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CONSOLIDATION OF DRY FORMED WEB THROUGH HOT PRESSING:

Effects of Pressing Parameters and Pulp Freeness on Tensile Strength

Master of Science Thesis
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ABSTRACT

Eveliina Airaksinen: Consolidation of dry formed web through hot pressing: Effects of Pressing Parameters and Pulp Freeness on Tensile Strength
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Airlaying is a dry web forming technology that is used for manufacturing hygiene products. Originally, the technology was developed to substitute traditional papermaking due to its many advantages, including low or no water consumption, meaning that the airlaying technology does not require an energy-intensive drying process compared to conventional papermaking. However, the technology has disadvantages, such as weak bonding ability that induces low strength in the fiber web structure. Generally, the fiber web bonding is enhanced by mechanical interlocking, chemical additives, or thermal methods which are based on the mixing of thermoplastic material that bind the structure upon melting.

This Thesis aims to study improving the strength of the airlaid webs through hot-pressing method without additives. The objective is to determine how pressing parameters including moisture content and press temperature, and pulp freeness affect the strength of airlaid webs. The subject was studied both by means of a literature review and experimental research.

The literature review discusses the main properties of paperboard, the characteristics of airlaying technology, and its current state-of-the-art. Additionally, it considers the effects of pressing, pressing parameters, and fiber properties on fiber bonding and the strength of the fiber web structure. The experimental part includes raw material preparation, formation of the sample sheets, and the measurements. The raw material used was chemi-thermomechanical pulp (CTMP) with 3 different freeness numbers. The pulps were dry disintegrated for airlaying, and wet disintegrated for the determination of pulp fiber geometrical properties and formation of wetlaid reference sheets. The airlaid sheets were produced through airlaying and hot pressing using different moisture contents and press temperatures. The reference sheets were formed by wetlaying following the standard, without hot pressing. The measurements included the determination of fiber geometrical properties and pulp freeness, imaging the sheets for optical formation analysis, and measuring the tensile test and brightness of the sheets.

From the results, it was observed that the fiber’s geometrical properties were very close to each other, and the pulp freeness numbers were a bit higher than the ones provided by the manufacturer. It was observed that the higher press temperature and the moisture content resulted in lower brightness, but the lowest hot press temperature used did not affect the brightness. The tensile strength results showed that hot pressing can be used to improve airlaid webs strength if the moisture content is increased in the airlaid structure. The moisture content has a significant effect on the airlaid web strength, but the used hot press temperatures have only a minor effect. The strength increased as the sheet's initial moisture content increased. The freeness affected strength so that the pulp with a lower freeness produced denser structures thus resulting in higher strength. However, when comparing the hot-pressed airlaid sheets to the conventional wetlaid sheets, the strength of the airlaid sheet was lower, especially when the moisture content and the pulp freeness were low. With fibers of the highest freeness number, the moisture content of about 37% in the airlaid sheet produced the same strength as in the wetlaid sheet.

Keywords: Dry web forming, airlaying, hot pressing, strength, airlaid sheet

TIIVISTELMÄ

Eveliina Airaksinen: Kuivarainatun kuituverkon lujittaminen kuumapuristamalla:
Puristusparametrien ja massan freeness-luvun vaikutus vetolujuuteen
Diplomityö
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Ilmarainaaminen on kuivarainattujen kuitutuotteiden valmistusmenetelmä, jota käytetään esimerkiksi hygieniatuotteiden valmistukseen. Alun perin menetelmä kehitettiin korvaamaan perinteinen paperinvalmistus sen monien etujen vuoksi. Menetelmä ei kuluta lainkaan vettä tai käyttää sitä vähemmän kuin perinteinen paperinvalmistus, joten se ei sisällä energiaintensiivistä kuivatusvaihetta ja on siten energiatehokkaampi vaihtoehto. Menetelmän rajoittava tekijä on kuitenkin kuiturainan heikko sitoutuminen ja siitä aiheutuva rakenteen alhainen lujuus. Tavallisesti kuiturainan sitoutumista lisätään mekaanisesti neulaamalla, kemiallisilla lisäaineilla tai termisillä menetelmillä, joissa kuituseokseen lisätään termoplastista materiaalia, joka sulaessaan sitoo rakenteen.

Tämän diplomityön tavoitteena on tutkia ilmarainatun kuiturainan lujuuden parantamista kuumapuristuksen avulla ilman lisäaineita. Tarkoituksena on selvittää miten kuumapuristusparametrit, kosteus ja lämpötila, sekä raaka-ainekuitujen freeness vaikuttavat ilmarainatun materiaalin lujuuteen. Aihetta tutkittiin kirjallisuuskatsauksen ja kokeellisen tutkimuksen avulla.

Kirjallisuuskatsauksessa käsitellään paperin ja kartongin ominaisuuksia, ilmarainausteknologian ominaispiirteitä sekä sen nykytilannetta. Lisäksi tarkastellaan puristuksen, puristusparametrien sekä kuitujen ominaisuuksien vaikutusta kuitujen sitoutumiseen ja kuiturakenteen lujuuteen. Kokeellinen osa koostui raaka-aineena olleen kemitermomekaanisen massan (CTMP) valmistelusta, näytearkkien valmistamisesta ja mittaamisesta. Raaka-aine kuivahajotettiin ilmarainaukseen sopivaksi sekä märkähajotettiin kuidun ominaisuuksien määritystä ja referenssiarkkien valmistusta varten. Näytearkit valmistettiin ilmarainaamalla ja kuumapuristamalla käyttäen erilaisia kosteuspitoisuuksia ja puristuslämpötiloja. Referenssiarkit valmistettiin vesirainaamalla standardin mukaisesti ilman kuumapuristusta. Lopuksi arkkien vetolujuus ja vaaleus mitattiin, ja arkit kuvattiin optisen formaation ja flokkikoon määritystä varten.

Tuloksista havaittiin, että raaka-ainekuitujen geometriset ominaisuudet olivat hyvin lähellä toisiaan, ja niiden freeness-luku oli hieman korkeampi valmistajan ilmoittamaan lukuun verrattuna. Vaaleustuloksista havaittiin, että korkeampi puristuslämpötila ja suurempi kosteuspitoisuus alentavat vaaleutta, mutta alin käytetty kuumapuristuslämpötila ei kuitenkaan vaikuttanut vaaleuteen. Tulosten perusteella voidaan sanoa, että kuumapuristuksella voidaan parantaa ilmarainatun materiaalin lujuutta käytettäessä riittävän suurta kosteuspitoisuutta. Kosteuspitoisuudella on merkittävä vaikutus arkkien lujuuteen, mutta käytetyillä kuumapuristuslämpötiloilla vain vähäinen. Arkkien lujuus kasvaa, mitä korkeampi kosteuspitoisuus on. Freeness vaikutti lujuuteen siten, että alhaisemman freeness-luvun massa tuotti tiiviimpiä ja siten myös lujempia arkkeja. Kuitenkin verrattaessa perinteisiä vesirainattuja arkkeja ilmarainattuihin ja kuumapuristettuihin arkkeihin, jäi ilmarainattujen arkkien lujuus selkeästi alhaisemmiksi erityisesti alhaisissa kosteuspitoisuuksissa sekä kuiduilla, joilla oli alhaisin freeness. Korkeimman freeness-luvun kuiduilla noin 37%:n kosteuspitoisuus ilmarainatussa arkissa tuotti saman lujuuden kuin saman kuidun vesirainatulla arkilla.

Avainsanat: kuivarainaus, ilmarainaus, kuumapuristus, lujuus, ilmarainattu arkki

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PREFACE

This Master's Thesis was conducted at VTT Technical Research of Finland from April to November. This thesis was part of the project, REPowerEU. I am grateful for the opportunity to participate in this project and research.

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Eveliina Airaksinen

CONTENTS

LIST OF FIGURES

LIST OF ABBREVIATIONS

BHKP	Bleached hardwood kraft pulp
CTMP	Chemi-thermomechanical pulp
CSF	Canadian Standard Freeness
HT-CTMP	High-temperature chemi-thermomechanical pulp
mc	moisture content
rpm	revolutions per minute
TMP	Thermomechanical pulp
T_g	Glass transition temperature
UBSKP	Unbleached softwood kraft pulp
SKP	Softwood kraft pulp

1. INTRODUCTION

Within the EU, the pulp and paper sector is the third biggest energy consumer of all industries [1], requiring also high volumes of fresh water. The conventional papermaking process relies on the disintegration and dispersion of fibers and additives with water. To remove water from the web, the process uses several energy-consuming unit operations. In particular, fiber web drying consumes alone approximately 40–60% of the energy of the whole papermaking process.

The development of new and more efficient industrial processes is crucial today due to increasing environmental challenges and global circumstances related to global warming and reducing the use of fossil fuels. Reducing energy consumption is essential to lower greenhouse gas emissions and achieve future's carbon-neutral goals. Additionally, freshwater sufficiency is one of the concerns of the future, which necessitates reduced water use in industrial processes. Consequently, developing waterless papermaking technologies would enhance the sustainability of the paper and board industry.

Dry web forming or drylaying is a promising option for waterless papermaking. There are two drylaying technologies: carding and airlaying, which are mainly used to produce nonwovens. This work focuses on airlaying technology, which is estimated to reduce the energy consumption of the papermaking process by 50% compared to conventional papermaking technology. Moreover, if fibers are processed with this technology, there is no or less need for drying or wastewater treatment. [2]

One of the challenges with airlaying technology is the weak bonding ability of an airlaid web. Traditionally, adequate strength of the airlaid web is achieved using additives such as latexes or thermoplastic fibers. This thesis aims to determine how the strength of the airlaid web can be improved without additives through compression at elevated temperatures. It also examines the effect of pressing parameters – time, pressure, temperature, and moisture – on the web's strength properties. Additionally, the effect of pulp freeness on airlaid sheet strength is investigated. This thesis includes a literature review on the topic, experimental research in the laboratory, and analysis of the results.

2. BASICS OF PAPERBOARD

Paperboards are single- or multi-ply products used in packaging, where strength properties are usually crucial. They are generally divided into three categories: cartonboards, containerboards, and specialty boards. Cartonboards are used for consumer product packaging, while containerboards are used in corrugated boxes, for example, as transportation containers. [3, p. 210], [4, p. 55] Specialty boards have various applications, such as wallpaper bases, core boards for paper rolls, plasterboard liners for gypsum board, and other specialty paperboards, such as book bindings [4, pp. 70–71].

Cartonboards are inner packaging products typically classified by their raw material into folding boxboard (FBB), liquid packaging board (LPB), white-lined chipboard (WLC), and solid bleached and unbleached boards (SBS/SUS). Generally, cartonboards require a certain level of mechanical strength and stiffness, although the specific properties depend on the final application. [4, p. 56] Containerboards, which are used for exterior packaging boards, consist of linerboards and corrugated mediums, and are used in manufacturing of corrugated containers and boxes. Linerboard is used as facings in corrugated boards and has usually a two-ply structure. Linerboards are utilized also as barrier-coated reel covers. Corrugated medium, also called fluting, is the material used in the middle layer of corrugated board. It is a strong and flexible material, and has a wave-like appearance. [3, pp. 219–220]

The basic properties of paperboard include basis weight, bulk, density, thickness, moisture content (mc), and filler content. Basis weight, or grammage, describes the weight of the paperboard per unit area and it is expressed as grams per square meter (g/m^2). Density is defined as the mass per unit volume and is calculated by dividing the grammage by the thickness. Bulk is the inverse of density, describing the volume per unit mass. [5, pp. 140–141]

Strength and stiffness properties are pivotal mechanical properties in paperboards. The most important strength properties of paperboards are presented and described in Table 1. Stiffness refers to the resistance to deformation forces and is related to the material’s elastic properties. In paperboard, stiffness is usually measured as tensile stiffness and bending stiffness. Tensile stiffness indicates the stiffness when the external load is applied parallel to the plane of the sheet. In other words, it describes the resistance to elongation under certain tensile load. Bending stiffness is the ability of a paperboard to resist a bending force applied perpendicularly to its plane. [5, pp. 151–152]

Table 1. *Paperboard strength properties and their description. [5, pp. 141–150][5, p. 221]*

Strength property	**Description**	**Units**
Tensile strength	The maximum force per unit width resisted before breaking when a load is applied parallel to the length of the strip.	N/m
Tensile index (TI)	Tensile strength divided by the grammage of the material.	Nm/g
Bursting strength	The maximum pressure resisted without breaking when pressure is applied perpendicular to the plane.	Pa, kPa
Tearing strength	The mean force needed to continue tearing from an initial cut.	mN
Zero-span tensile strength	The strength of the individual fibers.	N/m
Z-directional strength	The resistance to tensile loading in a z-direction.	kPa, kN/m
Folding resistance	The breaking resistance to folding under a certain load.	N, mN
Surface strength	The resistance to a force pulling out fibers from the surface. Expressed as Critical wax pick number or as picking velocity. [6] [7]	Wax pick number, m/s
Compression strength (SCT)	Short span compression test determines the maximum compression force per unit width of the test piece.	N/m, kN/m
Compression strength index (SCT index)	SCT divided by the grammage of the material	Nm/g

In addition to strength properties purity, runnability, and good appearance are also necessary for packaging cartons. Microbiological purity is especially required in food packaging to prevent food spoilage, and good appearance is needed for good printing quality and attractive packaging. Appearance is particularly important in consumer packaging, such as cosmetics, and good runnability is essential in packaging lines with very high speeds. [4, pp. 57–58]

3. AIRLAYING TECHNOLOGY

Airlaying technology is a dry web forming method that was primarily designed as an alternative to conventional papermaking and its early developments were mostly related to paper products [8, p. 161]. According to standard ISO 9092:2019, papermaking is defined as “the process of producing a thin material by pressing together, short, refined cellulose fibers formed on a screen from a water suspension of these fibers, and drying them, with hydrogen bonding as the predominant mechanism holding the web together” [9]. While conventional papermaking is based on wetlaying process, airlaying technology is also applicable [10, p. 10], and offers certain advantages for paper production. For instance, multi-ply board production was studied using a dry forming pilot machine at St. Anne’s Board mill in Bristol in the 1970s, and some continuous and commercial production was done with a prototype machine. The pilot line successfully produced various multi-ply structures, including solid bleached board, folding boxboard, and fluting medium. [11]

Nowadays, airlaying technology is mainly used in textile and nonwoven fabric production [8, p. 161]. According to ISO 9092:2019, a 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 papermaking”. Nonwovens are classified into drylaid, wetlaid and spunlaid categories based on their manufacturing processes [8, pp. 3–5, 9]. The drylaying and wetlaying processes use staple fibers, whereas spunlaid nonwovens are made of long filaments. In each nonwoven manufacturing process, the fibers are deposited on a forming surface, but the physical environment used depends on the process. Fibers are processed in either dry, wet, or air-quenched environments. [8, pp. 3–5, 9]

Airlaying technology is a method for fiber processing and web formation in a dry state, converting short natural or synthetic fibers into random-laid webs. Unlike the wetlaying process, which forms webs using water, the airlaying process utilizes an airstream. [8, pp. 3–5] Airlaying technology is highly versatile, allowing the use of various fibers and machine designs. The resulting products may have single or multilayer structures [8, p. 169], [10, p. 71], and they can be made from wood pulp, non-wood, ceramics, metal, carbon, aramid, and other high-performance fibers. However, airlaid products are primarily made from softwood fluff pulp with fiber lengths ranging from 1.5 mm to 6 mm, which is often blended with natural or synthetic short-cut (< 25 mm) man-made fibers. [8, p. 75], [10, p. 10] Examples of natural man-made fibers include regenerated cellulosic fibers such as viscose and lyocell. Synthetic man-made fibers include polymers such as polyamides, polyesters, and polyolefins. [8, pp. 147, 152]

3.1 Airlaid web properties and applications

Airlaid webs generally have high bulk, porosity, isotropicity, and absorbency [2], [8, p. 147] [10, p. 13]. The properties of the webs depend on the types of fibers used, the fiber blend ratio, web geometry, and the bonding process. Compared to conventional wetlaid webs, airlaid webs offer notable advantages, including high bulk and softness. When the basis weight of an airlaid web exceeds 50 g/m^2, it can produce voluminous, high-loft 3D structures with low density. [8, p. 147] Additionally, good compression recovery and high thermal resistance are typical features of airlaid webs. [8, p. 177] The MD/CD ratio, which describes isotropy varying in machine and cross-machine directions, can approach one in airlaid webs, and therefore they are often described as “random-laid” [8, p. 147]. However, airlaid webs orientate at some level, especially in z-direction, meaning that they are not truly isotropic in practice [8, p. 176].

Disadvantages of airlaid sheet include lower thickness uniformity, lower strength, and reduced smoothness [2]. The uniformity of the sheet is influenced by various factors, such as fiber opening and individualization before web formation or irregular airflow occurring near the walls. [8, p. 147]

Applications of airlaying technology involve different single-use or long-life products. The single-use airlaid products are lightweight and used as domestic and industrial wipes, absorbent cores, hygiene products, and medical fabrics. Additionally, they are employed in food packaging, napkins, and tablecloths. The use of airlaid cores in absorbent products enables thinner structures and improved performance. For instance, airlaid absorbent pads are utilized in food packaging, including meat, seafood, and fruit packaging, to absorb excess moisture and extend the product's shelf life. These pads are typically made from cellulose fibers or superabsorbent polymers. [8, pp. 177–178], [10, p. 108] Heavy-weight airlaids are utilized as high-loft waddings in long-life applications, such as mattress, furniture, clothing, insulation, filters, barrier materials, wall and floor coverings, moulded products, and automotive components. [8, pp. 177–178]

3.2 Manufacturing process

Airlaid manufacturing includes the following steps: fiber preparation, web formation, and web bonding [8, pp. 150, 151, 174]. At the beginning of the process, fibers are separated and individualized by using some separation technology, such as a hammermill, which is the most common method for fiber preparation in pulp airlaying. [8, p. 150], [10, p. 10] The fiber separation step is an essential and important step for forming a uniform web without any fiber flocs or clumps [8, p. 150].

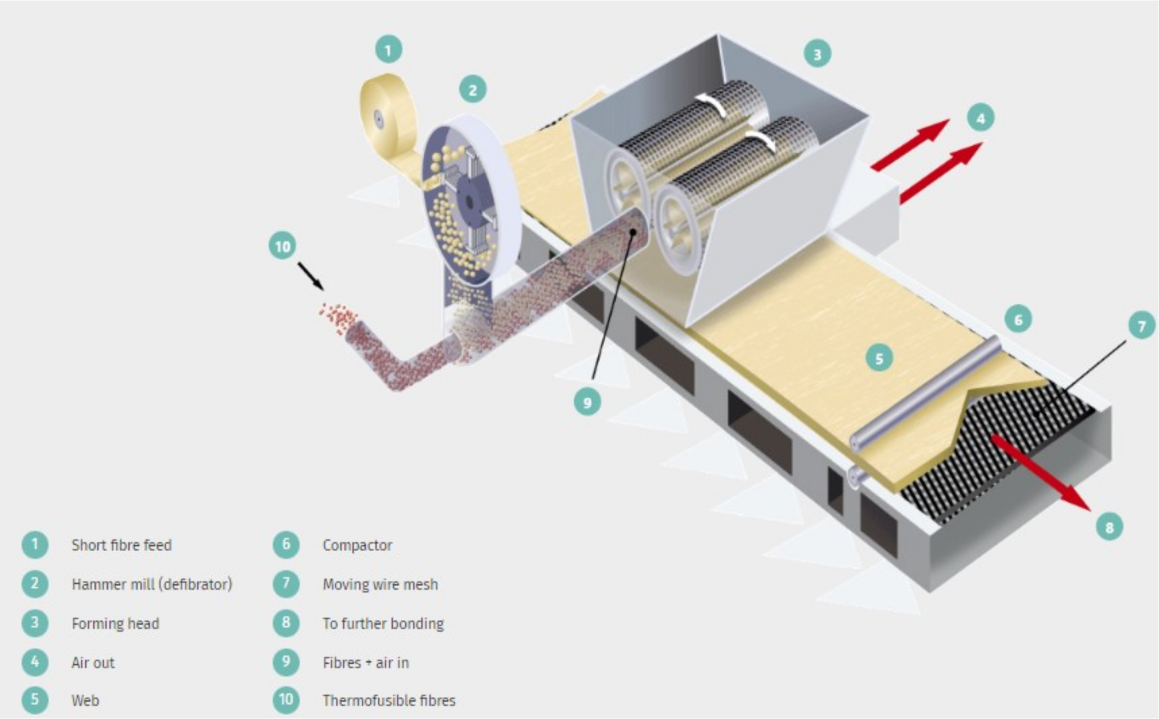

Figure 1. Airlaying process. Included with permission from the author, Edana [12].

Separated fibers are then conveyed by air to a permeable screen or conveyor for web formation. Transportation of fibers can be carried out with different methods, such as free fall, compressed air, air suction, closed air circuit, or a combination of compressed air and air suction. [8, p. 151] Other fibers, such as short cut or synthetic fibers can be fed into a forming web at this stage [10, p. 10]. During the web formation stage, the air is separated from the fibers, which are deposited with random orientation in the form of a web [8, p. 151].

The airlaid sheet is manufactured in dry state without additional water, so the technology does not require an energy-consuming drying section compared to the conventional papermaking process. Thus, the energy consumption of papermaking could be reduced by 50% by using airlaying. Additionally, airlaying technology does not either produce wastewater, so wastewater treatment is not required. [2] Traditional paper mills are usually located near rivers and lakes due to high water demand, but airlaid mills do not have the same location limitations. Because the location is not limited by water supply, there is a possibility of locating the mill near the source of raw material or close to a customer. [11]

The direct investment costs can be even 50% lower if airlaying technology is used for papermaking. However, the technology consumes more electricity, around 150 – 250 kWh per ton of paper. This additional electricity is necessary to power the motors and air streams. [2] Another disadvantage of the technology is the lower production speed of standard paper grades compared to conventional papermaking. On the other hand, the production efficiency is claimed to be higher in airlaying than in carding in the case of dry forming processes. [8, p. 147]

3.3 Web consolidation of airlaid web

Web consolidation is the process where the bonding of loosely bonded fibers is improved, and the strength and integrity of the web are increased. In other words, web consolidation means stabilization of the airlaid web structure mechanically, thermally, or chemically with different web consolidation methods. For example, fiber dimensions, web weight, and final required properties affect web formation and bonding, so they must be considered when choosing the proper bonding method. [8, p. 174]

Pulp fiber- based airlaid products were mostly bonded with chemical bonding methods in the early 2000s. Nowadays, thermal, or combined bonding methods are more common. Combined or multi-bolding airlaying (MBAL) techniques are used to develop higher strength and avoid the challenges of individual techniques [8, pp. 174–176].

3.3.1 Mechanical methods

Mechanical methods used for nonwoven bonding are needlepunching, stichbonding, and hydroentangling. In needlepunching, the fibers are interlocked mechanically by an oscillating, back-and-forth-moving barbed needle puncturing the web. However, this method is not suitable for fluff pulp or fibers less than 10 mm in length, but it is used for heavier airlaid webs and longer fiber webs. [8, p. 176] Stitchbonding is a bonding method that utilizes knitting elements to interlock the fibers. The consolidated web is formed by knitting through the web with yarns or sewing threads. [10, p. 205]

Fluff pulp or short-cut fibers are bonded mechanically by hydroentangling via water jets. Typical products made by this method are single-use hygiene fabrics or composite fabrics for medical, sanitary, or healthcare applications. [8, p. 176] The bonding is achieved by very fine and high-velocity jets of water. The pressure of applied jets is generally 0.5-25 MPa and the diameter of water jet headers ranges from 100 to 120 µm. In addition to water jets, the hydroentangling process also requires a vacuum system, filtration, and drying stage for removing the excess water from the web and achieving the proper dryness level. [10, p. 204]

3.3.2 Thermal methods

Thermal bonding methods are based on bonding the airlaid web composed of base fiber and the bonding component, and heating and cooling the web. The bonding component is thermoplastic fiber or particle. Heating is done to a softening temperature of the bonding component. Softened thermoplastics are in nature adhesive and have bonding capability in the web. Thermal energy is applied onto the web by a calendar, through air, radiation, or ultrasonic methods. [8, pp. 441–466] Smooth calendar rolls produce a uniformly bonded web, and patterned rolls produce an embossed web where some areas are more dense and tightly bonded. In the ultrasonic technique, thermoplastic fibers are melted with high-intensity ultrasonic energy. [10, p. 207]

Softened thermoplastics flow in the web structure to bonding regions by surface tension and capillary forces. Adhesive or mechanical bonds are formed at the crossing points between the fibers in the subsequent cooling stage. An adhesive bond is the physiochemical bond between two dissimilar materials, and a mechanical bond is formed by thermal shrinkage, which mechanically locks fiber interfaces. If both base and thermoplastic soften or melt, there can also occur cohesive bonding. Cohesive bonding occurs by interdiffusion of the molecules meaning that the interface of fibers may disappear. In thermal bonding, chemical reactions do not occur at the bonding points. [8, p. 442]

The main advantages related to thermal bonding are uniform bonding throughout the web cross-section, lower environmental impacts, and the possibility of recycling thermally bonded airlaids. Additionally, economic efficiency is better compared to chemical bonding due to lower thermal energy consumption and cheaper machinery. [8, p. 443] However, the thermal bonding process generates dust, causing cleaning requirements and stoppages in the process line. Final products can also have low or irregular tensile strength, particularly when a small amount of binder fiber is used. [8, p. 175]

3.3.3 Chemical methods

The chemical bonding method consists of adding adhesive binders, for example, with applicator rolls, spraying, foaming, or as a flowing thin film. Typically, binder solutions are water-emulsified latexes. Other types of binders are dispersions, solution binders, and solvent-based binders. [10, p. 208]

The binder is added by different techniques onto the airlaid web, which is then often heated and cured in an oven. The bonding obtained depends on the penetration of the binder into the web structure. Therefore, the web thickness together with binder properties affects the final web structure. [8, p. 175] Vacuum suction devices are often used to pull binders through the web. In addition, the chemically bonded web requires also drying to remove excess water. Thus, the lower amount of water in binder chemicals results in lower energy costs and may lead to higher production rates. [10, p. 208]

4. CURRENT STATE OF AIRLAYING TECHNOLOGY

Airlaying technology has a long history, but it was commercially used first time in 1980 by a Danish firm, Moeller and Jochumsen [2]. In 2022, the airlaid industry included 34 major and 24 minor producers, with 90 commercial lines and a nominal capacity of 624, 800 tons of product, making airlaid nonwovens the smallest of the major nonwoven markets [4].

4.1 Commercial production

The world's largest producer of airlaid nonwovens is Glatfelter having manufacturing facilities in the U.S. and Europe. The second largest airlaid supplier in the U.S. and the third largest in the world is Domtar. [13] Based on their websites and product information, these companies utilize both natural fibers, like fluff pulps, and synthetic man-made materials, such as super absorbent polymers, as raw materials in the airlaid production [14][15].

The global consumption airlaid nonwovens was 574,800 tons in 2022 including all fiber raw material options [13], while the consumption of packaging paper and board in Europe alone was about 43,000,000 tons [16]. It is estimated that the consumption of airlaid nonwovens will grow 6%, and the market value will increase by 7.7% between the years 2022 and 2027 [13][17]. This rising market demand empowers companies to drive product development and make investments. Despite the addition of a significant production line in North America in 2022, the markets in both North America and Europe remain fully supplied meaning that the investment did not lead to overproduction. [13] The demand-capacity ratio is even forecasted to increase from 92% to 94% by year 2027 [17].

4.2 Research and recent developments

The modern-day and future sustainability requirements force industries to develop more sustainable manufacturing processes and products and increase also the use of renewable raw materials. Replacing plastic products with alternative materials is also a prevailing trend in the world, especially after the SUP (Single-Use Plastics) directive published by the EU [18]. Recently, there has been announced several developments related to the airlaid products.

4.2.1 Packaging applications

Airlaid substrates have the potential for heavier grammage applications in the 500-1500 g/m^2 range. Such products are, for example, packaging, insulation, and molded consumer products. In packaging, airlaid products provide protective and insulating properties and have the ability to replace alternative plastic packaging materials, such as expanded polystyrene and other foamed plastics. Fiber-based molded consumer products can thus replace single-use plastics. [17] PulPac is a company that employs airlaid technology in the production of dry molded consumer products, such as trays, cutlery, and cup lids. The manufacturing process of PulPac involves milling pulp into fibers and airlaying them to form a dry web. After that, barriers are applied to the web, and the final shape is created by temperature and pressure with special design tools. [19]

The use of chemical binders is very common in airlaid products. Currently, research is being conducted on replacing fossil-based binders with bio-based alternatives. Related to this, SharpCell and OrganoClick have developed an airlaid material for napkins, which is claimed to be plastic-free. The fossil-based binder is replaced in the new material with OrganoClick's bio-based binder that is produced from food industry side streams, such as wheat, corn, lemons, and shrimp cells. [20] Glatfelter has also developed a material, GlatPure, that comprises cellulose fibers and organic binders, making the material fully plant-based. Additionally, Glatfelter and Blue Ocean Closures are aiming to develop a cellulose-based airlaid bottle cap by using press forming. [13]

4.2.2 Other applications

In addition to applications related to packaging, airlaying technology has also been developed for more distinctive applications. For example, a company called McAirlaid announced a new filter media for the tobacco industry in 2018. The airlaid filter, GENIA, is made with 100% virgin cellulose making it plastic-free and fully compostable. While a traditional acetate filter takes 15 years to decompose, it is said that GENIA decomposes within a few weeks. [21]

Airlaying technology can also be utilized in dry paper recycling. Nakamura et al. [22] have developed a recycling process in which wastepaper is first decomposed into fibers, then these fibers are formed into a new web by airlaying. Finally, the web is densified by pressing and binding technologies. The recycling process was commercialized as a recycling and papermaking machine for offices to take care of confidential documents and other office papers. With this application, the companies can reduce the risk of confidential leakage during transportation of wastepaper and recycle and produce paper locally.

The use of airlaid papers has also potential in sensor and energy applications. The use of airlaid papers has been researched, for example, in wearable electronics and 3D solar interfacial evaporators, which are applied for water purification using solar thermal energy. Lin et al. [23] examined replacing the polymer substrate with an airlaid sheet in flexible sensors. Airlaid paper was selected as an alternative material because it is flexible and has a low price, good availability, and high water absorption capacity. In the research, the airlaid paper was combined with $Ti_3C_2T_x$ MXene nanosheets to make a conductive composite material for the sensor. As a result, they found that MXene/airlaid paper can be used as a wearable device for motion monitoring, and can be applied, for example, in health care.

In addition, Xu et al. [24] compounded airlaid paper with polypyrrole to produce material with good solar absorption ability. The airlaid paper was chosen due to its microstructure, which enables efficient photon capture and water transport ability. They believed in the potential of this kind of material to replace complex material preparation and structures. Secondly, Ly et al. [25] examined power-generating material composed of airlaid paper and carbon ink. The power generation was based on the interaction between carbon ink and water. This interaction produced free, along the paper transferring ions, which induced the generation of electricity. According to the researchers, this material has the potential to be employed for powering wearable electronics, such as watches, and used in extreme situations, such as after natural disasters.

4.2.3 New patents

In recent years, there have been announced various new patents related to airlaying technology and airlaid applications. Airlaying technology patents cover advancements in the structure of airlaying machines, and in the way of manufacturing the airlaid web. Various patents have also been published for new airlaid structures, raw materials, and material combinations. Recently published patents are mainly related to packaging, insulation, sound absorption, respiration, and wiping applications.

For example, Stora Enso Oyj has published several airlaid packaging patents. The patent US2023256702 (A1) considers a 3D-shaped airlaid product formed by hot pressing. The product made from at least 70 % natural fibers and less than 30 % thermoplastic binder is recyclable in the existing repulping process. [26] The patent number US2023249889

(A1) comprises the folding of 3D airlaid packaging products [27]. The product is more environmentally friendly compared to foamed polymers, and is suitable for cushioning and thermal insulation of packaged goods [26][27]. In addition, they have also published two patents (SE2230307, SE2230308) for a foldable packaging insert, which is made of cellulose-based airlaid or solid foam substrates. The insert material is foldable because of hinge sections and can be applied within the packaging to protect packaged goods. [28][29]

Additionally, several airlaid nonwoven patents have also been published for applications other than packaging. Glatfelter Gernsbach Gmbh has recently patented a method that utilizes a combination of airlaid structure and foam. The foam is applied either to the surface of the airlaid structure or embedded either partially or entirely inside the structure. [30] In addition, Glatfelter Corp has a patented method for producing airlaid nonwovens with low dust or lint content [31]. Other examples of newly patented material developments by various companies include an antimicrobial roll-up floor cover, a cleaning sheet, and a cosmetic sheet, all of which use an airlaid sheet as a part of their material structure. [32], [33], [34]

5. COMPRESSING OF FIBER WEB

Fiber web structure and strength can be influenced by compression. The effect of compression depends on several parameters, such as compression time, moisture content, temperature, and pressure. The impact of these parameters on lignocellulosic fibers is generally similar, regardless of whether the web is made by airlaying or wetlaying processes. The main difference lies in the initial strength of the webs: wetlaid webs typically exhibit higher initial strength due to the superior inter-fiber bonds formed during the wetlaying process compared to those produced by the airlaying process.

5.1 The effect of pressing parameters on web strength

Lignocellulosic material is viscoelastic, meaning that its behavior is influenced not only by fiber characteristics but also by temperature and moisture content. The deformation response, for example in compression, is also dependent on time. A short load pulse results in a smaller deformation than a long load pulse. [35]

When aiming to optimize airlaid web strength, it is important to consider the impact of both individual and combined effects of the parameters. According to the research of Kononov et al. [36] the effect of temperature and pressure on the tensile strength of high-temperature chemi-thermomechanical pulp (HT-CTMP) sheet was not linear meaning that many temperature-pressure combinations resulted in the same tensile strength value. They found that temperature had the strongest effect on tensile strength, and the combined effect of temperature and pressure had the second strongest within used pressing conditions.

It has been found that the tensile strength of airlaid and wetlaid sheets can be enhanced by hot pressing. Although strength properties are usually desirable for paperboard applications, it is also important to consider how pressing affects other than strength properties. Pressing of fiber web typically results in lower bulk values increasing the strength properties but reducing tear resistance, flexibility, and absorption properties. Figure 2 summarizes generally the effects of temperature, pressure, and pressing time on tensile strength, bulk, and final dry content of the airlaid sheet, which is presented as percentages.

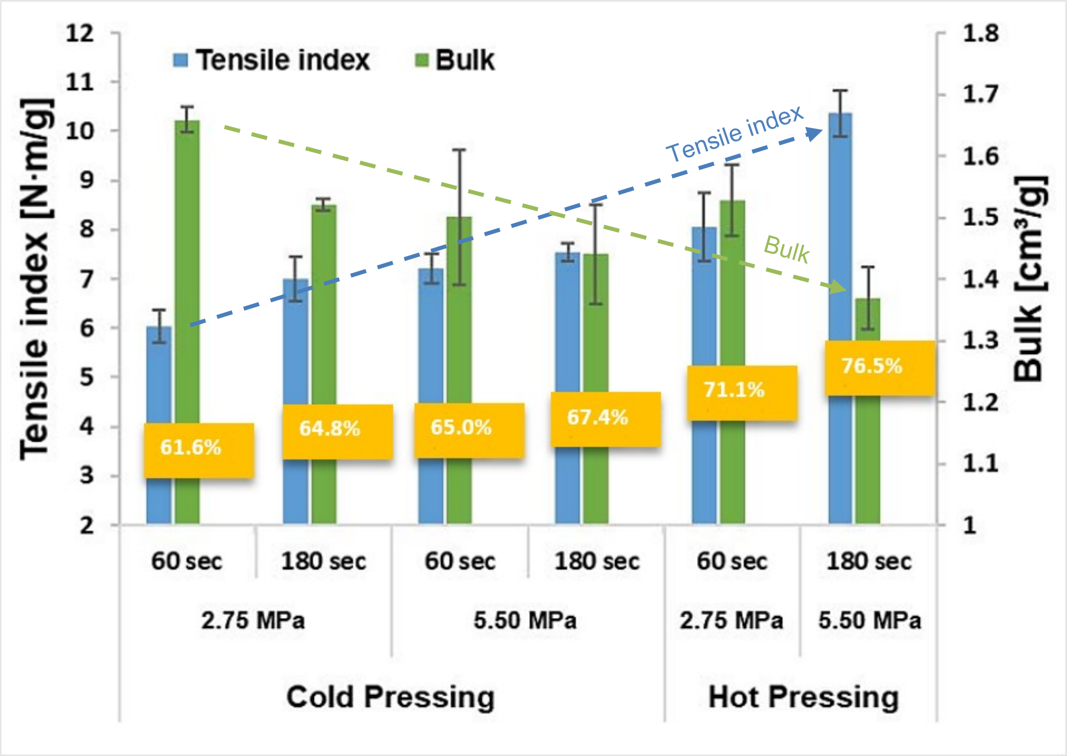

Figure 2. The pressing results of the airlaid sheet made from bleached hardwood kraft pulp (BHKP). Modified from [37].

In Figure 2, the higher pressure, higher temperature, and longer pressing time increase the tensile index, which is inversely proportional to bulk. So, higher bulk leads to a lower tensile index and vice versa. With high pressure and temperature, the fibers are forced physically close to each other, which facilitates the fiber-to-fiber bond formation.

5.1.1 Time

The behavior of fibers under compression is time-dependent due to their viscoelastic nature. The effect of pressing time is especially important in high-speed production lines, where minimizing processing times is essential for achieving maximum production volumes. Hot pressing time influences heat transportation within the sheet structure, thus affecting fiber softening. If hot pressing times are too short, the temperature of the press impacts only the surface layer of the sheet rather than the entire structure, which may result in no improvement in sheet strength. [35] For instance, Mattsson et al. [38] observed that using a 100 ms pressing time, the differences between samples were small regardless of the sheet's initial moisture content and pressing temperatures (180 °C and 260 °C), and differences were more prominent when 250 ms or longer pressing times were used. Additionally, both dry and wet strength increased at 180 °C with pressing times up to the longest tested duration (60 minutes). Therefore, increasing hot pressing time generally results in better bonding and higher strength when temperature is such that thermal degradation does not occur.

On the other hand, the longer pressing times lower the production line speed and may result in thermal degradation when higher pressing temperatures are applied. When longer times are used, the heat has enough time to be carried throughout the entire sheet structure, and thermal degradation can occur over a longer period. For example, the pressing times of approximately 60 seconds or longer at elevated temperatures (260 °C) resulted in thermal degradation observed as decreased strength values. [38]

5.1.2 Moisture content

For a fiber bond to form, the fibers must be close enough to each other. This proximity of fibers, and thus the bonding, can be enhanced by increasing moisture content. Moisture makes fibers more flexible, enhancing their bonding ability, and lowering the softening temperature of cellulosic materials by acting as a lubricant in the structure. [39] [40, p. 92] Additionally, moisture on fiber surfaces generates capillary forces between fibers. Those capillary forces become especially stronger when the water is removed during drying. Water removal causes the fibers to become flatter, increasing surface contact area, and enhancing hydrogen bonding. [41][42] Studies indicate that hydroxyl groups of the fibers must be within 0.25 to 0.35 nm to form inter-fiber hydrogen bonds [37][42]. Besides hydrogen bonds and capillary forces, other important mechanisms in inter-fiber bonding include Van der Waals forces, Coulomb forces, molecular chain interdiffusion, and mechanical interlocking of fiber surface fibrils [39][42].

Due to the nature of the hydrogen bonding mechanism, which is highly dependent on moisture, bonding dry fibers without additives is challenging. According to Mattsson et al. [38], fibers were not as well bonded when a wetlaid sheet made from chemi-thermomechanical pulp (CTMP) was hot pressed as dry, containing only 7 ± 1% of moisture compared to a sheet with 25 ± 1% of moisture. The weaker bonding of the dry sheets was due to a smaller inter-fiber contact area, which was caused by the rougher surfaces of dry fibers. In other words, moisture causes fibers to swell, making their surfaces smoother and enhancing their bonding ability by increasing the inter-fiber contact area. [38]

Additionally, processing dry, non-flexible fibers at excessively high pressures can damage the fiber walls and cause cracks. Such cracking reduces the strength and modulus of elasticity of fibers. To prevent cracking, fibers can be softened by increasing either temperature or moisture content. Cracking of fibers has been observed, for instance, during calendering of dry paper webs. [43]

The moisture content also affects the temperature reached in the sheet during hot pressing. Using lower moisture content allows the sheet to reach higher temperatures [38][39]. On the other hand, the sheet reaches the vaporization temperature faster with higher initial moisture content [39].

The bonding ability of the fibers is better if irreversible morphological changes, such as hornification, are avoided. To achieve this, the water content in the fiber cell wall should remain above 30-40% from fiber disintegration until the start of web consolidation. [44] According to Santos et al. [45], inter-fiber bonding increased, and therefore the strength of the airlaid hardwood eucalyptus sheet was improved when the moisture content was increased from 20% to 40%. The research of Byrd [39] (Figure 3) and Kim et al. [46] also indicated similar observations.

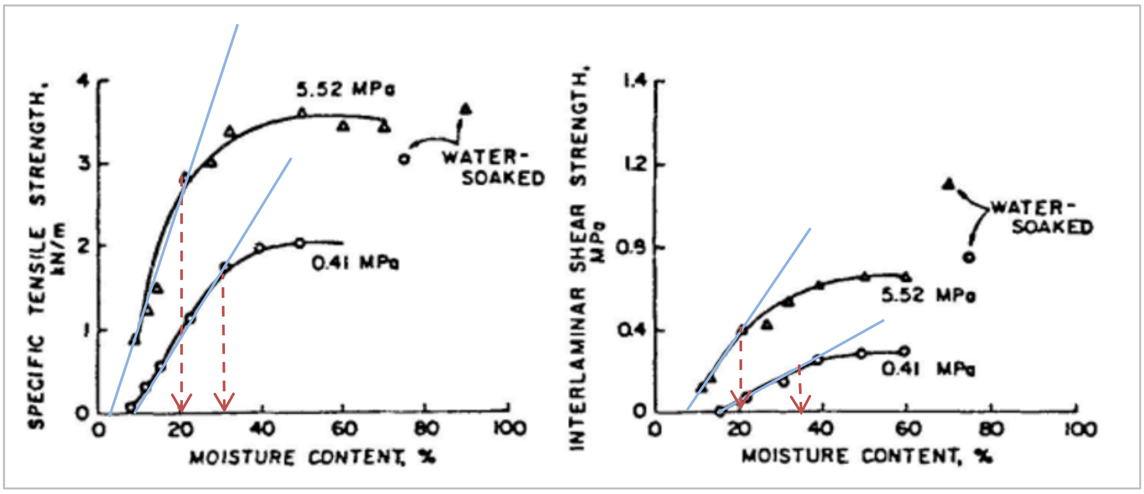

Figure 3. The effect of initial moisture on strength properties of airlaid sheet made from unbleached softwood kraft pulp (UBSKP), when the sheets were press-dried at 150 °C. Modified from [39].

In Figure 3, the strength properties increase significantly up to a moisture content of approximately 20% at 5.52 MPa and 30% at 0.41 MPa. Beyond this point, increasing the moisture content did not affect strength values much. Similar moisture-dependent behavior of tensile strength, as shown in Figure 3, was also obtained for airlaid made from BHKP in the research of Kim et al. [46] They found that the highest bulk and the lowest tensile index were obtained with the lowest initial moisture content (39%) when pressing was done at 25 °C for 3 minutes. Figure 4 shows that the tensile strength, and thus inter-fiber bonding, improved significantly up to a moisture content of 53%. After this point, the tensile strength increased only slightly. However, there are no measurement points between moisture contents of 39% and 53%, so it is not clear if 53% moisture content is the critical point where the significant increase in tensile strength ends. Thus, the linear increase in strength may end between moisture contents of 39% and 53%, similar to what is shown in Figure 3.

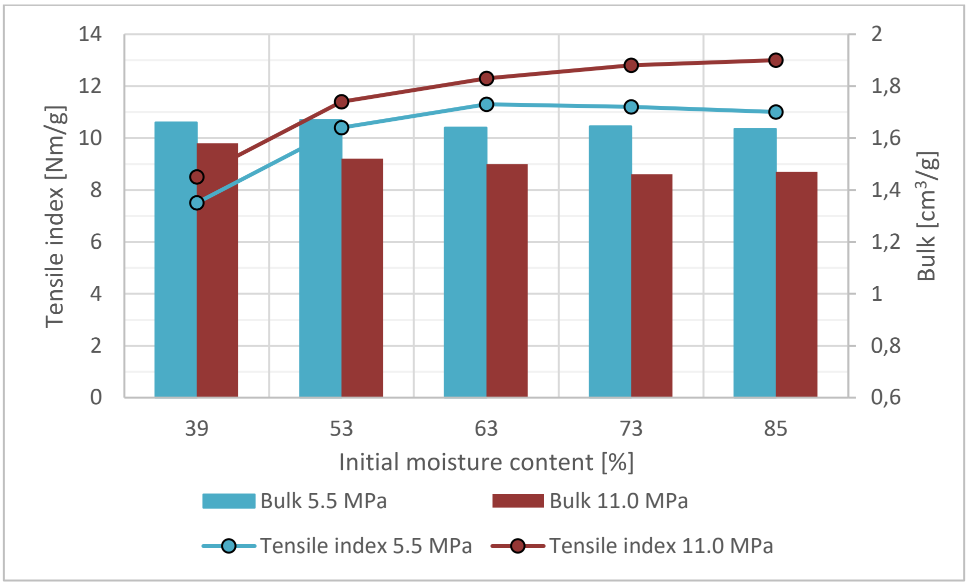

Figure 4. The effect of moisture on bulk and tensile strength of the airlaid BHKP sheet. Modified from [46].

A moisture content of 25-50% was also found to be effective in increasing the bonding of sheets made of thermomechanical pulp (TMP) and CTMP, which are mechanical pulps [47]. Therefore, the moisture content is an important factor in bonding regardless of the pulp type. However, moisture must be added uniformly throughout the fiber web structure to enhance bond formation. For example, increasing moisture content to 20% and 50% by spraying water vapor did not affect tensile strength, because moisture remained on the surface and did not penetrate the internal fiber structure, thereby failing to enhance fiber flexibility and bonding. [37]

Based on Figures 3 and 4, adjusting the moisture content is an easy and low-cost way to enhance bonding in airlaid sheets. Additionally, the use of synthetic binders in airlaid web bonding can be reduced by enhancing water-cellulose interactions [45]. Nonetheless, the improving effect of moisture is still not enough for the pressed airlaid sheets to achieve the strength of pressed wetlaid sheets when sheets are made of chemical pulp [37][39][46][48][49].

One of the main problems with airlaid sheets is their low strength compared to wetlaid sheets. Kononov et al. [35][43] observed that by rewetting airlaid sheets to a moisture content of 70% during the web consolidation stage and using hot pressing, the properties of airlaid and wetlaid sheets became similar. This kind of result was obtained when HT-CTMP, TMP, and unbeaten softwood kraft pulp (SKP) were used as raw materials.

However, the moisture content of 70% is higher than the moisture content at the beginning of the drying section in a conventional paper machine, which is approximately 50%. In other words, rewetting the airlaid web to such a high moisture content reduces the energy efficiency and low water usage benefits of the airlaid process. The higher moisture content requires more energy to remove the excess water, thus lowering the energy efficiency.

Consequently, these studies validate the importance of water in achieving the strength of the fiber web without additives, regardless of pulp type. As previously mentioned, water enables the formation of hydrogen bonds and softens the fibers, allowing them to move close enough to each other so that intermolecular bonds can be formed. Hence, water is an important factor in fiber bonding regardless of pulp type, but the softening phenomenon is particularly important for lignin-rich fibers, which are stiffer than chemical pulp fibers.

5.1.3 Temperature

The use of elevated temperature is effective in compensating for the effect of water on fiber softening. Fiber softening is related to a glass transition occurring in the amorphous regions of the polymer structure. Lignocellulosic fibers are polymeric materials composed of semicrystalline cellulose, amorphous hemicellulose, and amorphous lignin, so softening occurs especially in the hemicellulose and lignin structures. At the glass transition temperature (T_g), the solid amorphous structure changes from rigid to soft and rubbery-like. [40, p. 89] The softening effect is typically reached when the temperature is about 50-75 °C higher than T_g [39]. For cellulose, the T_g occurs between 200 °C and 250 °C, for hemicellulose between 150 °C and 220 °C, and for lignin between 120 °C and 200 °C. [40, p. 89] The values for T_g vary a lot because it is dependent, for example, on the polymer structural properties and moisture content. Water plasticizes the molecular chains of lignin and hemicellulose, thereby decreasing their T_g. Water can also plasticize amorphous regions of cellulose, but not the crystalline regions. For this reason, water does not affect the large-scale movement of cellulose molecule chains, and thus does not lower the T_g of cellulose. [50]

Several research have observed that strength is improved with increasing hot pressing temperature for both chemical and mechanical pulps [38][49][51]. According to the research of Joelsson et al. [49], higher temperatures resulted in higher density for lignin-containing pulps (mechanical pulps), leading to higher dry and wet tensile strengths. However, increasing temperature did not improve the strength of bleached kraft pulp that much due to its fiber properties. Bleached kraft pulp fibers are denser and have collapsed due to the removal of lignin and most hemicellulose, so hot pressing has less effect on the properties of chemical pulp compared to mechanical pulp.

The strength-improving effect of temperature can be observed even at relatively low temperatures. According to the research of Kim et al. [37], the tensile index of BHKP airlaid sheets improved when the temperature was increased from 20 °C to 90 °C. However, Klinga et al. [52] found that increasing the temperature from 25 °C to 60 °C improved strength properties but increasing the temperature from 60 °C to 93 °C had no additional effect. Therefore, 60 °C was a sufficient temperature for fiber softening and bond forming in the case of wetlaid HT-CTMP and TMP sheets, and it was observed that temperature affected only the drying time. However, the significant softening of fibers and improved bonding can be achieved at higher temperatures. For example, the highest dry strength value was obtained at 280 °C for wetlaid CTMP sheets with an initial moisture content of 7 ± 1%. For sheets with a moisture content of 25 ± 1%, the highest dry strength value was obtained in the temperature range of 240-260 °C. The highest wet strength for both dry and moist sheets was achieved at the highest temperature, 300 °C, with a pressing time of 3.5 seconds. [38]

On the other hand, using excessively high temperatures can cause thermal degradation of the fibers. Degradation of hemicelluloses begins above 100 °C through acid hydrolysis and dehydration mechanisms, but significant weight loss occurs mainly between 230 °C and 315 °C [53]. Lignin degrades over a wider temperature range, 200-500 °C [54]. Thermal degradation affects both the visual and physical properties of the sheets, causing them to darken and reducing their strength. In the research of Mattsson et al. [38], thermal degradation in strength was observed at 260 °C but not at 180 °C, and visible color changes were seen at 240 °C and higher temperatures. Additionally, delamination of the sheet can occur at elevated temperatures. For example, wetlaid TMP sheets with a Canadian standard freeness (CSF) of 55 ml delaminated at 200 °C [49]. Delamination of sheets is affected by factors such as temperature, pressure, and fines content [55].

Consequently, the effect of temperature on strength properties is high and can be even the highest, as shown in the previously mentioned research of Kononov et al. [36]. Temperature softens the fibers, enabling better inter-fiber contact and facilitating bond formation. Strength properties can be improved at relatively low temperatures, but a better strengthening effect is achieved at higher temperatures, near softening temperatures of fiber components. However, when increasing the temperature, it is important to consider other processing parameters together with the pulp type. A temperature that is too high may result in delamination and thermal degradation of the fibers.

5.1.4 Pressure

Generally, higher pressure results in a higher tensile index and lower bulk [37], [39], [46].These observations are seen in Figures 3, 4, and 5. Additionally, higher pressure led the strength of the airlaid web to increase with a higher slope when the strength was presented as a function of moisture content (Figure 3). This finding is especially important regarding the energy efficiency of the strength improvement process because lower initial moisture content needs less drying energy.

The improvement in strength from increased pressure can be explained by the fact that higher pressure forces fibers closer together, increasing the contact area between fibers and potentially enhancing bonding under appropriate conditions. Therefore, the effect of pressure on results varies and depends on the processing conditions and, for example, the fiber type. According to Kononov et al. [24] the effect of pressure alone was smaller than the effect of temperature and combined effect of temperature and pressure, with a temperature range of 100-190 °C and a pressure range of 0.4-1.6 MPa. However, the effect of pressure was observed to be higher than the effect of temperature when sheets were processed at temperatures ranging from 25 °C to 90 °C and pressures from 0.1 MPa to 0.4 MPa [52].

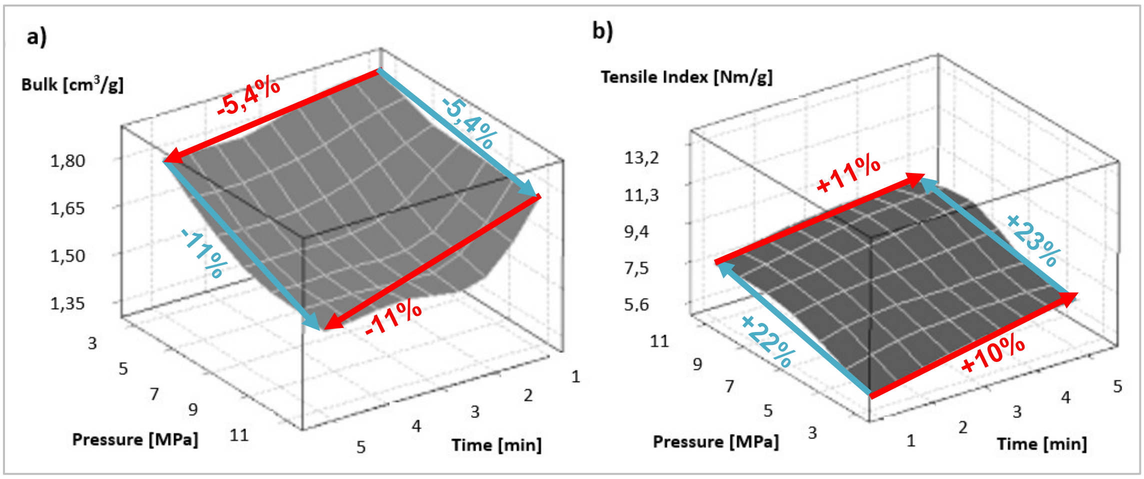

Figure 5. The effect of pressing time and pressure on a) bulk and b) tensile index of airlaid BHKP sheet with an initial moisture content of 39%. Modified from [46].

While higher pressure generally improves strength, it can also negatively impact the tensile index. According to the research of Kim et al. [37], pressing at 90 °C with 5.50 MPa increased tensile strength until a pressing time of 30 seconds. However, beyond that point, the tensile index started to slowly decrease from approximately 11 to 9.5 Nm/g over the time range of 30 to 90 seconds, despite a decrease in bulk and an increase in density throughout the entire pressing period. This reduction in strength was explained by sheet delamination, which is caused by too high vapor pressure that degrades the fiber web structure. This phenomenon did not occur at the lower pressure, 2.75 MPa. However, the 5.52 MPa pressure did not cause any reduction in strength in Figure 3, where the airlaid sheet was press-dried at 150 °C. This difference may be due to the higher temperature, which softens the fibers and makes them more adaptable, thus preventing delamination. Therefore, the combination of press temperature and pressure must be considered when aiming to improve the strength of fiber webs.

In summary, pressure is an important pressing parameter together with temperature because it enhances fiber bonding by pushing the fibers close to each other. Higher pressure generally increases the strength of fiber webs, but exceptions also occur. Excessively high pressure may cause delamination of fiber web structures, so the pressure level used needs to be optimized likewise other pressing parameters to avoid strength-reducing effects during pressing.

5.2 The effect of fiber characteristics on web strength

In addition to compression parameters, the fiber characteristics also affect web consolidation and fiber bonding. The properties of chemical and mechanical pulps differ because chemical pulp undergoes a process where hemicellulose and lignin are removed, leaving mainly cellulose in the pulp, while mechanical pulp includes all these components. Additionally, fibrillation and fines content in fibers are also factors that affect inter-fiber bonding and moisture absorption.

5.2.1 Lignin

The relative amount of cellulose, hemicellulose, and lignin in a biomass cell wall varies depending on the type of biomass. Softwoods and hardwoods contain approximately 40-55% cellulose, 24-40% hemicellulose, and 18-35% lignin. Cellulose and hemicellulose are polysaccharides composed of glucose units, whereas lignin is an aromatic heterogeneous polymer composed of phenyl-propane units. [56, pp. 11–13] The chemical structure of lignin is irregular due to that phenylpropane units are not systematically linked to each other [57, p. 55].The main function of lignin is to strengthen the cell wall structure by binding cellulose and hemicellulose together, acting like a glue between them. [56, pp. 11–13]

Fibers rich in lignin are stiff and inflexible below their glass transition temperature, resulting in poor inter-fiber bonding ability [47], [49], [58]. Fiber bonding and thus the strength can be enhanced by optimizing processing conditions to be more suitable for the pulps with high lignin content. For instance, increasing temperature softens lignin and induces densification of sheets during pressing. In the research of Norgren et al. [58], the densities of mechanical pulps increased significantly from 420 kg/m^3 to 760 kg/m^3 for CTMP and from 310 kg/m^3 to 730 kg/m^3 for HT-CTMP when wetlaid sheets were pressed in the temperature range from 25 °C to 200 °C. However, the same temperature range had a lower impact on the density of the sheet made of kraft pulp, whose density increased from 730 kg/m^3 only to 800 kg/m^3. This was due to a lack of lignin and reduced bonding ability of already collapsed kraft pulp fibers. Additionally. Joelsson et al. [48], [49] observed also that it is possible to achieve sheet properties similar to those made from chemical pulp by hot pressing lignin-containing pulp.

In addition to pressure and temperature, initial moisture content and pressing time are also important to consider when optimizing the strength of high-yield pulps. As mentioned earlier, by increasing the moisture content the T_g of lignin decreases, which enables fiber softening at lower temperatures. Pressing time influences the heat transfer within the sheet structure.

It has been found that many advantageous properties can be achieved on fiber sheets by utilizing high-yield pulps and hot pressing, compared to chemical pulp, whose properties are not as strongly affected by the hot-pressing procedure. According to Negro et al. [59], the hot pressing of wetlaid CTMP sheet for 3 seconds at 260 °C with 3.5 MPa almost doubled the tensile index and compression strength (SCT index) values compared to non-pressed reference sheets. Hot pressing of sheets with a moisture content of 30-35% decreased also air permeability from 2100 mL/min to 400 mL/min and tear resistance from 210 mN to 150 mN.

Additionally, improved wet tensile strength is an advantage of hot-pressing lignin-containing sheets. This improvement is most significant at the highest temperatures when fibers contain 7-12 % lignin. The strengthening mechanism is lignin inter-diffusion, which results in stronger inter-fiber bonds under wet conditions. Lignin makes bonds water resistant and by that increases the wet strength. [51] Wet strength is mainly affected by the temperature, but solids content also influences it. Higher temperatures accelerate lignin inter-diffusion, enhancing bonding, while solids content affects the temperature reached in the sheet. [38]

In summary, high-yield pulps containing lignin are seen as a potential alternative for kraft pulps when hot pressing is performed in suitable conditions. The strength-improving effect of lignin may also offer a simple option for the compacting of airlaid webs compared to web consolidation using additives.

5.2.2 Fibrillation and fines content

Refining is a mechanical treatment for pulp fibers aimed at improving the properties of the final fiber product by affecting various fiber web properties, such as density, porosity, and formation. It influences the mechanical and geometrical properties of the fibers by increasing the amount of fines and enhancing internal and external fibrillation. [60] Internal fibrillation means delamination of the P and S1 layers of the fiber wall, resulting in a greater swelling potential of the fibers, which in turn leads to greater fiber conformability. Additionally, the delamination of the fiber wall increases fiber flexibility, which together with conformability, results in larger bonded areas and stronger inter-fiber bonds. However, external fibrils that are attached to the fiber but peeled off from a fiber's surface reduce the tensile strength of a fiber web. This effect is explained by lower fiber strength and weaker inter-fiber bonds. [61]

The refining degree is usually determined using the Canadian Standard Freeness (CSF) or Schopper-Riegler (SR) methods. The tensile strength of the fiber web and refining energy correlate such that more refined pulp results in higher strength and a lower CSF number or a higher SR number. [61][62] Additionally, the higher density caused by refining, leads to higher tensile strength [62], [64].

Fines are the smallest components in lignocellulosic material and can be divided into primary and secondary fines, with primary fines formed during the initial pulping process and secondary fines produced during further processing, such as refining. Fines typically consist of short fibers, fiber fragments, and fibrils and are characterized by screens with a certain size of holes. Both chemical and mechanical pulp contain a certain amount of fines, but mechanical pulp typically has more due to its different manufacturing method. Mechanical pulp contains about 20-40% fines by weight, while chemical pulp contains less than 15%. [60]

Fines have many effects on fiber processing and final sheet properties. They affect pulp bleaching and the drainage of water from fibers. [60] Due to their small particle size and large surface area, fines bind more water and swell more than fibers. The composition of fines is almost the same as that of fibers, containing similar proportions of cellulose, hemicellulose, lignin, and extractives. However, fines in chemical pulps typically have higher hemicellulose content, while those in mechanical pulps have more lignin than fiber fractions. Therefore, hydrophilic hemicellulose in fines binds more water and swells more compared to fines with hydrophobic lignin. [65, p. 69]

Additionally, fines fill the voids between fibers and promote also inter-fiber bonding. For example, the improved inter-fiber bonding produced by fines was observed in the research of Pettersson et al. [66], where wetlaid sheets made from a mixture of CTMP and kraft pulp (80/20) were pressed at temperatures ranging from 80-100 °C with both low and high nip pressures. When sheets were pressed at 100 °C with high nip pressure, the tensile index of CTMP pulp with higher freeness (720 ml) was approximately 43 Nm/g, while for pulp with 220 ml freeness, it was 65 Nm/g. Additionally, SCT values increased from 19 to 33 kNm/kg by lowering the freeness from 720 to 220 ml.

The same observation about the effect of fines was made in the research of Santos et al. [45], who studied airlaid sheets made from eucalyptus fibers and eucalyptus-PLA fiber blends. They observed that a high fines content of eucalyptus fibers resulted in better bonding, while a low fines content led to higher bulk and absorption capacity. Furthermore, the high surface area of the high fines group was found to favor interactions with PLA fibers, resulting in higher strength properties.

Consequently, fines content affects fiber bonding and sheet strength in both airlaid and wetlaid sheets. However, the effect of fines may vary depending on their characteristics. For example, fibrillar fines can especially improve bonding by bringing fibers into closer contact during drying. On the other hand, flake-like fines formed from lamellar parts of the fiber wall may reduce inter-fiber bonding because of high lignin content hindering fiber-to-fiber bonding. [65, p. 71]

6. MATERIALS AND METHODS

In this thesis, the effect of compacting and pressing on airlaid web strength is studied. The focus is especially on how pressing parameters and pulp freeness affect tensile strength. Airlaid sheets were produced using three different chemi-thermomechanical pulps (CTMPs), and the sheets were compacted under various pressing conditions. All performed trial points are listed in Appendix A. The strength of the sheets was tested mechanically by tensile test. Additionally, sheet brightness was measured, optical formation was imagined, and pulp properties were determined. Consequently, the experimental work performed at VTT Jyväskylä included pulp preparation, test sheet preparation, and measuring the properties of the test sheets and pulps.

All standards used in the experimental part are listed in Table 2. The standards used were mainly paper and board standards to allow comparison of the properties of airlaid sheets. Only sheet thickness was measured following tissue paper standards due to the porous structure of airlaids. Measuring the thickness according to the tissue standard provided the most realistic result for the airlaid sheets.

Table 2. *Standards used for sheet conditioning and measurements.*

Procedure	**Standard**	**Source**
Wet disintegration	ISO 5263-3:2023 Pulps — Laboratory wet disintegration, Part 3: Disintegration of mechanical pulps at ≥85 °C	[67]
Wetlaying	ISO 5269-1:2005 Pulps — Preparation of laboratory sheets for physical testing, Part 1: Conventional sheet-former method	[68]
Sample conditioning	ISO 187:2022 Paper, board and pulps — Standard atmosphere for conditioning and testing and procedure for monitoring the atmosphere and conditioning of samples	[69]
Thickness and density	ISO 12625-3:2014 Tissue paper and tissue products, Part 3: Determination of thickness, bulking thickness and apparent bulk density and bulk	[70]
Grammage	ISO 536:2019 Paper and board — Determination of grammage	[71]
Canadian Standard Freeness	ISO 5267-2:2001 Pulps — Determination of drainability, Part 2: "Canadian Standard" freeness method	[72]
Fiber Tester	ISO 16065-2:2014 Pulps — Determination of fibre length by automated optical analysis, Part 2: Unpolarized light method	[73]
Brightness	ISO 2470-1:2016 Paper, board and pulps — Measurement of diffuse blue reflectance factor, Part 1: Indoor daylight conditions (ISO brightness)	[74]
Tensile strength, tensile index	ISO 1924-3:2005 Paper and board — Determination of tensile properties, Part 3: Constant rate of elongation method (100 mm/min)	[75]

6.1 Pulp preparation

The pulps used in this Thesis were spruce CTMP with three different Canadian standard freeness numbers: 600, 400, and 350, provided by Rottneros Ab (Sunne, Sweden). The pulps required specific preparation methods for airlaying, wetlaying, and determining fiber and pulp properties. For airlaying, the pulps were dry disintegrated using a hammermill. For both wetlaying and property determination, the pulps were wet disintegrated.

6.1.1 Dry disintegration by a hammermill

The solid-like pulps were prepared for airlaying using a hammermill. Initially, the pulps were pre-crushed using the Weima crusher (Appendix B) and manually broken down to ease feeding into the hammermill. The laboratory hammermill, provided by Anpap Oy (Valkeakoski, Finland) mechanically separated the fibers from each other with rotating blades (Figures 6a). The separated fibers passed through a 3 mm sieve plate with the assistance of a vacuum and ended up in a fabric bag where they could be collected for use in airlaying.

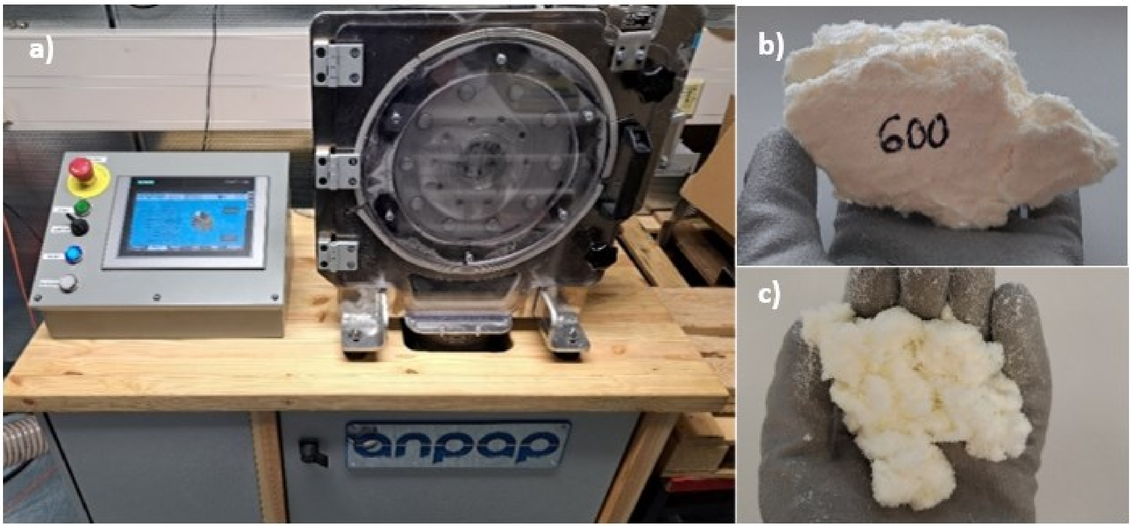

Figure 6. a) The hammermill. b) Non-disintegrated CTMP 600. c) Dry disintegrated pulp.

6.1.2 Wet disintegration

Wet disintegration of fibers is based on fiber separation from each other by mechanical treatment so that the structural properties change as little as possible. All hammermilled pulps and CTMP 600 and 400 from the bale were wet disintegrated. First, 50 ± 5 grams of pulp were weighed and dissolved in 1500 ml of deionized water for a minimum of 4 hours. Then, 1000 ml of deionized water was added to the fiber-water suspension and the suspension was heated over 85 °C in a pot. The heated suspension was added to a wet disintegrator (Appendix B) of which rotating blades mechanically disintegrated the fibers, and the number of rounds was 30,000. Finally, the suspension was cooled to 20 °C by adding cold deionized water so that the final consistency of the suspension was between 0.3 and 1.5%.

6.2 Test sheet preparation

This study focused on the properties of airlaid sheets. For comparison of properties and different manufacturing methods, wetlaid sheets were also prepared. The preparation of airlaid sheets involved airlaying, moisture adjustment, and hot pressing, while the preparation of wetlaid sheets included wetlaying and wet pressing.

6.2.1 Airlaying and airlaid sheet compressing

Airlaid test sheets were produced so that there were three samples treated identically per trial point (Appendix A). Airlaying was performed using a laboratory-scale airlaid drum former device (Walkisoft, Anpap, Finland), which was located at VTT Jyväskylä (Figure 7a). The desired amount of dry disintegrated fibers was weighed to produce airlaid sheets with a grammage of 150 g/m^2. The dry content of the fibers was determined using a dry content analyzer and was taken into account when weighing the fibers. The weighed portion of fibers was fed into the machine's slit drum with 1.5 x 20 mm holes. After that, the chamber was closed, and the airlaid sheets were produced by rotating the drum until it was empty, or the fibers could no longer pass through. This process took about 30 seconds in total. Most of the fibers exited the drum in the first 10 seconds, so the rotation direction was changed after only 5 seconds to ensure as uniform sheet formation as possible. The drum's rotation speed was 40 rpm, and the vacuum intensity setting was 8.

Moisture was added to the dry airlaid sheets by water-spraying to achieve the desired moisture content. The moisture contents of the airlaid sheets examined in this thesis varied between 7-9% and 45%. At first, the objective was to investigate only low moisture contents (≤ 25%) to obtain information on how adding moisture affects the tensile strength of airlaid sheets. Subsequently, also higher moisture contents than 25% were studied to see how far the strength curve of airlaids continues to rise as moisture content increases. However, a moisture content of 45% was chosen to be the highest since the ultimate goal of this study was to minimize water consumption in papermaking. Additionally, it was assumed that the strength increase would end at the latest around 45% moisture content based on the previous research [39][46][47].

Water-sprayed sheets were stored in sealed plastic bags for a minimum of 4 hours to allow moisture equilibration in the sheets. Some sheets were left "dry", meaning that no additional water was sprayed on them, and they contained only the moisture absorbed by the fibers from the atmosphere. The amount of absorbed moisture was determined using a dry content analyzer on the fibers, and it was approximately 7-9% when the relative humidity in the laboratory was between 37% and 50%.

Pressing of both dry and moistened sheets was performed using a planar pressing machine (Figure 7b) with a pressing capacity of up to 100 bars. The work pressure used in the test series was 100 bar, meaning that the pressure on one sheet was approximately 8.35 bar (0.835 MPa). In the literature, the pressure range used in airlaid pressing varied approximately between 0.41 MPa and 11.0 MPa [37][39][46]. So, the maximum possible pressure of the machine was chosen for these experiments to bring the fibers as close to each other as possible for bond formation. The effect of pressure was not investigated in this work due to the limitations of the press machine. In the additional tests, a higher pressure (3.34 MPa) was applied by cutting a sheet into 4 parts, resulting in each part experiencing 4 times the pressure of the whole sheet. However, this increased pressure did not enhance the sheet's strength and cutting caused the samples to break easily. Therefore, further investigation of pressure was not conducted with the available equipment.

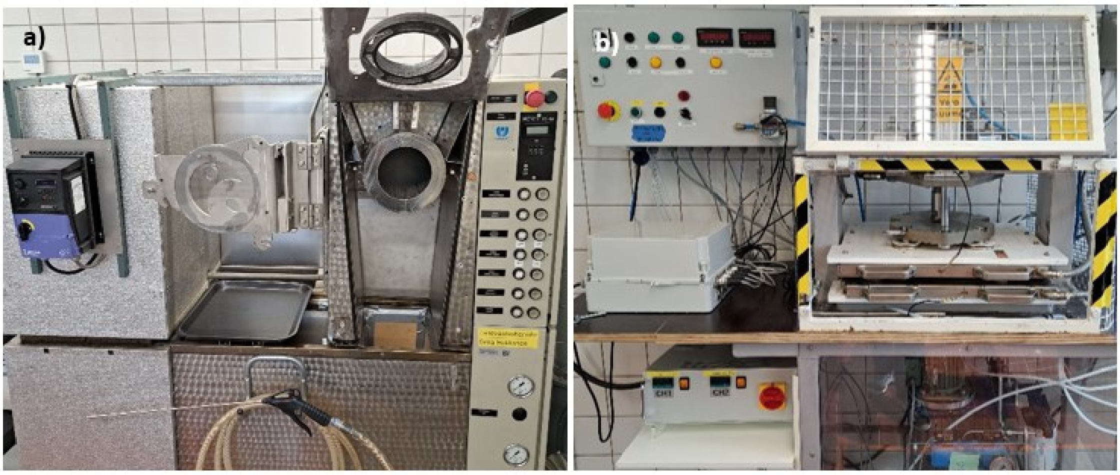

Figure 7. a) Walkisoft drum former for airlaying. b) VTT's pressing machine.

Hot pressing was conducted for 1 minute so that only the upper plate was heated, and the temperatures used were 180, 200, and 220 °C. A time of 1 minute was chosen as the pressing time based on previous tests and studies, and it was considered a long enough time for fiber softening and sheet drying. These tests did not focus on optimizing compression time, so it was kept constant during the experiments. The temperature range was chosen by taking into account the softening temperatures of the fibers, the limitations of the pressing device, and the materials used during hot pressing.

Dry sheets were pressed between baking papers, but moistened test sheets were pressed between different materials to ensure effective moisture removal and avoid breakage due to sticking. From top to bottom, the layers consisted of baking paper, a moistened test sheet, filter cloth, three blotting papers, felt, and baking paper. After pressing, the airlaid sheets were conditioned and measured according to the standards listed in Table 2.

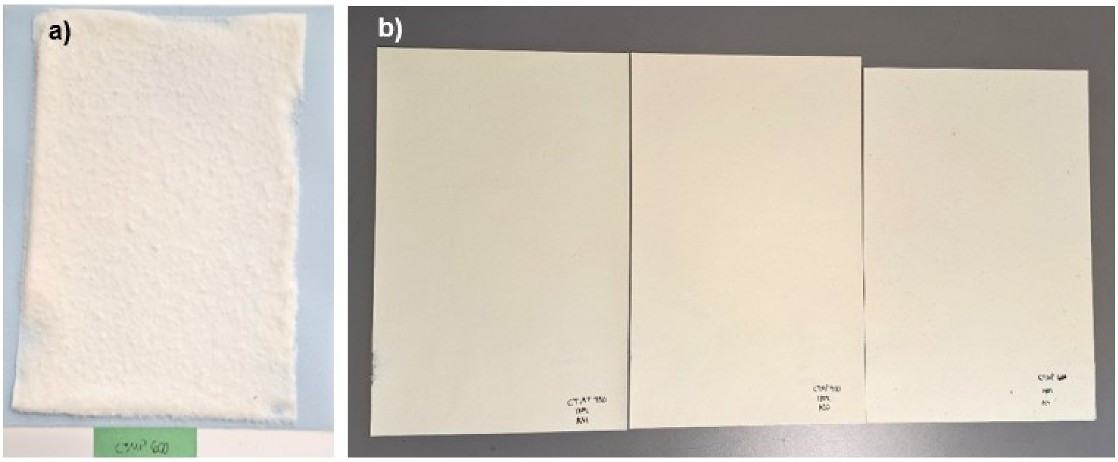

Figure 8. a) An airlaid sheet prior to hot pressing. b) Airlaid sheets pressed at 180 °C and die cut.

6.2.2 Wetlaying of reference sheets

The wetlaid reference sheets were prepared from the same pulps used for the airlaid sheets to compare the properties of airlaid and wetlaid sheets. The hammermilled fibers were wet disintegrated before wetlaying, as described in Section 6.1.2. Wetlaying of sheets with a grammage of 150 g/m^2 was done from the water-fiber suspension following ISO 5269-1:2005, using the L&W laboratory sheet former (ABB AB/Lorentzen & Wettre, Kista, Sweden) shown in Figure 9a. The sheets were wet pressed between metal plates and blotting papers at 3.5 bar pressure for 5 minutes using the L&W laboratory pressing device (ABB AB/Lorentzen & Wettre, Kista, Sweden) shown in Figure 9b. After that, the sheets were reversed, the wet blotting papers were replaced with dry ones, and the sheets were wet pressed again at 3.5 bar for 2 minutes. Then, the sheets were left to dry for a minimum of 24 hours under standard conditions (ISO 187:2022).

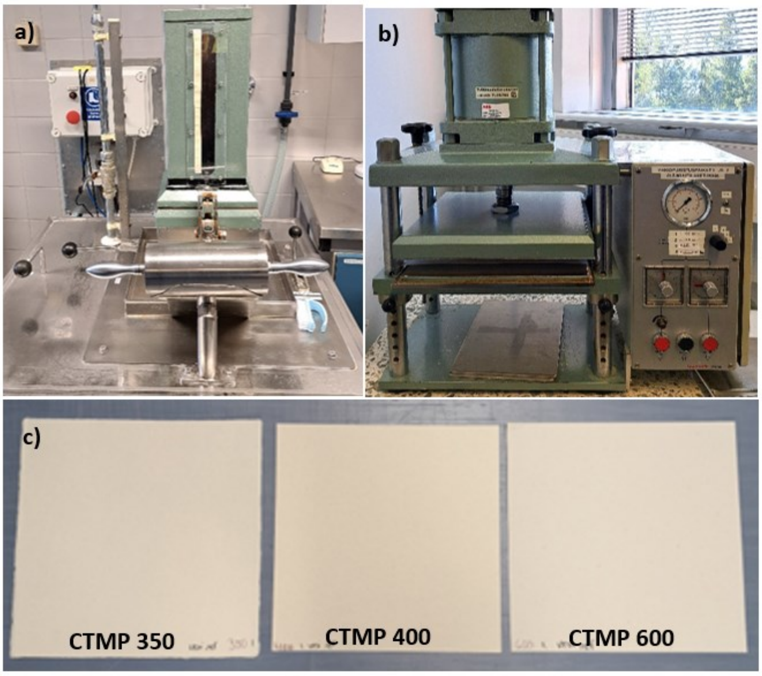

Figure 9. a) The wetlaying setup. b) The wet press. c) Dried wetlaid sheets.

6.3 Pulp and Fiber Characterization

The properties of pulps and fibers affect both airlaid and wetlaid sheet properties. The characterized properties included Canadian Standard Freeness for pulp and the geometrical properties for fibers.

6.3.1 Canadian Standard Freeness

Canadian Standard Freeness (CSF) is a method that is used for the determination of the drainability of a pulp suspension in water. Drainability is a pulp property that describes dewatering rate of a dilute pulp suspension. [72] In general, drainability is affected by various fiber and pulp properties including fines content, fiber length, flexibility, and swelling. In addition, the pressure difference and density of the fiber mat on the wire affect drainage. CSF describes drainability in such a way that the faster the water draining slows down, the smaller the CSF number, and vice versa. [76, pp. 479–480] CSF does not indicate pulp dewatering properties on a paper machine very well [72], but it is used to describe the coarseness of mechanical pulp after refining.

Before CSF number determination, all dry disintegrated pulps and non-disintegrated CTMP 600 and 400 were wet disintegrated, as described in Section 6.1.2. CSF numbers were then determined in accordance with ISO 5267-2:2001 so that 1000 ml of pulp suspension with a consistency of 3 g/l was filtered through a screen plate placed in a funnel. The funnel had openings at the bottom and the side, and the filtered water flowing to the side tube was collected and its volume measured. This volume is the initial CSF number. The final CSF number, expressed in ml, was obtained after adding temperature and consistency corrections to the initial value. For these corrections, the stock temperature was measured, and the fibers remaining on the wire were dried and weighed to get the exact consistency of the pulp suspension.

6.3.2 Geometrical properties of pulp fibers

The geometrical properties of all pulp fibers treated, as described in Sections 6.1.1 and 6.1.2, were analyzed in accordance with the standard ISO 16065-2:2014 using the L&W Fiber Tester Code 912 Plus – device (ABB AB/Lorentzen & Wettre, Kista, Sweden). Determined geometrical properties included for example fiber length, fiber width, fiber shape, fibril area, fibril perimeter, and fines content. The measurement is based on image analysis in which fibers are examined in water-fiber suspension.

Additionally, the device can be used to analyze how particles with different diameters absorb and scatter UV- and IR-lights. Smaller particles absorb and scatter UV light more than the IR-light, and the larger particles affect more the IR-light. The ratio of absorbed and scattered UV-light and IR-light is described as crill quota, which is larger the smaller particles there are in the sample. [77][78] Small particles, so-called crills, have a diameter that is approximately 100 times smaller than the fiber diameter. The measurement range for crill quota is typically 0.7-2.0. [78]

Samples were diluted to 1.50 g/l consistency and 100-200 ml of sample was applied on a decanter whereof the device took the sample for analyzing. The analyzer dilutes the sample for a certain volume, removes air by vacuum, and transports the sample through a gap in a measuring cell. The cell consists of two glass plates, a LED light, and a camera. The camera, located on the opposite side of the LED light, takes images of the sample, which the device analyzes.

6.4 Test sheet characterization

Finally, the performance and quality of the airlaid and wetlaid sheets were determined. These evaluated properties included sheet brightness, optical formation, and tensile strength. The optical formation focused on floc size and grayscale deviation providing information about the uniformity and distribution of fibers. The tensile strength, measured in the sheet’s dry state, was determined to assess the effectiveness of the compacting method.

6.4.1 Brightness

ISO brightness R_{457}, expressed as %, is measured by illuminating a sample diffusively in a standard instrument and the reflected light from the sample is measured. The light is reflected normal to the surface, and it is measured either by an optical filter and a photodetector or by an array of photosensitive diodes which react differently on each wavelength. Hence, the brightness is either a direct output of the photodetector or a calculation from the photosensitive diode outputs. [74] ISO brightness is 100% for an ideal diffuser and 0% for black, non-reflecting material [5, p. 165].

The brightness of the sheets was tested in accordance with ISO 2470-1:2016 using a Minolta CM-3610d spectrophotometer (Minolta, Osaka, Japan). All samples were conditioned in accordance with ISO 187:2022. The measurement procedure included calibration of the instrument and measuring 10 points from one trial sample both upside and underside. Since there were only three similarly treated airlaid sheets, the brightness was tested by stacking three sample sheets and seven white A4 papers on top of each other and taking the required ten measurement points from the three test sheets. Wetlaid reference sheets were measured according to the standard by stacking 10 sheets made of the same pulp and taking one measurement point from each sheet.

6.4.2 Optical formation and floc analysis

The optical formation of a fiber sheet can be determined in various ways. Usually, some kind of imaging and image analysis is done. A simple way to describe the optical formation of a sheet is the grayscale intensity of image pixels and the deviation calculated from it. A greater grayscale deviation value indicates poorer formation. [79]

Optical formation and floc sizes were determined from non-pressed and pressed airlaid sheets and wetlaid sheets so that the effect of the sheet preparation method could be analyzed. The method for determination of optical formation and floc sizes taking images from the sheets on top of a light table and analyzing the images using software. Images were taken of dry airlaid sheets on top of wires prior to hot pressing because the sheets were too fragile to handle without the wire. After hot-pressing, images were taken without the wires, and for wetlaids, the figures were taken after drying.

Image analysis was performed on the images to determine the desired properties. The analysis was done using MATLAB software. The betaformation measurement was also considered for the determination of the sheet formation, but it failed due to too long exposure time caused by too high grammage of the test sheets (150 g/m^2).

6.4.3 Tensile strength

Tensile strength is a strength property that is determined by straining the test sample to break at a constant rate of elongation. During testing, the testing machine records tensile force and elongation. Thus, various tensile properties can be determined, such as tensile strength, tensile stiffness, strain at break, tensile energy absorption, and modulus of elasticity. In addition, the tensile index and tensile energy absorption index can also be calculated if the grammage of the sample is known. [75]

All tested sheets were conditioned in accordance with ISO 187:2022 and cut into 15 x 150 mm test pieces. A tensile test was performed with the Lloyd LS5 device in accordance with ISO 1924-3:2005 using mainly a 100 N load cell. In the case of the cold-pressed airlaid sheet, a 20 N load cell was used due to the high fragility of the sample. Ten test pieces were tested per each sample sheet. The test pieces were placed in the clamps having a distance of 100 mm ± 0,5 mm and strained with an elongation rate of 100 mm/min. Both airlaid and wetlaid sheets were tested in only one direction due to a lack of orientation of fibers.

7. RESULTS AND DISCUSSION

Two test series were carried out to qualify the effect of pressing, pressing parameters, and the effect of freeness on dry formed web strength. The experimental work and the measurements done are described in chapter 6. In this chapter, results of measurements for different pulp and sheet characteristics are shown and combined to gain an improved understanding of how previously mentioned variables affect the strength of airlaids.

7.1 Canadian Standard Freeness

Canadian Standard Freeness was measured to determine the exact freeness of the pulps, as the freeness stated by the manufacturer may vary slightly. Freeness was measured from both non-hammermilled pulps from bale and hammermilled pulps to assess whether hammermilling affects freeness. The measured and corrected CSF numbers are listed in Table 3.

Table 3. *Measured Canadian Standard Freeness values.*

Pulp type	**Canadian Standard Freeness [ml]**
CTMP 600, from bale	655
CTMP 600, hammermilled	681
CTMP 400, from bale	461
CTMP 400, hammermilled	483
CTMP 350, hammermilled	417

Based on Table 3 results, the CSF numbers of CTMP 600 and 400 are slightly higher than those stated by the manufacturer, so a similar estimate can be done for the non-hammermilled CTMP 350. Additionally, the results show that the CSF value increases slightly when comparing non-hammermilled and hammermilled pulps, but the differences are less than 5%.

7.2 Geometrical properties of pulp fibers

The geometrical properties of pulp fibers were determined using the Fiber Tester device, and the results are listed in Table 4. The formulas explaining how the values were calculated by the device are added in Appendix C. The results show that all the determined properties of CTMP 400 fall between those of the CTMP 600 and CTMP 350 properties, but are closer to CTMP 350, as expected. There are no significant differences in the geometrical properties of the pulps because they are all produced with the same manufacturing method – chemi-thermomechanical pulping – and the raw material for all the pulps is spruce. For example, the mean length of fibers is quite similar in the case of CTMP 350 and 400, and the mean length of CTMP 600 fibers is only 0.03 mm greater. Additionally, the fines contents are close to each other, with CTMP 350 having a slightly higher fines content than CTMP 600.

Table 4. *The geometrical properties of pulp fibers.*

Pulp	**CTMP 350**		**CTMP 400**		**CTMP 600**	
Property	**Average**	**StDev.**	**Average**	**StDev.**	**Average**	**StDev.**
Mean length [mm]	1.127	0.004	1.123	0.008	1.153	0.006
Mean width [µm]	36.100	0.000	37.150	0.071	38.550	0.071
Mean fibril area [%]	5.200	0.071	4.750	0.071	3.200	0.212
Mean fibril perimeter [%]	17.000	0.071	16.700	0.000	11.150	0.354
Mean fines [%]	68.050	0.354	67.250	0.636	67.050	0.071
Primary fines [%]	14.050	0.212	14.100	0.141	13.450	0.212
Secondary fines [%]	53.950	0.212	53.150	0.495	53.600	0.283
Crill Quota UV/IR	1.422	0.008	1.414	0.011	1.373	0.008

The most significant difference between CTMP 600 and CTMP 350 is observed in the fibril area and fibril perimeter, which are clearly higher for CTMP 350. Additionally, CTMP 350 has the highest crill quota value. This observation supports the theory that refining the pulp increases the number of small particles, thereby increasing also the crill quota.

7.3 Brightness

The brightness of the sheets was measured to get information about how the color changes at a certain hot-pressing temperature. Discoloration indicates the fiber's possible thermal degradation and how evenly the pressing heat is distributed, which in turn affects the strength of the sheet.

Figure 10 presents the effect of temperature on sheet brightness for dry airlaid sheets, airlaid sheets having a moisture content of 25%, wetlaid reference sheets, and for the airlaid cold-pressed sheet. The standard deviations of the results are plotted as error bars. The brightness of wetlaid sheets CTMP 600 and 350 are almost the same, but for

CTMP 400 the measured brightness is about 8% lower than those declared by the manufacturer, which was 75% brightness for all pulps.

When looking at the brightness results of airlaids, the brightness decreases as a function of press temperature, so the higher temperature causes sheets to darken, as expected. However, it should be noted that the brightness levels of dry airlaid sheets pressed at 180 °C and wetlaid reference sheets are similar for all pulps. Consequently, 180 °C press temperature did not cause any discoloration, and only 200 °C or higher press temperature caused the color to change. This observation also follows the theory, that the degradation of lignin and hemicelluloses occurs approximately at 200 °C or higher temperatures.

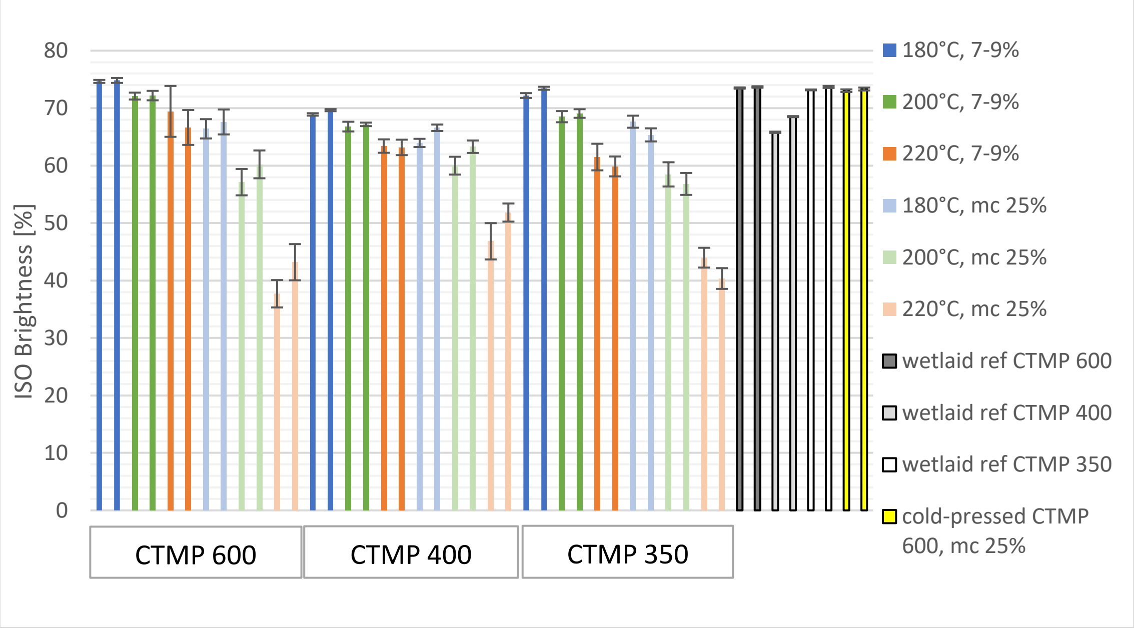

Figure 10. The effect of press temperature on sheet brightness.

Figure 11 presents sheet brightness pressed at 200 °C as a function of moisture. Based on both Figures 10 and 11, moisture content affects the sheet discoloration. Higher moisture content generally causes lower brightness when the sheets are pressed at the same temperature. Figure 10 shows that the higher the temperature, the greater the difference in brightness between dry (mc 7-9%) and moistened sheets (mc 25%). For example, in the case of CTMP 600, the difference is approximately 10% at 180 °C, 19% at 200 °C, and 41% at 220 °C. Similar observation can also be done for other pulps.

The difference between dry and moistened sheets may be due to varying heat transfer during hot pressing [39], which is caused by the different thermal conductivities of fibers and water. Water has a higher thermal conductivity (0.599-0.618 W/(m*K) at 20-30 °C) than lignocellulosic material (0.076 W/(m*K) at 25 °C) [80][81, p. 337], so a higher moisture content may lead to a higher heating rate of the sheet, which can cause more discoloration. On the other hand, lignin interdiffusion may also explain the differences in brightness results. The effect of lignin interdiffusion is the greatest at the highest press temperatures and moisture contents [51]. These mechanisms affecting sheet brightness could be better understood by measuring the instantaneous temperature in the sheet during hot pressing and testing lignin-free fibers as a sheet raw material.

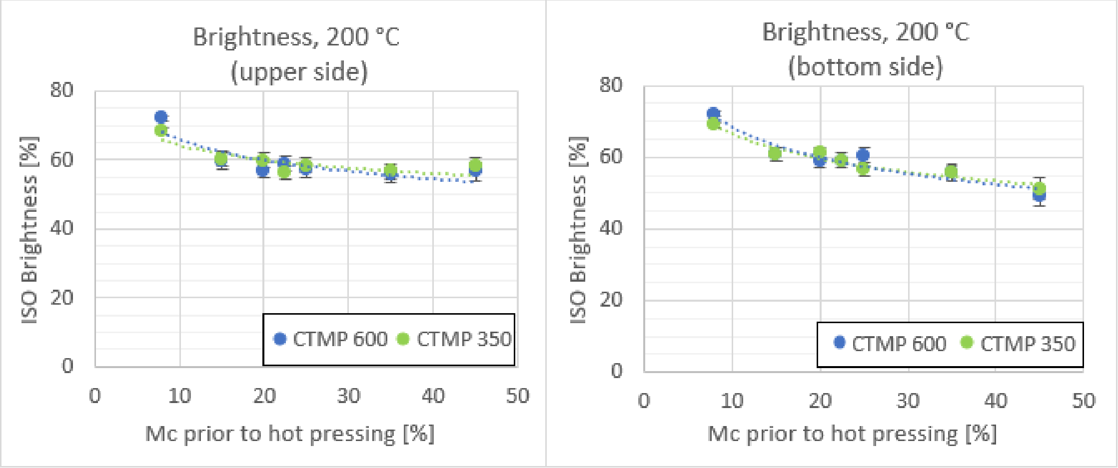

Figure 11. The effect of sheet moisture content on the brightness of the a) upper side and b) bottom side of the sheet when pressed at 200 °C.

In Figure 11, the brightness value decreases by approximately 8 to 12 percentage points when mc is increased from 7-9% to 15%, after which the 8-12 percentage point decrease occurs when mc changes from 15% to 45%. In other words, the brightness changes significantly between 7-9% to 15% moisture contents, while after that the change in moisture does not affect that much. This may be explained by how water is absorbed in the fiber web structure. 7-9% moisture is bound to hydroxylic and carboxylic groups of fibers [65, p. 271], and sprayed water may be on the surface of the fibers. The water on the fiber surfaces increases heat conduction, which results in lower brightness.

Additionally, the standard deviation of the brightness results, plotted as error bars, increases slightly as a function of press temperature in Figure 10. The brightness deviation may be caused by the uneven heating of the plates of the pressing machine. The sheets may have also been placed in a different position in the press and the point from which the brightness was measured could have been different. Additionally, uneven distribution of moisture in the case of moistened sheets could have caused uneven heating of the sheet and thereby uneven discoloration. However, the deviations are overall insignificant, only a few percent, so the sheets were quite uniform in color.

7.4 Optical formation

The airlaid and wetlaid sheets were imaged on top of a light table, and the images were analyzed using MATLAB software. Figure 12 represents examples of analyzed images, where black dots indicate fiber flocs.

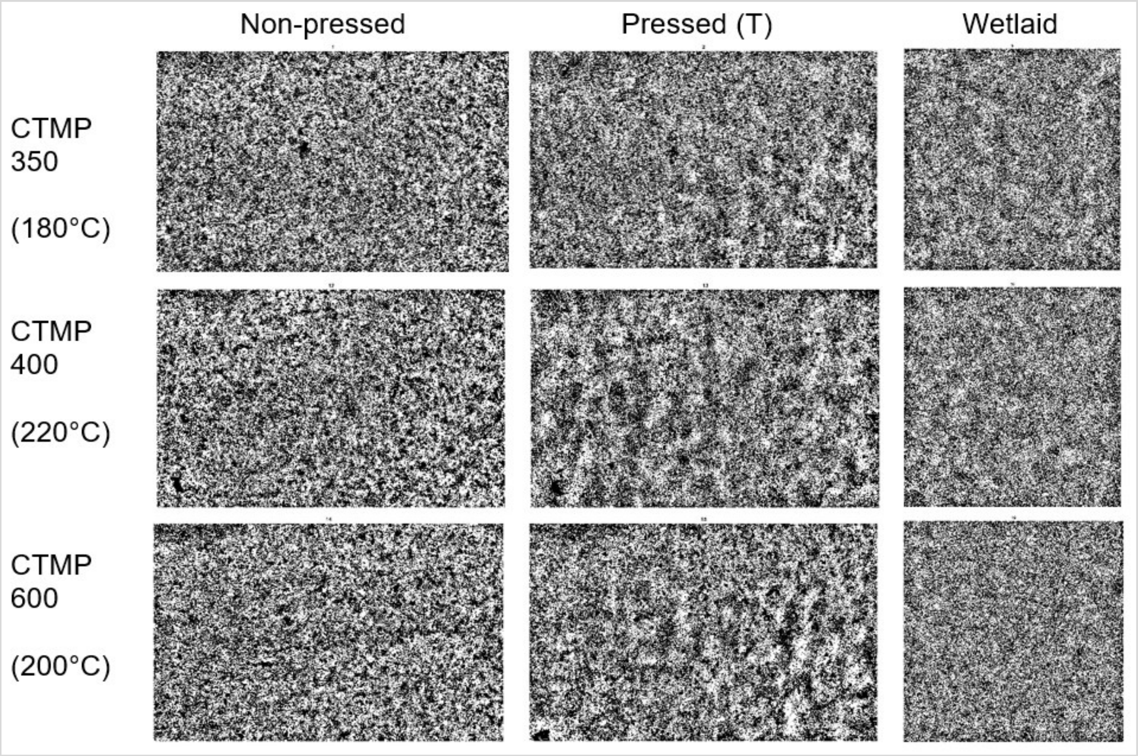

Figure 12. Images analyzed in MATLAB for floc size and grayscale deviation.

Figure 13 presents the floc sizes occurring in the airlaid and wetlaid sheets. For airlaids, the floc size is approximately the same as the mean length of fibers presented in Table 4. It can be observed that the floc size almost doubles in airlaids compared to wetlaids. The difference in floc sizes is caused by different fiber treatments; dry and wet disintegration. For airlaying, the fibers were only dry disintegrated, whereas, for wetlaying the fibers were both dry and wet disintegrated. The wet disintegration likely degraded existing flocs further. During this process, the fibers swell and soften due to the wet conditions, and when treated mechanically, they separate more from each other, reducing floc size.

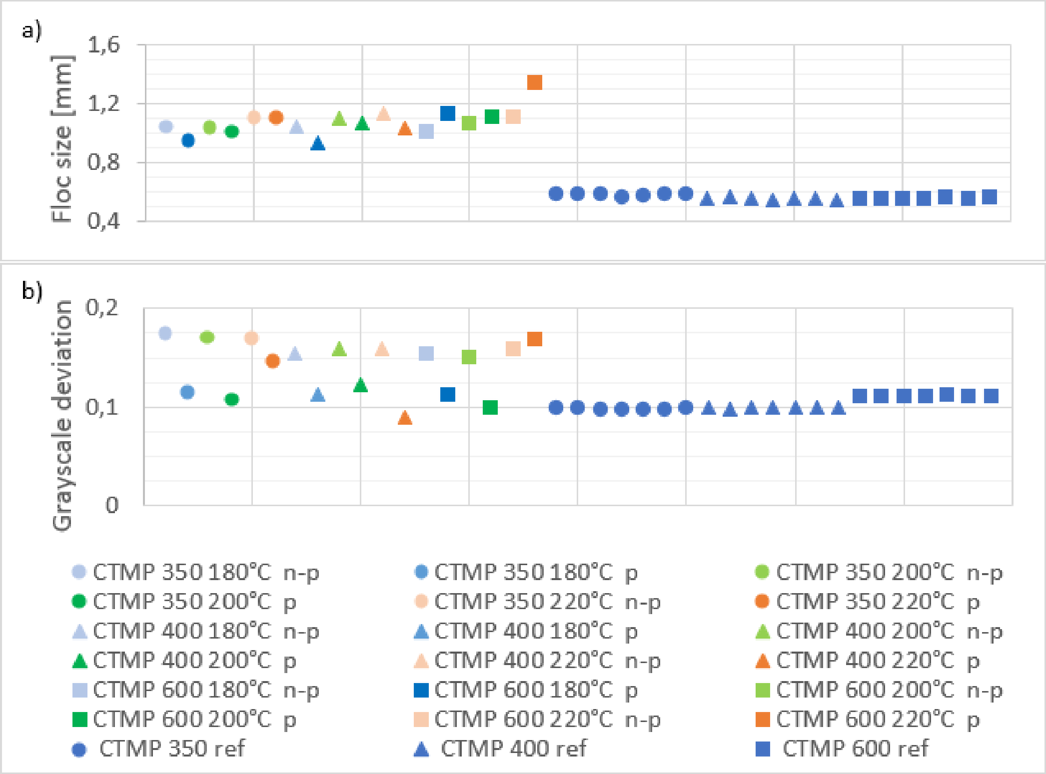

Figure 13. a) Floc sizes and b) grayscale deviation of non-pressed and pressed airlaid sheets and wetlaid sheets. (n-p = non-pressed, p = pressed)

In Figure 13, it seems that the floc size decreases slightly in the case of CTMP 350 and 400 when comparing non-pressed and pressed airlaids, but in CTMP 600 sheets, the floc size is larger in pressed sheets. This may be caused, for example, by the inaccuracy of the image analysis.

The optical formation of the sheets can be described by grayscale distribution, more specifically taking its standard deviation. The lower the standard deviation is, the better the formation of a sheet. Based on Figure 13, pressing of airlaid sheets produces lower deviation meaning that pressing improves the formation slightly. In other words, the hot pressing produces more uniform structures from the spongy, non-pressed airlaid sheets. Based on the results, the deviation for pressed airlaids and wetlaid reference sheets seems to be quite the same on average meaning that the formation would be the same in the sheets.

7.5 Tensile strength

The following tensile test results are significant in the context of this thesis. The purpose of tensile testing was to evaluate possible bonding and strength improvement in airlaid structures, which are crucial properties in paper products. The tensile strength results are presented as the tensile strength index to eliminate the variation caused by different sheet grammages.

7.5.1 Temperature series

Figure 14 shows the effect of press temperature, moisture content, and pulp freeness on the tensile strength of the airlaid sheets. The standard deviations of the results are plotted as error bars. The tensile indexes of wetlaid reference sheets are also added to the figure for comparison of the manufacturing methods.

In accordance with the theory, the results show that the wetlaid reference sheets have better tensile strength than airlaids due to better inter-fiber hydrogen bond formation. It can be stated that the addition of moisture content from 7-9% to 25% in airlaids is not sufficient to reach the strength of wetlaid sheets for any pulps, particularly for wetlaid CTMP 400 and 350. CTMP 350 has the highest tensile strength and density of the pulps used, both in wetlaid and airlaid sheet. This can be explained by the fact that CTMP 350 has the highest refining degree, which results in the highest fiber flexibility and conformability. The more flexible and adaptable the fibers are, the closer they get to each other and the larger the contact surface between them, thus improving inter-fiber bonding and producing a denser structure.

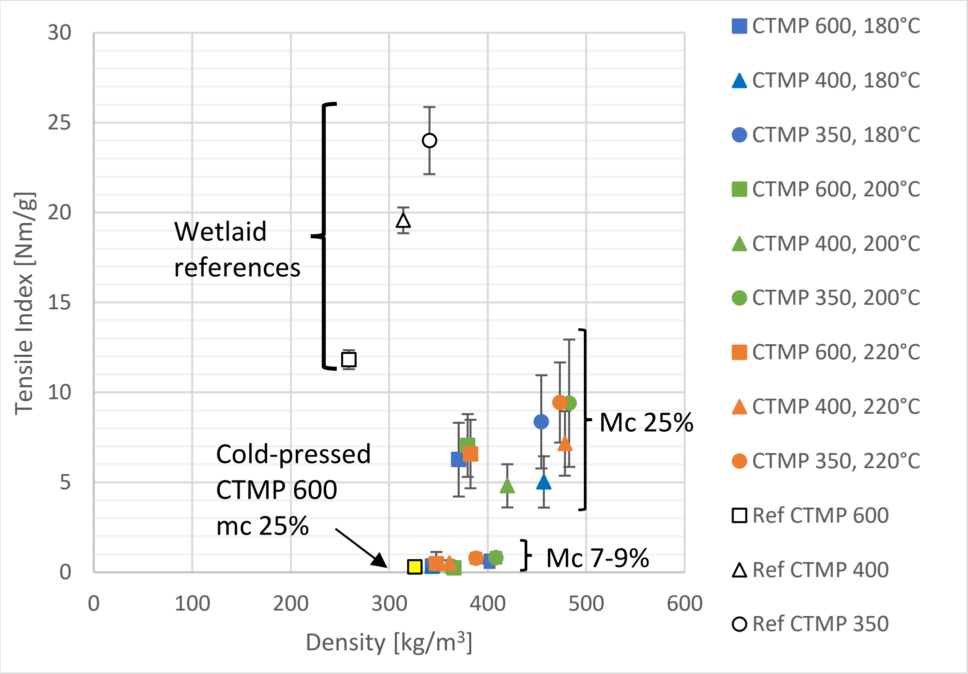

Figure 14. The effect of press temperature, sheet moisture content, and pulp freeness on tensile strength.

Cold pressing of CTMP 600 at 21 °C with a moisture content of 25% resulted in similar strength properties to hot-pressed sheets having a moisture content of 7-9%. In addition, a cold-pressed sheet with mc 7-9% tested in the additional series was so weak that the tensile strength could not be measured. Consequently, cold-pressing conditions were insufficient to produce strength for almost dry fibers, and increased moisture content only produced a barely measurable amount of strength. However, in the research of Kim et al. [46], the cold-pressing conditions (25 °C) resulted in 7.5 Nm/g and 8.5 Nm/g when airlaid sheets were pressed at 5.5 MPa and 11.0 MPa with 39% mc. These results are probably explained by the higher initial moisture content and chemical pulp (BHKP) as a raw material, which has better bonding ability and does not require softening of fibers that much compared to mechanical pulps.

Hot pressing of airlaid CTMP sheets with mc 7-9% produced a tensile index of approximately 0.5-1.0 Nm/g. When comparing the previous research, press-drying of airlaid UBSKP sheet with mc 8.0% at 0.41 MPa produced a tensile index of 0.5 Nm/g and mc 8.4% at 5.52 MPa produced 3.2 Nm/g [39]. Hence, the results obtained in the experiments were similar to those in the previous research, when pressed with lower pressure. However, higher pressure resulted in significantly higher strength than in the experiments of this thesis. The higher strength can be due to the different pulp or different pressure on the sheet. Chemical pulp fibers are more flexible and have better bonding ability than mechanical pulp fibers. The pressure used in the trials was only 0.835 MPa, which corresponds to the lower pressure used in the research of Byrd [39]. Thus, it is not possible to say whether the difference is due to a specific parameter or to the combined effect of the raw material and the pressing conditions.

Hot pressing of airlaid sheets with a mc of 25% produces significantly improved strength results compared to airlaids with a mc of 7-9%. From the perspective of pressing parameters and strength improvement, increasing the mc from 7-9% to 25% and switching from cold pressing to hot pressing have a similar effect on tensile strength. In other words, both moisture and elevated temperatures are needed to achieve the desired conditions for fiber bonding, including fiber softening and the formation of strong capillary forces that facilitate bond formation. In Figure 14, a mc of 25% resulted in a tensile index of approximately 5-9 Nm/g. In the research of Byrd [39], a mc of 22.3% at 0.41 MPa produced a tensile index of 5.75 Nm/g, and a mc of 26.9% at 5.52 MPa produced 15 Nm/g, so the obtained results are again similar to the results of Byrd [39], but lower than those obtained at the pressure of 5.52 MPa.

However, when comparing moisture content and press temperatures, moisture content has a greater effect on tensile strength than press temperatures under hot pressing conditions. An increase in moisture content from 7-9% to 25% multiplies the tensile indexes of all pulps, whereas increasing temperature from 180 °C to 220 °C has barely any effect. Based on Figure 14, press temperature does not improve the strength of dry sheets and causes only approximately 10% variation in moistened CTMP 600 and 350 sheets. On the other hand, a press temperature of 220 °C produced 29% higher tensile strength for CTMP 400 compared to pressing at 180 °C and 200 °C. The tensile indexes of airlaid CTMP 400 are still lower than expected. This contradicts the assumption that the wetlaid sheet strength would fall between CTMP 600 and 350, similar to the pulp fiber properties. Thus, it can be concluded that an error may have occurred during the experimental work with airlaid CTMP 400.

According to the theory, a higher temperature should soften the fibers and thus improve their flexibility. However, this phenomenon is not observed in the results of hot-pressed CTMP 350 and 600 sheets. The reason may be that the temperature range used is relatively small, and the effect of temperature may disappear by variations in the strength caused by poor formation and fiber flocs in the web structure.

Additionally, the temperatures fall within the T_g range of fiber components. Since the temperatures are not clearly above the glass transition temperatures, the fibers may still have the potential to soften further. For example, in the research of Mattson et al. [38], a clear difference in strength was observed when temperatures of 180 °C and 260 °C were used within a press time scale from 10 to 60 seconds. Furthermore, an additional test conducted in the experiments for CTMP 600 with a moisture content of 25% and a pressing temperature of 250 °C resulted in a tensile index of 9.2 ± 1.9 Nm/g, which is approximately 29% higher than for the sheet pressed at 220 °C. Hence, higher temperatures may have the potential to produce even greater strengths for airlaid sheets.

7.5.2 Moisture series

In the moisture series, airlaid sheets were moistened to different moisture contents and pressed at 200 °C using the same press time and pressure as in the temperature series. In this series, only CTMP 600 and 350 were studied. The results in Figure 15 show how sheet moisture content affects tensile strength and sheet density.

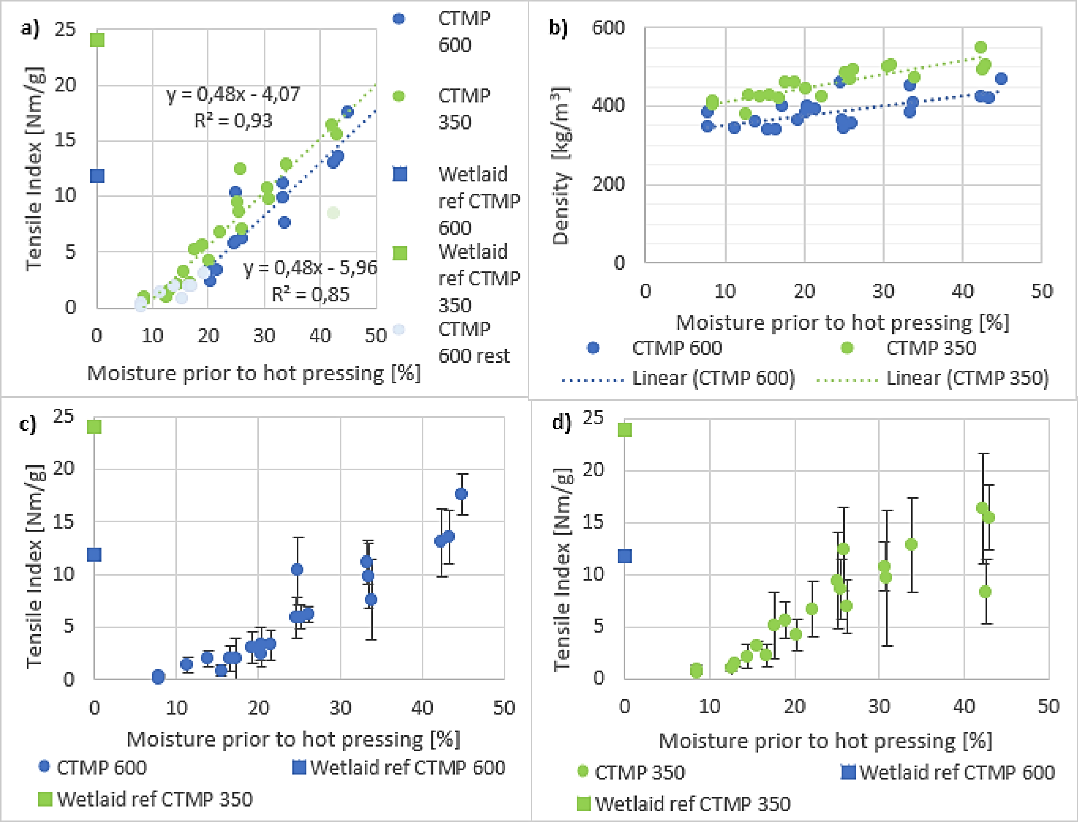

Figure 15. The effect of moisture content on a) tensile strength, b) density, c) strength deviation of CTMP 600, and d) strength deviation of CTMP 350 when sheets were pressed at 200 °C.

The strength of CTMP 350 is higher in Figure 15a compared to CTMP 600, which can be due to better flexibility and conformability of CTMP 350 fibers resulting in higher density. The density of CTMP 350 increases with a slightly higher slope compared to CTMP 600, which can be caused by different structural properties or potential measurement errors caused by fiber flocs in the web structure. Additionally, the higher fibrillation degree of CTMP 350 (Table 4) may also enhance the mechanical interlocking of fibers and result in stronger inter-fiber bonds and higher strength.

The results show that the tensile strength of both pulps increases linearly and with the same slope as a function of moisture content. However, the point at which this linear behavior begins differs between the two pulps. The tensile strength of CTMP 350 increases continuously as moisture content increases, whereas for CTMP 600, the increase with the same slope does not occur until the moisture content reaches 20%. This may be because CTMP 600 fibers are stiffer, less conformable, and less swellable compared to CTMP 350 fibers, meaning that CTMP 600 requires more moisture to make the fibers more flexible and increase their bonding.

The linear behavior observed continues at least up to approximately 45%, which aligns with the theory that a 20-53% moisture content is significant for strength improvement. However, the point at which this linear behavior ends, and moisture no longer significantly affects strength varies. In some research, significant strength improvements ended at moisture contents between 20% to 30%, while in other studies, it was 53%. [37], [39], [46]. One reason for the linear increase in strength may be that the hot pressing conditions also caused a linear increase in density as a function of moisture content (Figure 15b). In other words, higher moisture content softens fibers more and enables more inter-fiber bonding, resulting in a denser web structure and higher strength.

Regarding the fiber type, high fines content or the presence of lignin in the used pulps may also explain the linear strength improvement. It has been shown that lignin interdiffusion has especially effect on the wet tensile index, but it may also affect the dry tensile index. However, the mechanisms behind the dry tensile index are complicated, so the effect of interdiffusion is uncertain. [51] Future research could examine if lignin interdiffusion occurs during the hot-pressing of fragile airlaid sheets, which do not have strong bonds in advance, unlike wetlaid sheets. Additionally, the continuity of the linear behavior as a function of moisture could be further investigated to get more information about how moisture produces strength. Overall, several different factors, such as fiber properties and used fiber type (CTMP), the airlaying process, hot pressing conditions, and how water is bound in the structure could influence the linear strength improvement and the moisture range where it occurs.

Additionally, the deviation of tensile index results increases as the moisture content of the sheets increases (Figures 14, 15a, and 15b). This is likely due to uneven moisture distribution in the sheet, which can cause uneven bonding in the sheet structure. The uneven formation of the sheets can also explain the deviation of the results. When the formation is poor, the tensile test strips taken from one airlaid sheet have varying quality, and the strips break at the thinnest point resulting in varying strengths. The deviation of the results seems to be bigger in the case of CTMP 350 than CTMP 600.

Table 5 presents the maximum tensile index obtained in the experiments and the results from the previous research for hot-pressed airlaids, indicating approximately the same initial moisture content. The maximum strength obtained in this thesis falls within the range of previous research and is even better compared to sheets pressed below 100 °C, so from this point of view, the results are successful. Additionally, the maximum strength obtained with chemical pulp was almost reached with the mechanical pulp used in these experiments. As previously mentioned, mechanical pulp typically has lower strength than chemical pulp due to reduced flexibility and high lignin content hindering bond formation

[82, p. 899]. However, with these test arrangements, clearly higher strengths compared to previous studies were not achieved. Therefore, further research is necessary to determine if even higher strengths can be achieved using the hot-pressing method.

Table 5. Maximum strength obtained and corresponding values from the literature.

Source	**mc [%]**	**T [°C]**	**P [MPa]**	**TI [Nm/g]**	**Pulp**
Figure 15	43	200	0.835	16	CTMP 350
Figure 15	43	200	0.835	14	CTMP 600
Byrd [39]	43	150	0.41	9	UBSKP
Byrd [39]	43	150	5.52	17	UBSKP
Kim et al. [46]	39	25	5.50	7.5	BHKP
Kim et al. [46]	39	25	11.0	8.5	BHKP
Kim et al. [37]	50	90	5.50	11.3	BHKP

Overall, a moisture content of 37% was approximately sufficient to achieve the same strength as in wetlaid reference sheets in the case of CTMP 600. However, for CTMP 350 even a moisture content of 43% in the airlaid is insufficient to achieve the strength of the reference sheet made from the same pulp. When aiming for a specific strength, the energy efficiency of the pulps used comes into question. The CTMP 350 achieves the specific strength with a lower initial moisture content than CTMP 600, in which case the drying energy for CTMP 350 is also lower. On the other hand, CTMP 350 has a higher refining degree, which means that more energy has been used to refine it. Therefore, it's important to consider whether it is more energy-efficient to use less water in the airlaid structure or less refined pulp. The indicative energy consumption calculations are added to Appendix E.

To reach the tensile index of 12 Nm/g, the airlaid CTMP 350 could save only drying energy by 34% and the CTMP 600 by 26%, if it is assumed that paper moisture content is 50% prior to entering the drying section of paper machine, and if it is assumed that the water is bound in the same way in the airlaid and wetlaid structures. When considering both drying and refining energies, airlaid CTMP 350 would consume 4% less energy than CTMP 600. However, the calculations included many assumptions, so these energy consumptions are only rough estimates. Thus, more accurate energy consumption determinations and calculations should be done when comparing the energy efficiency of the pulps and web formation technologies.

8. CONCLUSIONS AND FUTURE PROSPECTS

In this thesis, hot pressing has been shown to be a promising method for improving the strength of dry formed fiber webs. However, hot pressing alone is not sufficient for achieving significant strength improvement for the airlaids; it becomes successful when combined with additional moisture in the airlaid structure. In the experiments, the temperature range used did not affect significantly tensile strength results, but elevated press temperatures were shown to be necessary for the strength improvement. The moisture content and elevated temperatures significantly influenced the tensile strength, with higher moisture levels resulting in greater strength. The effect of pressing pressure was not notable in additional tests of the experimental part, although higher pressures induced better strength results in the literature. Additionally, the press time also affects fiber web strength, but it was not investigated in the experiments of this thesis. Based on the literature, the press time must be precisely managed: it should be long enough to ensure adequate fiber softening and web drying, but not so long that it causes thermal degradation.

The effect of pulp freeness was also studied. The lower freeness produced higher sheet densities and thus higher tensile strength but with less water in the airlaid structure. Pulp freeness also influenced the tensile strength-moisture behavior. For the lower freeness pulp, the behavior was continuously linear when moisture content increased, whereas for the higher freeness pulp, the linear increase with the same slope began only after a certain moisture content.

Despite the improving effects of hot-pressing temperature, moisture content, and lower pulp freeness, the strength of hot-pressed airlaid sheets was generally lower compared to wetlaid reference sheets. This was observed especially with low moisture contents and pulp freeness. However, for pulp with the highest freeness, a moisture content of approximately 37% in the airlaid sheet produced strength comparable to that of the wetlaid reference sheet. This could save drying energy by 26% compared to drying in paper machine. To achieve the same strength, it was assessed that the energy consumption could be 4% less for the airlaid CTMP 350 compared to CTMP 600 when both drying and refining energies were considered.

When it comes to brightness results, higher press temperature caused lower brightness, but the lowest hot-pressing temperature did not affect sheet brightness. Higher moisture content prior to pressing resulted in lower brightness, with the difference between the brightness of dry and moistened sheets increasing at higher temperatures. However, moisture content did not affect brightness results linearly.

The results obtained were as good and partly even better than the strength results for airlaids in previous studies, although in this work CTMP was used as a raw material, which generally has lower strength than chemical pulp. So, the results indicate that the hot-pressing method can be applied also to airlaid sheets made of mechanical pulp. Overall, the results are successful, and provide new information to the field about how airlaid structure can be compacted and how it behaves under hot-pressing conditions. Although hot-pressing conditions as a method for structure compacting and bond formation should be further developed to achieve even better strength results, the findings highlight the potential of airlaying technology as an alternative to conventional papermaking. These results also serve as a good basis for further research on airlaying technology.

The hot-pressing effect on airlaids could be further investigated using other fiber types to get more information, for example, about the effect of lignin in the airlaid structure. In addition to tensile strength, also other paperboard properties could be measured, such as bursting strength and bending stiffness. Wet tensile strength could also be measured to determine if lignin interdiffusion occurs in the airlaid structure. The effect of moisture on sheet brightness could be studied using thermocouples to get precise information about time-temperature variation in the sheet during hot pressing.

From the perspective of energy consumption, further study on water bonding in airlaid structures could provide information on how water is bonded within the structure and how it affects drying energy. For example, measuring the drying energy of a wetlaid, never-dried sheet with a moisture content of 40% and an airlaid sheet with an additional moisture content of 40% would give information about the energy efficiency of airlaying technology. Additionally, the linear behavior of airlaid web strength as a function of moisture content could be further investigated to determine how long the strength continues to increase when moisture is increased. Different moisture adjustment methods could also be further studied to achieve more uniform water distribution within the structure.

Moreover, hot pressing conditions could be further developed by testing different press temperatures, pressures, and times to achieve maximum strength and/or lowest energy consumption. For example, testing lower press temperatures (<180 °C) would provide information on the minimum temperature required for significant strength improvement, while higher temperatures could further enhance strength results. Furthermore, using a nip press as a pressing machine could be tested. The nip press would produce more impulse-like pressing, and it is more applicable for larger, higher-speed production.

Consequently, this thesis provided new information about the consolidation of dry formed web structures through hot pressing treatment without additives. It was shown that hot pressing is a promising option for saving energy and fresh water compared to conventional papermaking. However, further research and development are needed to optimize hot pressing for wider use.

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APPENDIX A: TRIALPOINTS

Table 6. *Trial points of temperature series.*

Series	**TP**	**Pulp**	**Moisture content [%]**	**Press temperature [°C]**	**Press time [min]**	**Pressure [bar]**
Temperature series	1	CTMP 600	7-9	180	1	0.835
	2	CTMP 600	7-9	200	1	0.835
	3	CTMP 600	7-9	220	1	0.835
	4	CTMP 600	25	180	1	0.835
	5	CTMP 600	25	200	1	0.835
	6	CTMP 600	25	220	1	0.835
	7	CTMP 400	7-9	180	1	0.835
	8	CTMP 400	7-9	200	1	0.835
	9	CTMP 400	7-9	220	1	0.835
	10	CTMP 400	25	180	1	0.835
	11	CTMP 400	25	200	1	0.835
	12	CTMP 400	25	220	1	0.835
	13	CTMP 350	7-9	180	1	0.835
	14	CTMP 350	7-9	200	1	0.835
	15	CTMP 350	7-9	220	1	0.835
	16	CTMP 350	25	180	1	0.835
	17	CTMP 350	25	200	1	0.835
	18	CTMP 350	25	220	1	0.835

Table 7. *Trial points of moisture series and additional tests.*

Series	**TP**	**Pulp**	**Moisture content [%]**	**Press temperature [°C]**	**Press time [min]**	**Pressure [bar]**
Moisture series	19	CTMP 600	15	200	1	0.835
	20	CTMP 600	20	200	1	0.835
	21	CTMP 600	2.5	200	1	0.835
	22	CTMP 600	35	200	1	0.835
	23	CTMP 600	45	200	1	0.835
	24	CTMP 350	15	200	1	0.835
	25	CTMP 350	20	200	1	0.835
	26	CTMP 350	22.5	200	1	0.835
	27	CTMP 350	35	200	1	0.835
	28	CTMP 350	45	200	1	0.835
Additional tests	29	CTMP 600	7-9	21*	1	0.835
	30	CTMP 600	25	21*	1	0.835
	31	CTMP 600	7-9	220/220	1	0.835
	32	CTMP 600	7-9	220/220	1**	0.835
	33	CTMP 600	25	220/220	1	0.835
	34	CTMP 600	7-9	240/240	1	0.835
	35	CTMP 600	25	240/240	1	0.835
	36	CTMP 600	7-9	250	1	0.835
	37	CTMP 600	25	250	1	0.835
	38	CTMP 600	7-9	220	1	3.34
	39	CTMP 600	25	220	1	3.34

*Cold-pressing conditions.

**Sheet was not turned over during hot-pressing.

APPENDIX B: EXTRA FIGURES FROM EXPERIMENTAL WORK

Figure 16. a) L&W wet disintegrator and b) L&W Fiber Tester device.

Figure 17. a) PTI GMBH’s CSF device and b) Minolta spectrophotometer.

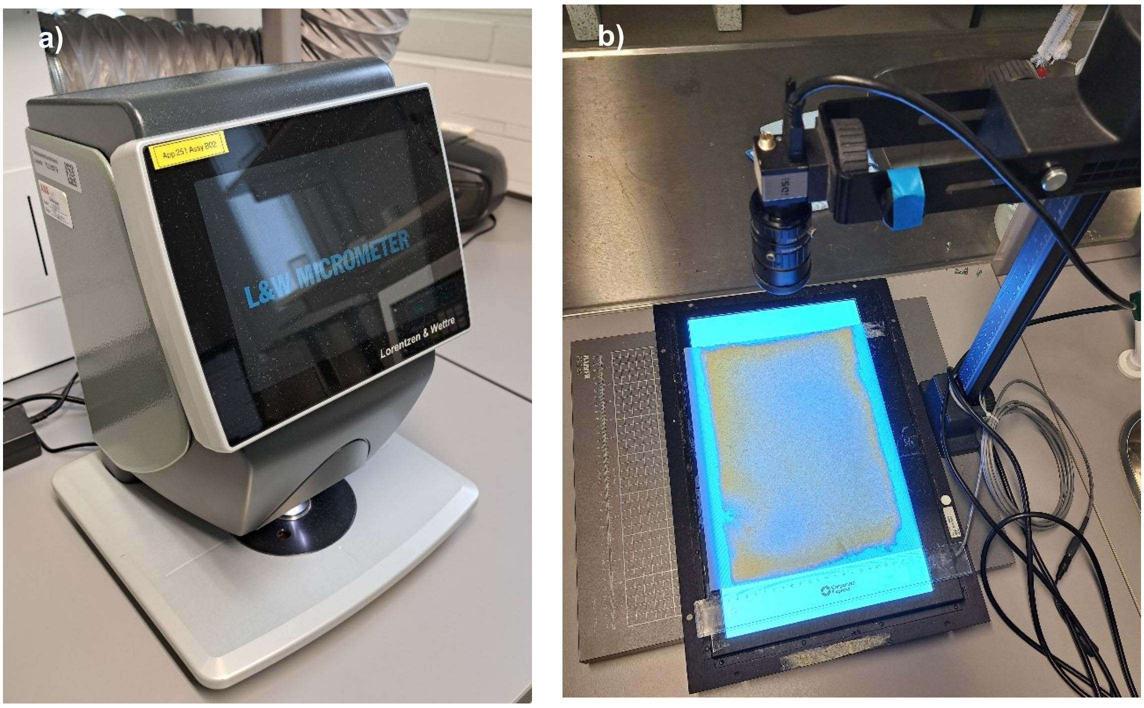

Figure 18. a) The L&W micrometer for tissue thickness determination. b) The camera setup for optical formation images.

APPENDIX C: EQUATIONS FOR FIBERTESTER RESULTS

The weight factor means the ratio of fibers in each length category.

$$Mean\ length = \frac{\sum_i^n (Weight\ factor\_i * fiber\ length\_i)}{\sum_i^n Weight\ factor\ \_i} \quad (1)$$

$$Mean\ width = \frac{\sum_i^n (Weight\ factor\_i * fiber\ width\_i)}{\sum_i^n Weight\ factor\ \_i} \quad (2)$$

$$Mean\ fibril\ area = \frac{\sum_i^n (Weight\ factor\_i * \frac{fibril\ area_i}{fibril\ area_i + fiber\ area_i})}{\sum_i^n Weight\ factor\ \_i} \quad (3)$$

$$Mean\ fibril\ perimeter = \frac{\sum_i^n (Weight\ factor\_i * \frac{fibril\ perimeter_i}{fibril\ perimeter_i + fiber\ perimeter_i})}{\sum_i^n Weight\ factor\ \_i} \quad (4)$$

$$Mean\ fines\ [\%] = \mathrm{Fines\ P} + \mathrm{Fines\ S} \quad (5)$$

$$Fines\ P\ [\%]\ (coarse\ fines) = \frac{Fines\ P\ total\ length}{Fines\ P\ total\ length + Fiber\ total\ length} * 100 \quad (6)$$

$$Fines\ S\ [\%]\ (finer\ fines) = \frac{Fines\ S\ total\ length}{Fines\ S\ total\ length + Fiber\ total\ length} * 100 \quad (7)$$

APPENDIX D: TENSILE TEST DATA AND RESULTS OF ADDITIONAL TESTS

Table 8. *Tensile test data.*

TP	Grammage [g/m^2]	Thickness [µm]	Density [kg/m^3]	Bulk [cm^3/g]	Strain at Break %	Modulus of Elasticity (N/mm²)	Tensile Stiffness index (MNm/kg)
1	156	441	354	2.83	0.352	600	0.678
2	150	412	365	2.74	0.415	525	0.767
3	153	441	348	2.9	0.3	567	0.513
4	144	388	371	2.70	0.523	641	1.73
5	156	410	380	2.67	0.565	655	1.74
6	147	386	377	2.65	0.562	633	1.66
7	159	466	343	2.93	0.391	539	0.160
8	152	419	364	2.75	0.417	256	0.101
9	160	442	361	2.77	0.406	351	0.776
10	156	341	457	2.19	0.465	726	1.58
11	154	369	420	2.39	0.467	615	1.46
12	149	313	478	2.10	0.662	787	1.64
13	157	391	402	2.49	0.441	369	0.914
14	157	384	408	2.45	0.314	387	0.989
15	156	403	466	2.58	0.374	354	0.540
16	154	340	455	2.21	0.619	896	1.97
17	156	324	483	2.07	0.684	969	2.01
18	155	327	473	2.11	0.748	892	1.88

TP	Grammage [g/m^2]	Thickness [μm]	Density [kg/m^3]	Bulk [cm^3/g]	Strain at Break %	Modulus of Elasticity (N/mm²)	Tensile Stiffness index (MNm/kg)
19	151	436	347	2.88	0.401	360	1.06
20	146	397	368	2.73	0.462	400	1.08
21	151	386	392	2.55	0.322	570	1.45
22	142	343	416	2.42	0.565	981	2.37
23	145	330	439	2.28	0.822	1160	2.63
24	154	377	410	2.45	0.406	349	0.852
25	154	353	436	2.30	0.545	533	1.22
26	149	336	444	2.26	0.508	699	1.58
27	147	297	493	2.03	0.635	1200	2.45
28	154	298	517	1.94	0.744	1370	2.64

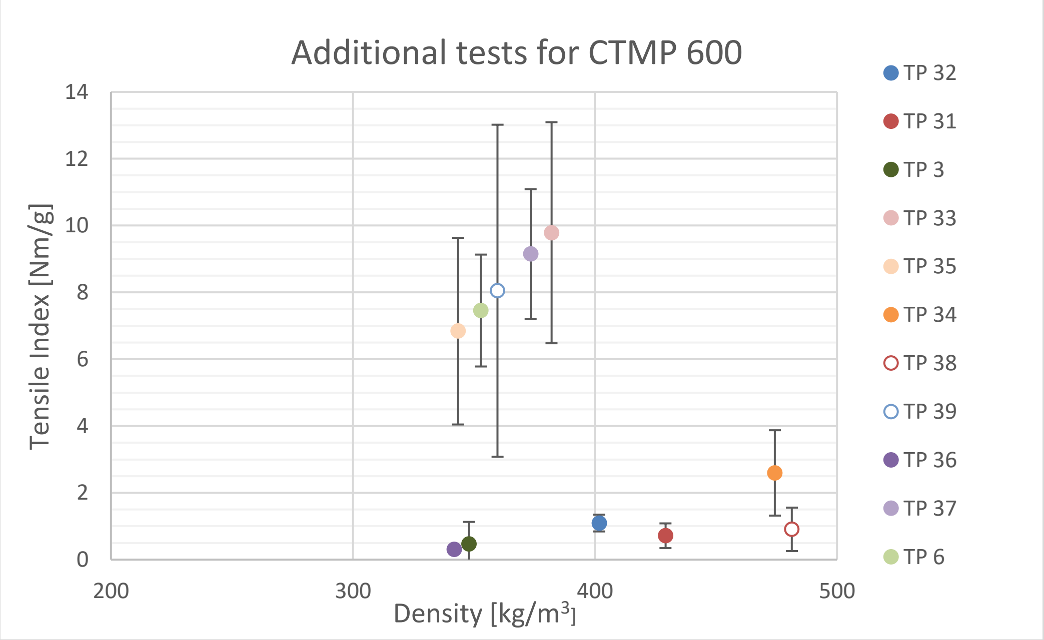

Figure 19. Tensile strength results from additional tests conducted on CTMP 600.

APPENDIX E: INDICATIVE ENERGY CONSUMPTION CALCULATIONS

Assumptions for calculations:

- Moisture content of paper is approximately 50% when entering the drying section.
- Drying energy is about 40-60% of paper machine's total energy consumption.
- Drying of airlaid sheet consumes the same amount of energy as wetlaid sheet if the moisture contents are same.
- Refining energy for spruce CTMP is approximately the same as for spruce HT-CTMP.

Table 9. *Energy consumption calculations for airlaids.*

Explanation	**Energy**	**Source**
Total energy use of paper machine for packaging paper (steam and heat)	2.361 MWh/t (or 8.5 GJ/t)	[83]
Drying energy is 40-60% of the total energy consumption of paper machine.	If 40%, drying energy is: $0.4 * 2.361 \frac{MWh}{t} \approx 0.944 \frac{MWh}{t}$ If 60%, drying energy is: $0.6 * 2.361 \frac{MWh}{t} \approx 1.417 \frac{MWh}{t}$	
Moisture content of paper is 50% when entering drying section. To reach 12 Nm/g, the mc is 33% for CTMP 350 and 37% for CTMP 600.	Drying energy for CTMP 350 is: $\frac{33\%}{50\%} * 0.9444 \ldots \frac{MWh}{t} \approx 0.623 \frac{MWh}{t}$ (minimum) $\frac{33\%}{50\%} * 1.4166 \ldots \frac{MWh}{t} \approx 0.935 \frac{MWh}{t}$ (maximum) Drying energy for CTMP 600 is: $\frac{37\%}{50\%} * 0.9444 \ldots \frac{MWh}{t} \approx 0.699 \frac{MWh}{t}$ (minimum) $\frac{37\%}{50\%} * 1.4166 \ldots \frac{MWh}{t} \approx 1.048 \frac{MWh}{t}$ (maximum)	

Explanation	**Energy**	**Source**
Drying energy saved in airlaying compared to wetlaying.	CTMP 350: $100\% - \frac{33\%}{50\%} = 34\%$ CTMP 600: $100\% - \frac{37\%}{50\%} = 26\%$	
Specific energy consumption for certain freeness. (Low consistency refining)	Spruce HT-CTMP: CSF 350: $0.250\ \frac{MWh}{t}$ CSF 600: $0.200\ \frac{MWh}{t}$	[84]
Energy consumption of refining and drying	CTMP 350: $\left(\frac{0.623 + 0.935}{2} + 0.250\right)\frac{MWh}{t} = 1.029\ \frac{MWh}{t}$ CTMP 600: $\left(\frac{0.699 + 1.048}{2} + 0.200\right)\frac{MWh}{t} = 1.074\ \frac{MWh}{t}$	
Energy consumption of CTMP 350 compared to CTMP 600.	$\frac{1.029 - 1.074}{1.074} * 100 = -4.139 \ldots \% \approx \mathbf{-4}\%$	