Tampere University of Applied Sciences

Comparison of staple fibres in wetlaid nonwoven sheet

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ABSTRACT

Tampereen ammattikorkeakoulu
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Comparison of Staple Fibres in Wetlaid Nonwoven Sheet

Bachelor's thesis 49 pages, appendices 1 page
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The thesis was commissioned by Tampere University of Applied Sciences (TAMK) in cooperation with research project SUSTAFIT – Sustainable fit-for-purpose nonwovens. The research is related to the need to develop nonwoven markets to a more sustainable direction.

The object of the thesis was to study different staple fibres in wetlaid nonwoven sheet for instance concerning the refining effects to the staple fibres and the wetlaid nonwoven sheet properties. The studied staple fibres were polyester, viscose, recycled cotton, and recycled polyester. Birch fibres were used as a reference for the staple fibres.

The work was carried out in TAMK's paper laboratory. The effect of refining on the staple fibres was determined by examining the structure of the fibres. Sheets were made from refined and unrefined fibres to study the effect of refining on sheet making and sheet properties. The sheets made from refined fibres were measured for basic properties and especially strength properties.

The structure of the fibres changed considerably during the refining. Compared to the unrefined fibres, the refined fibres performed better in the sheet making. Of the staple fibres, the viscose and recycled cotton fibres performed best in the refining and sheet making in this research.

Key words: nonwoven, refining, wetlaid

TIIVISTELMÄ

Tampereen ammattikorkeakoulu
Biotuotetekniikan tutkinto-ohjelma

AALTO, AINO:
Katkokuitujen vertailu märkärainatuissa kuitukangasarkeissa

Opinnäytetyö 49 sivua, joista liitteitä 1 sivu
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Opinnäytetyö tehtiin Tampereen ammattikorkeakoululle yhteistyössä SUSTAFIT – Sustainable fit-for-purpose nonwovens -hankkeen kanssa. Työn taustalla oli tarve kasvattaa kestävämpien kuitukankaiden markkinoita. Työ keskittyi kuitukankaiden märkärainaukseen sekä katkokuitujen jauhatukseen.

Työssä tutkittiin erilaisista katkokuiduista märkärainauksella valmistettuja kuitukangasarkkeja. Tarkoituksena oli selvittää, miten katkokuitujen jauhatus vaikuttaa kuitujen rakenteeseen ja märkärainattujen kuitukangasarkkien ominaisuuksiin. Tutkitut katkokuidut olivat polyesteri, viskoosi, kierrätetty puuvilla ja kierrätetty polyesteri. Puukuitu toimi työssä vertailukohteena katkokuiduille. Työssä käytetty puukuitu oli koivua.

Työ toteutettiin TAMKin paperilaboratoriossa. Jauhatuksen vaikutusta kuitujen rakenteeseen määritettiin tutkimalla kuitujen rakennetta ennen jauhatusta ja sen jälkeen. Ennen ja jälkeen jauhatusta katkokuiduista valmistettiin arkkeja märkärainausmenetelmällä, jotta voitiin selvittää kuitujen jauhatuksen vaikutusta kuitukangasarkkien valmistukseen ja ominaisuuksiin. Myös jauhetuista puukuiduista valmistettiin arkkeja. Jauhetuista kuiduista valmistetuista arkeista mitattiin perusominaisuuksia ja erityisesti lujuusominaisuuksia.

Tulokset osoittavat, että tutkittujen katkokuitujen jauhatus on mahdollista kyseisellä menetelmällä. Kuitujen rakenne muuttui huomattavasti jauhatuksessa. Jauhamattomiin kuituihin verrattuna jauhetut kuidut toimivat paremmin arkkien valmistuksessa. Katkokuiduista valmistetut arkit eivät kuitenkaan saavuttaneet yhtä hyviä lujuusominaisuuksia kuin puukuidusta valmistetut arkit. Tässä tutkimuksessa katkokuiduista jauhatukseen ja arkkien valmistukseen parhaiten sopivat viskoosi ja kierrätetty puuvillakuitu.

Asiasanat: kuitukangas, jauhatus, märkärainaus

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ABBREVIATIONS AND TERMS

AHP	absorbent hygiene product
EDANA	European Disposables and Nonwovens Association
filament	continuous fibre
staple fibre	fibre with a certain length

1 INTRODUCTION

In the manufacturing of nonwovens, technologies that can only use thermoplastic polymers as a raw material, are dominating the nonwoven market. In developing the nonwoven market to a more sustainable direction, technologies where it is possible to use more sustainable alternatives, such as natural or cellulose-based materials, are offered an opportunity to increase their market. Wetlaid technology is one of these technologies where the sustainable raw materials can be used. (Tuni n.d.)

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The object of this thesis is to study wetlaid nonwoven sheet properties containing different staple fibres and how refining of the staple fibres effect to fibre structure and sheet properties of the wetlaid nonwovens. The studied staple fibres are polyester, viscose, and recycled fibres, such as polyester and cotton. Wood pulp is used as a reference for the staple fibres to compare the refining effects and sheet properties. The used wood fibre is birch.

To study the effect of refining, fibre structures are studied before and after refining and wetlaid nonwoven sheets are made. The wetlaid sheets are made from unrefined and refined fibres to determine the effect of refining to sheet properties. Properties including basic sheet properties, strength properties and surface properties are measured from the sheets. The work is carried in TAMK’s paper laboratory.

2 NONWOVENS

2.1 Definition

Nonwovens are fibre-based fabrics. The definition of nonwovens is defined by identical standards, ISO 9092 and CEN EN 29092 standards. (EDANA n.d.e.) In SFS-EN ISO 9092:2019 standard (2019, 5) nonwoven is defined as an "engineered fibrous assembly, primarily planar, which has been given a designed level of structural integrity by physical and/or chemical means, excluding weaving, knitting or paper making".

The term "fibrous assembly" in the definition of nonwoven is defined in the SFS-EN ISO 9092:2019 standard (2019, 5) as "predetermined amount and arrangement of natural or manufactured fibrous material such as, but not limited to fibres, continuous filaments, or chopped yarns of any length or cross-section". In the SFS-EN ISO 9092:2019 standard (2019, 5) the term has a note: "It can be a two- or three-dimensional alignment of fibrous materials made by a web forming process".

2.2 Applications

Nonwovens are widely used in consumer and industrial applications. With designing, nonwovens can be made thin and light weight to strong and durable depending on the application. Other properties that nonwovens can offer are for instance absorbency, biodegradability, flame resistance, liquid repellence, rot resistance and softness. (EDANA n.d.e.) Nonwovens can be categorised into single-use, multiple-use and long-life products varying the service life between few seconds to decades depending on the application (Russell 2022, 15).

According to EDANA (n.d.d), the main nonwoven market segments in 2019 were hygiene (28,7 %), wipes for personal care (12,3 %), construction (9,8 %), automotive (6,2 %), civil engineering (5,4 %), filtration (3,6 %) and food and beverage

(3,3 %) (EDANA n.d.d). As hygiene and wipes hold the two largest nonwoven market segments, they are discussed in more detail.

2.2.1 Absorbent hygiene products

Absorbent hygiene products, also referred as AHPs, are mainly single use products containing baby diapers, feminine hygiene, and adult continence management products. Volume of absorbent hygiene products has been growing for many years due to wide availability, convenient use, performance, and low cost. (Russell 2022, 16–17.)

Absorbent hygiene products are multilayered, including a top sheet, an acquisition-distribution layer, an absorbent core, and a back sheet. Object of the top sheet is to take in liquid from skin and pass it to the acquisition-distribution layer without retaining the liquid. The acquisition-distribution layer promotes effective liquid spreading to the absorbent core and prevents top sheet wetback. The absorbent core is made with hydrophilic material to absorb and retain the liquid. Object of the back sheet is to prevent liquid leakage and invading from the absorbent core. (Russell 2022, 16–17.)

Along excellent absorption, absorbent hygiene products also include many other properties such as comfort and fit, stretchability, smoothness, and strength. The AHPs are made from natural or man-made materials. The raw materials are selected, and manufacturing is performed under strict quality criteria to ensure hygienic products. (EDANA n.d.b.)

2.2.2 Wipes

The object of wipes is to remove any substances from skin or other surfaces. Wipes are mainly single use and can be either dry or premoistened, including flushable wipes. Premoistened wipes have been moistened with aqueous liquid to add function. The liquid level of premoistened wipes is between 80 to 450 %. (Russell 2022, 19–21.)

Wipes can be categorised into consumer products containing personal care and household care products, or to professional products containing industrial wipes and medical wipes. Personal care wipes include for instance baby wipes, cosmetic wipes, and flushable moist toilet tissues. Household care wipes include disinfection wipes and cleaning wipes like floor wipes and kitchen wipes. Industrial wipes include wipes for food industry and electronic and computer industry for instance. Medical wipes are categorised into hospital and community disinfectant wipes and patient care wipes. (EDANA n.d.c.)

The flushable wipes can be flushed down a toilet if they are designed specifically to not cause problems in the sewer system. The flushable wipes need to follow strict guidelines and cannot harm the environment or water management. Designing of the flushable wipes is a challenge because they must remain intact during use but disperse in the sewer system. (Russell 2022, 22.)

The effectiveness of the wipes is ensured by effective removal of liquids and solids and retention of the substances. Personal care wipes are normally in contact with skin which is why softness and conformability are important properties along liquid management. Cleaning efficiency in household care wipes depends on added cleaning agents and the liquid management. Industrial wipes are specifically designed to have a high ability to hold particles without shedding and they can be also used to reduce static electricity from surfaces. Medical wipes are used to disinfect healthcare station surfaces, or in patient care to reduce transmission of infections. (Russell 2022, 21, 23–25.)

2.3 Manufacturing methods

The manufacturing methods of nonwovens are categorised into drylaid, wetlaid and spunlaid web forming methods. The web forming is the first stage in nonwoven manufacturing which is followed by a web bonding stage. The web bonding stage is needed to increase initial strength of the web and it is categorised into thermal, mechanical, and chemical bonding methods. The web bonding method is selected according to final product functions and used raw material. Finishing treatment may be included to enhance desired fabric properties after web bonding. Finally, the nonwoven is converted from rolls to the final products. (EDANA n.d.a; Russell 2022, 3.) Difference between traditional textiles and nonwovens are that nonwovens are made from staple fibres or filaments and bonded without weaving or knitting (Russell 2022, 49).

The drylaid web forming is performed in a dry state most commonly by carding the fibres into a web (Russell 2022, 5). Carding process starts with opening of staple fibre bales and blending of the fibres. With a carding machine, the fibres are formed into a web. The fibres can be laid to a machine direction as mostly parallel-laid or randomly oriented. With parallel-laid web, properties such as good tensile strength, low tear strength and low elongation are achieved in the machine direction. In the spunlaid web forming method, the raw material is thermoplastic polymer granulates that are extruded to continuous filaments. The filaments are cooled and stretched before laydown to a web structure on conveyor belt. Compared to carding, spunlaid method can result to increased strength. (EDANA n.d.a.) The wetlaid manufacturing method is discussed in more detail in chapter 3.

3 WETLAID NONWOVEN

3.1 Manufacturing

Wetlaid nonwoven applications include consumer and industrial products such as hygiene products, filtration applications and construction materials for instance. According to Russell (2022), wetlaid manufacturing method for nonwovens holds the smallest segment in nonwoven production. However, the demand for wetlaid nonwovens from sustainable materials is likely to increase due to sustainability concerns, especially related to single use products, and restrictions in fossil-based materials. (Russell 2022, 185.)

The wetlaid web forming method is similar to paper making. In the wetlaid method, fibres are dispersed to water and when water is removed, paper like structure is formed as a result. Difference between wetlaid nonwoven and paper is that nonwovens can contain longer fibres and their structural integrity can be achieved by other means than hydrogen bonding. (Russell 2022, 181.)

3.1.1 Web formation

The manufacturing process of wetlaid nonwovens starts with web formation (figure 1), where fibres are arranged to a web structure. The web formation starts with combining raw materials, such as long fibres (1), wood pulp (9) and water (2) into a slurry (3). The slurry is uniformly delivered by a headbox to a moving wire screen, where the web is formed (4). The wire screen consists of a forming fabric and dewatering units. Excess water is drained in the wire screen (8) with machine width dewatering machines. Dewatering of the slurry depends on the used raw material depending on how much water the material absorbs. Synthetic man-made fibres dewater quicker than slurries containing wood pulp, natural fibres, or cellulosic man-made fibres. The removed water is usually recycled for further use. Binders can be added on the wire screen (5). After the dewatering on the wire screen, the web is still wet and needs further dewatering. The web is pressed between rollers, where the water transforms from the web to a felt, and finally dried with driers (6). The finished fabric is windup to a roll (7). Multilayer nonwovens can be produced by making individual layers separately and attaching them together after, or by using a multilayer headbox. (EDANA n.d.a; Russell 2022, 202–207.)

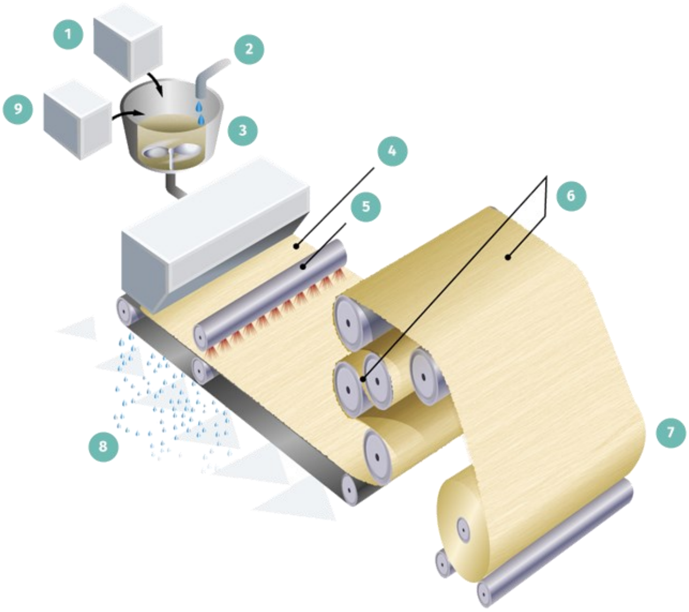


FIGURE 1. Wetlaid web formation (EDANA n.d.a).

3.1.2 Bonding

After the web formation, strength of the web is limited and therefore needs bonding. Bonding of wetlaid web is achieved either by hydrogen bonding, thermal bonding, mechanical bonding, or chemical bonding, depending on used fibres or final application. The bonding methods can also be combined to achieve desired fabric properties. (EDANA n.d.a; Russell 2022, 208.)

Hydrogen bonding appears in wetlaid webs made of cellulose fibres. If the cellulose fibres are fibrillated before web formation, hydroxyl groups of fibres can form hydrogen bonds in wet pressing and drying sections. However, wet strength of hydrogen bonded nonwovens is poor which is why coating for instance might be added to improve the physical properties of the fabric. (Russell 2022, 208.)

Thermal bonding is based on fibre thermoplastic properties. When low melt thermoplastic fibres are added to wetlaid webs, the webs can be thermally bonded, and heat sealed in final product conversion. Most commonly, synthetic polymer bicomponents and copolyesters are used for thermal bonding. Thermal bonding method is usually through-air bonding which takes place in hot air stream. (EDANA n.d.a; Russell 2022, 210.)

Mechanical bonding is usually performed with hydroentangling for wetlaid webs. Web strength is achieved in the hydroentanglement with fluid forces increasing fibre friction with high pressure water jets that entangle the fibres with concentrated energy towards the web. When high wet strength is required, chemical bonding can be used as combination with the mechanical bonding. (Russell 2022, 209.)

In chemical bonding, additives such as binders, superabsorbers and low-melt fibres are added to the web. The chemical bonding for wetlaid nonwovens can be performed using latex binders which are added before or after web formation. If added before, latex is mixed with the water slurry. (Russell 2022, 209–210.)

3.1.3 Finishing

Finishing includes unit operations whose purpose is to add functionality. The unit operations are typically calendering or creping in the finishing of wetlaid web. Calendering consists of one or more nips between calender rolls, through which the nonwoven is led. One of the rolls is usually heated steel roll and the other is covered with synthetic rubber. Calendering smoothens the surface of nonwoven and increases gloss with the impact of heat and pressure. (Russell 2022, 210–211.)

Creping is commonly used to improve softness of nonwovens, especially if nonwoven is made from wood pulp or regenerated cellulose fibres. Creping is performed by bringing a moist web onto a hot cylinder which causes the web to adhere to it. With release agents and creping doctors, the web is then removed from the cylinder which decreases internal bond strength resulting to a softer sheet. (Russell 2022, 211.)

3.2 Raw materials

The most common fibres used in wetlaid nonwovens are wood fibres and man-made fibres. Wood fibres and other natural fibres form hydrogen bonds in web formation due to cellulose content and disperses easily in water which is why the fibres are ideal for wetlaid forming. Compared to natural fibres, petroleum-derived man-made fibres are hydrophobic which is why the fibres do not react with water easily. Natural and bio-based fibres are sustainable with ability to recycle and compost industrially. With different additives, dewatering for instance can be improved. (Russell 2022, 185–187, 189.)

Wood pulp is a relatively cheap material. It absorbs liquids easily but has a low wet strength. In addition to wood fibres, natural fibres used in wetlaid nonwovens contain nonwood fibres such as cotton, abaca, flax, hemp, and agricultural waste, including wheat straw. Cotton is a seed fibre which consists of 80 to 90 % of cellulose. Cotton fibres that are mechanically recycled from clothing, are also used in nonwovens. (Russell 2022, 75–76, 189.)

Bio-based fibres are man-made fibres, but they are produced from natural raw materials, such as cellulose, starch and sugar. The bio-based fibres include viscose and lyocell, but also bio-based polyesters derived from plant sugars are included. The starting material for viscose is usually wood pulp containing 40 % cellulose in average. Viscose is produced from the same polysaccharides as natural fibres, but it is chemically processed from cellulosic feedstock. (Russell 2022, 67–68, 190.)

Petroleum-derived man-made fibres are synthetic of which polyesters and polyolefins are mostly used in nonwoven manufacturing. Synthetic fibres and filaments are produced by spinning long-chain polymers either by wet, dry or melt spinning. Staple fibres are produced by cutting filaments into a certain length. In wetlaid forming, meltable petroleum-derived fibres with low melting point improve sheet strength in thermal bonding. (Russell 2022, 52–53, 190–191.)

4 REFINING

4.1 Object

Refining is a mechanical treatment for wood pulp. The object of the treatment is to modify the pulp suitable for paper making. Fibres are made flexible and bonding abilities between fibres are improved in the refining. Targeted paper properties are mainly high strength and formation. Chemical pulps and recycled pulps are primarily influenced in the refining, as mechanical pulp properties develop already in mechanical pulping stages before refining. (Ek, Gellerstedt & Henriksson 2009, 121.)

Refining is a part of stock preparation which is located between a pulp mill and a paper mill. The mills can be either integrated or non-integrated. In case of integrated mills, pulp is pumped directly to the paper mill from the pulp mill and in case of non-integrated mills, pulp is delivered in bales. (KnowPap version 24.0. 2023d.) The target of the stock preparation is to modify the ingoing raw material to paper machine to fill the requirements and demands of the paper machine and the final product. The raw material is either virgin pulp or recycled paper. Suspension in stock preparation consists of fibres, water, and debris particles. (Holik 2013, 351, 355.)

4.2 Refining process

Refining takes place in refiners, where fibres are led through a small gap between refiner bars. The refiners consist of a stator and a rotor with refining plates. (Holik 2013, 455.) Surface of the plates are formed by bars and grooves. The plates are either in one piece or in segments depending on refiner size. (Ek et al. 2009, 126.) Refining is performed at low consistency refining (LC) or at high consistency refining (HC). Low consistency refining is mainly used for virgin fibres with consistency of three to six percent and high consistency refining is mainly used in the refining of reject with about 30 % consistency. (Holik 2013, 455.)

In the refining process, the stator bar holds still, and the rotor bar moves against the stator bar. The refining takes place in three refining phases. First, fibres pile up on the edges of the rotor bar. This is enabled with vortex flows in the grooves of the bar. After piling follows the actual refining process. Fibre bundles receive a short shearing compression when the bar edges cross. When the rotor bar moves aligned with the stator bar, the bundles are compressed between the bars and receive the refining treatment while held compressed. Fibres are normally in water slurry during refining. (KnowPap version 24.0. 2023c.)

4.3 Refiner types

For low consistency refining, especially conical refiners and double-disc refiners are used in the paper industry and for high consistency refining, special HC refiners are used (Holik 2013, 458–459). Conical refiners and double-disc refiners are both suitable for all refining functions, but conical refiners are often used in the refining of chemical pulp and disc refiners in the refining of mechanical pulp. In both refiner types, the refining effect is adjusted with gap size between the rotor and the stator bars. Pulp flow is adjusted with a discharge pipeline valve. (KnowPap version 24.0. 2023c.)

Conical refiners consist of a cone-shaped rotor and a stator with attached refining plates (figure 2, left). Pulp is led into the conical refiner from smaller end between the bars. Low cone angle is used in the conical refiners due to its affordability. Increased angle enhances bar diameter and no-load power which refers to the power taken by the refiner when the refiner is rotating filled with water. Efficiency of conical refiners is 80 to 90 % at best. (KnowPap version 24.0. 2023c.) The angle of the conical refiners is normally ≤30° (Ek et al. 2009, 125).

Disc refiners are either single-disc or double-disc refiners. Single-disc refiner consists of one rotating disc and one stator disc. Double-disc refiner consists of two stator discs and one rotating disc between the two stator discs (figure 2, right). In the middle of the disc is a feed connection, through which the pulp is fed between the disc with hydraulic pressure and centrifugal force. (KnowPap version 24.0. 2023c.) In the double disc refiner, the plates are attached to both sides of the rotor which moves against the stator bar plates. The double disc refiner has easy maintenance and economical operation which is why it is the most successful refiner globally. (Holik 2013, 458.)

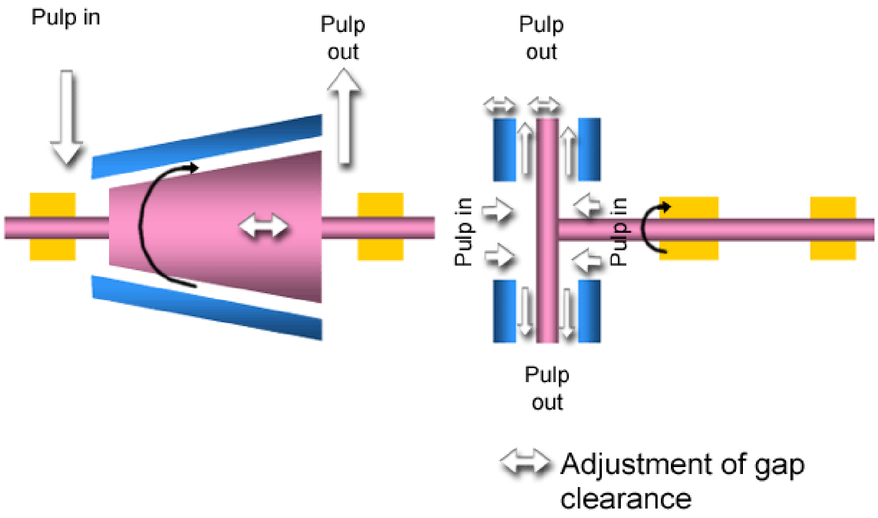


FIGURE 2. Conical refiner (left) and double-disc refiner (right) (KnowPap version 24.0. 2023c).

4.4 Effects on wood fibres

The low-consistency refining modifies the structure of wood fibres. The fibres swell and become flexible, conformable, and fibrillated. (Koskenhely 2008, 95.) The effect of refining may vary widely between individual fibres depending on how they avoid the treatment. The main structural changes include removal of primary wall, delamination and swelling of fibres, external and internal fibrillation, fibre shortening, fines creation and straightening of fibres. (KnowPap version 24.0. 2023a.)

Wood fibres consist of four layers (figure 3, left). The most outer layer is the primary wall. Under the primary wall is S1 layer, S2 layer and finally S3 layer. The removal of the primary fibre wall is important in refining because the removal causes water invading into the fibre causing the swelling. After the primary wall is removed, the detachment of S1 layer starts. In case some outer layer particles are still attached, some fibrillation may appear at this point. (KnowPap version 24.0. 2023a.)

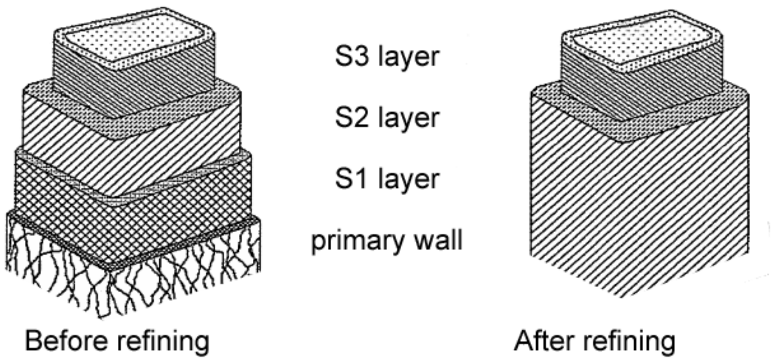


FIGURE 3. Wood fibre layers before and after refining (KnowPap version 24.0. 2023a).

Detachment of the primary wall and the S1 layer reveals the S2 layer (figure 3, right). Exposure of the S2 layer starts the external fibrillation of fibres. Micro-fibrils of the S2 layer are oriented in fibre axle direction easing the fibrillation. The fibrillated structure is formed by fibrils remaining partially attached to the fibre surface. External fibrillation enlarges fibre surface and causes bonding between fibres more easily. Internal fibrillation causes loosening of internal layers making the fibres swell. Loosening is caused by hydrogen bonds breaking between the internal layers. Effects of internal fibrillation are more flexible fibres, increased outer surface, increased contact surfaces and better bonding between fibres. (KnowPap version 24.0. 2023a.)

Shortening of fibres is an unavoidable effect of refining. Shortening of fibres has mainly a negative effect, but it might also have a positive effect. Shortening reduces strength properties of paper such as tear strength but increases uniformity of sheet formation. Shortening appears especially at high refining intensity. Shortening causes also fines creation among external fibrillation and outer fibre surface detachment. Increased fines content enhances bonding of fibres and paper strength properties. (KnowPap version 24.0. 2023a.)

Chemical pulp fibres are curled after pulping due to fibre damaging. Curled fibres have lower tensile strength than straight fibres which is why the fibre straightening is important for paper strength properties. In low consistency refining some curling and deformations of fibres can be recovered, but some parts are permanently deformed. High consistency refining on the other hand curls the fibres. (Koskenhely 2008, 98.)

4.5 Effects on paper properties

All paper properties are somewhat affected by refining. As some properties are improved and some are impaired, only necessary amount of refining should be performed to achieve the best outcome. (Ek et al. 2009, 121–122.) However, also the severity of refining effects the paper properties which can develop different properties between gentle and sever refined pulps. From general properties of paper such as bulk, air permeability, density and formation, bulk and air permeability are reduced, and density and formation are improved in refining. (KnowPap version 24.0. 2023b.)

Paper strength properties such as tear strength, tensile strength, folding strength and bursting strength are mainly improved in refining. However, tear strength and folding strength are improved only to certain points. Tear strength reaches its maximum already at the very beginning of refining. After reaching the maximum the value drops. Tear strength is improved in the beginning due to increasing fibre bonding ability. The drop happens when the bonding ability of fibres no longer increases but fibres are weakened in further refining. The maximum depends for instance on raw material. Folding strength increases in refining before reaching its maximum due to increased fibre bond strength. After the maximum is reached at a certain point, the folding strength drops. Higher fibre bond density and compressed fibre elements result that the fibre cannot resist folding stresses, causing decreased folding strength. (KnowPap version 24.0. 2023b.)

Paper optical properties, including opacity, brightness, and light scattering coefficient, are mainly impaired in refining. When fibre contact area and bonding increases in refining, light scattering is decreased, and optical properties reduced. Flexible fibres make the surface of the paper denser. As a result, paper surface properties such as smoothness is improved, and roughness is impaired. (KnowPap version 24.0. 2023b.)

5 RESEARCH METHODS

5.1 Overview

The research methods included refining and hand sheet making with sheet pressing and drying. The refining was performed for staple fibres and birch fibres. The work was performed with paper making equipment due to the similarity between wetlaid and paper making processes. The sheets were made from unrefined and refined fibres. Final sheet properties were measured to compare the results between different raw materials. The studied sheet properties included basis weight, thickness, density, roughness, and strength properties.

The studied staple fibres were polyester, viscose, recycled cotton and recycled polyester and cotton (rPESCO) from textile waste. The length of the viscose fibres was 40 mm, and the polyester fibres were 38 mm. The recycled cotton fibres were 4 mm long, and the rPESCO fibres were 18 to 25 mm. The birch fibres were approximately 1 mm long.

5.2 Refining

Refining was performed with a Valley-Hollander refiner (picture 1). The refiner includes a container and a rotating bar. The refining gap of the refiner can be either open or closed. By adjusting the refining gap, fibres are either slushed or refined. During the slushing, the pulp circles in the container without refining effect. The refining effect is achieved with adding a weight to the side of the refiner which closes the bar gap and starts the refining.

PICTURE 1. Valley-Hollander refiner.

Slurries for the refining were made beforehand to let the fibres soak in water. The fibres were soaked at least a day. The slurries were made by adding 30 grams of fibre to five litres of water. Wood fibres were obtained of a dried birch pulp plate. 30 grams of the plate was weighted and torn to small pieces and added to five litres of water.

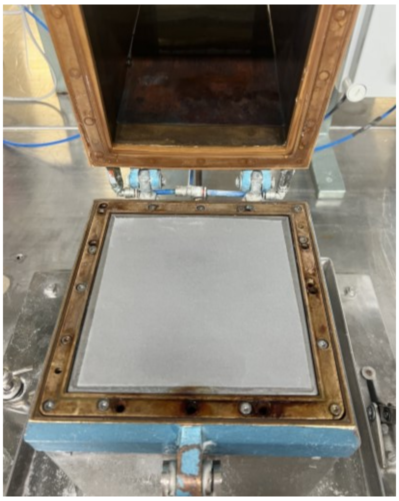
The refining was performed with 2 g/l consistency. The refiner was filled with 10 litres of water and the refiner was turned on. When the refiner was on, the 5-litre slurry was carefully added. After the slushing, the refiner was turned off while adding the weight. Refining time started from turning the refiner back on. All the different raw materials were refined individually. The refining time for birch, recycled cotton, and viscose fibres was 10 minutes. The birch and recycled cotton fibres were slushed for 10 minutes and the viscose fibres for five minutes. The refining times for the polyester and rPESCO fibres are explained in chapter 6.

5.3 Sheet making

The sheets were made with a Handsheet-former (picture 2). The main parts of the sheet former are a container, where water and fibres are added and a wire screen, where the sheet is formed. The slurries were stirred for at least 10 minutes before starting the sheet making. The slurries were left mixing while making the sheets, to avoid any fibres sinking to the bottom of the vessel and to keep the right consistency.

PICTURE 2. Handsheet-former.

The sheet former was cleaned before starting the sheet making. To start, the former was closed tightly, and the container was filled with water to approximately 25 cm from the wire screen. A 0,8-litre sample of a slurry was poured to the former and mixed with a turbulence created by the former. After mixing, water was drained through the wire screen. When all the water had drain, the former was opened, and the sheet formed on the wire (picture 3) could be removed.



PICTURE 3. Viscose sheet on the wire screen.

To remove the sheet from the wire screen, a clean blotting paper was placed on top of the hand sheet. The sheet was kept attached to the paper until dried. On top of the clean paper, two used blotting papers were placed to absorb water. A metal plate was then placed on top of the blotting papers. To remove water from the hand sheet, a metal rolling pin was rolled back and forth on top of the metal plate five times. Finally, the hand sheet was carefully removed with the clean blotting paper. The wire was cleaned between every sheet.

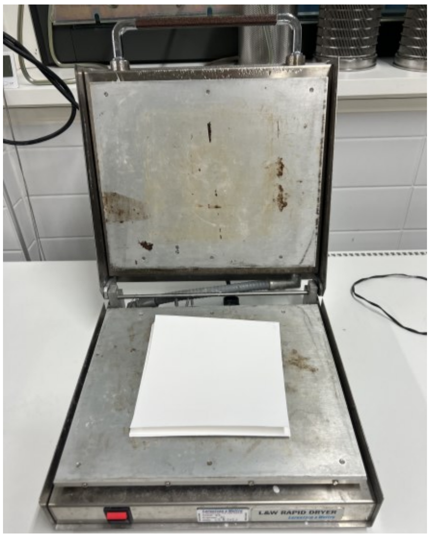
The hand sheets were assembled to a pile, while making the sheets. The order of the sheets starting with a metal plate was two used blotting papers, the made hand sheet attached to a clean blotting paper and a clean blotting paper on top of the hand sheet. The sheets continued to be piled at this order ending to two used blotting papers and a metal plate on top. Over ten sheets were aimed to produce from each raw material.

5.4 Sheet pressing and drying

The sheets were pressed after the sheet making with L&W Sheet Press. The sheet pile between the metal blades was placed in the pressing machine (picture 4). Dry blotters were added on top to make the pile higher to efficiently press the sheets. The pressing machine pressed the pile for 5 minutes with approximately 3,8 bars. All the sheets were pressed once, and the sheets with different fibre contents were pressed individually.

PICTURE 4. Sheet pressing with L&W Sheet Press.

The sheets were dried with L&W Rapid Dryer. The sheets were dried one at a time so that the made hand sheet was in between two clean blotting papers and a dry used blotting paper on both sides (picture 5). All the sheets were dried for five minutes. The sheets were removed from the blotting papers as the sheets had cooled.



PICTURE 5. Sheet drying with L&W Rapid Dryer.

5.5 Sheet properties

The sheets were stored and the measurements for sheet properties were done in a standard humidity room. The studied basic properties were basis weight, thickness, and density. The strength properties included tensile strength, tear strength and bursting strength. From surface properties, roughness was studied. The sheets had no machine direction or cross direction which is why the direction of samples in the measurements were not considered.

The measurements of paper properties and measuring devices are standardized (table 1). The standards have been utilized in the measurements of this research but note that the standards and devices are determined for measuring paper and not nonwovens.

TABLE 1. Devices and standards for measuring paper properties.

Measurement	Device	Standard
Basis weight	0,01 g accuracy scale	ISO 536
Thickness	L&W Micrometer	ISO 534
Tear strength	L&W Tearing Tester	ISO 1974
Tensile strength	L&W Tensile Tester	ISO 1924-3
Bursting strength	L&W Bursting Strength Tester	ISO 2758
Roughness	L&W Bendtsen Tester	ISO 8791-2

5.5.1 Basic properties

Basis weight expresses the sheet weight in grams per square meter (Levlin 1999, 140). To measure the basis weight the sheets were cut to 0,01 m^2 samples. The samples were cut with a paper cutter so that edges of the sheets were cut off. The samples were weighted in grams on a scale with an accuracy of 0,001 grams. To determine the basis weight in g/m^2, the weight of a sample was multiplied by 100. Every sheet was measured individually, and the measurements were performed on ten samples.

Single sheet thickness expresses the thickness of a one sheet (µm) (Levlin 1999, 140). The thickness was measured with L&W Micrometer device. Hand measurement mode was used for the measurements. By using the hand mode, one sample at a time was placed under the measuring head so that the measuring head was in the middle of the sample (picture 6). Only one measurement in the middle of the sheet was performed on each sample. The measurements were performed on the same ten samples as the basis weight.

PICTURE 6. L&W Micrometer.

Density expresses the sheet mass per unit volume (kg/m^3). Apparent density is calculated based on the ratio between the basis weight and the single sheet thickness. (Levlin 1999, 141.) The calculation formula for density is

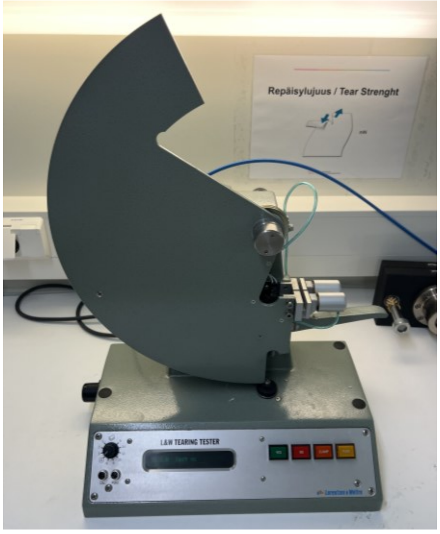
$$x = 1000 \cdot \frac{w}{t}, \tag{1}$$

where x is the density (kg/m^3), w is the basis weight (g/m^2) and t is the thickness of a sample (µm) (KnowPap version 24.0. 2023e). The density was determined on the same ten samples as the basis weight and thickness and calculated based on the results of the basis weight and thickness.

5.5.2 Strength properties

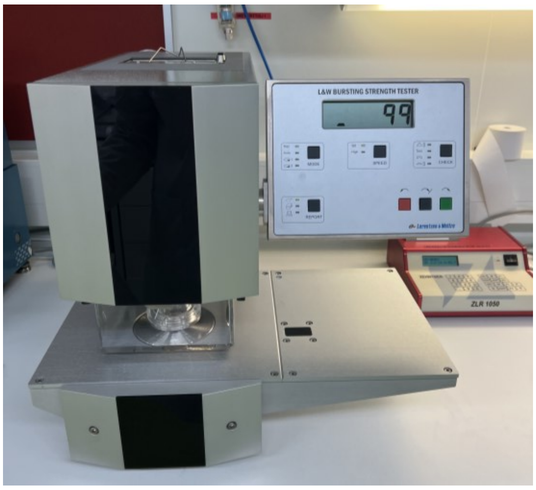
Tensile strength expresses how much force per unit width must be applied to a paper strip lengthwise for it to break (kN/m) (Levlin 1999, 142). The tensile strength was measured with L&W Tensile Tester. Sheets were cut according to the standard. The average result of the basis weight was used as the basis weight in the measuring device. Five parallel measurements were done of the tensile strength.

Tear strength expresses how much force in newtons is needed to tear a sheet from an initial cut (mN) (Levlin 1999, 145). The device for measuring the tear strength was L&W Tearing Tester (picture 7). Samples were cut according to the standard and applied in piles of four to the device. Three parallel measurements were done of the tear strength.



PICTURE 7. L&W Tearing Tester.

Bursting strength expresses the maximum pressure that paper withstands without breaking from vertical pressure (kPa) (Levlin 1999, 144). The bursting strength was measured with L&W Bursting Strength Tester (picture 8). The measurements were made for top and bottom sides. The samples were placed under the measuring head so that from the same sample both sides could be measured. Five parallel measurements were done for the top and bottom sides of the samples.



PICTURE 8. L&W Bursting Strength Tester.

5.5.3 Roughness

Roughness is defined by how the surface of paper prevents air flow between the surface of paper and a measuring head. Roughness measures the volume of air flow per time (ml/min). (Levlin 1999, 156–157.) The device for measuring the roughness was L&W Bendtsen Tester (picture 9).

PICTURE 9. L&W Bendtsen Tester.

The roughness was measured from the top and bottom sides of the samples. The samples were placed under the measuring head individually so that the measuring head was in the middle of the sheet. Five parallel measurements were done of the roughness.

6 RESULTS

6.1 Fibre processability

Before starting the refining, the processability of the staple fibres were assessed. The consistency was the same 2 g/l as in the refining. To two litres of water, 4 grams of fibre was added to achieve the consistency. The slurries were mixed for 10 minutes.

The results showed that from the staple fibres, only the recycled cotton fibres were dispersed to water. The other fibres were tightly wrapped around the mixing blade without dispersing to water (picture 10).

PICTURE 10. Fibres wrapped around the mixing blade.

6.2 Refining time

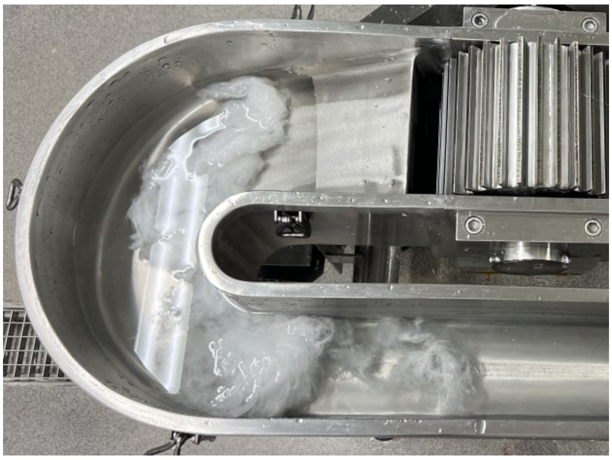
The refining time for the fibres was determined by testing multiple different refining times. The aim was to keep the refining time the same for all the fibres to compare the results in fibre structure and sheet properties. To determine the best suiting refining time, different refining times were experimented on the fibres (table 2).

TABLE 2. Results of experimented refining times.

Experiment	Raw material	Refining time	Conclusion
1	Birch	90 min	Problems in sheet making
2	Viscose	60 min	Fibres were cut more than intended
3	Birch	30 min	Problems in sheet making
4	Polyester	10 min	Fibres were dispersed
5	rPESCO	30 min	Fibres did not refine after 15 min
6	Polyester	20 min	Fibres did not refine after 15 min
7	Birch	10 min	Successful
8	Viscose	10 min	Successful
9	Recycled cotton	10 min	Successful

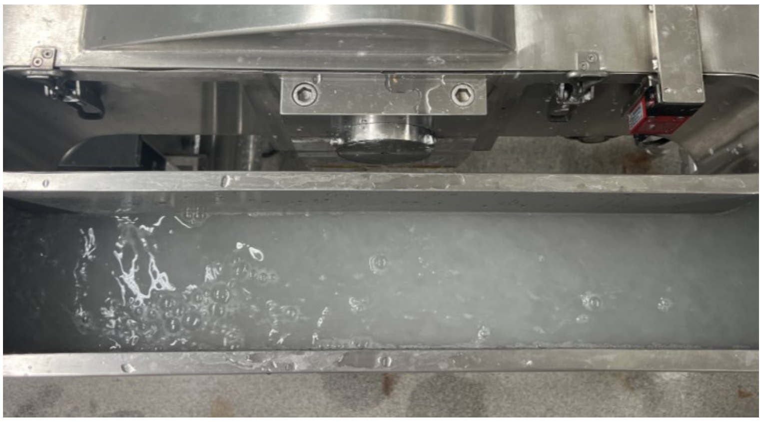
The birch fibres were first refined for 90 minutes. However, it was discovered that the 90-minute refining time was not suitable for sheet making. Because of the result of 90-minute refining time, the refining time was set to 30 minutes, but the results were similar compared to the 90-minute refining time. Fibres were slushed for 20 minutes in these experiments.

In the refining of the viscose fibres, the fibres were slushed for 10 minutes, until it was discovered that the fibres only got even more attached to each other than in the beginning of the slushing (picture 11). As a result, the refining was started after the 10 minutes of slushing.



PICTURE 11. Viscose fibres after slushing.

At about five minutes from the start of the refining, the viscose fibre bundles had broken (picture 12). However, the viscose fibres were refined for 60 minutes in total. After the 60 minutes, it was discovered that the viscose fibres had cut to a short length and the slurry was more like suspension. The results showed that the 60 minutes was too long for the viscose fibres, because the intention was not to cut the fibres that much.



PICTURE 12. Viscose fibres after five minutes of refining.

To determine the best refining time after the first experiments, the polyester fibres were refined a minute at a time to see when the fibres were dispersed and shorter in length but not cut more than needed. In total, the polyester fibres were refined for 10 minutes until it seemed like the fibres had dispersed (picture 13). The polyester fibres were slushed before refining for five minutes until it seemed like the fibre bundles were evenly mixed to water.

PICTURE 13. Polyester fibres after 10 minutes of refining.

Even though the polyester fibres had been refined only for 10 minutes, the rPESCO fibres were tried to refine for 30 minutes. The rPESCO fibres were slushed for 10 minutes before refining. When starting the refining, the suspension started to foam significantly. To control the foaming, 0,5 ml of a defoaming agent was added to the slurry. After about 15 minutes of refining, the fibres no longer circled in the refiner and gathered on the surface of the water (picture 14). At this point, 0,6 ml more defoaming agent was added to the slurry and the slurry was refined for five more minutes. However, the results remained the same.

PICTURE 14. rPESCO fibres gathered on the surface of water.

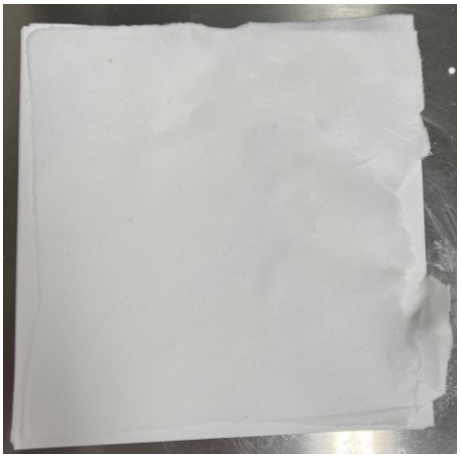
To test if the polyester fibres would react the same way as the rPESCO fibres, the polyester fibres were refined further. The slurry with the refining time of 10 minutes was refined further for 20 minutes. It was discovered that the polyester fibres followed the same pattern as the rPESCO fibres. Somewhere around 15 minutes of refining the fibres gathered on the surface of water.

Because it was discovered that the viscose fibres disperse already in the beginning of refining, sheets from the unrefined cotton fibres were managed to be made of and the birch fibres need to be refined less than 30 minutes, the refining time was set to 10 minutes for the birch, viscose, and recycled cotton fibres. The 10-minute refining time was successful, because the fibres had dispersed, and sheets were managed to be made of the refined fibres. The polyester and the rPESCO fibres were not studied further because of results in sheet making.

6.3 Sheet making of unrefined fibres

Because the recycled cotton fibres were the only fibres that dispersed in water when the processability of unrefined staple fibres were assessed, sheets from the unrefined fibres were only made from the recycled cotton fibres. The other staple fibres were not expected to work. The slurry was made with 20 grams of fibres and 2 litres of water. The slurry was stirred for ten minutes without soaking the fibres in water first. After stirring, 8 litres of water were added to the mix to achieve 2 g/l consistency.

The sheets turned out even to the wire screen, but they were hard to remove which is why the sheets were torn and got wrinkled (picture 15). Here only one blotting paper was used to absorb water before removing the sheet from the wire. The sheets were not pressed or dried, because any good sheets were not managed to be obtained. The sheets turned out very fragile which is why any properties were not measured either.



PICTURE 15. A sheet made from unrefined recycled cotton fibres.

6.4 Sheet making of refined fibres

Sheets made from refined fibres were made from the experimented refining times (table 3). The success of the sheet making was evaluated based on how intact the sheets could be removed from the wire screen.

TABLE 3. Results of sheet making of refined fibres.

Raw material	Refining time	Conclusion
Birch	90 min	Not successful
	30 min	Not successful
	10 min	Successful
Viscose	60 min	Successful
	10 min	Successful
Polyester	10 min	Not successful
rPESCO	20 min	Not successful
Recycled cotton	10 min	Successful

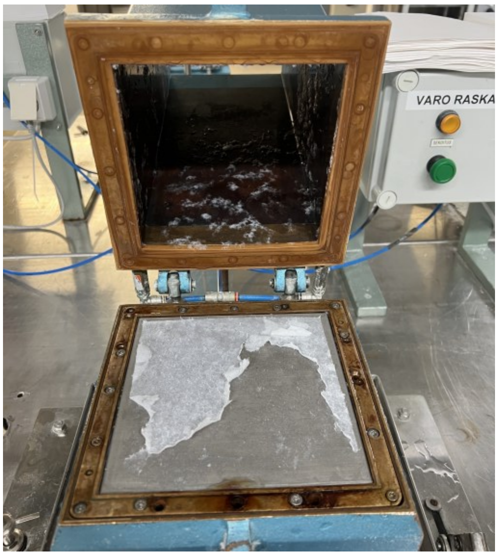
When sheets were made from refined birch fibres with the 90-minute refining time, water did not drain properly, and the sheets were not managed to be removed from the wire screen. The results were similar with 30-minute refining time.

Sheets made from refined viscose fibres were made with the refining time of 60 minutes. The sheets did not turn out perfect, but they were managed to be removed from the wire screen in one piece. The sheets were allowed to dry on their own. After drying, the sheets seemed rather smooth and strong. But as the fibres were cut more than intended, the sheets were not studied further. However, the sheets were evaluated as successful because good sheets were obtained.

Sheets made from refined polyester fibres were made with the refining time of 10 minutes. The sheets were not managed to be removed properly from the wire screen resulting wrinkled sheets (picture 16). The sheets had poor strength and some fibres were attached to the walls of the former. Because the sheets were deformed, pressing, drying, or measuring of the sheet properties were not performed.

PICTURE 16. Sheets made from refined polyester fibres.

The sheet making results were similar for refined rPESCO fibres as to the refined polyester fibres. Not a single good sheet was managed to be made with the refining time of 20 minutes, because the sheets were not managed to be removed as one from the wire screen (picture 17). Like some of the polyester fibres, also some of the rPESCO fibres were attached to the walls of the former.



PICTURE 17. A torn sheet made from refined rPESCO fibres.

Successful sheets were obtained from the birch, viscose, and recycled cotton fibres with the refining time of 10 minutes. The sheets were easy to remove from the wire, resulting to even and intact sheets. For previous sheets, only one blotting paper was used to absorb water, but here two blotting papers were used.

The sheets made from the birch fibres (picture 18) were strong, but thin. The surface of the sheets was smooth, and the sheets had typical paper appearance.

Some curling of the sheets appeared in drying, but the sheets were easy to remove from the blotting paper after cooled.

PICTURE 18. A sheet made from refined birch fibres.

The viscose fibre sheets (picture 19) felt the most fragile, but soft in touch. The viscose fibre sheets were the hardest to remove from the blotting paper without tearing or otherwise damaging. However, intact sheets were obtained for measuring of the sheet properties.

PICTURE 19. A sheet made from refined viscose fibres.

The recycled cotton fibre sheets (picture 20) felt stronger than the viscose fibre sheets, and more intact sheets were obtained. Even though the recycled cotton fibre sheets felt stronger than the viscose fibre sheets, the sheets were softer than the birch fibre sheets.

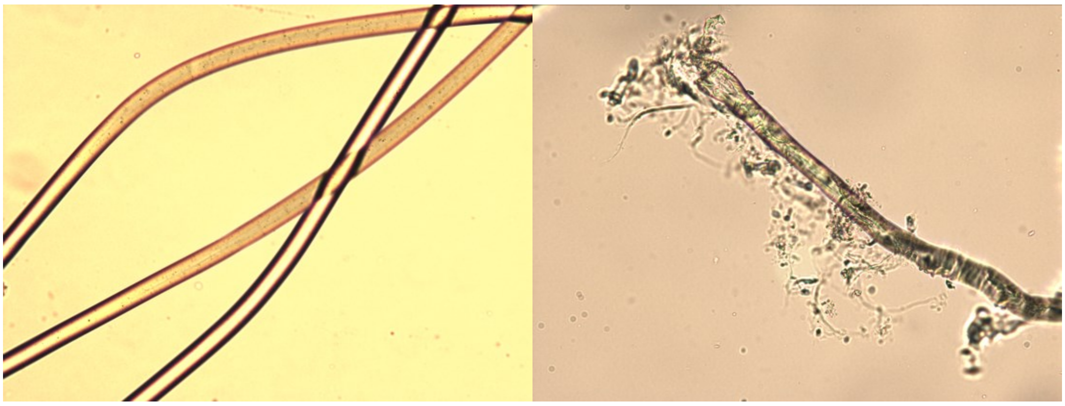
PICTURE 20. A sheet made from refined recycled cotton fibres.

6.5 Structural changes of fibres

Fibres before and after refining were studied under a microscope. The object was to study structural changes of the fibres in the refining. The birch fibres had no fibrillation before refining and the fibres were intact (picture 21, left). After refining, the fibres have a lot of fibrillation (picture 21, right). The refined birch fibres studied, had been refined for 30 minutes. Note that the unrefined birch fibres were studied with 20 x zoom and the refined birch fibres with 10 x zoom.

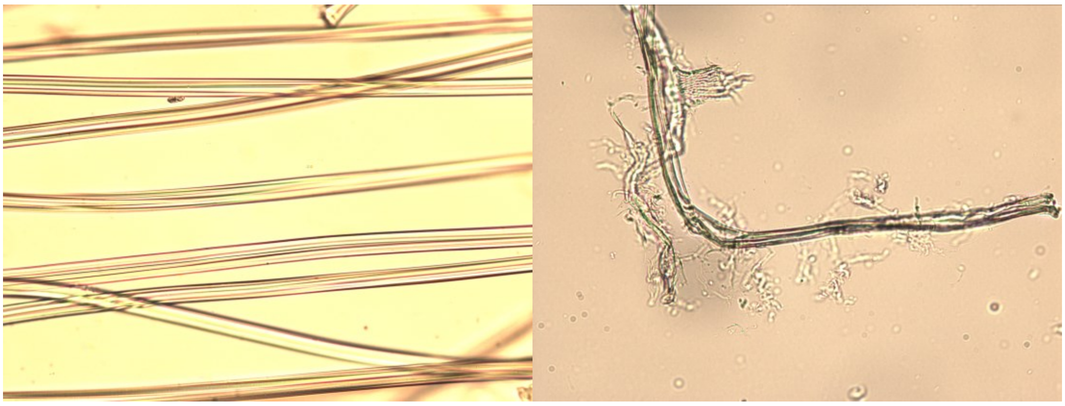
PICTURE 21. Unrefined (left) and refined (right) birch fibres.

Before refining, the surface of the polyester fibres was smooth, and the fibres seemed rather stiff (picture 22, left). The refined polyester fibres have fibrillation, and the fibres seem shorter in length (picture 22, right). The effect of the refining on the polyester fibres was studied from 20-minute refining time.



PICTURE 22. Unrefined (left) and refined (right) polyester fibres.

The viscose fibres seemed very stiff and smooth like the polyester fibres before refining (picture 23, left). After refining, the refined viscose fibres clearly have fibrillation and they have lost the stiffness (picture 23, right). The results are rather similar compared to the polyester fibres. The refined viscose fibres were studied from 10-minute refining time.

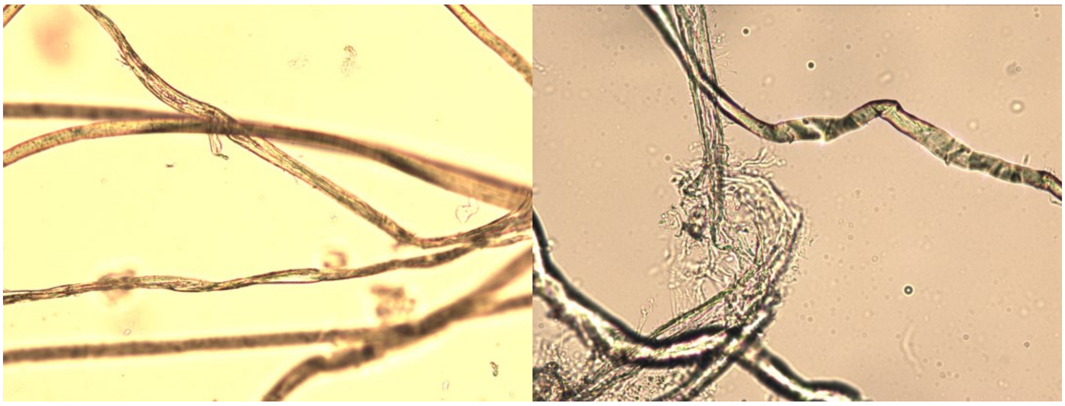


PICTURE 23. Unrefined (left) and refined (right) viscose fibres.

The recycled cotton fibres were not as stiff as the viscose and polyester fibres, but there was no fibrillation before refining (picture 24, left). However, there were some breaking on the fibres. The refining has increased the breaking and the fibres have a lot of fibrillation (picture 24, right). The refined recycled cotton fibres were refined for 10 minutes.

PICTURE 24. Unrefined (left) and refined (right) recycled cotton fibres.

The rPESCO fibres, like the other studied fibres, had no fibrillation before refining (picture 25, left). After refining, the rPESCO fibres have clearly some fibrillation and the fibres seem more flexible than before refining (picture 25, right). The refined rPESCO fibres were refined for 20 minutes.



PICTURE 25. Unrefined (left) and refined (right) rPESCO fibres.

6.6 Sheet properties

The viscose and recycled cotton fibre sheets follow a similar pattern in basic sheet properties (table 4). The differences between basis weight, thickness and density of the staple fibre sheets are low. Especially the average single sheet thickness is close between the two. The largest difference is in density where the density of a single sheet in average is higher for recycled cotton fibre sheets compared to the viscose fibre sheets. However, the difference is minor.

When compared the staple fibre sheets to the birch fibre sheets, differences in average basis weights are not significantly large. The birch fibre sheets have the highest basis weight in average but for instance the difference between the birch fibre sheets and the viscose fibre sheets is under 10 g/m^2. The most outstanding differences are in thickness and density. The thickness of the birch fibre sheets is less than half compared to the thickness of the staple fibre sheets. This has resulted to a much higher density in average of the birch fibre sheets compared to the viscose and recycled cotton fibre sheets. Measuring table of the basic properties is presented in appendix 1.

TABLE 4. Average results of ten parallel measurements of basic properties.

	Birch	sd.	Viscose	sd.	Recycled cotton	sd.
Basis weight (g/m^2)	58,7	0,84	49,2	1,4	54,4	1,4
Thickness (µm)	101,2	2,3	211,7	9,9	213,9	7,6
Density (kg/m^3)	580,6	12,8	232,7	12,5	254,4	10,5

Based on the results of tear strength, the average tear strength (table 5) is the lowest for the viscose fibre sheets. The tear strength of the recycled cotton fibre sheets is over twice as much in average compared to the viscose fibre sheets. Although, when comparing the viscose and recycled cotton fibre sheet results to the birch fibre sheets the difference is significantly greater. The birch fibre sheets have a much more higher tear strength in average compared to the staple fibre sheets. The results support the appearance of the sheets.

Tensile strength was only managed to be measured of the birch fibre sheets (table 5). The tensile strength of the viscose and recycled cotton fibre sheets was not able to be measured, because the samples did not withstand in the measuring device.

TABLE 5. Average results of three parallel measurements of tear strength (mN) and five parallel measurements of tensile strength (kN/m).

	Birch	sd.	Viscose	sd.	Recycled cotton	sd.
Tear strength (mN)	345,0	20,4	19,0	1,7	45,0	2,0
Tensile strength (kN/m)	3,0	0,07	-	-	-	-

The average bursting strength of the viscose and recycled cotton fibre sheets is the same, and the top and bottom sides of the sheets have no differences (table 6). The bottom side of the sheets is the side that was attached to the blotting paper before drying. The bursting strength of the birch fibre sheets is approximately twice as high as the bursting strength of the staple fibre sheets. The results of the top and bottom sides of the birch fibre sheets do not differ significantly. Measuring table of the strength properties is presented in appendix 1.

TABLE 6. Average results of five parallel measurements of bursting strength (kPa).

	Top side	sd.	Bottom side	sd.
Birch	153,4	8,3	141,6	0,9
Viscose	74,4	0,5	74,0	0,0
Recycled cotton	74,0	0,7	73,8	0,4

The average results of roughness of the sheets (table 7) have a lot of deviation between the samples, especially of the viscose fibre sheets. The results of the top and bottom sides of the sheets are in the same range for all the fibres. The average roughness of the recycled cotton fibre sheets is higher compared to the viscose fibre sheets. The results are however very close. When comparing the viscose and recycled cotton fibre sheets to the birch fibre sheets, the roughness of the birch fibre sheets is much lower. Measuring table of the roughness is presented in appendix 1.

TABLE 7. Average results of five parallel measurements of roughness (ml/min).

	Top side	sd.	Bottom side	sd.
Birch	1209,8	135,5	1091,4	109,4
Viscose	5324,0	684,8	5199,4	701,9
Recycled cotton	5703,4	43,7	5750,8	71,5

7 CONCLUSIONS AND DISCUSSION

The object of the research was to study different staple fibres in wetlaid nonwovens concerning the effects of refining to the structure of the staple fibres and sheet properties of the wetlaid nonwovens. The studied staple fibres included polyester, viscose, recycled cotton and rPESCO fibres.

Different refining times were tested on the fibres to determine the best suiting time, where the fibres are not cut too much but sheet making can be performed. It was discovered that all the fibres were somewhat able to be refined with the method in use, but sheets were not managed to be made of all the fibres. Interesting finding in the refining of the staple fibres was that the viscose fibres dispersed to water already after about five minutes of refining. The polyester fibres seemed to be dispersed to the water after 10 minutes of refining, but the fibres did not refine after about 15 minutes. The results were the same with the rPESCO fibres as the polyester fibres. The best suiting refining time was assessed by how well the sheets could be removed from the wire screen and how much the fibres were cut.

Sheets were managed to be made of refined viscose and recycled cotton fibres with a refining time of 10 minutes. The same refining time worked for the birch fibres. From the polyester and rPESCO fibres, any sheets were not managed to be made with the used method. The birch fibres were assumed to work because their use in paper making. As a common factor of the succeeded sheets is that the fibres are natural based containing cellulose. The polyester fibres are synthetic and the rPESCO fibres include partly synthetic fibres. The property of the synthetic fibres to not disperse to water probably caused the problems in the refining and in the sheet making where the fibres attached to the walls of the sheet former. The ability of natural based fibres to form hydrogen bonds could have been one of the factors of succeeded sheets.

Sheets from unrefined recycled cotton sheets were made, but the sheets turned out very fragile. The other unrefined staple fibres were not suitable for the sheet making, because the fibres did not disperse to water but gathered around a mixing blade when mixed with water mostly probably due to fibre length. Although any properties could not be measured from the unrefined fibre sheets, the strength of the recycled cotton fibre sheets seemed to be improved after the refining. The sheets were easier to remove from the wire and the sheets did not tear as easily. Viscose fibre sheets made of 60-minute refining time were either measured for sheet properties, but the longer refining time seemed to effect positively to the strength properties compared to the 10-minute refining time. With 60-minute refining time, the fibres appeared to be cut to a much shorter length which probably affected positively to the sheet making results.

The effect of refining in fibre structure was similar to the staple fibres compared to wood fibres. The fibres did not have fibrillation before refining when the structure of the fibres was studied. Especially the polyester fibres and the viscose fibres seemed stiff and smooth. After refining all the studied fibres had fibrillation and the fibres seemed more flexible. Some fibre cutting appeared and fines were created. The results of the birch fibres supported the theory of the refining of wood fibres.

Sheet properties were measured from the birch, viscose, and recycled cotton fibre sheets. The results of the measured sheet properties showed that the results of the viscose and recycled cotton fibre sheets were similar. The results between the staple fibre sheets and the birch fibre sheets were significantly different. Especially the strength properties were much higher for birch fibre sheets than the viscose and recycled cotton fibre sheets. Other differences were in thickness, density, and roughness. The average density of the birch fibre sheets was much higher compared to the staple fibre sheets, but the average thickness and roughness were lower. The results support the observations made after the sheet making. Especially the viscose fibre sheets were more fragile compared to the birch fibre sheets. The factors of the differences between the birch fibre sheets and the staple fibre sheets might be fibre length and bonding abilities.

The reliability of the measurements of the sheet properties were considered. The main factors effecting to the reliability are the used measuring devices and the number of the measurements. The devices are not designed for measuring nonwoven sheets. The results can also vary depending on the measured point of a sample. The more measurements are made, the more reliable the results are. In this work, some measurements remained small due to the lack of samples. The refiner and the sheet making devices were also not designed for longer fibres and nonwoven sheet making. The reliability of the findings can also be affected if some fibres have been mixed with other fibres when using the same equipment for all the fibres.

A significant factor in the work was the strength properties of the wetlaid sheets. Therefore, in further studies of the topic it could be studied how the sheet strength properties could be improved. For instance, if combining different fibres such as natural based and synthetic fibres together, would influence on the sheet strength properties, but other properties as well. The strength properties could also be studied by enhancing fibre bonding with some bonding methods like chemical or thermal bonding.

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APPENDICES

Appendix 1. The measuring tables of sheet properties.

	Basis weight (g/m^2)			Thickness (µm)			Density (kg/m^3)		
Sample	Birch	Viscose	Recycled cotton	Birch	Viscose	Recycled cotton	Birch	Viscose	Recycled cotton
1	59,1	48,1	55,1	102,7	206,7	213,4	575,5	232,7	258,2
2	58,8	49,2	56,2	99,3	213,8	210,0	592,1	230,1	267,6
3	59,1	52,0	52,5	101,7	195,5	211,4	581,1	266,0	248,3
4	58,1	48,0	54,9	103,5	209,3	206,0	561,4	229,3	266,5
5	58,5	50,5	52,8	98,6	226,1	212,7	593,3	223,4	248,2
6	59,8	49,0	53,9	99,9	216,0	200,3	598,6	226,9	269,1
7	57,9	49,4	53,8	97,8	211,2	216,9	592,0	233,9	248,0
8	58,4	49,1	54,2	102,7	219,4	222,5	568,6	223,8	243,6
9	57,5	46,7	57,0	101,1	197,5	224,2	568,7	236,5	254,2
10	60,2	49,8	53,3	104,8	221,9	222,0	574,4	224,4	240,1
average	58,7	49,2	54,4	101,2	211,7	213,9	580,6	232,7	254,4
sd.	0,8	1,4	1,4	2,3	9,9	7,6	12,8	12,5	10,5

	Tensile strength (kN/m)	Tear strength (mN)			Bursting strength (kPa)					
Measurement	Birch	Birch	Viscose	Recycled cotton	Birch		Viscose		Recycled cotton	
					ts	bs	ts	bs	ts	bs
1	3,03	361	18	47	163	141	75	74	74	73
2	2,92	322	18	43	152	142	75	74	75	74
3	2,94	352	21	45	145	141	74	74	74	74
4	3,08				146	141	74	74	74	74
5	3,02				161	143	74	74	73	74
average	3,0	345,0	19,0	45,0	153,4	141,6	74,4	74,0	74,0	73,8
sd.	0,07	20,4	1,7	2,0	8,3	0,9	0,5	0	0,7	0,4

	Roughness (ml/min)					
Measurement	Birch		Viscose		Recycled cotton	
	ts	bs	ts	bs	ts	bs
1	1330	1221	5481	5372	5745	5834
2	1249	1102	5625	5496	5648	5660
3	1324	1126	4112	3954	5679	5810
4	1132	1089	5762	5568	5750	5710
5	1014	919	5640	5607	5695	5740
average	1209,8	1091,4	5324,0	5199,4	5703,4	5750,8
sd.	135,5	109,4	684,8	701,9	43,7	71,5