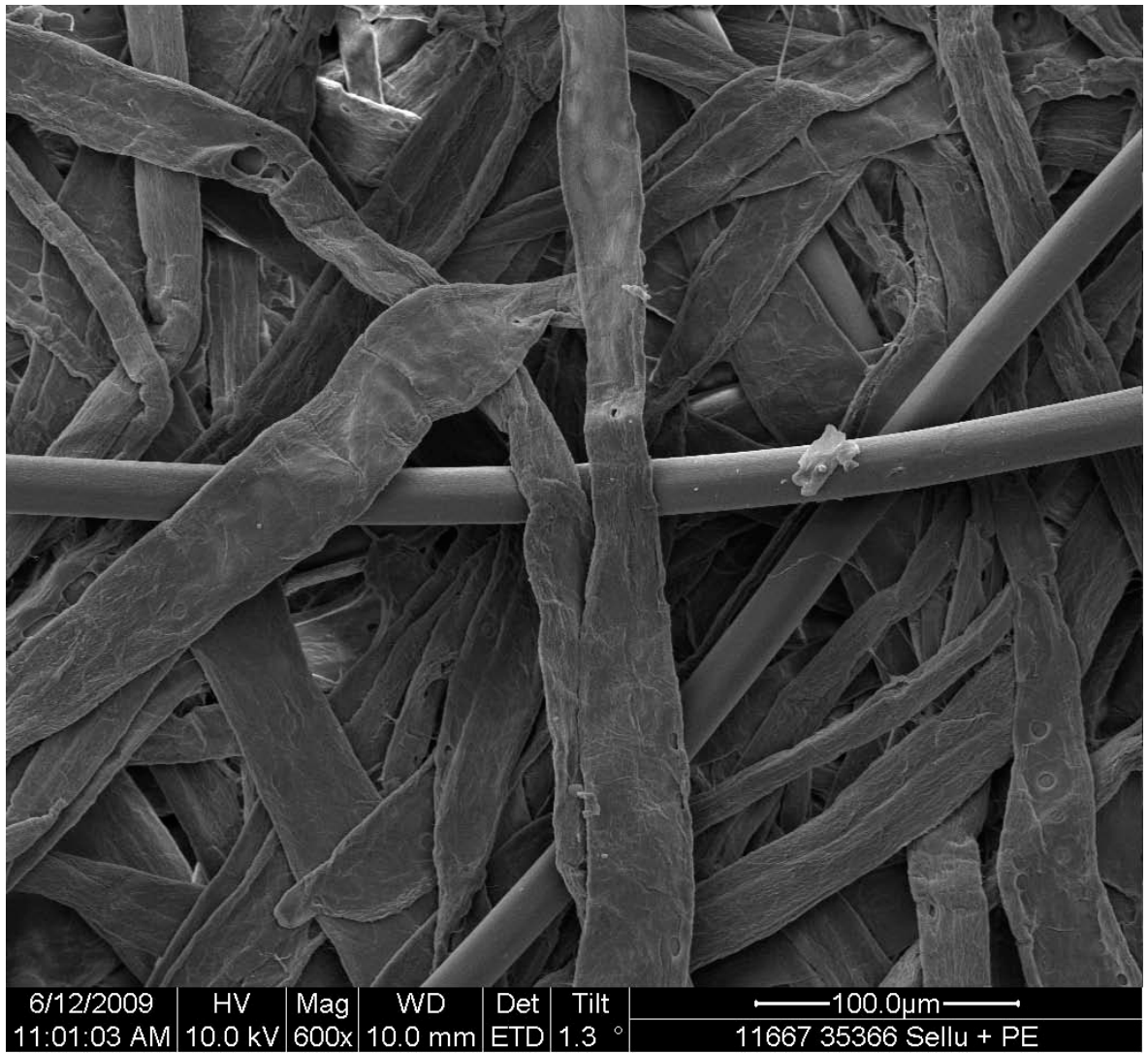


Figure 30. Cellulose + PE fibres.

SEM pictures of cellulose + PP fibres

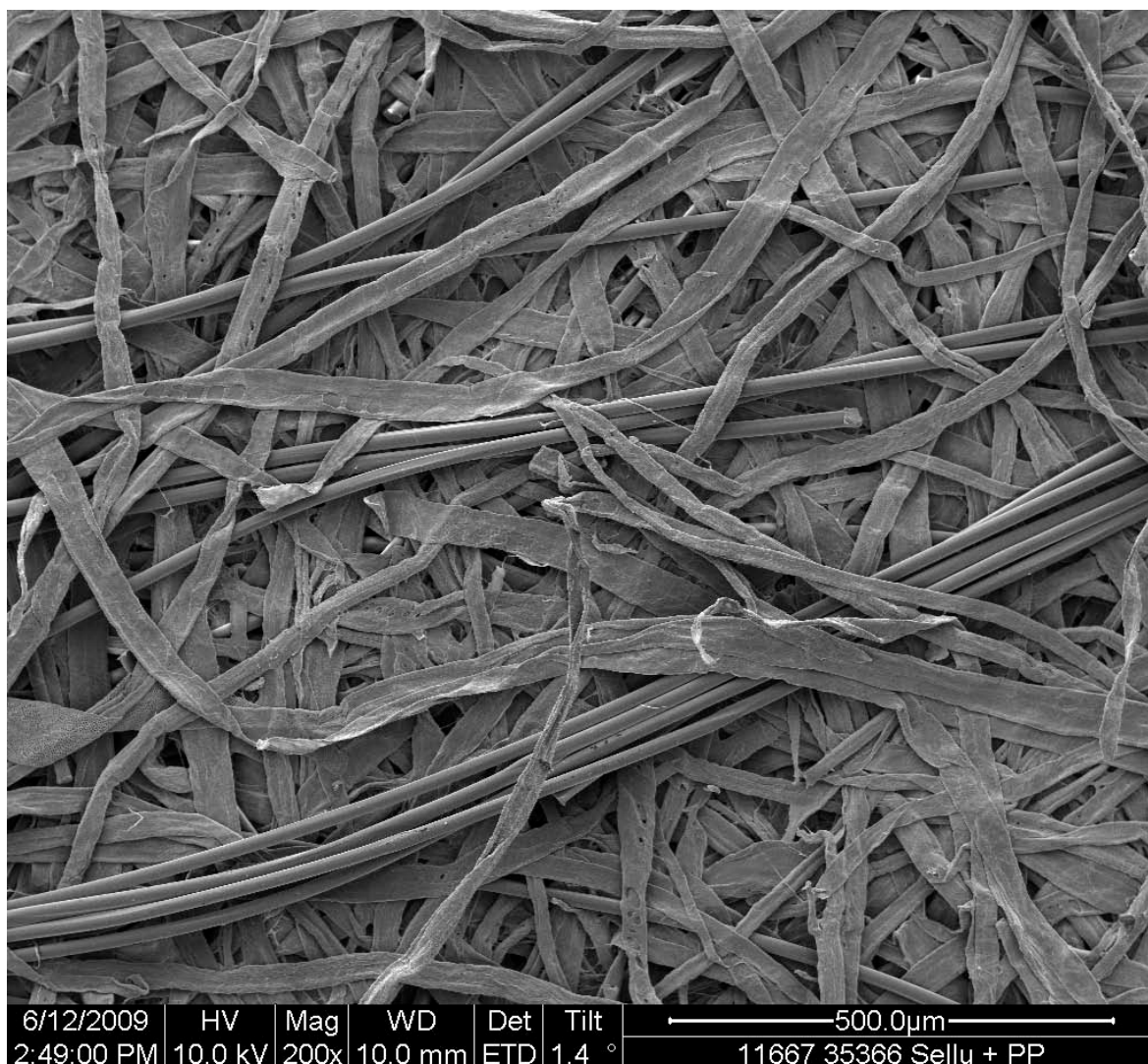


Figure 31. Cellulose + PP fibres.



Figure 32. Cellulose + PP fibres.



Figure 33. Cellulose + PP fibres

SEM pictures of cellulose + viscose fibres

Viscose fibres are well blended with cellulose fibres. Viscose fibres are long, straight and non-fibrillated.

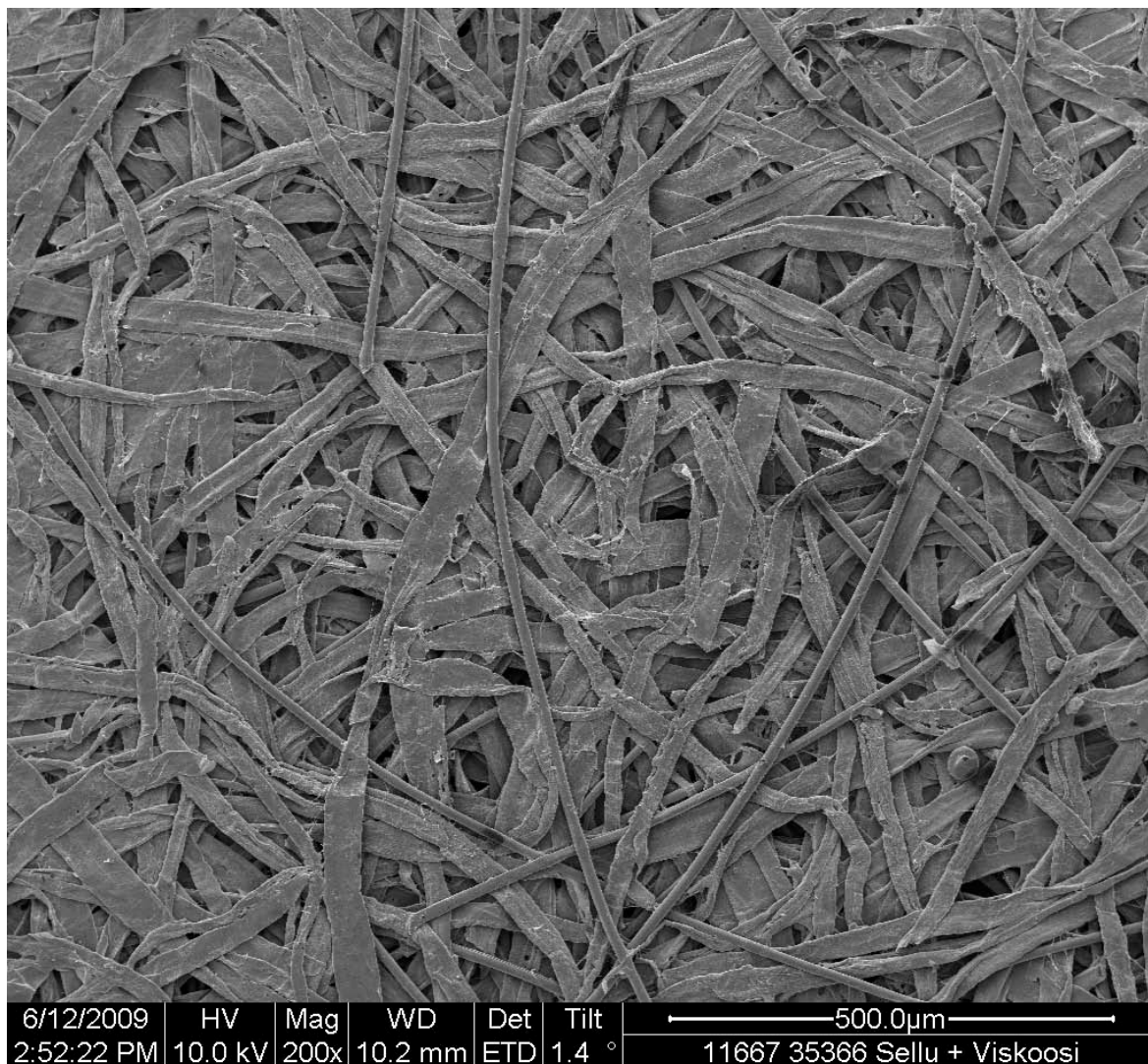


Figure 34. Cellulose + viscose fibres.

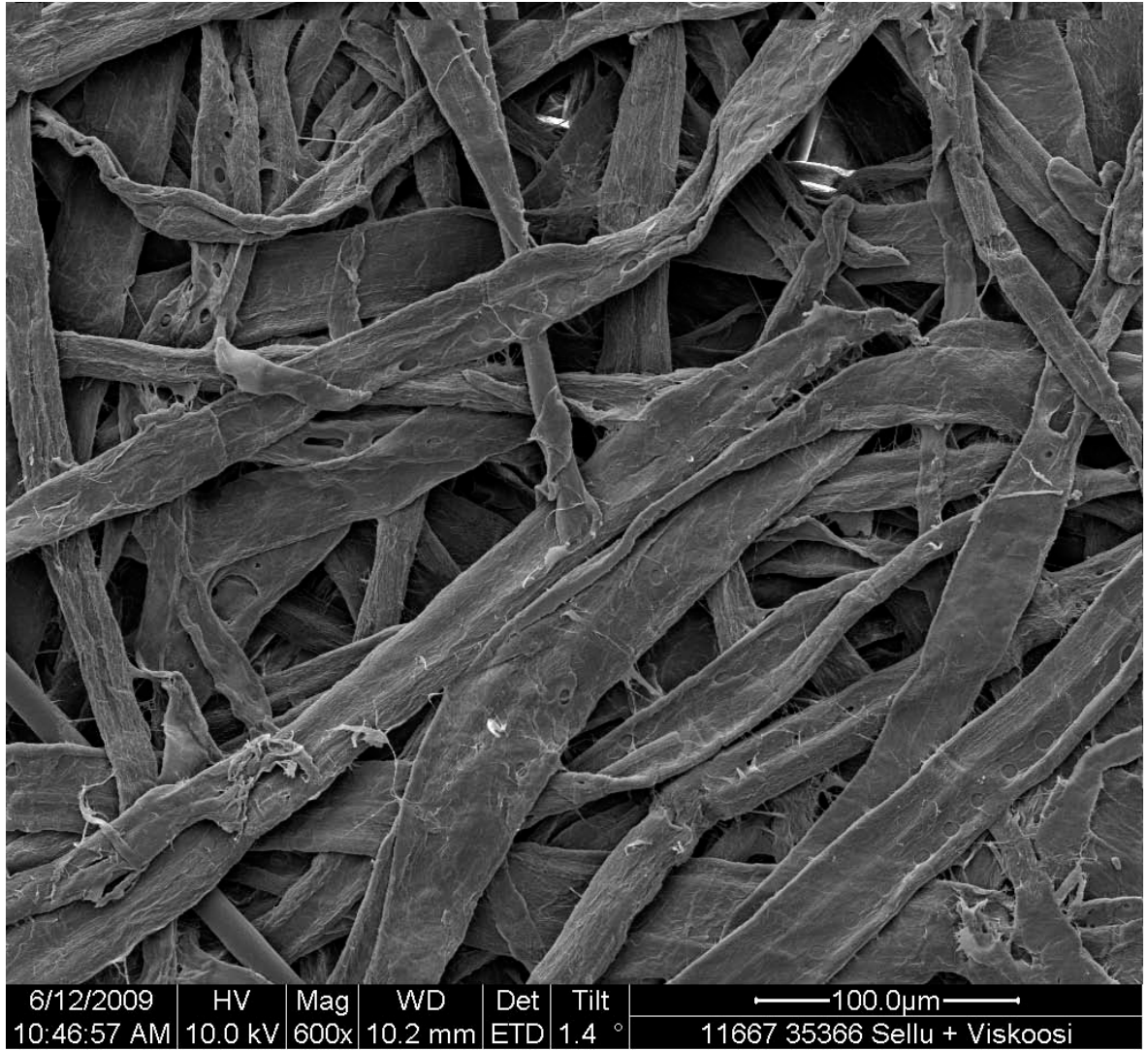


Figure 35. Cellulose + viscose fibres.

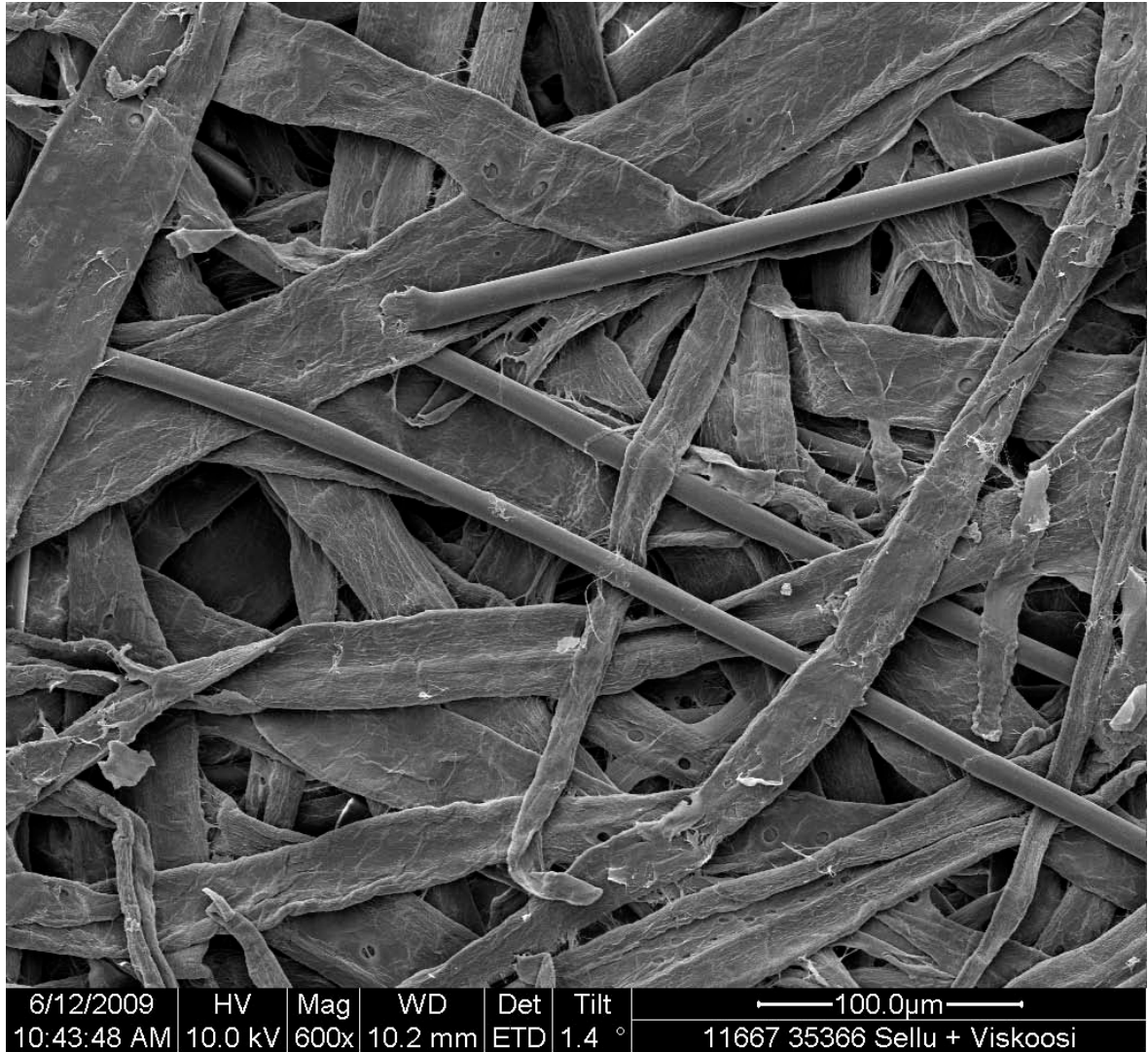


Figure 36. Cellulose + viscose fibres.

13.7 Problems during tests

When the hand sheets were heat treated it was not possible to modify calendaring temperature or calander rolls. It was not possible to calander the hand sheets with a soft calander. Soft roll could have given better bonding results to the paper sheet and consequently, higher strength when the fibers bonding capacity would have increased. During the tests, the calander temperature was about 100 °C. In order to bond thermally, PE fibres would have required a temperature of about 128 °C and PP fibres 155 °C.

It was not possible to test the effect of surface sizing on paper properties. Sizing should increase the number of fibre bonds. Sizing agent is capable of forming hydrogen bonds and gluing the fibres together.

As said in the theory part of the study, the following paper properties have the most significant impact on tensile strength: basis weight, moisture, fibre orientation, ash content and formation. When making the hand sheets, it was not possible to influence on the other properties than on basis weight. Thus, further trials on paper machine would be necessary.

Bicomponent fibres and polyester fibres would have been interesting to test. Some producers of these fibres were contacted and asked for a trial delivery. Unfortunately the producers did not reply to the inquiry thus it was not possible to test these fibres.

It would have been useful to test fibres of higher lengths (mm). So far, only the lengths specified above were tested.

13.8 Need for further experiments

After the literature search and making the laboratory sheets, it would be natural to continue trials on paper machine. The trials on paper machine are not in the scope of this study.

As stated in chapter 4, cellulose pulp has the best bonding capacity. This was proven when evaluating the strength properties of the hand sheets.

The effect of IR drying and hot calendaring should be tested for PE and PP fibres on paper machine. Then it would be possible to evaluate their thermal bonding capacity with cellulose fibres.

PP fibres seem to provide better strength than PE fibres, thus it should be considered whether it is worth continuing to test PE fibres at all. Maybe the future focus should be on PP and Viscose fibres, and on some other new fibres, such as polyester and bicomponent fibres, which were not tested in this study.

Bicomponent fibres offer benefits. They are combinations of two polymers which have different melting temperatures, for example side by side bicomponent fibres. When the polymer with a lower melting temperature softens, it bonds the whole bicomponent fibre with cellulose but the armature part of the bicomponent fibre stays intact and gives strength.

The literature sources recommend the use of binders when PP fibres are added to natural fibres. It should be tested how to use binders with PP fibres, what are the suitable binders and what is the right proportion of binders. It would be interesting to evaluate what is the real effect of PP fibres with binders to paper properties. It could be possible to reach very good strength and stretch values.

Generally, it will be challenging to use PP fibres on paper machine, as they are not natural fibres that can be recycled in the wet end the same way as cellulose pulp. PP fibres are light and they may want to stay on the top of the sheet. PP fibres

may be challenging to mix with cellulose pulp. If PP fibres would stay on the surface of the sheet rather than get regularly mixed with cellulose fibres, it could be possible to use the PP layer as sealing layer. PP fibres could act as heat sealable layer. This could bring a huge added value to the paper. Usually the heat sealing polymer layer is added by coating the paper. Coating requires an additional costly manufacturing step. If the PP fibres would stay on the surface of the paper and if their amount would be right, polymer coating could be totally avoided. The new PP paper could be used for heat sealable pouches such as for tea bags.

Viscose fibres should be easy to use on paper machine, because they are natural fibres like cellulose. They should be usable the same way as cellulose fibres and they don't require additional binders.

14 CONCLUSIONS

The starting point for this study was to examine what kind of fibres there are in the market that could be used in paper making for the improvement of tensile strength and elongation. Tensile strength and elongation depend partly on each other and it is not easy to increase both properties simultaneously. When tensile strength increases, elongation at break may suffer.

Many paper and pulp makers are constantly working on finding stronger fibres. New fibres are tested regularly in fibre laboratories at paper and pulp mills and at, for instance, Abo Akademi. Theoretical studies on fibres and the production of hand sheets give the guideline how to continue the study of new fibres. In paper making, it is always necessary to trial new fibres on paper machine. This Master's thesis proves that there exists a great variety of synthetic fibres that can be used in paper making. It could be verified that the fibres can be added to soft wood cellulose. The test fibres functioned as expected and changed the properties of the hand sheets. In order to verify the strength or elongation improving effect of the synthetic fibres, it is necessary to thermal bond or glue the synthetic fibres with cellulose.

APPENDICES

APPENDIX 1. TRADE NAMES OF MAN-MADE FIBERS

In the chart below there is a list of some trade names of man-made fibres. The fibres presented in this study are marked with bold letters.

Generic Name	Chemical Constitution	Example Names	Trade
Acetate	Secondary cellulose acetate	Dicel	
Acrylic	At least 85% by mass of acrylonitrile	Acrilan , Courtelle, Orlon	Dralon,
Alginate	Metallic salts of alginic acid	Calcium alginate	
Aramid	Composed of linear macromolecules of aromatic groups joined by amide or imide linkages	Nomex, Conex, Kevlar, Technora, Twaron	
Chlorofibre	At least 50% by mass of poly(vinyl chloride) or poly(vinylidene chloride)	Rhovyl, Leavil, Saran	
Cupro	Regenerated cellulose produced by the cuprammonium process	Cuprama	
Elastane	At least 85% by mass of polyurethane elastomer	Enkaswing, Spanzelle	Lycra,
Elastodiene	Natural or synthetic polyisoprene		
Fluorofibre	Polymer made from fluorocarbon monomer	Polifen, Teflon	
Glass	Mixed silicates	Fibreglass, Marglass	
Modacrylic	Polymer made from 50-85% by mass of acrylonitrile	Dynel , Teklan	
Modal	Regenerated Cellulose made by a high wet-modulus process	Vincel	
Nylon (Polyamide)	Polymer with the recurring functional group -CO-NH-	ICI Nylon, Enkalon, Perlon, Celon	
Polycarbamide	Polymer with recurring functional group -NH-CO-NH-		
Polyester	At least 85% by mass of an ester of a diol and terephthalic acid	Terylene, Trevira	Dacron,
Polyethylene	Polyethylene polymer	Courlene, Drylene	
Polypropylene	Polyethylene where one carbon in two carries a methyl side chain	Fibrite, Meraklon	
Polyurethane	Polymer with the recurring functional group -O-CO-NH-		
Triacetate	Cellulose with at least 92% by mass of hydroxyl groups acetylated	Tricel, Arnel	
Trivinyl	Vinyl terpolymer of which no single component forms more than 50% by mass		
Vinylal	Poly(vinyl alcohol)	Kuralon, Vinylon	
Viscose	Regenerated cellulose obtained by the viscose process	Fibro, Sarille, Evlan	

(<http://www.analytical-s.co.uk/reference.htm>)

APPENDIX 2.

CONVERSION TABLE Nm to tex and denier

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Polyester Fibres

*Conversion Table
Nm to tex and denier*

Tex	Nm	Denier	Tex	Nm	Denier
0-13	7500	1.2	9	110, 113	82, 80
0-14	6900	1.3	10	100	90
0-16	6400, 5300	1.4	11	90	100
0-17	6000	1.5	13	75	120
0-18	5600	1.6	15	65	140
0-2	5000	1.8	17	60	150
0-22	4500	2.0	18	55	165
0-28	3600	2.5	20	50	180
0-3	3300	2.75	22	45	200
0-34	3000	3.0	23.5	43	210
0-36	2800	3.2	30	34	265
0-39	2570	3.5	34	30	300
0-42	2400	3.75	44	22.5	400
0-44	2250	4.0	47	21.4	420
0-5	2000	4.5	50	20	450
0-56	1800	5.0	68	15	600
0-68	1500	6.0	76	13	690
0-76	1300, 1285	7.0	94	10.7	840
0-88	1125	8.0	100	10	900
1	1000	9.0	122	8.2	1100
1-1	900	10	125	8	1125
1-3	750	12	130	7.5	1200
1-6	640	14	150	6.5	1385
1-7	600	15	170	6	1500
1-8	560	16	184	5.5	1650
2	500	18	188	5.4	1680
2-2	450	20	250	4	2250
3-4	300	30	260	3.8	2370
4-2	240	38	340	3	3000
4-4	225	40	370	2.7	3330
5	200	45	400	2.5	3600
5-6	180	50	500	2	4500
6-8	150	60	680	1.5	6000
7-6	130	69	1000	1	9000
8-4	120	75			

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Specialists' statements

Recommendations of Andrew x, Lenzing Fibres Limited, U.K

Recommendations of xx, Asota GES.M.B.H. Austria