

Tailored low consistency refining for targeted fiber properties

Master of Science Thesis

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Preface

This Master of Science thesis has been written as a part of the Master's Degree Programme in Chemical Engineering at Abo Akademi, Finland. The experimental part has been done in the Fiber Technology research group (part of Laboratory of Natural Materials Technology), Gadolinia, under the supervision of Jan Gustafsson.

The idea of the Thesis topic has been generated by Jan Gustafsson. My heartiest thanks go to Jan Gustafsson for being such a fantastic mentor and providing me with such flexibility during my lab work. His guidance has made the entire completion process much more comfortable and transparent.

I would also like to thank Tom Lundin for his amazing doctoral thesis on Low consistency refining. This has been a pathfinder for my thesis writing, and his knowledge as expressed in the thesis is both clear and vast, which has helped to gain a clear understanding of the topic.

At last, I would like to show my respect to my workplace supervisor Andreea Bejinariu for her continuous support and encouragement. She has been a blessing for me by providing me with all the possible flexibility that has enabled the completion of this thesis .

Abstract

The main aim of the study has been to analyze the impact of refining on the physical and optical properties of paper sheets with respect to change in three refining parameters. The three parameters that have been changed are the volumetric flow rate of the feed during refining, fiber concentration in the feed, and pumping direction in the refiner. In this study, three volumetric flow rates have been maintained. These are 60 l/min, 100 l/min, and 120 l/min. Two pulp consistency have been maintained, which are 2% and 4%. Bleached pine (softwood) kraft pulp was used as raw material and refining was done through pumping and non-pumping directions for all samples.

After collecting the samples at 50 kWh/t, 150 kWh/t, 200 kWh/t, and 250 kWh/t SEC_{Cum} , paper sheets were made, and properties were measured. Sheet thickness, drainability, air permeability, brightness, tensile strength, tear strength, water retention value, amount of fines, fiber lengths were measured and analyzed.

After analyzing, it has been understood that refining intensity had a significant impact on paper properties, but no significant changes have been observed in the features due to the change in the refining parameters. Interestingly, properties such as drainability, fines percentage, air permeability, and brightness for refining samples that were controlled by stator and rotor gap instead of power control showed changes in values . Further studies can be proposed to understand the impact of gap-controlled refining on paper sheet properties.

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Abbreviations

LC- Low consistency

SEC- Specific energy consumption

SR- Schopper Riegler

HW- Hardwood

SW- Softwood

CTMP- Chemi thermo mechanical pulp

SEL- Specific energy load

NBSK- Non bleached softwood kraft

SEC_{Cum} – Specific energy consumption commulative

WRV- Water retention value

1. Introduction

Fiber-related products are being used worldwide for various purposes, and the demand has been decreasing day by day with the advancement of other materials for uses, so the scientific challenges to improve the properties of fibers are increasing. Much research is being carried out currently to develop a new quality of fiber products by changing the features throughout the pulping and papermaking process as well as the refining process. The production of the final paper-based product starts from the raw material as wood chips. The whole process from wood chips to the final product goes through many processes, which include mechanical and chemical treatment. Refining is a mechanical treatment process for pulp that is done to achieve the desired paper quality. By changing refining parameters such as temperature, consistency, pulp type, raw material source, chemical treatment, refining intensity, refiner stator, and rotor gap, pumping speed, type and structure of refiner fillings can be altered. This change in fiber structure changes the properties of final products. Colossal energy consumption is required for the total pulping process, which is costly. One of the many scientific challenges has also been to find out the balance between achieving the desired quality of paper product and cost involved due to energy consumption.

The study aim was to optimize the fiber properties of wood fibers towards a targeted application by using a treatment procedure known as low consistency refining. In this study, the main focus has been analyzing the changes happening to the properties of fibers due to the refining done by a conical segment refiner ProLab at Abo Akademi University. During the refining, parameters such as pump speed, the rotational direction of the rotor, and pulp consistency have been changed to analyze the changes in fiber structures, their physical properties, and optical properties.

Some of the changes in pulp due to refining are still not fully understood, as so many complicated situations are responsible for a change in any properties of pulp.

1.1. Objective

The objectives of this thesis are to observe the refining actions carefully from mild to harsh taking account of the fiber-fiber and fiber-bar interactions to evaluate out the influence of volumetric flow or pumping speed variation at varying pulp consistencies for softwood pulps and to assess the changes in fibers due to the changes in refining parameters for enhanced understanding of the impact of low consistency refining.

1.2. Thesis outline

This thesis analyzes tailored low consistency refining of softwood pulp (pine bleached softwood kraft pulp) at varying pumping speed of 60 l/min, 100 l/min, and 120 l/min at both pumping and non-pumping rotor direction and pulp consistency of 2% and 4% has been performed. During the lab work Schopper Riegler (°SR) Freeness, water retention, opacity, air permeability, tensile strength, tear strength testing, fiber length and fines percentages have been analyzed for all samples to discover the changes in fiber properties.

2. Theory

The theory part consists of the basic understanding of pulps and refining factors and refining impact on fibers due to the refining. Low consistency refining of the pulp is a complex process as many parameters are involved, which have effects on the refining intensity and pattern.

2.1. Fibers

Wood fibers are different in dimensions and structure, depending on the type of tree or plant. The cells living in the tree can be different depending on the main functions and according to their role in the stem. The cells are tube-like structures, and the wall thickness depends on the purpose, and the common goal is to provide strength and storage of liquid and nutrition. Pits connect the cells. Softwood mainly consists of cells called tracheids, which provide support and conduction and parenchyma cells that work as storage. Softwoods comprise 90% tracheids and 5-10 % parenchyma cells. Hardwood consists of cells called tracheids and thick-walled fibers that provide mechanical support and parenchyma that provides storage and vessels works as conducting cells. Fibers are the cells that are dead and empty when functional. Parenchymas are brick-like cells; tracheids are fibers that provide earlywood conduction and latewood support, whereas vessels are vertical tubes [1]. Hardwood has more complex structures compared to softwood (Figure 1). Hardwood has vessels or pores of different sizes, shapes and cell wall structure. Softwood has a simpler cellular structure. Softwood only consists of tracheids and parenchyma cells whereas hardwood consists of fibers, cell, parenchyma and vessels.

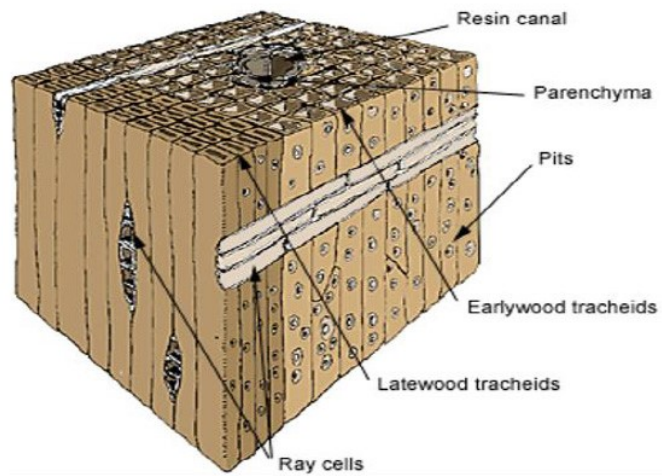


Figure 1: Cross-sectional view of Softwood cell structure [2]

2.2. Fiber structure

A fiber cell wall is made up of four layers. They are the intermediate lamella, primary wall, secondary wall, and the tubercular core. The secondary wall has three layers called an outer layer, middle layer, and inner layer. [3] The main chemical composition of the cell walls consists of cellulose, hemicellulose, and lignin. (Figure 2). The percentage of their presence differs from softwood to hardwood, so does the fiber characteristics and properties. (Table 1). Cellulose can mostly be found in a secondary wall in the form of the crystalline or amorphous phase. Cellulose and hemicellulose contribute to the strength properties of a paper made of the pulp as they connect to each other through strong hydrogen bonds. [4]

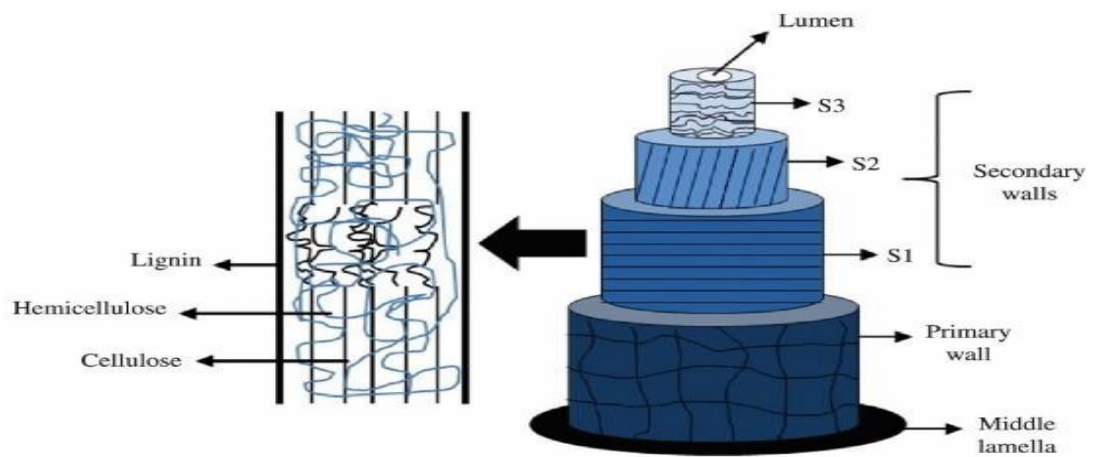


Figure 2: Fiber cell structure

Table 1: Chemical Composition of Hardwood and Softwood[5]

Composition	Hardwood	Softwood
Cellulose	40-44 %	40-44 %
Hemicellulose	15-35 %	30-32%
Lignin	18-25 %	25-32%
Extractives	2 %	5 %

The composition of pulp also changes with the pulping process. From Table 2, it is observed that unbleached kraft pulp has a higher lignin percentage than Bleached SW and HW Kraft pulp. Bleached SW kraft and HW kraft pulp have almost the same chemical composition, whereas for unbleached kraft pulp, a decrease in cellulose content has been observed. A significant deviation has been observed for CTMP. The cellulose percentage has been reduced to 60% compared with HW and SW kraft

pulp. Fines amount has shown a doubled value compared to other pulps. There has been no difference in water retention value with the variation of pulp types. Depending on the required properties of the pulp, the treatment is performed.

Table 2: Variation in chemical and physical properties for types of the pulping process[6]

Pulp type	Bleached softwood kraft pulp	Bleached hardwood kraft pulp	Unbleached kraft pulp	Chemi-thermomechanical pulp
Sample abbreviation	SWBKP	HWBKP	UKP	CTMP
Cellulose (%)	82.48	81.5	71.91	53.85
Hemicellulose (%)	16.14	16.80	20.32	25.35
Lignin (%)	0.56	0.83	6.82	18.81
Mean length (mm)	2.17	0.77	2.34	0.89
Mean width (µm)	30.70	17.28	28.20	27.33
Fines (%)	18.33	17.01	17.20	41.72
WRV (g/g)	1.63	1.59	1.71	1.35

2.3. Fiber raw material

Wood is the most common raw material used for fibers. Different types of wood species are used as raw material for different types of pulp grades. Softwood is mostly used as raw material when the desired output is a higher strength of papers, whereas hardwoods are used for paper needed higher quality of printing properties. [7]

Softwood has long and thick fibers with higher lignin content than hardwood, which gives the pulp more tensile strength and flexibility, whereas hardwood has short and thin fibers with a high density of fibers, resulting in excellent printing properties, opacity, and strong absorption capability. [8]

For making paper-related products, mostly used softwoods are spruce, pine redwood, douglas, birch, and most used hardwoods are beech, balsa, maple and oak. [9]

2.4. Papermaking fiber sources

Fibers used to make paper products are used depending on the availability of the raw materials in that geographical region. In 2013, a total of 403 million tons of paper were produced in total. Approximately 51% of the total paper production was used for packaging materials, whereas 33% was used for writing purposes. In 2018, the amount of paper consumed was 423 million tons. Out of the total amount, 55% was used for packing materials and 26% for writing purposes. [10]

In 2016, the majority of the world's entire paper was produced in Asia, secondly in Europe. Germany was leading with a supply of one-fourth of the aggregate demand, whereas Finland and Sweden combined supplied one fourth (Figure 3).

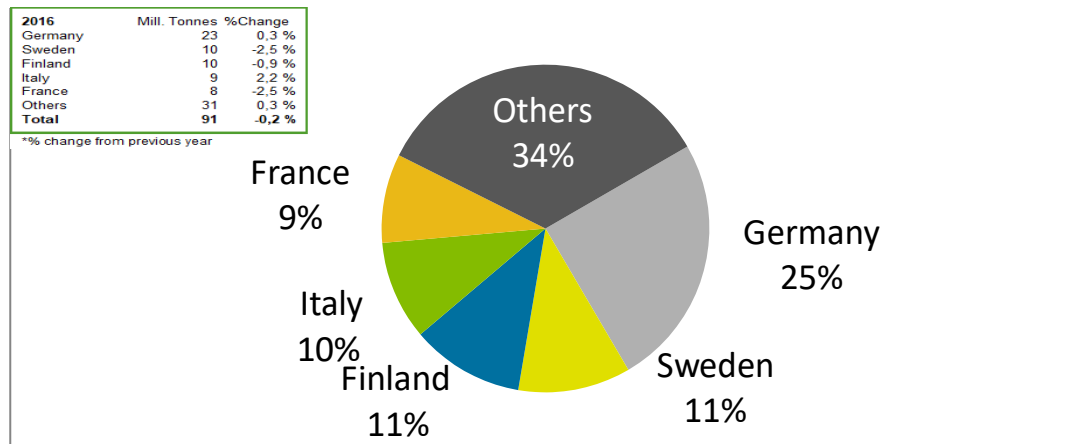


Figure 3: Paper and board production by country in Europe 2016[11]

3. Refining

Refining is a treatment process used for pulps to bring changes in the properties of papers depending on the desired paper quality. In the early days, refining was done by beating pulp with a stick in the early days. At that time, the beater that was used was called Hollander beaters before the refining process came into play effectively. As a result of refining process of pulp, the fiber bonding properties improves, so does the smoothness and printing properties depend on the extent of the refining process. When the intensity of refining is increased, more fibrils are formed, which causes increased features of papers such as opacity, absorbance quality, and porosity [12].

A significant amount of energy is consumed for refining purposes in the paper industry. Also, it should be mentioned that not all energy consumed by a refiner is required for fiber treatment. The rotor of the refiner dissipates approximately 20% of the total energy consumed by a refiner. [13]

3.1. LC Refining mechanism

Low consistency refining is implemented using fibers diluted in water (2-7% consistency). LC refining is used to save energy expenses due to low energy consumption and has a good effect on low-quality fibers. The fiber-water solution is treated in the refiner between metallic bars. The solution enters between the rotating rotor and stationary rotor filling, where the fiber floc is compressed by the pressure created by the leading edge of the stator bar and rotor bar. How much pressure it will build on the pulp suspension depends on the gap clearance. The refining continues between both rotors by the bars between them. The impact of refining depends on the width of the bars of rotors and also the angle of bars. The width in the grooves is vital for better refining percentages of fibers. During the

movement of the rotor bar from the static bar, vortex flows strongly in the grooves; this helps the fibers to be stapled on bar edges, increasing the percentage of fibrillation. Refining also has an impact on the straightening of the fibers, creates a compressed portion of fibers, kinks, and nodes. Moreover, if the grooves are too narrow, then the fibers get shucked in the grooves and leave the refiner without refining [14].

During the refining, when fibers flow between the two bars, preliminary dewatering happens up to 15-30 %. Then, the mechanical pressure of 6.9-34.5 MPa applies to the fiber flow, which causes water expulsion of 50% approximately. Then the sliding wads get under pressure (Figure 4). Afterward, while the moving bar starts moving from the stator bar, mechanical pressure starts releasing, and water reabsorption starts. At last, dispersion happens, and wad gets ready for the next refining cycle [15].

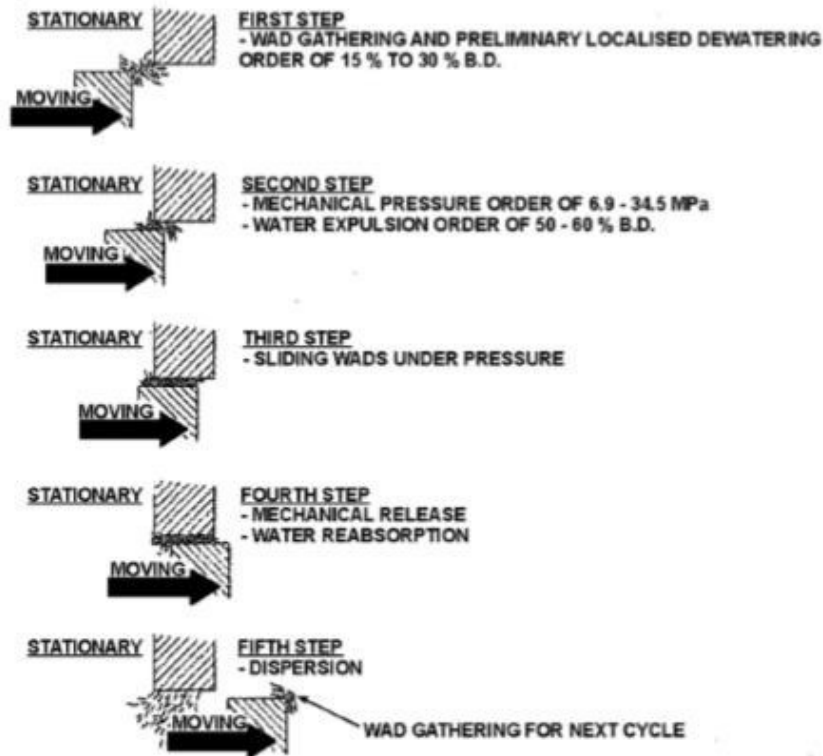


Figure 4: Refining mechanism between stator and rotor bars[16]

Different types of forces are observed in fibers due to bar pressure in refining. The fibers experiences three directional forces. Due to the movement mechanism of the rotor from the stator, normal force, shear force, and edge force applies in a fiber causing the fibrillation and compression(Figure 5).

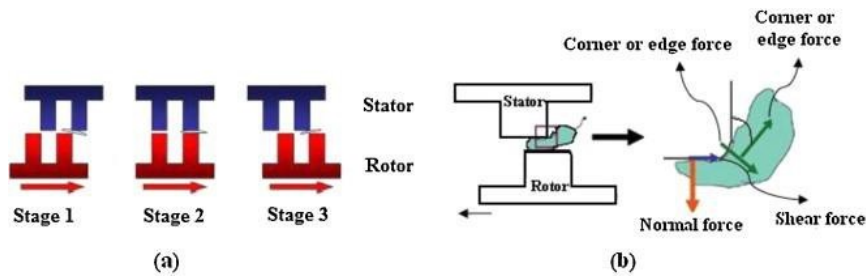


Figure 5: Refining impact on fibers between stator and rotor bars [17]

3.2. Types of Refiners

Various kinds of refiners are used for pulp tailoring. The three designs are Conical designs, cylindrical designs and disk designs.

3.2.1. Conical Designs

The conical designs refer to the conical shape rotor filling that is fixed with the refining motor and a stator filling. The gap between the rotor and stator impacts the refining intensity. In the time of the invention, the conical refiners were expensive as high energy was required and was not able to cope up with the capacity of refining needed by the paper mills. This design was best applicable for refining pulp with higher length of fibers, which became a significant issue for the pulp companies when short length of hardwood fibers came into play and which required dense refining [18].

OptiFiner Conical Refiner

OptiFiner conical refiner is a current technology developed by Valmet, Finland (Figure 6). The most significant of this refiner is the precisely controlled gap clearance between stator and rotor, which provides precise refining of pulp. This refining unit has a high refining zone, and the flow pattern of pulp suspension ensures more fiber to bars interaction providing high refining intensity. This design offers a wide range of filling patterns. Through this refining process, higher printability quality, uniform refining, a better solution for frequent web breaks and better machine run ability are ensured. This refining process is famous for lower energy consumption and lower maintenance cost. The top-notch parameter control system and high-end automation have been the main improvements seen in the OptiFiner refiner. In this refiner, a newly developed sealing has been used. As the breaking of sealing is a common problem in refiners, which leads to less efficiency

and high cost of refining, this sealing provides long life service. This sealing mechanism provides high efficiency for refiners, where sealing water is difficult to manage [19].

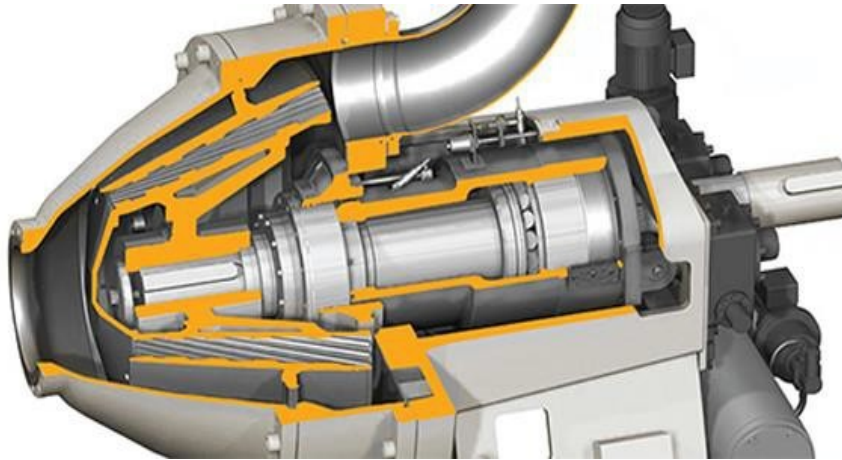


Figure 6: Cross sectional view of OptiFiner Refiner

Jordan Mill

Jordan refiners are typically used for softwood refining. This refiner was the first conical refiner that was built after the beater concept. The stator and rotor of the refining were set to an 11-16 degree angle. One offset was changing the fillings of the refiner as the refiner shaft had two bearings on each side, which made it time-consuming [20].

Clafin Mills

After the Jordan refiner, the Clafin refiner was invented, which had an angle of 30 degrees between rotor and stator filings. This is the widest angle of all conical-shaped refiners. This refiner is currently used for currency papers and high-density paper qualities. It has the same drawback as the Jordan refiner due to the bearings

on both sides of the refiner shaft.

3.2.2. Cylindrical designs

Hollander beater was first developed in 1680 by Dutch. Hollander beater is the most used in recent time for producing specific grade paper. In this process, pulp slurry passes through a refining beater. The slurry keeps circulating in the circular tank and keeps passing through the beater

The gap between the beater and plate is used for the pulp to pass in between and perform refining. The gap is adjusted to increase and decrease the refining intensity [21].

The power efficiency is high as the idling power and rotational speed has lower value. Later on, the principle was used by various paper industries by changing the type of beaters for the desired properties [22].

3.3. Types of bars

Valmet refiner Attack Bars

Attack bars are designed to be tilted and contain sharp bar edges (Figure 7). This helps the fibers to move effectively in the disk gap. The increased bar gap helps the fibers to be treated effectively, resulting in higher strength properties and reducing energy consumption [23]. With the use of attack bars, higher average fiber length can be obtained by consuming less energy (Figure 8).

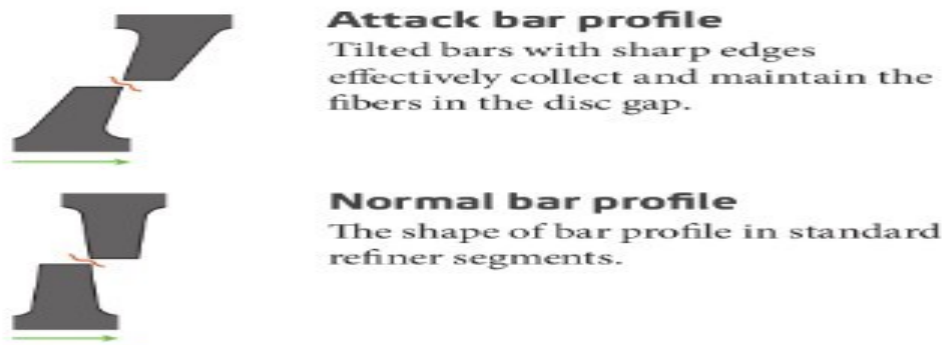


Figure 7:Refining impact difference between attack bars and normal bars

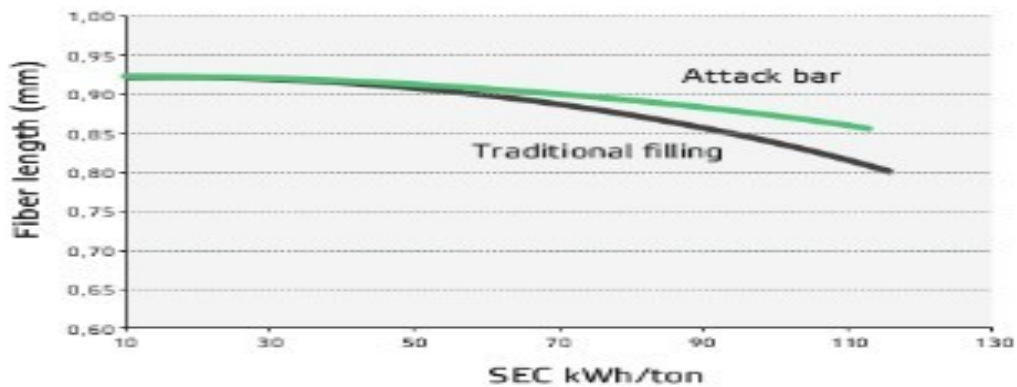


Figure 8: Energy consumption vs. fiber length(mm) for attack bar refining compared with traditional bar filling.

Micro Bar

Micro bar is designed for the higher runnability of the refiner. This orientation and shape of bars provide dense refining zone and long cutting-edge length (Figure 9). This design helps the refiner to consume 10% less energy while refining hardwood and 20% less energy while refining softwood and mixed pulp. This design is used for all fiber lengths that provide a longer runnability without the need of filling change, which is time-consuming. As a result of longer cutting edges of the micro bars, the load can be more than general as the fibers get more area of refining grooves. The total load can be increased by up to 50% with micro bar refining [24].

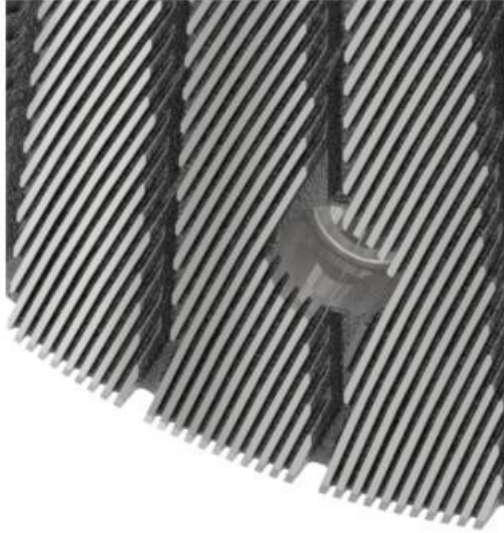


Figure 9: Bar orientation of microbar in a refiner

As there is higher edge length, more fibers experience refining treatment resulting in external and internal fibrillation. The increase of tensile strength of paper sheets can be observed while comparing with standard refining as a result. (Figure 10)

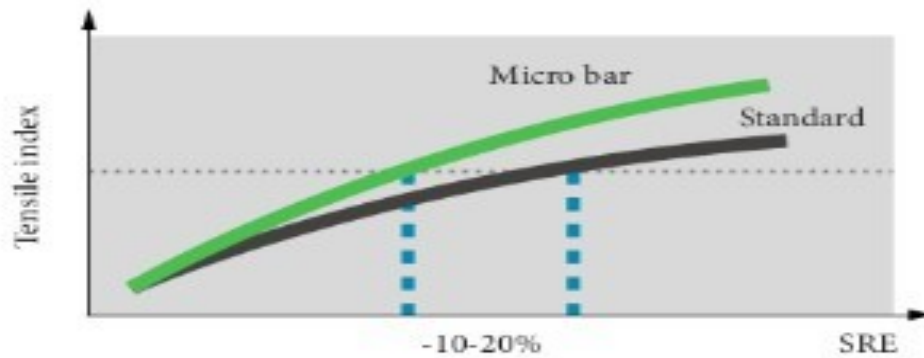


Figure 10: Energy consumption vs. fiber tensile strength for micro bar refining compared with traditional bar filling.

Parallel Bar

Parallel bars are used widely for low-intensity refining. The parallel bar has one specific bar at a fixed angle, and other bars have comparatively higher angles (Figure 11). As this setup has more bars edge crossing, it provides higher distance covered per revolution during refining. The parallel bar also provides better hydraulic capacity and breakage resistance.

Groove depth plays a critical role while meeting the required refining intensity. If the groove depth is lower, the refining intensity will be higher as the fibers will receive more treatment. If the groove depth increases the intensity will decrease as there will be fiber trapped in the grooves. But more width among grooves will provide more efficiency than groove depth. Moreover, energy consumption will be higher for increasing depth as it will need more energy for the rotation of the refining bars [25].

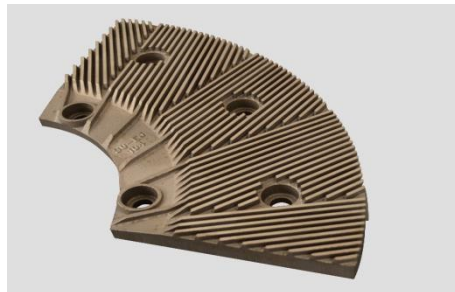


Figure 11: Bar orientation of parallel bar in refiner

3.4. Impact of refining on fibers

The fibers that are being refined the effect depend on the raw pulp chemical composition, morphology, and fiber orientation. The amount of lignin in the pulp, the porosity, and rigidity has a big influence on refining intensity. The refining outcome also has a considerable contributor which is the rheological behaviour of the suspension. If the fibers are left untreated, which means not refined, the paper

made out of it will show uncontrolled properties. The distribution of the fibers along the sheet will be highly uneven. There will be fewer hydrogen bonds among the fibers resulting in poor formation. Refining increases the conformability and interfiber bonds due to the result of external and internal fibrillation. Along with maintaining good fiber strength and average fiber, length conformability is achieved due to the refining [26].

Traditionally the only chemical treated pulps are refined by low consistency refining mechanism. But in the earlier years, mechanical pulps were also being treated as it was found that LC refining is able to produce the same required properties of paper as HC refining. This means the same quality can be achieved using less energy. But the refining condition control and parameter control was a bit more sophisticated to reduce the fiber curl and, at the same time, produce less number of fines to maintain good bonding properties. Welch came to the conclusion that de-latent pulp could be produced without latency removal step if refining was done by LC refining [27].

The impact of refining depends mostly on the type of pulp that is being refined, and the changes in variables such as pulp consistency, rotor speed and the width of grooves in bars.

The main impacts of refining are the opening of the primary fiber wall, fibrillation of the secondary wall, swelling of fibers, shortening of fibers, and production of fines. Fibrillation of fibers causes more bonds among fibers, which causes an increase of tensile strength and tensile stiffness. Internal fibrillation causes an increase in the surface area of paper, which improves the paper flexibility [28]. Shortening of fibers or fines produced due to refining is a result of cuts at the bar edges due to extreme refining. Fines produced by refining cause low paper strength and decreases drainability due to the high density of fibers. As a secondary effect of refining is fibers delamination of fibers, fiber stretching and collapse, fiber straightening, fiber

curling, and also redistribution of hemicellulose is observed [12].

It has been observed that the amount of hydroxyl groups in a paper sheet also depends on the intensity of refining and bonding. The amount of free hydroxyl bonds increases when the sheet is made from unrefined pulp. If the pulp is refined, the amount of bonded hydroxyl groups increases. From figure 12, it can be observed that for unrefined pulp deuterated hydroxyl group percentage was higher by 1.4% than refined pulp. The x-axis indicates the number of free OH-groups. The number was reduced as the degree of inter-fiber bonding increased that was measured as higher sheet strengths. Depending on the refining intensity, 0.5-2 % of hydroxyl groups are responsible for the increase in the number of fiber bonds in the paper sheet [29].

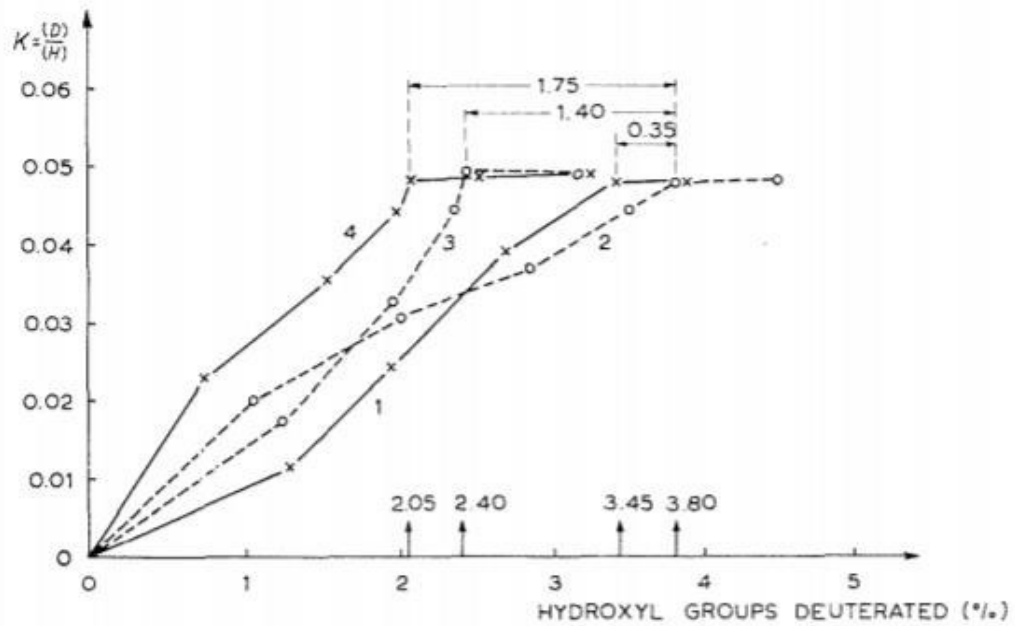


Figure 12: . Deuteration curves of cellulose fibers and paper made by Corte and Schaschek: (1) sheet from unbeaten fibers; (2) isolated fibers; (3) sheet from beaten fibers; (4) sheet from fibers beaten longer than (3) [30]

The mechanism of internal fibrillation due to the impact of refining can be explained by Wang's theory. According to the explanation, for never dried pulp, the refining had negligible effects on small pores and significant impact in large pores. On the other hand, for dried pulp, the larger pores got expanded, and small pores reopened (Figure 13). Due to drying, large pores get closed, and a negligible amount of small pores get closed [31].

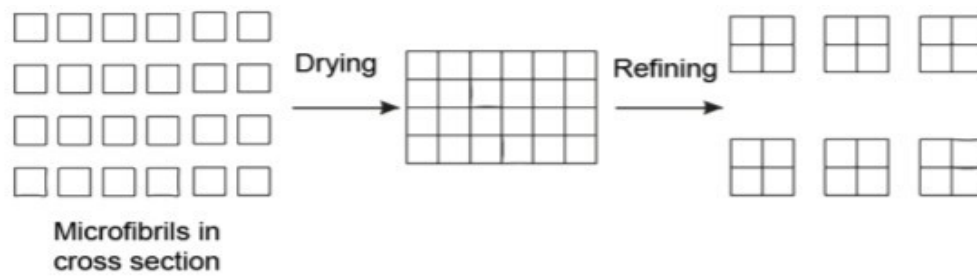


Figure 13: A schematic of proposed changes in fiber cell wall ultrastructure due to the beating of a previously dried pulp [31]

The Internal fibrillation results from compression of fibers according to Wang (Figure 14). During refining, the fibers are compressed. As a result, the areas of the fibers where the crease stress is created results in breakage of cell wall structure [31].

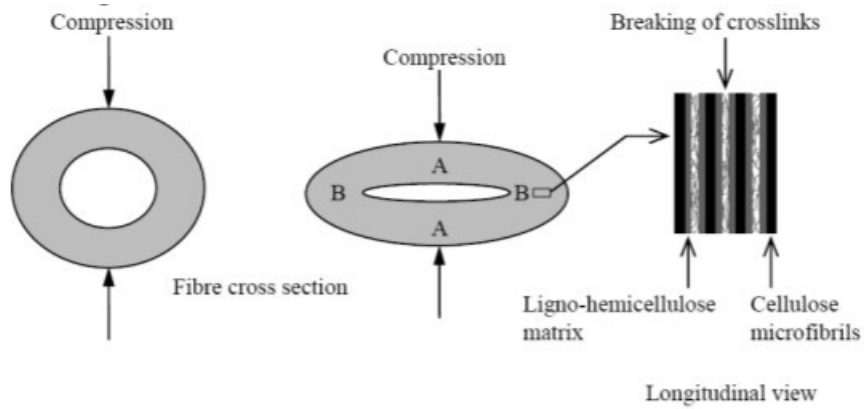


Figure 14: A proposed mechanism for internal fibrillation created by compressive action. Compressive action flattening and compressing the fibre (A) that causes deformation resulting in breakage of cross links between microfibrils (B)

The percentage of fines also impacts the optical properties such as opacity, light scattering, and brightness. Fibril amount increases with the increased time of refining that provides more surface area causing more absorption of lights into the fiber [32].

3.5. Refining Management

To measure the intensity of refining, the parameter that is calculated is SEC (specific energy consumption), which is measured as energy consumed to treat the fiber.

Specific Energy Consumption describes the net power used by the refiner eliminating the portion of the energy that is lost to hydro dynamics to refine the pulp. The formula used for determining SEC is :

$$SEC = \frac{P_{Total} - P_{no\ load}}{M} \quad \text{Eq:1}$$

where,

P_{total} = Total motor load in the refiner with pulp, kW

$P_{no-load}$ = Total motor load in the refiner without pulp, kW

M = Mass flow rate of pulp, t/h

Specific energy load, SEL is also called the refining intensity. The equation for determining SEL is,

$$SEL = \frac{P_{Total} - P_{no\ load}}{\left(\frac{RPM}{60}\right)(Bar\ Edge\ Length)} \quad Eq:2$$

where,

P_{total} = Total motor load in the refiner with pulp, KW

$P_{no-load}$ = Total motor load in the refiner without pulp, KW

$$Bar\ Edge\ Length = \int_{R_1}^{R_2} \frac{n_r n_s}{\cos \varphi} dr \quad Eq:3$$

Bar edge length is also called the cutting edge length. In Eq:3, the φ symbol stands for the angle made by the bar in the radial direction, and n represents the number of bars in radius [33].

As the fiber flocs are collected on the bar edges, it is definite that a higher number of bar edges will give higher refining impacts. Bar edge length formula calculates the inner and outer diameter of the bars, their groove widths, and the average radial angle. BEL, in general, provides the factor of an average number of crossing points of fibers where they can be refined by the edges of the bars on the stator and rotor disks [33].

3.6. Impact of refining on physical and optical properties

Absorbing capacity is one of the essential properties of the fiber. The mechanism that helps to achieve higher absorbing capacity is the maximization of internal fibrillation. When internal fibrillation increases, the number of pores among the fibers increases as well as the size of the pores, which holds more water. This process is called swelling of fibers. When internal fibrillation occurs, external fibrillation occurs as well.

Water retention value is a method to determine the capability of a paper sheet to absorb water [34]. Tissue paper has higher WRV than standard paper as tissues are manufactured to absorb more water.

For experiment, WRV 2 g/L solution is prepared from the pulp fiber solution. Then the solution is passed through a wired filter that is used for dewatering the pulp from the solution. Then the extracted fiber pad is rolled and centrifuged in a centrifugal rotor. The centrifugal force that is maintained is 3940 rpm at 23° C for 15 min. The weight of the pulp pad is measured afterward. After that, the pulp is oven-dried at 105° C for 4 hours. The weight of the oven-dried pulp pad is measured. The formula that is used to find WRV is

$$WRV = \frac{\text{Weight of centrifuged wet test pad}}{\text{Weight of oven-dried test pad}} - 1 \quad \text{Eq:3}$$

$$WRV = (\text{Weight of centrifuged wet test pad} / \text{Weight of oven-dried test pad}) - 1$$

From figure 15 it is clear that water-absorbing capability increases with the refining intensity. It has been observed that for NBSK pulp, less energy is required to achieve a high WRV value compared with bleached bamboo pulp. For bleached bamboo pulp, 25 kWh/t more energy is needed for making water retention value close to 1.9 g/g. From the graph, it can be stated that NBSK requires less specific energy

compared to other pulp samples to achieve better water retention value. NBSK pulp is a better choice for a paper product that requires the higher absorbing capability of liquid with less energy consumption .

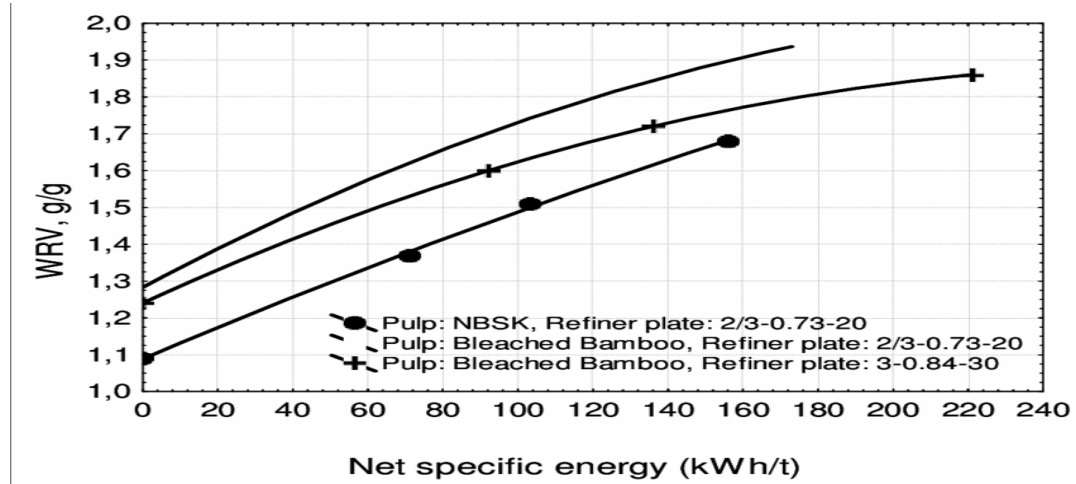


Figure 15: Effect of refining energy on the water retention value (WRV) of three different pulp fibers

To determine the drainability of the pulp suspension °SR, Schopper-Riegler testing is done. The main idea behind this test is to understand the impact of refining on pulp fiber’s thickness and porosity at wet state. If the fibers result in more internal and external fibrillation due to refining , the SR value will increase as the drainability will decrease due to the increased area of the fibers. In general, this value helps the research with an assumption of the impact of the mechanical refining of fibers. The results can be unreliable, as the value can change with the variation of temperature, water hardness, and the presence of fibrils, which can easily pass through the filtration net [35].

The opacity of a paper is determined to realize the printing quality of a paper. The higher the opacity is, the better the ability of the sheet to hide the color on the backside of the paper. The more air space available among fibers of a sheet, the more opacity is achieved as more light can be scattered through the sheet. When

fibers are refined or mechanically treated, the fibers are internally and externally fibrillated, and the fiber-fiber bonds increased, causing a decrease in air space, which decreases opacity [36].

Meanwhile, with an increase of fines, the opacity increases as the pulp fines have high surface areas and irregular shapes. The main challenge is to reach a point where the sheet will provide high opacity and excellent strength. Bulky sheets have high opacity with low strength and refined pulp sheets have good strength but low opacity. The brightness of a paper sheet is measured as ISO Brightness (%). When light arrives in a sheet of paper, four different types of action take place. Some portion of the light creates scattered reflection which causes brightness, some creates specular reflection creating gloss of the paper, some light gets absorbed providing color, and some has permeance through the paper causing opacity (Figure 16) These values change with the change in the structure of the fibers in the paper sheet due to refining [37].

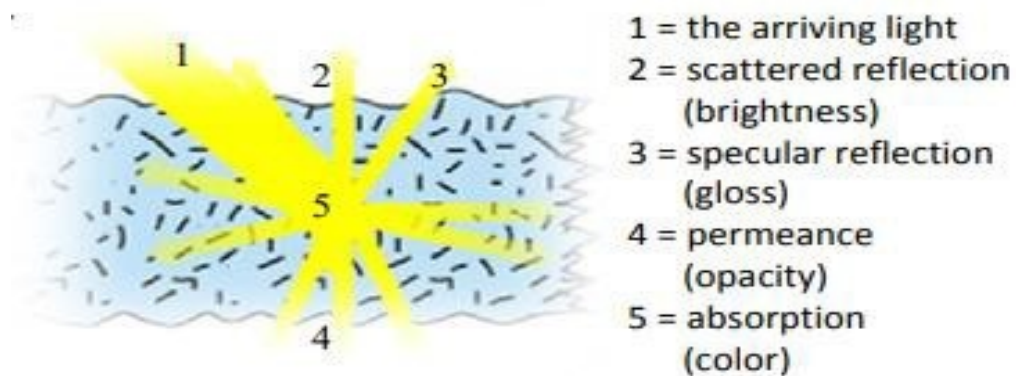


Figure 16: Effects of light on paper when in contact and refining effect on light scattering coefficient

Air permeability is one of the properties that is dependent on the thickness and air porosity of a paper. The higher the porosity, the higher the value of air permeability is achieved. The higher the thickness is, the lower the air permeability value goes.

Air permeability is the measurement of air flow passing the paper sheet per unit area which is independent of sheet thickness [38].

If the pulp is refined, the internal and external fibrillation occurs along with fibrils formation, which lowers the porosity in the paper. The longer time the pulp is refined, the more the air permeance value decreases (Fig 17). Air permeance is measured as air permeability per unit thickness. However, this parameter can show a difference in behavior depending on the raw material, intensity of refining, fiber properties, and orientation. When calculated for air permeability, the value increases as the number of pores increases per unit area due to the expansion of fibers and formation in fibrils (Figure 18). If the refiner load is lower, there will be less fiber to refiner bar interaction, causing less fibrillation of fibers and fewer fines formation. This will create a high air permeance value of paper sheets [39].

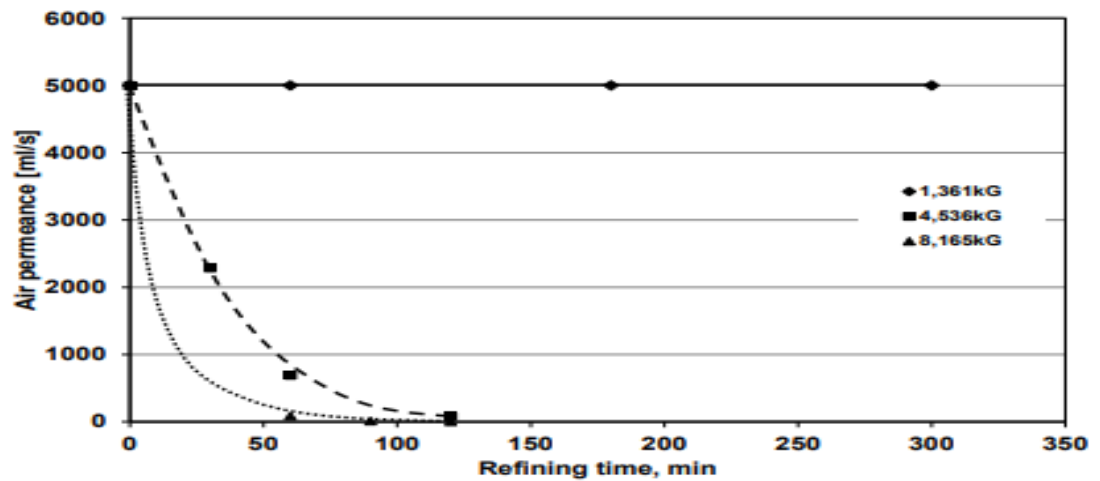


Figure 17: Impact of refining duration with Air permeance

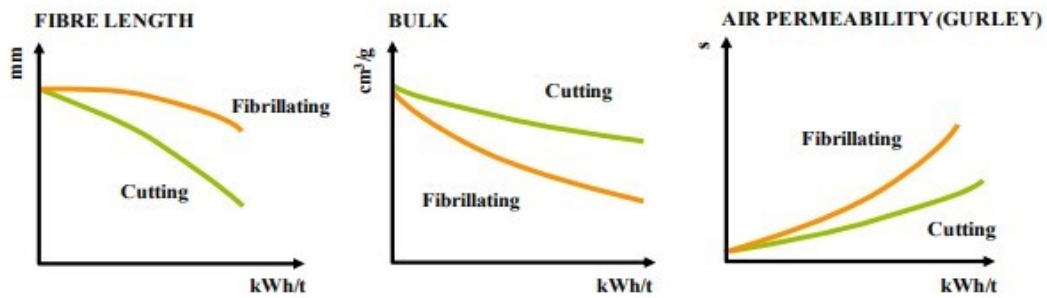


Figure 18: Impact of refining on fiber length, bulk and air permeability[20]

When pulp is introduced to mechanical stress or refining, the fiber surfaces increase and results in an increase of fiber-to-fiber bonds. This is a result of internal and external fibrillation and the formation of fibrils due to refining. As a result, the tensile index increases in the paper; meanwhile, the thickness of paper decreases. This makes the fiber flexible [37].

The internal fibrillation is the result of the opening of the primary wall and first secondary wall caused by the cyclic compression due to the forces of the refiner. External fibrillation refers to the exposure of the second secondary layer, which causes an increase in surface area. This results in a rise in bonding among fibers, as some hydrophilic compounds are discharged from the cell wall that forms gel-type layers between fibers. This is a result of the impact of compressive and shear force in the refiner due to the movement of the rotor. With a high amount of refining, shortening of fiber occurs along with fines are formation[40].

Tear Index is the measurement of the force or strength required to tear a paper sheet [41]. The tear resistance reaches higher value with the increase of fiber-fiber bonds when refining is applied. However, with the rise of refining, more fibrils are created, and more bonds occurring between fibers decreases the sheet flexibility, which causes a decrease of tear strength (Figure 19). This parameter also depends on the length of the fibers[41].

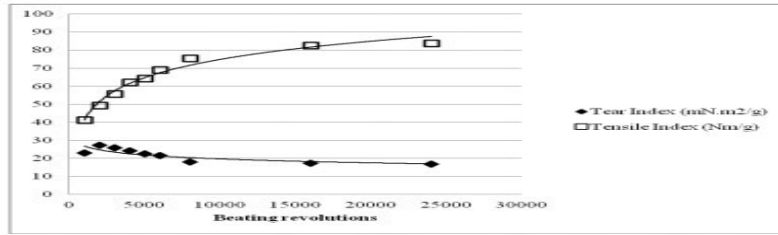


Figure 2: Tear and tensile index for beaten *Semantan* bamboo paper

Figure 19: Change in tear index and tensile index with refining intensity

4. Experimental

4.1. Raw Material

For this experiment, bleached kraft softwood pine has been used as raw material. The raw material was stored in sheet form. Mainly two consistency of the solution was used for the total experiment. One was 2 % consistency of pulp, and the other was 4 % consistency of pulp.

4.2. Refining

Prolab Refiner of the Laboratory of NMT at Åbo Akademi has been used for the experiment. The refining unit consists of a pulp mixer, a screw mixer, a stock pump, a refiner, and 6 sample collecting units(Figure 20). The refiner operates as a closed batch system [42]. The pulper has a capacity of 50 liter solution.

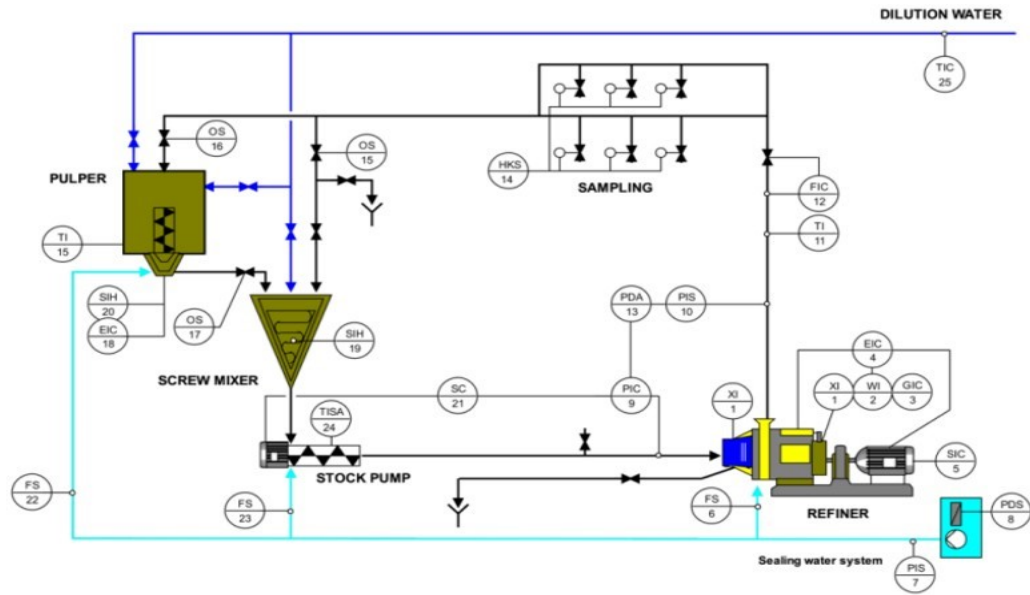


Figure 20: Process flow of ProLab [42]

4.3. Pulp Preparation

Dry sheet of pulp was calculated and mixed with water to make the desired consistency of pulp. It was assumed that the pulp sheet contained 5 % moisture. So taking that into account, the calculation was made targeting the most precise weight of dry pulp weight for the desired consistency.

4.4. Process of refining

At first, the no-load is measured only for each different volumetric flow rate for different rotational speeds by using water. No-load power for 60 l/min, 100 l/min, and 120 l/min has been measured for pumping direction and non-pumping direction (Table 3). It has been observed that the increased flow rate in pumping direction the energy consumption has reduced while vice versa occurred for non-pumping direction.

Table 3: Change of no-load power for different volumetric flow rate at pumping and non-pumping direction

Volumetric Flowrate, l\min	Energy Consumption, kW (For pumping Direction)	Energy Consumption, kW (For non- pumping Direction)
60	3,13kW	4,16 kW
100	3,10 kW	4,21 kW
120	3,04 kW	4,27 Kw

Then zeroing is performed, which refers to the point where the rotor and stator come to a close touchpoint. The gap between the stator and the rotor is stored as the zero point. While experimenting, the refiner load is controlled automatically or manually by controlling the gap between the rotor and stator. If the gap is close, the vibration level increases, which can be controlled by increasing the gap. Pumping direction refers to the rotational direction of the rotor of the refiner towards the pumping direction of the pulp flow. Non-pumping direction refers to the opposite rotational direction of the tilted rotor bars towards the pulp flow direction.

The pulp solution first is disintegrated in the pulper unit for 15 minutes. Then the solution is sent to a screw mixer where it is continuously mixed passes to the refiner and gets refined. The intensity of refining is controlled by controlling the gap between the stator and the rotor. While the gap was reduced, refining showed an increase in energy consumption, which is a result of the energy required for the refining. The sample collecting points are selected manually. Sample collection points are set as targeted in SEC_{Cum} . When the refining reaches to the target point of SEC_{Cum} , the sample collecting valve opens automatically and collects the sample.



Figure 21a : Image of ProLab refiner



Figure 25b: LM refiner used for refining during the experiment

4.5. Parameters

During the experiment, the parameters that have been fixed are :

Table 3: List of fixed refining parameters

Parameters	Value
Raw Material	Bleached Pine kraft pulp
Refiner rotational speed (1\min)	3000 rpm
Temperature	Not controlled and varying slightly
Refining Segment	One LM refiner (Figure 21b)

During the experiment, the variables that have been studied are :

Table 4: List of changed refining parameters

Parameters	Value
Pulp Consistency (wt%)	2% and 4%
Pumping Speed (l\min)	60 l\mn,100 l\min,120 l\min
Rotational Direction	Pumping and non-pumping
Sample collection Point (kWh\t)	50 kWh\t, 150 kWh\t, 200 kWh\t,250 kWh\t

4.6. Sample Prepared

For each pulp consistency, each rotational direction, each pumping speed four samples were collected (Table 5). Table 5: List of collected samples for analyzing to determine physical and optical properties

Pulp Consistency	Rotational Direction	Pumping Speed (l\min)	Sample Collection Point (kWh\t)	Total Experimental Sample
2%	Pumping	60, 120	50, 150, 200, 250	8
2%	Non Pumping	60, 120	50, 150, 200, 250	8
4%	Pumping	60,100, 120	50, 150, 200, 250	12
4%	Non Pumping	Pumping	60,100, 120	12
				Total=40

4.7. Sample analysis method

To observe and evaluate the changes in the physical and optical properties of the fibers due to the various changes done in refining process parameters; the parameters that have been analyzed are :

1. Schopper Riegler ($^{\circ}$ SR) freeness testing
2. Density measurement
3. Grammage measurement
4. Optical properties testing
5. Air permeability testing
6. Tensile strength testing
7. Tear strength testing
8. Water retention value testing
9. The average fiber length measurement
10. Fines percentage detection

5. Results and Discussion

For all pumping speed in pumping and non-pumping direction, the increase in °SR value has been observed with the increase of specific energy consumption by the refiner, which clearly indicated the increase of refining intensity causing more external and internal fibrillation (Figure 22) Comparatively higher change in °SR value has been observed for the sample with pumping direction, 4 % pulp consistency, 60 l/min flow rate and pumping direction, 2 % pulp consistency, 120 l/min flow rate with the increase of refining intensity.

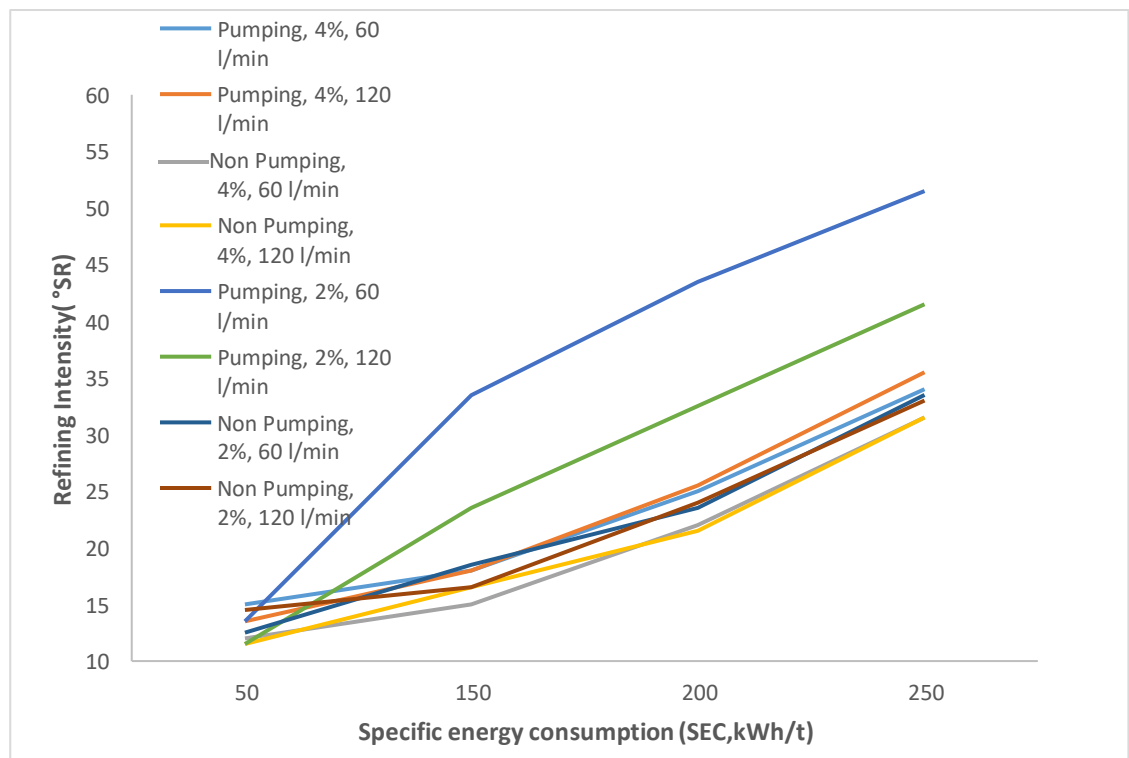


Figure 22: Change in °SR value with respect to SEC for all collected samples

For all experiments, the refining intensity has been controlled by controlling the power consumption by the refiner except the refining done at 60 l/min and 120 l/min speed in pumping direction for 2 % pulp consistency, which has been done by gap control. Comparatively higher °SR values have been observed with the increase of refining energy SEC for gap controlled refining than power controlled refining. The hypothesis behind this can be explained as, with the manual control done by the gap, the gap was set smaller compared using the power option. This increased the fiber-bar contact causing more internal and external fibrillation and formation of fines. As a result, more surface area was created, resulting in a decrease of drainability and increase in °SR. Moreover, when the refining was being controlled by gap control, the gap between the stator and rotor was reduced in a short period of time. As a result, the refining intensity was higher. On the other hand, while using power controlled refining, the gap between the stator and rotor was reduced gradually taking more time which can be explained as the reason of less refining intensity compared with gap controlled refining.

From figure 23, it is seen for both pumping and non-pumping direction regardless of pumping speed; the curve follows a trend where with the increase of °SR values, the thickness decreases. This is explained as a high intensity of refining, causing external and internal fibrillation decreasing the thickness with an increase of °SR values. The decrease of thickness can be explained as; the density of fiber is more per volume as a presence of more fibrillated and swollen fibers.

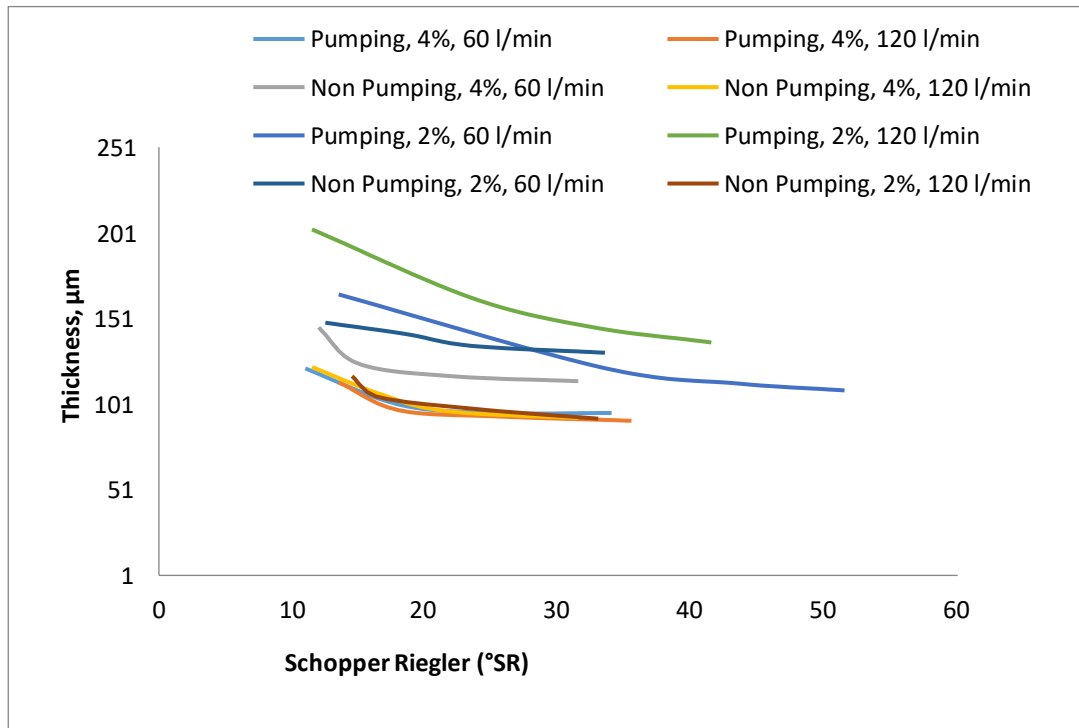


Figure 23: Effect on Thickness, μm with respect to Schopper Riegler ($^{\circ}\text{SR}$) values for all samples

There have been no significant changes in the light scattering coefficient due to the changes in pulp consistency, pumping speed, or pumping direction. However, it has been clearly observed that with the increasing of refining intensity, the brightness showed a decreasing curve (Figure 24). The increase of fiber-to-fiber bonds due to external and internal fibrillation caused by refining decreased the air space per area of the sheet, which hindered more light from scattering through the sheet.

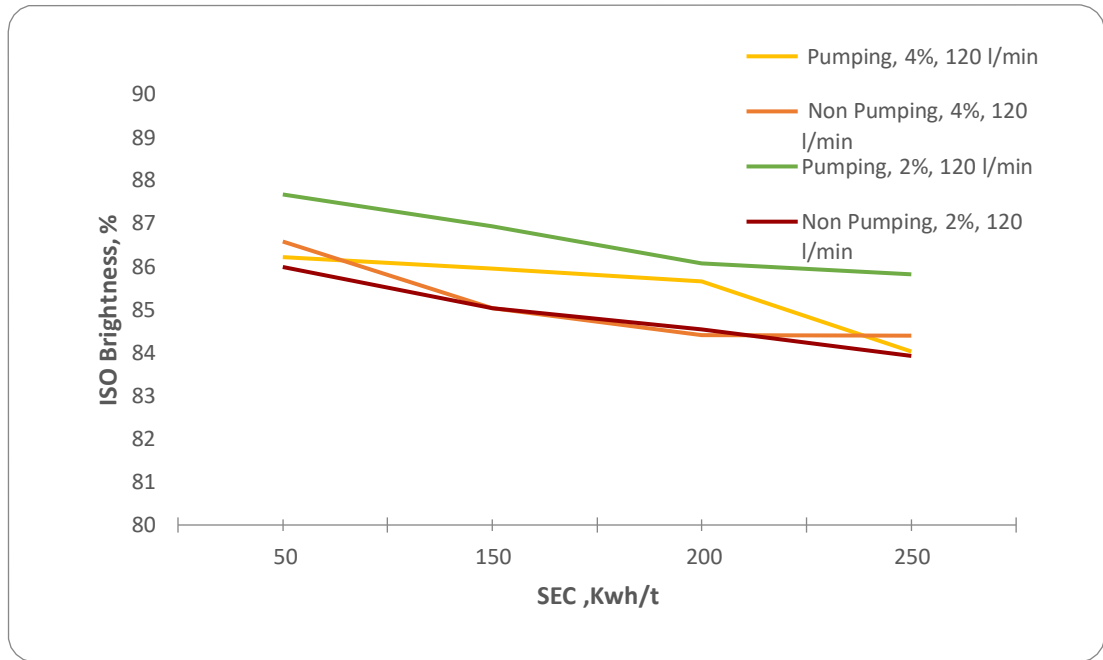


Figure 24: Changes in ISO Brightness (%) with respect to refining intensity

While analyzing air permeability for all experimental samples, the results have shown similar behavior. A decrease in air permeability was observed with the increase of refining degree. Formation of more fines result in the porosity per unit area decrease as a result of reduced thickness. Moreover, a significant decrease of air permeability has been observed along with refining intensity for 2 % pulp consistency at pumping direction for 60l/min pumping speed and at a non-pumping direction for 120 l/min speed(Figure 25 a).

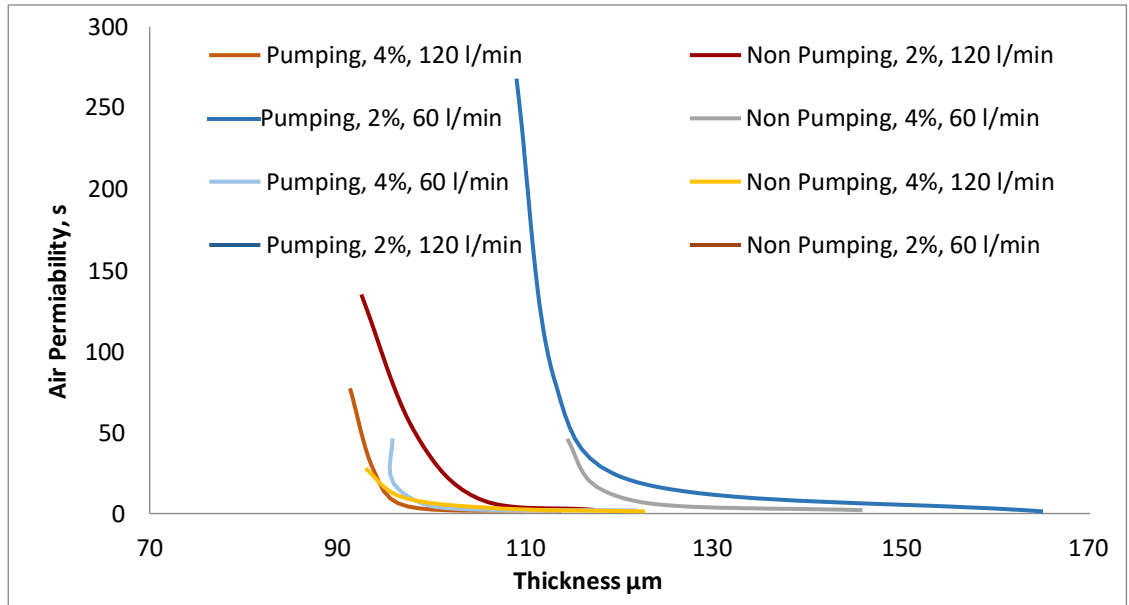


Figure 25a : Effect on air permeability with respect to thickness, μm value for different samples

The air permeability also has an impact due to variation in porosity. With the increase of area, air permeability increases as porosity increases (Figure 25b).

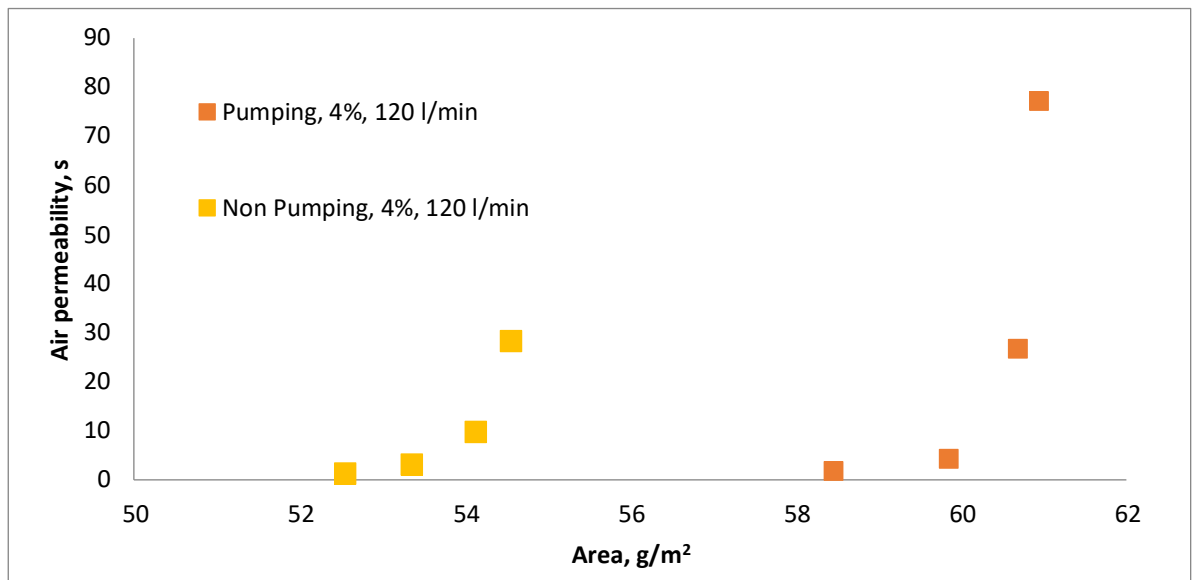


Figure 25b : Effect on air permeability with respect to area, g/m^2 values

While analyzing the amount of fines at 120 l/min pumping speed for both pumping and non-pumping direction with 2 % and 4 % pulp consistency, it was observed that the amount of fines increased with the increase in refining intensity (Figure 26). However, the difference between the percentage of fines was not significant enough, which can be explained as less fiber-bar interaction during refining, as the reason behind the creation of more fines depends on the level of the fibers friction with the refiner bars. Also, no major change has been observed in the fines percentages due to the change in direction or pulp consistency.

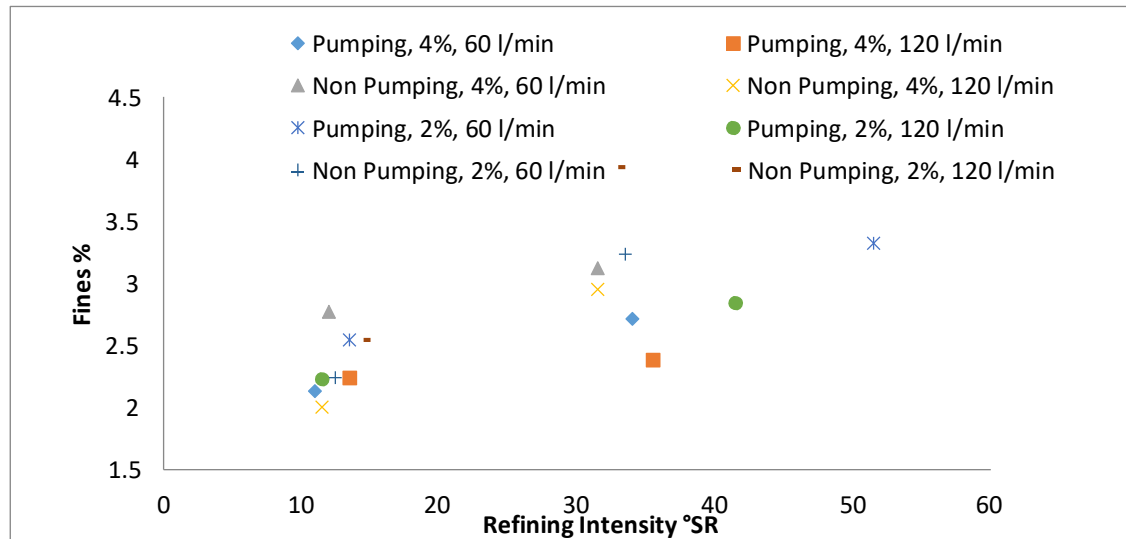


Figure 26: Variation in fines with respect to °SR values

During the analysis of the fines content for all samples at different refining intensity, it has been observed that the amount of fines has increased with the increase of intensity with prolonged refining. For the samples (2 % consistency, 60 l/min flow rate, and pumping direction) and (2 % consistency, 60 l/min flow rate and pumping direction), the amount of the fines has been seen to increase by 0.5% units compared to other samples along with the increase of SEC value. The reason for the deviation can be assumed as the refining control method. For these 2 samples, the refining has been controlled by controlling the gap whereas the other samples have

been controlled by SEC value. This requires further research to determine the changes in properties due to refining intensity controlled by gap control between the stator and rotor.

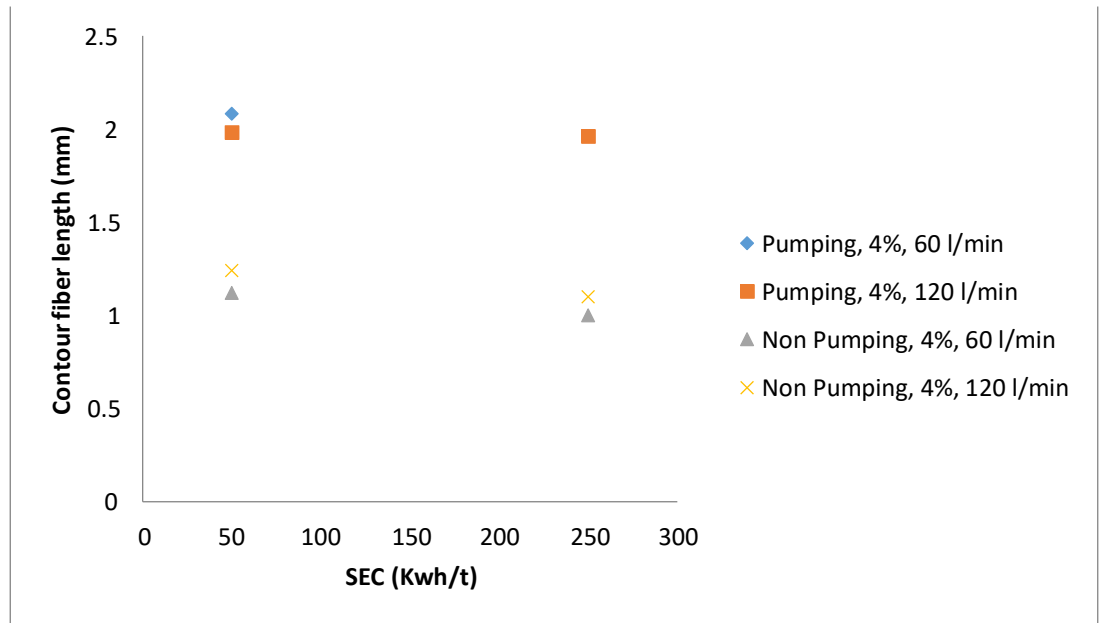


Figure 27a: Deviation in average contour fiber length (mm) with respect to refining intensity for pumping and non-pumping direction.

The average contour length of fibers showed a difference in length with the change in pumping direction regardless of pumping speed or pulp consistency. Contour fiber length has a relation with bars. These fibers are more refined and shortened compared with pumping direction. The higher average length of fibers has been observed for pumping direction (Figure 27a). This can be explained as, in pumping direction, there should be less fiber-bar interaction and more fiber-fiber interaction. With the increase of refining intensity more fibrillations have been observed which is the reason of reduced average contour length. From figure 27b, it has been seen that in non pumping direction higher number of fibers are refined with the increase of refining intensity while compared with pumping direction of flow. The pulp

suspension flows in the pumping direction with more force compared to the non-pumping direction. So during non-pumping direction, the fibers have more time inside the refiner causing more interaction. However, this change showed no significant impact on the other properties compared to other samples.

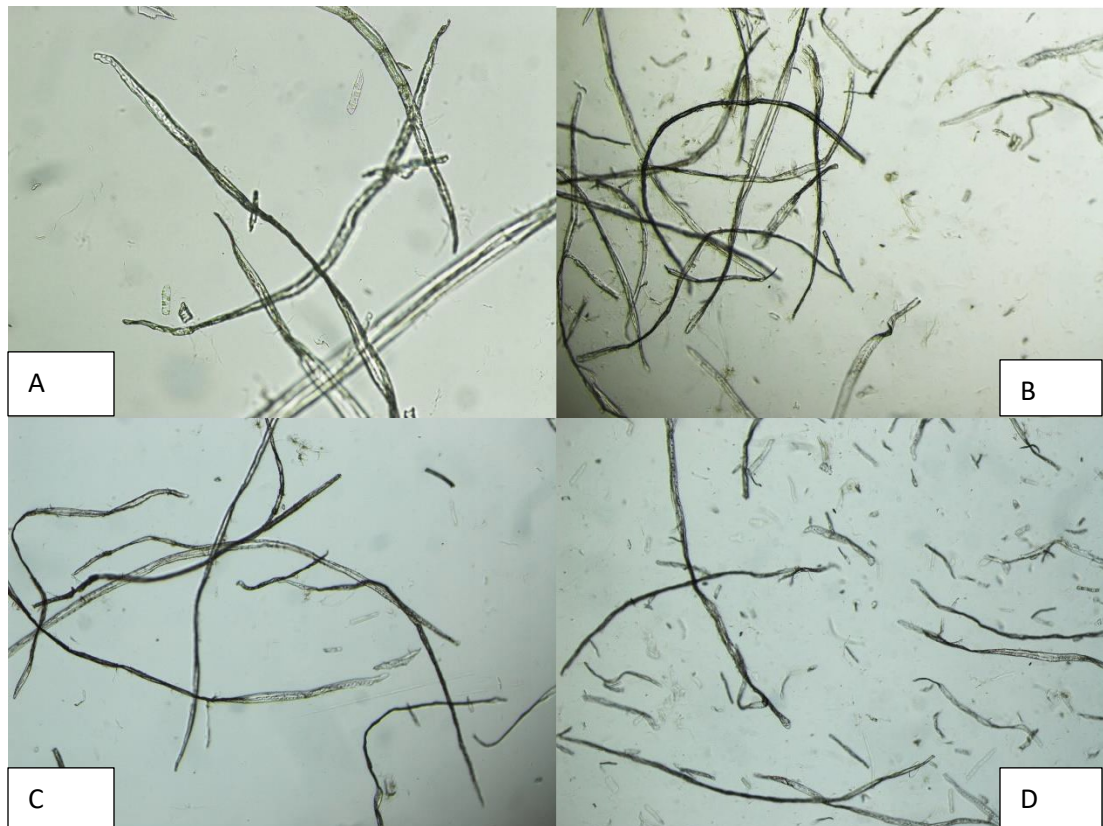


Figure 27b: Microscopic image of refined fibers at

- A. Pumping direction,4 % pulp consistency,50 kWh/t SEC
- B. Pumping direction,4 % pulp consistency,250 kWh/t SEC
- C. Non pumping direction,4 % pulp consistency,50 kWh/t SEC
- D. Non pumping direction,4 % pulp consistency,250 kWh/t SEC

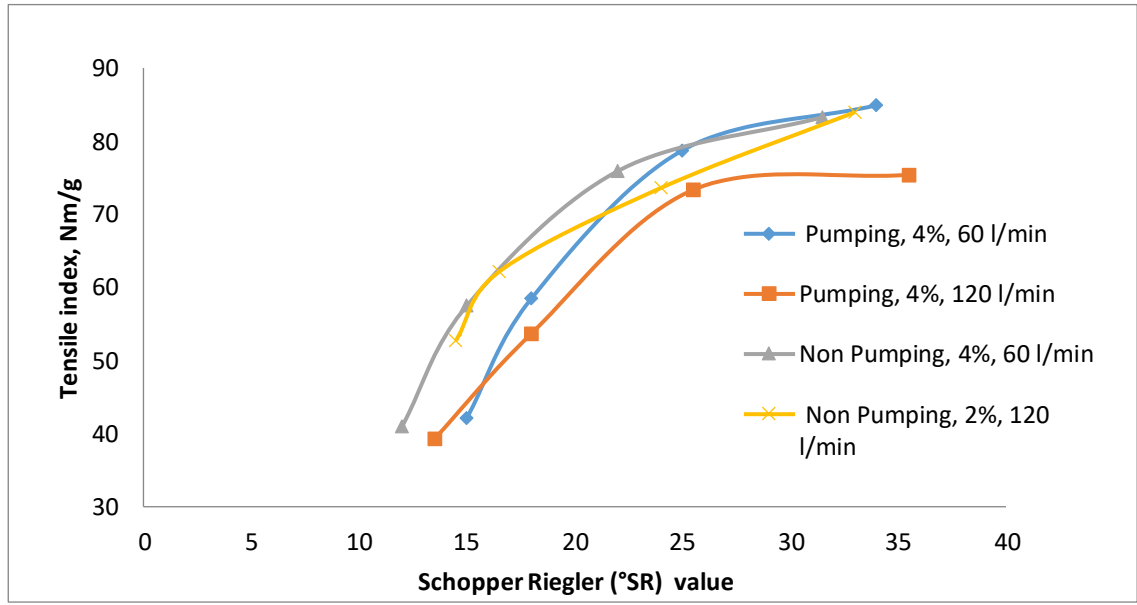


Figure 28: Impact on tensile index (Nm/g) with respect to °SR values

For all the experiments, according to the figure 28, a trend of higher tensile strength index has been noticed with respect to the increase in refining intensity. With the increased SEC value, the refining impact increases. As a result, the fibers present in the pulp experiences fibrillation externally and internally, which creates more bonds among fibers. From the figure, it is clear that with higher SR value higher tensile index is obtained. No drastic change has been observed in tensile strength due to the change in pulp consistency, pumping speed, or pumping direction.

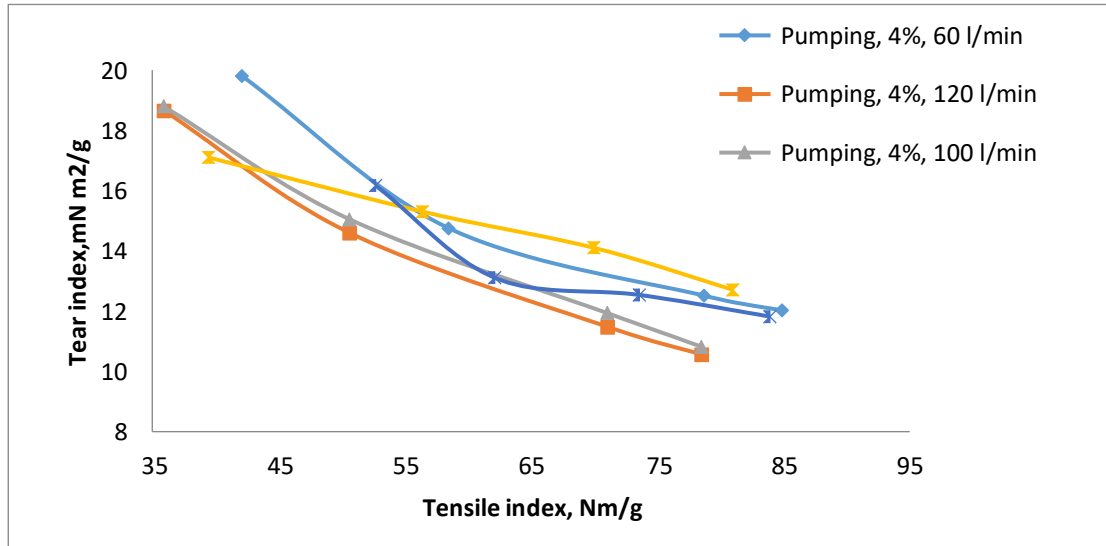


Figure 29 : Relation between tensile strength and tear index

When analyzing the relation between tensile strength and tear strength is has been observed that they are inversely proportional to each other. An increase in tensile strength shows a decrease in tear strength (Figure 29). With the increase of refining intensity, more fibers are impacted on fibrillation, which creates more fiber to fiber bonds and fines, resulting in higher tensile strength. However, the creation of fines decreases the tear strength as weak bonds exist among the fines. No particular deviation has been noticed due to changes in volumetric flow rate, pumping direction, and pulp consistency.

After plotting the graphs between WRV (g/g) and SEC (kWh/t) in Figure 30, it has been seen that with the increase of SEC value, the Water Retention Value increases. For all experiments, an identical type of curve has been observed. As the fibers experience fibrillation, and more fines are formed, the internal fibrillation of fibers increases, and more pores are formed in between fibrils and in fibers. These help the fibers to hold more water than before, resulting in a rise in WRV value. No significant changes have been noted in the water-absorbing capacity with the changes in pumping speed or pumping direction. Variation in pulp consistency also

showed no significant change in water retention value. Refining pulp of 2% consistency in pumping direction at 60 l/min pumping speed showed a notable increase in SR value, which reflects the high intensity of refining, but the WRV value did not show higher value as expected (Figure 30). This can be explained as there have been no changes in the severity of internal fibrillation that is majorly responsible for swelling that provides high WRV value.

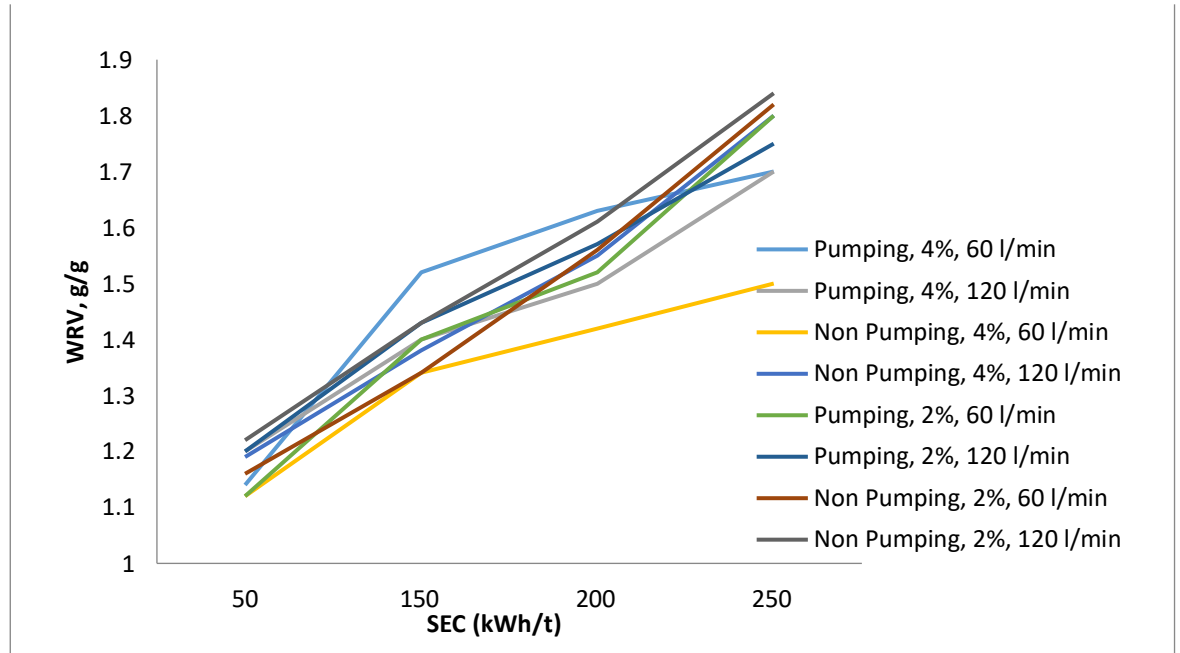


Figure 30: Effect of refining intensity on WRV value in sample

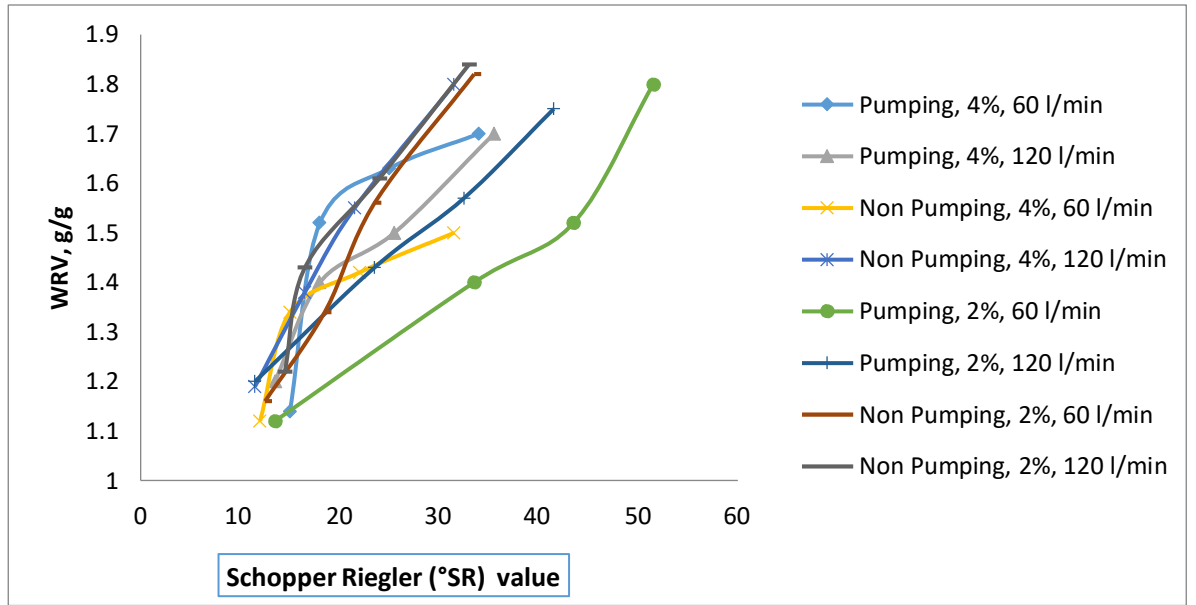


Figure 31: Relation between WRV (g/g) and Schopper Riegler (°SR) value for all samples

With the increase of the °SR value, an increase in WRV has been observed (Figure 31). The reason behind the higher SR value is internal and external fibrillation, which caused a decrease in drainability. This is directly related to WRV value as with the increase of fibrillation, the capability of the fiber to absorb water increases proportionally.

6. Conclusion

The main aim of this research was to investigate and analyze the changes in the physical and optical properties of paper sheets due to changes in some refining parameters. During this study, three pumping speeds have been utilized for 2% and 4% pulp consistency for both pumping direction and non-pumping direction. The refiner from where the refining samples have been collected is ProLab refiner. Finnish bleached pine softwood has been used during the whole experiment. The sample collecting points were achieved when the cumulative specific energy reached 50 kWh/t, 150 kWh/t, 200 kWh/t and 250 kWh/t during refining. These samples were further analyzed to study the impact on physical and optical properties.

From the experimental results has been observed that with the increase of refining intensity from 50 kWh/t to 250 kWh/t, the Schopper Riegler value increased. This degree of change implies that the fibrillation increased along with refining intensity. Interestingly a deviation has been noted for 2% consistency in pumping direction at 60 l/min and 120 l/min compared with other samples results in S-R value.

There has been a slight decrease in ISO brightness with the increase of refining intensity. However, no major change has been observed due to change in volumetric flow rate or pulp consistency or pumping direction.

Air permeability has increased with refining intensity, but for 2% concentrated pulp at 60 l/min flow rate at pumping direction showed 50 % lower air permeability value than other values .

Tear strength, tensile strength, and WRV value have shown increased value with respect to refining intensity, but no significant changes have been notified due to the change in the flow rate of fiber concentration, pulp consistency in solution on pumping direction.

At the end of the study, we controlled the gap of the stator and rotor for increasing the refining intensity manually for 2% pulp consistency in pumping direction for 60 l/min and 120 l/min volumetric flow rate whereas, for the other experiments we controlled the refining intensity by power control. This parameter can be an idea for future research. It can be studied if the increase in refining intensity caused by gap control shows a difference in optical and physical properties compared with the power-controlled refining.

In conclusion, the main purpose has been to analyze if any changes occur in the properties of the paper sheet due to changes in these three parameters. From this study, it can be stated that there have been no significant changes in the properties. Thus, it can be said that changes in these parameters do not impact the changes in paper sheet properties, and further investigation can be done by controlling the refining intensity with a gap control and for power control method.

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