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Comparative Refining Characteristics of Northern and Southern Hemisphere Bleached Softwood Kraft Species

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Comparative Refining Characteristics of Northern and Southern Hemisphere Bleached Softwood Kraft Species

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Submitted in fulfillment of the Academic requirements for the degree of Masters of Sciences in the School of Chemical Engineering (University of Kwazulu Natal)

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Abstract

An experiment was designed to test the hypothesis that each softwood pulp is unique and requires a specific, well defined mechanical treatment to derive its maximum strength potential.

Three bleached softwood Kraft pulps and respective wood samples were sourced from both the Northern and Southern Hemispheres. The raw fibre characteristics of *P. patula* (Southern Hemisphere), *P. menziesii* (Northern Hemisphere) and *P. mariana* (Northern Hemisphere) were measured and compared. The raw pulp sheets were refined at different energies and intensities under controlled laboratory conditions using a 12” single disc pilot refiner. Results were assessed to determine the raw fibre characteristics, optimum refining conditions and the relative refined strength potential for each of the three samples.

Results from anatomy measurements on the three wood samples differed significantly. *P. patula* exhibited a relatively high proportion of springwood growth in the early growing years. As the *P. patula* aged and formed mature wood there was a significant increase in the frequency of latewood formation. This was characterized by an abrupt and significant increase in the wall thickness, beyond that of the two Northern softwood samples. When the cell wall thickness increased, the lumen width and fibre diameter of the *P. patula* decreased significantly, yielding extremely coarse, stiff fibres.

The Northern *P .mariana* and *P. menziesii* samples were characterized by a relatively consistent transition between high and low densities from the pith to the bark of the tree. The Southern *P. patula* had a unique density trend with an increasing frequency of high density peaks indicative of an increased latewood formation from the pith to the bark.

The slower growing Northern *P. menziesii* and *P. mariana* samples did not have as clear a differentiation in fibre characteristics between juvenile and mature wood formation. The Northern samples did however contain a significantly higher proportion of juvenile latewood growth than the *P. patula*. However, the difference in fibre characteristics between earlywood and latewood formation was not as significant as that noted with the Southern *P. patula*

Fibre morphology measurements on the unrefined bleached Kraft pulps also revealed significant differences between the three samples. The average MORFI LAB01 results on the *P. patula* defined fibres with a high coarseness and relatively low number of fibres per gram of pulp. The extremely coarse latewood fibres formed during mature wood growth being the most likely

source. However, *P. patula* was also characterized with a high fibre flexibility and large lumen, characteristics consistent with earlywood fibres. The Pulmac Z-Span 3000 was used to define the individual fibre strength, when due consideration was given to the number of fibres per gram, the corrected Pulmac results suggested *P. patula* had the strongest fibres.

When refined, using a standard disc refining programme, *P. patula* exhibited a fast freeness development. Conventional thinking would suggest that this was an indication of a weaker fibre. However, this species had a robust morphology compared to the Northern Hemisphere woods. The theory developed in this dissertation suggests that the effect of coarseness and the concomitant number of fibres per gram plays a significant role. These two parameters are not included in the “traditional” refining calculations. The applied refining load and intensity was calculated on the flow of the pulp passing through the refiner. The calculation did not consider the actual number of fibres present in that specific volume. The implication is that when a fixed refining load is applied to a pulp with coarse fibres there may be a higher effective load on those fewer fibres (resulting in fibre cutting and fines generation). In this case, the Northern samples have a comparatively low coarseness and more fibres per gram with each receiving a smaller portion of the total load and intensity.

In terms of refined pulp properties, *P. patula* developed a relatively high bulk and tear index consistent with coarse, rigid fibres. The Northern *P. mariana* and *P. menziesii* samples produced a pulp with good tensile properties, consistent with a greater number of finer, collapsible fibres with a higher relative bonding area.

P. patula fibres were extremely heterogeneous in nature containing the smallest relative lumen width during latewood formation and the largest lumen width during earlywood growth. As a result, *P. patula* contains extremes of both fine and coarse fibres in the same blend. It may be more beneficial for this species than the others to improve both the tear and tensile properties through fibre fractionation with appropriate development of the separate accepts and rejects streams.

In terms of fibre development, low intensity refining parameters maximized the tensile strength of the Southern *P. patula*. The Northern *P. mariana* and *P. menziesii* samples had a greater number of fibres per gram of pulp requiring both a higher refining energy and intensity to develop the pulp to its maximum potential. To develop optimum tear results, high intensity refining, with a relatively low specific energy provided optimum results for all 3 samples.

Results confirmed that there were significant differences in the fibre morphology both between the three different species and between the two Hemispheres. There was strong evidence that the fibre characteristics dictate the manner in which a fibre responds to refining which in turn determines the relative contribution to specific refined pulp properties. It may be possible to use fibre characteristics to determine the appropriate refining parameters for optimal fibre development which will enhance the value of the end product.

To derive the maximum strength potential from *P. patula* pulp samples, it is recommended that further studies investigate Hydracyclone fractionation and the concomitant benefits of refining the separate streams. Furthermore, a separate study on fibre morphology and refining characteristics of the same species grown in both the Northern and Southern Hemisphere would provide valuable insight.

Preface

The laboratory studies carried out in this investigation were performed at the Sappi Technology Centre located at the Innovation Hub in Pretoria, South Africa. The author, employed by Sappi was registered with the School of Chemical Engineering at the University of Kwazulu Natal, Durban from January 2007 to December 2009. Dr. Charlie Clarke, head of the Sappi Technology Centre and Mr. I. Kerr from the University of Kwazulu Natal supervised this study.

Declaration

I, the undersigned hereby declare that the work contained in this dissertation is my own original work and has not previously in its entirety, or in part, been submitted in any form for any degree, or diploma, to any tertiary institution. Where use has been made of the work of others it is duly acknowledged in the text.

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B. Palmer Date

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I. Kerr Date

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List of Abbreviations

NBSK	Northern Bleached Softwood Kraft
SBSK	Southern Bleached Softwood Kraft
SEC	Specific energy control
SRE	Specific refining energy
SSL	Specific Surface Load
SEL	Specific Edge Load
SEL_0	Reference Specific Edge Load
kWh/t	Kilowatt hour per ton of pulp
CSF	Canadian Standard Freeness
ºSR	Degree Schopper Riegler
MFA	Micro-fibril angle
FS	Fibre Strength
FB	Fibre bonding
gsm	Grams per square metre
PLC	Programmable logic controlled
CCD	Charge coupled device

Glossary

Angiosperm: Any large group of plants that produce flowers, they produce seeds from ovules contained in ovaries and the seeds are enclosed by fruits.

Bark: The outer covering of stems and branches of trees.

Beating / refining: Mechanical treatment of fibres to increase surface area and flexibility of pulp fibres. This promotes bonding when dried.

Bleaching: The process of purifying and whitening pulp by chemical treatment to remove coloring material so that the pulp takes on a higher brightness.

Coarseness: Weight per unit length of fibres (mg/m)

Consistency: Weight percentage of oven dried fibre in a fibre and water mixture.

Chemical pulp: Pulp obtained from the chemical cooking or digestion of wood or other pulp material

Digester: Reaction vessel in which cooking process takes place

Earlywood / Springwood: The wood of a tree produced early in the growing season for each year. It is characterized by larger widths and thinner cell walls than that produced later in the growing season which is called Summerwood or Latewood

External Fibrillation: Partial detachment of fibrils from the outer layer of a fibre

Fibre brushing: A gentle, low intensity refining action to fibrillate fibres

Fibre cutting: A harsh high intensity refining action that cuts fibres

Fibrils: Thread like elements unraveled from the walls of native cellulose fibres

Fines: Small fine particles smaller than 100 μm in length

Floc: Fibre aggregates in pulp slurries

Freeness: A term used to define how quickly water is drained from the pulp. A pulp with a high freeness will drain rapidly whereas pulp with a low freeness drains slowly

Gymnosperm: Cone bearing types of trees whose seeds are not enclosed in an ovary, used as a source of pulpwood, often referred to as conifers.

Hand sheets: Circular sheet formed on a fine screen from a pulp suspension of fibres

Hardwood: Wood formed from trees of Angiosperms, usually with broad leaves. Hardwoods grow faster than softwoods but have shorter fibres than softwoods

Head-box: A flow chamber located at the head of a fourdrinier paper machine. It receives the diluted stock slurry and regulates the head or level to provide uniform and even flow across the width of the wire (forming section)

Hemicellulose: The alkali-soluble, non cellulosic polysaccharide portion of the wood cell wall

Internal fibrillation: Refers to the loosening of internal bonds within a fibre resulting in fibre swelling

Juvenile Wood: The portion of the wood structure of a pulpwood tree that is formed during the early years of life and differs from the older structure by having short, weaker and less dense fibres – also termed corewood

Kraft pulp: Pulp obtained using the Kraft pulping process. In this process chemical pulping is achieved by using solutions of Sodium Hydroxide and Sodium Sulphide.

Latewood: The portion of a tree that grows during the late summer and autumn seasons of the year. It is a slower growing wood and produces cells with thicker walls and narrow cavities – sometimes referred to as summerwood

Lignin: A complex constituent of the wood that holds the fibres together

Lumen: The centre void portion of a fibre

Mature wood: The portion of the wood structure of a tree that is older and closer to the outer surface.

No-load Power: Power required to simply rotate the refiner plates with the normal pulp flow.

Pilot refiner: Equipment used to mechanically treat fibres on a laboratory scale

Pith: The central part of stems or branches of trees

Porosity: That property of the paper and paperboard related to the ability of fluids to pass through them. It is an indication of the size, shape and distribution orientation of the pores in a sheet and compactness of the fibres

Refining intensity: This relates to the how hard the refiner bars hit the fibres (Ws/m)

Round-wood: Logs delivered to the pulp mill, with bark attached and cut to specified lengths

Softwood: Wood obtained from evergreen, cone bearing species of trees, such as pines, spruces, hemlocks, etc, that are characterized by having needle shaped leaves

Shives: Small bundles of fibres that have not been completely separated during pulping

Tensile strength: The resistant property of a sheet to pull or stress produced by tension. It is expressed as a force per unit width of a sample tested to the point of rupture

Tear strength: The resistance of a paper sheet to tearing. It is usually measured by the force required to tear a strip under standardized conditions.

SRE: Specific Refining energy, relates to the effective amount of energy that has been applied to the fibres after subtracting the no-load power of the refiner. Units of measure are kWh/t of pulp

SEL: Specific edge load – a term used to describe how the energy is applied to the fibre, ie the harshness of the impact as the bars hit the fibre. Units of measure are Ws/m

SSL: Specific surface load, is another means of describing the refining intensity calculated as the Specific edge load divided by refiner bar width factor (Watt-Sec/m2).

CSF: Canadian Standard Freeness. A measure of the rate of drainage of a dilute pulp suspension expressed in terms of freeness.

SR: Schopper Riegler. A measure of pulp wetness tested in a similar manner to CSF using different apparatus

Microfibril angle: The winding angle of cellulose molecules in the dominating S2 layer of the secondary cell wall of Softwood tracheids.

Compression wood: Compression wood or reaction wood as it is also known forms below the bent part, pushing it up. Compression wood is rich in lignin. As a rule, compression wood is undesirable in any commercial application, primarily as its mechanical properties are different: it breaks the uniformity of timber

Acknowledgements

My greatest thanks and appreciation goes to my family whose unconditional support and patience allowed me the time to complete this study.

I would like to thank my colleagues, Justin Ngobese and Mershan Naidoo at the Sappi Technology Centre who eagerly assisted with the pilot refining and fibre testing. Your dedicated approach and attention to detail was highly appreciated.

My thanks and appreciation also goes out to Tammy Bush at the CSIR who assisted with anatomy and densitometry testing and to Mr. Iain Kerr who supervised the study.

To my manager, Dr. Charlie Clarke, your guidance kept me focused and motivated. Thank you for providing this opportunity and giving me the freedom to explore

CHAPTER 1

1.1 Introduction

Refining or beating of pulp involves the application of mechanical forces to modify fibres so that they can be formed into paper or board with the desired properties (Lumiainen, 2000). The efficient and optimized use of low consistency refiners in fibre processing therefore has the potential to add tremendous value to paper and board products.

For most paper and board grades, refining is the largest single, controllable, factor determining the finished product quality (Joy, *et al*, 2001, p.1)

There are many different grades of pulp that require refining. Market pulp grades are broadly classified into two categories as either hardwoods or softwoods with refining parameters that are suited to each.

This study focuses on softwood refining. The felling age of a pulpwood softwood tree is dependant on the place where the trees are grown but generally ranges from 12 years to 100 years. Once felled, it takes hours to process the wood into a usable pulp fibre and only a second in the refiner to irreversibly modify the fibre characteristics. The digester and bleaching operations concentrate the fibrous material in preparation for the required mechanical treatment in the refiner. It could be said that the final refining operation determines the true value of the fibre that has been growing for up to 100 years.

Market pulps are further categorized into “commodity” pulps and these are loosely defined according to the region of origin, level of bleaching, wood type and pulping process. Northern Bleached Softwood Kraft pulp (NBSK) and Southern Bleached Softwood Kraft (SBSK), are commercially accepted “prime” grades of market pulp (Button *et al*, 2005). Beyond considering pulp in broad commodity classes the paper industry has given morphology little consideration. (Nanko, H. *et al*, 2005, p.35). Unfortunately, the commodity pulp classifications do not include all the all the specific details that are of interest to the papermaker. Some important aspects to consider are, the tree’s graphical location, proportions of different species in the grade or, the ratio of sawmill chips to round-wood. These factors all have a significant impact on the respective refining characteristics and potential value added to the final paper quality.

In the paper-mill there are two specific control parameters used to monitor and adjust the refining forces applied to a fibre. The first parameter being the specific energy consumption (SEC) and the other, the specific edge load (SEL). Both parameters were formulated in the 1960's and, 50 years later are still synonymous to refining systems worldwide. Together, the two theories provide a simple tool for the control of a refiner but they do not provide a direct measure of the forces applied to the fibre (Joy *et al*, 2001, p.1).

In general, compared to hardwoods, softwoods are usually treated with a high refining intensity and a high specific energy to achieve the desired freeness target. The refining intensity relates to the energy level of each fibre impact by the refiner bars and the specific energy relates to the number of fibre impacts. Historically, refining recipes for Northern softwoods have been widely applied to the Southern softwood grades without considering the nature of the fibre and the vastly different growing conditions. It is proposed that this generalized approach does not provide for optimum fibre development.

In the paper mill, the degree of refining is generally adjusted according to the drainage characteristics of the refined pulp. Two measurements are commonly used, either the Canadian Standard Freeness (CSF) or Schopper-Riegler (ºSR). In many cases, the refined freeness target is easily achieved but often at the expense of optimum fibre development. This is primarily due to an incorrect force being applied to the fibres which generates fines and quickly reduces the freeness to the set target. In some cases, the refined fibres may deliver improved paper properties but additional development could have been possible through a more appropriate refining action.

It is hereby proposed that the fibre characteristics of each individual raw pulp grade should first be established in order to understand the refining characteristics over a wide range of refining conditions. Due consideration should be given to all the refining theories and relevant refined pulp properties to provide for optimum refined fibre development at the required freeness target.

There are many softwood species grown and processed globally. Each species differs in respect to its individual fibre characteristics. Significant differences also exist between the same species grown in different areas and elevations. It is proposed that the fibre morphology of a pulp sample determines the manner in which a fibre will respond during refining.

This study evaluates the fibre morphology of three bleached softwood Kraft samples produced from Softwood trees grown in different regions of the world. These include, *P. patula* (Southern Hemisphere), *P. menziesii* (Northern Hemisphere) and *P. mariana* also from the Northern Hemisphere. Fibre characteristics from both wood and pulp samples are related to the refining characteristics and the resultant refined pulp strengths to determine the contribution of Fibre morphology to the final paper quality.

CHAPTER 2

Literature Review

2.1 Softwood as a raw material

Wood is a seed plant categorized into two types, Angiosperms and Gymnosperms. Angiosperms produce seed in encapsulated vessels and are hardwoods. Gymnosperms (softwoods) are much older in the fossil record and produce seed outside of the flower. Hardwoods have vessels for transporting water and softwoods do not. Softwoods have bordered pits on the sides of their fibres and hardwoods do not. Softwood fibres are longer, wider and more flexible than hardwood fibres (Biermann, 1996),

In South Africa, softwood trees can be harvested for pulpwood after 14 years of growth, compared to 50-100 years for softwood trees grown in the Northern hemisphere (Pamsa, 2002).

In order to separate fibres in the wood, the trees are first chipped. The chips are then fed to a cooking vessel where a combination of temperature, pressure and chemicals are used to dissolve the lignin binding the fibres.

The cellulose fibres have their own unique structure with a layered cell wall (Figure 2.1).
The primary cell wall is thin (approximately 0.05µm – Smook, 1992) and has a high amount of lignin, hemicelluloses and pectin, the cellulose micro-fibrils within this primary wall show a low crystallinity without any definite orientation. The secondary cell wall is thicker with a high cellulose content and little lignin, the cellulose micro fibrils are deposited onto sub-layers (S1 ≈ 0.1-0.2µm, S2 ≈ 2-10µm and S3 ≈ 0.1µm) of varying orientation (Puera, 2007). The centre of the fibre is hollow and is referred to as the lumen.

With refining, most of the mechanical activity is applied to the secondary wall and more specifically the S2 layer containing the majority of the cellulose.

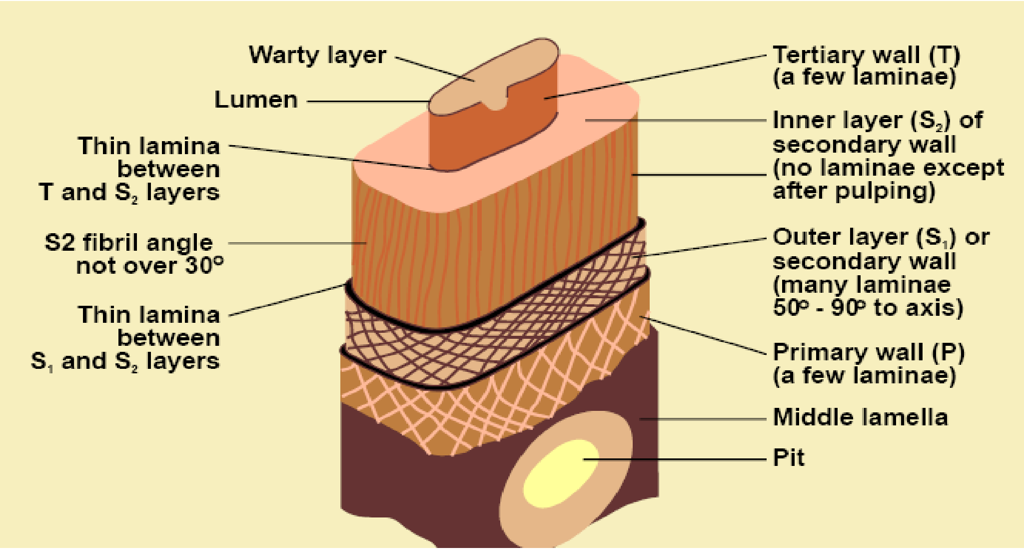


Figure 2.1: Sketch of a typical fibre (Bradley, 2003)

2.2. Juvenile and mature wood.

In the early years of growth, trees produce juvenile wood, a zone of wood extending outward from the pith. During this early growth period, the characteristics of the wood produced from year to year in each successive growth ring change markedly. During a "transition" period from 5 to 20 years of age, characteristics of the wood produced gradually improve to form thicker cell walls until they become relatively constant. This material is known as mature wood.

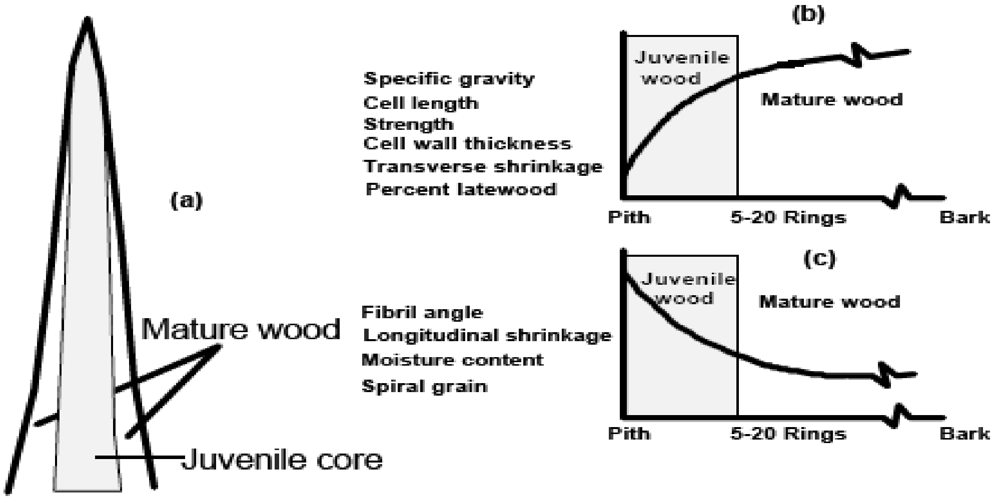


Figure 2.2: Effect of juvenile wood on physical and mechanical properties (Kretschmann, 1998)

(a) Juvenile core located in interior of tree bole;

(b) Properties that increase from juvenile to mature wood; and

(c) Properties that decrease from juvenile to mature wood.

In conifers, juvenile wood, compared with mature wood, has lower strength, higher longitudinal shrinkage, lower specific gravity, more compression wood, thinner cell walls, greater fibril angle, lower cellulose content, higher lignin content and a lower percentage of latewood (Kretschmann, 1998)(Figure 2.2).

All trees have juvenile wood, but proportionally this is a small amount when the timber supply is primarily old-growth trees grown in natural forest conditions. In these trees, the juvenile wood core is small because early growth is suppressed by competition from surrounding trees. Additionally, the percentage of juvenile wood in the total volume is small because larger trees are harvested (Kretschmann, 1998*).* On the other hand, plantation grown trees such as *P. patula* in the Southern Hemisphere grow rapidly and are harvested at a younger age so that the juvenile portion of the tree is significant.

2.3. Earlywood and latewood

Each annual growth ring contains earlywood (sometimes called springwood) and latewood (sometimes called summerwood). Earlywood is laid down in the early part of the growing season and is characterized by large cells with thin cell walls (Figure 2.3). Latewood is characterized by small cells with thick cell walls. Earlywood is low density wood designed for conduction of water and latewood is high density wood for strength to support the tree (Biermann, 1996). Slow growing softwoods such as the *P. mariana* and *P. menziesii* have a high proportion of latewood. In terms of fibre strength, latewood is known to have a lower micro fibril angle in the S2 layer. Fibres with a lower fibril angle have higher fibre strength (Biermann, 1996).

Wood densitometry tests on *P. patula* (Naidu, 2003) indicated a low density during juvenile growth attributed to the high proportion of thin walled cells and also to the relatively small number of latewood cells, the density however increased as the tree aged during mature wood formation indicative of an increased proportion of latewood growth.

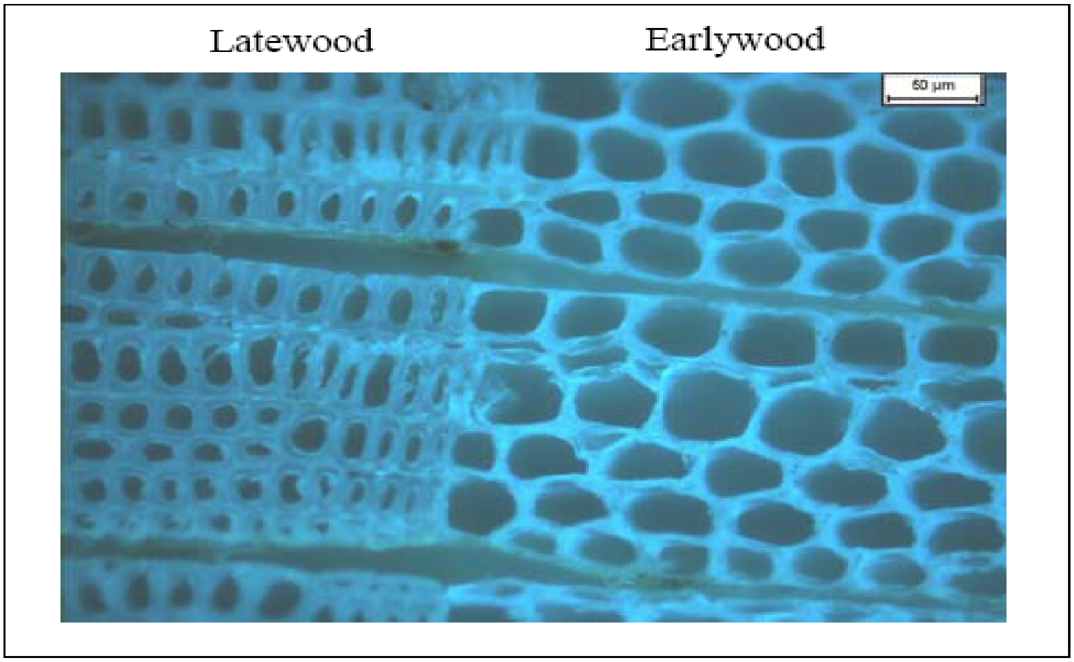


Figure 2.3: Image showing early-; late wood boundary (scale bar = 50µm) (Naidu, 2003)

2.4 Fibre Strength

The individual fibre strength is a characteristic of the fibre wall thickness and overall fibre diameter. Paper strength is defined more by the inter-fibre bonding and this is achieved through fibrillation (release of the micro-fibrils in the S2 region) and fibre flattening. In both cases a greater surface area of contact between fibres increases paper strength.

There could be a trade-off between the strength of the individual fibres and the strength of inter-fibre bonding. In unrefined pulp, the “weak” link in the paper is the strength of the fibre-fibre bond. In pulp which is over refined, the “weak” link is the strength of the individual fibres.

The accurate measurement of the strength of individual fibres is a complex exercise mainly due to the size and orientation of the fibres, fibre deformations, and shear stresses applied in the testing method. The use of the Pulmac Z-span test measurement has come under scrutiny (Ramezani and Nazhad, 2004) however the results do suggest some good correlations with the paper strength. The best available technique is the Pulmac Zero span tensile test which provides an inferred fibre strength measurement. According to Cowan the Pulmac PQ system is a reliable, rapid measure of pulp quality. However, when comparing Northern and Southern pulps, the relative coarseness and subsequent number of fibres per gram of each pulp must be accounted for to give a relative fibre strength measurement.

To test for fibre strength, the wet zero span value is determined by the number of fibres clamped, the orientation of the fibres relative to the direction of loading and the average strength of the individual fibres. In the laboratory, maintaining constant basis weight and random fibre orientation means that the changes in the wet zero span value can only be due to changes in the strength of the fibres. (Cowan, 1989)

Fibre Strength = Avg. of 12 Wet zero spans * (Actual basis weight / Target basis weight)

The orientation of micro fibrils in cellulose is characterized by the micro fibril angle (MFA), which is the angle between the micro fibrils and the longitudinal cell axis (Figure 2.4). The MFA in the S1 and S3 sub layers varies between 40 degrees and 120 degrees. The mean MFA in the S2 layer is considerably smaller and in mature wood the micro fibrils in this layer are almost parallel to the cell axis (Puera, 2007).

Fibre strength has been examined in terms of the MFA. It has been found that the fibril angle varies strongly with the position in the tree. In particular, the Juvenile wood in the pith generally has a much higher fibril angle than mature wood (French et al., 2000). The prevailing paradigm is that the mean MFA is negatively correlated to the tensile strength (Wathen, 2006). In recent studies, (Puera, 2007) the role of the MFA distribution in determining the tensile properties of normally grown Norway spruce wood with a small mean MFA was found to be less dominant than what has been reported before by using samples with higher mean MFA. In 2005, Drummond suggested that the fibril angle imparts directional behavior, affecting the swelling and shrinkage and directional strength properties.

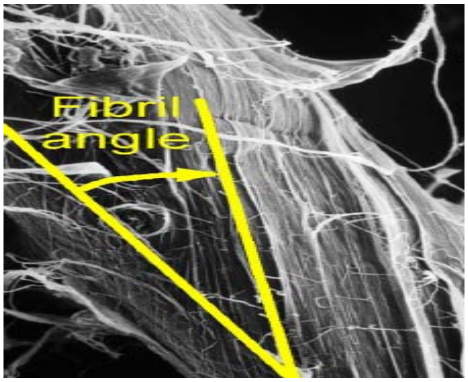


Figure 2.4: Fibril angle – angle between the long axis of the fibre and S2 fibril direction (Drummond, 2005)

Page *et al., (*1972) pointed out that the fibril angle of latewood tends to be lower than that of earlywood in Spruce. It was also suggested that latewood fibres were stronger than the earlywood fibres which has been reported in literature with other species as well (Biermann, 1996).

2.5 Fibre morphology and the refining effect

The successful conversion of pulp into a marketable product is linked to a combination of the original fibre properties. As a result of the great variety of fibre morphologies within the softwood genera, the physical properties of a sheet of paper from one species can vary significantly from a similar piece of paper from another species, although process conditions may have been identical (Horn, 1974).

This raises the question, what are the ideal fibre properties for paper products? The answer is dependant on the final product and the selection of an appropriate fibre blend. Due consideration should also be given to the logistical and economical factors such as the availability of wood supply and production costs. As the paper requirements change, so do the preferred characteristics of the pulp fibres (Ellis and Rudie, 1991).

The actual classification of each fibre type is made possible through the use of modern instruments using mainly image analysis to measure characteristics such as the fibre length, fibre width, coarseness, fibre kink, fibre curl, cell wall thickness and fibre strength. The impact of each of these measurements on the final quality of the paper is now receiving more and more focus to the point where these instruments are being set-up on line to control and optimize the quality of pulp fed to the paper machine.

2.6 Effects of fibre morphology on paper properties

Often there is more than one definitive fibre characteristic working together to affect a significant change in a single paper property, (Horn, 1974).

The wall thickness is a key parameter defining the flexibility and collapsibility of a fibre. Thin walled fibres are more flexible with a greater propensity to intertwine with adjacent fibres increasing the number of fibre/fibre contact points; they are also more collapsible increasing the relative bonded area providing for a higher tensile strength, elastic modulus, burst strength and fold.

Another aspect critical to the degree of bonding is fibre length. Long thin walled fibres have a greater likelihood of bonding with other fibres than short thick walled fibres. Thick walled fibres do not collapse readily resulting in a higher bulk, tear and porosity but low burst strength, tensile strength and fold (Rampersadh, 2005).

Studies conducted by Horn (1974) showed that the cell wall thickness exerted considerable influence on the tensile properties. It was suggested that 82% of the tensile variation is accounted for by the cell wall thickness in the unbeaten fibre and 76% for the beaten fibre (Figure 2.5).

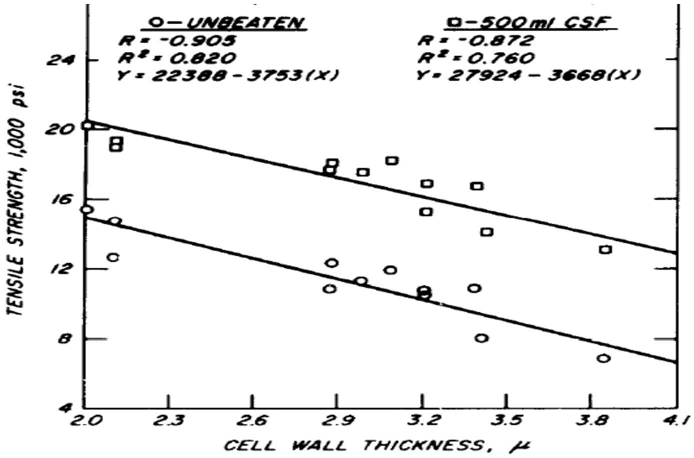


Figure 2.5: Relationship of tensile strength to cell wall thickness of unbleached pulp sheets from unbeaten and beaten Kraft pulp fibre (500 ml CSF) (Horn, 1974)

The direct relationship between wood density and cell wall thickness (Figure 2.6) and the number of fibres per cubic centimeter (Figure 2.7) has several implications, not only to paper strength but to economic considerations. For instance, papers from fibres with thick cell walls are lower in bursting and tensile strength.

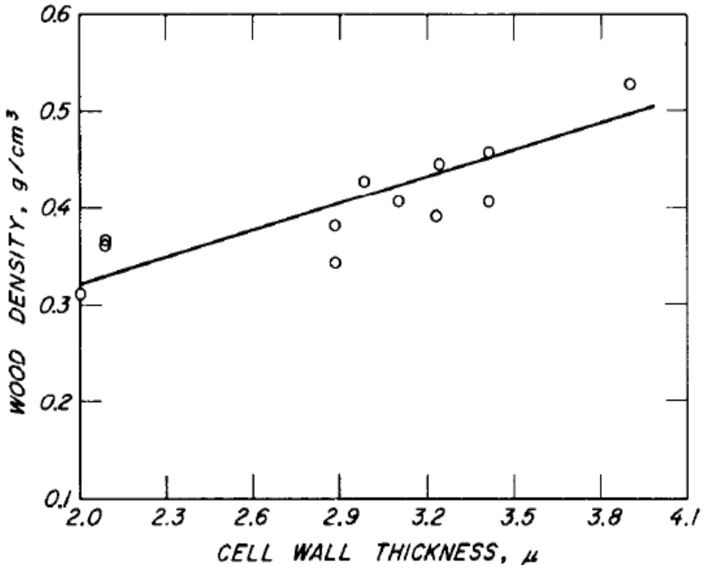


Figure 2.6: Relationship of cell wall thickness to the wood density of 12 Western U.S. softwoods (Horn, 1974)

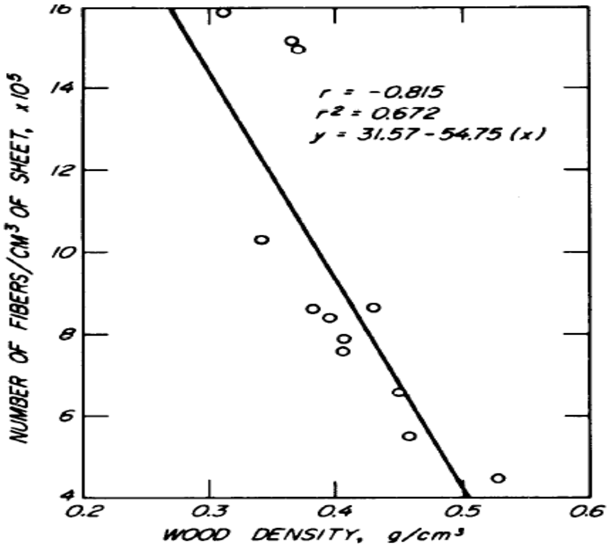


Figure 2.7: Relationship of number of fibres per cubic centimeter of pulp sheet to the wood density of 12 Western U.S. softwoods
(Horn, 1974)

As shown, cell wall thickness has a positive correlation with wood density and it is those species with thick walled fibres that contain fewer numbers of fibres per sheet volume. Therefore, papers of fibres from high density woods will have fewer fibres for the same weight of paper than papers from species of low density. Because paper is commonly made on a weight basis, the importance of the number of fibres per unit volume is evident. For instance, increasing wood density to increase fibre yield per acre or yield per digester or both may not always be most advisable. If the resultant fibre has to be refined at greater power consumption or the paper produced at higher-than-normal basis weights to obtain adequate strength properties, it would seem that the effects of fibre morphology on the manufacture of paper should be part of the overall consideration for obtaining optimum performance (Horn, 1974)

In earlier studies, a long fibre length was seen to be the predominant driver behind high tear measurements. A more recent study has shown that the maximum tear strength of paper depends on the product of fibre length and the square of the individual fibre strength (Karenlampi, 1996). Other studies suggest that for unbeaten pulps the tearing resistance is primarily influenced by the fibre cross sectional area and by cell wall thickness but for beaten pulps, the fibre coarseness accounts for the greatest variation in tear (Horn, 1974).

Fibre coarseness is defined by the weight per unit length of a fibre and is dependant on the fibre diameter, cell wall thickness, density and fibre cross section (Ramezani and Nazhad, 2004). Based on these fundamentals it is not surprising that fibre coarseness also has a significant effect on the final paper structure (Figure 2.8). Fibres with a high coarseness will have fewer fibres per gram of pulp limiting the available fibre to fibre Hydrogen bonding sites.

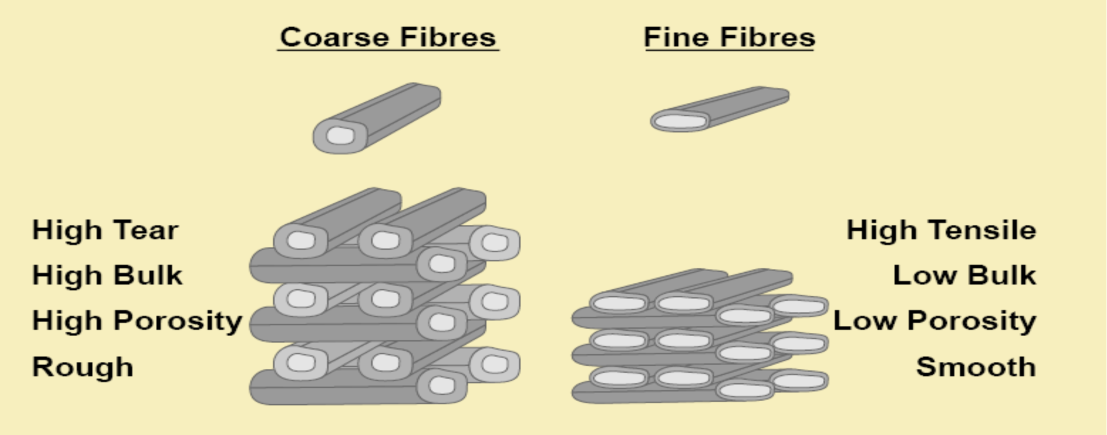


Figure 2.8: Coarse vs. fine fibres (Bradley, 2003)

2.7 The influence of refining on papermaking

Refining is a mechanical action on the fibres designed to strip the outer wall, release micro fibrils from the S2 layer and assist in the collapse of the fibre lumen so they form a flat interlinked matrix as the basis of paper or board with the desired properties (Lumiainen, 2000). The saying that “paper is made in the beater” (Glasl, 1971) is becoming more of a reality as the papermaker is forced to accept a wider variety of pulp grades.

One of the principal refining objectives is to increase the flexibility of the fibre cell wall to promote increased intra-fibre contact area. This is referred to as internal fibrillation (Figure 2.9), generally described as the breakage of cross-links between micro fibrils (Wang *et al*, 2007). The mechanical refining action causes some of the bonds within the cell wall to rupture resulting in osmotic and entropic forces and fibre swelling.

To produce internal fibrillation, fibres need to be turned over and treated at various points when undertaking compression (Kerekes, 2005). This finding was supported with results in a separate study (Wang *et al*, 2007) where refining results showed the Lampen mill developed internal fibrillation at a low consistency but not at a high consistency. Wang agreed that fibres need to be turned over in refining and compressed from different directions in order to disrupt their internal structure and break the cross-links between micro fibrils (Wang *et al*, 2007). Internal fibrillation occurs in the early stage of refining and results in denser paper with a significant increase in the tensile and tensile stiffness.

Another important refining objective is external fibre fibrillation. This occurs later in the refining stage after internal fibrillation and relates to the fine cellulosic hairs being raised on the fibre surface by the abrasive refining forces. These exposed hairs further promote the formation of Hydrogen bonds between adjacent fibres and increases the total surface area available for fibre to fibre bonding. External fibrillation does not appear to have a major effect on the tensile result but it does improve the development of Scott Bond (Wang *et al*, 2007)

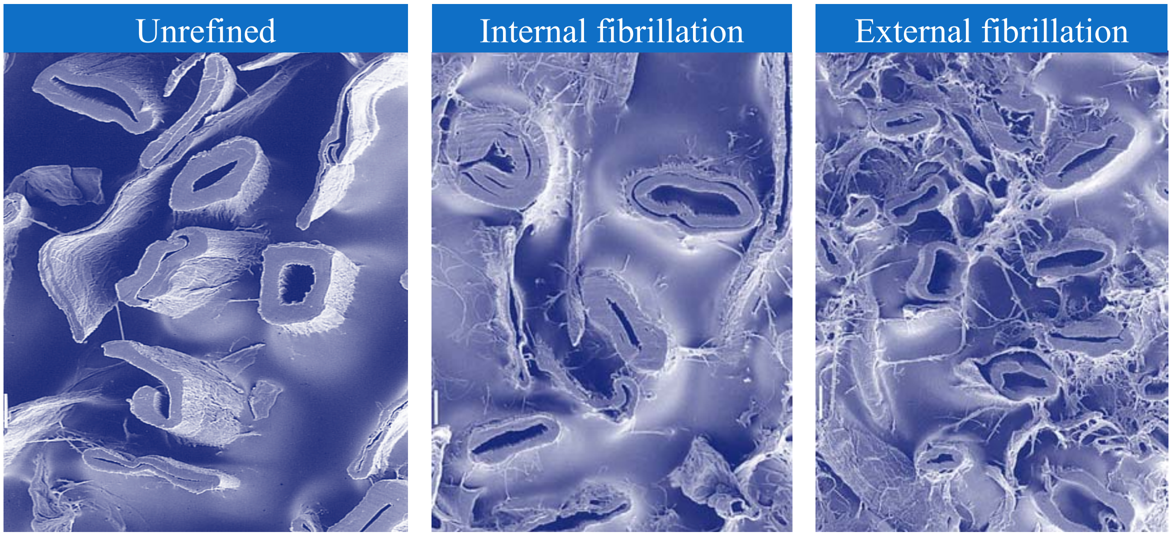


Figure 2.9: The effect of refining has on fibres

Refining produces desirable and undesirable effects because in the process of fibrillating and collapsing the fibres some fibre cutting occurs. It is not possible to develop fibres without some cutting but the objective should be to maximize the beneficial effects while minimizing the undesirable ones. At the very least, refining increases the dewatering resistance due to fibre shortening and fines generation (Glasl, 1971).

When paper is formed, the individual refined fibres come together to form a tangled web. The fibres should lie in a flat plane and are attached to one another at many points of contact where one fibre lies across another fibre. The strength of the paper is largely determined by the strength of the attachments at these fibre crossing points. The strength of the individual fibres also contributes to the strength of the resulting paper but it is often the case that paper fails when the fibre-fibre bonds fail (www.finebar.com, 2001).

2.8 Refining mechanism

The evolution of refining equipment has progressed from the cylindrical type batch beater, conical Jordan, steep angle Claflin to the double disk refiner in common use today. In this assessment refining was carried out using a single disc refiner (LaCroix, 1990).

It is reasonable to assume that refiners treat multiple fibres at a time rather than as individuals because the typical gap size between rotor and stator is 0.1-0.2 mm. This gap is several times the thickness of an individual fibre. Evidence that refiners apply forces to fibres as mats comes from direct observations in the refining zone (Bachelor *et al*, 2006,).

During refining, fibre flocs are treated in the presence of water by rotating metallic bars. The plates or fillings fitted to the refiners are grooved so that the bars that treat the fibres and the grooves between bars allow fibre transportation through the refiner. Figure 2.10 demonstrates the refining stages. At first, fibre flocs are collected on the leading edges of the bars. During this fibre pick-up stage the consistency is typically 3%-5% and the fibre flocs comprise mainly water.

When the leading edge of the rotor bar approaches the leading edge of the stator bar the fibre floc is compressed and receives a strong compression impact. As a result, most of the water is squeezed from the floc. Simultaneously, short fibres with low flocculation ability are probably peeled off and flow into the grooves between the bars. Only those fibres remaining in the floc are compressed between the metallic bar edges and are refined.

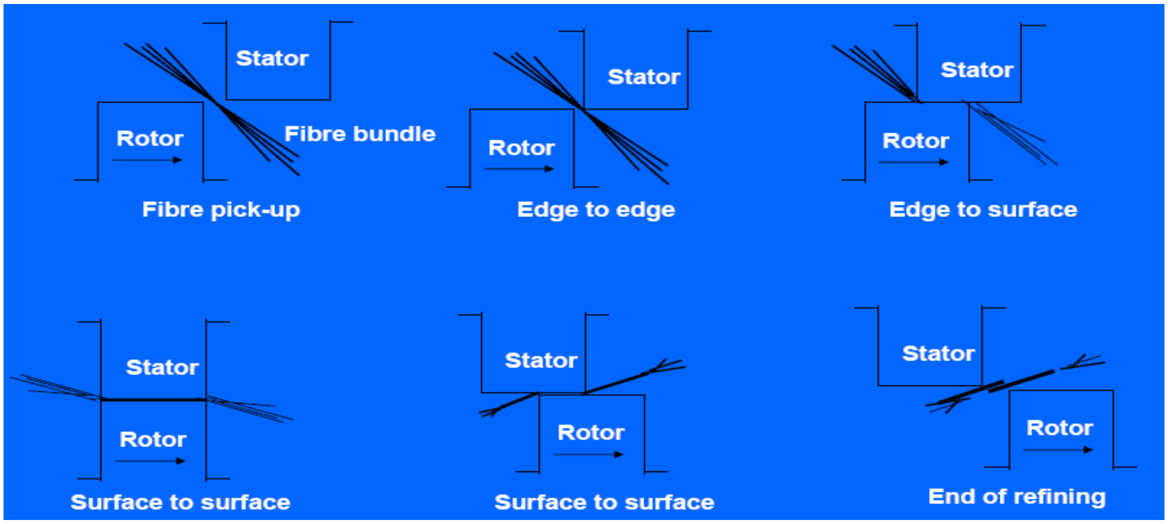


Figure 2.10: Fibre treatments within a refiner

After this, both leading edges slide along the fibre floc and compress it against the flat bar surface. The average gap clearance is 100 µm which corresponds to the thickness of 2-5 swollen fibres or 10-20 collapsed fibres. Most of the refining is performed during this edge to surface stage when the actions on the fibres are mechanical impacts from the bar edges as well as friction between fibres within the floc. This stage continues until the leading edges reach the trailing edges of the opposite bars. After the edge to edge surface stage the fibre bundle (floc) is still pressed between the flat bar surfaces until the tailing edge of the rotor bar has passed the tailing edge of the stator bar.

In theory, there is only one refining impact on each fibre bundle and the length of the refining impact depends on the width and intersecting angle of the bars.

When the rotor bars move across the stator bars there are strong vortex flows in the grooves between the bars which helps position the fibre flocs on the bar edges during the fibre pick-up stage. If the grooves are too narrow or plugged, fibres or fibre flocs cannot rotate in the groove and do not get positioned on the bar edges and as a result pass through the refiner without any impacts (Lumiainen, 2000). .

2.9 Refining theories

One of the best known and most widely used theories is the “specific edge load theory” (Lumiainen, 2000). In 1958, Wultz and Flucher introduced the term “refining intensity” as the quotient of effective refiner load and edge length per second. Then Brecht and Siewert defined the “refining intensity” term as specific edge load in 1966. This theory comprises two factors which describe how much the fibres are treated and how intensively they are hit. The amount of refining is calculated from the specific energy consumption, (SEC) also termed the specific refining energy (SRE), in net [kWh/t] as shown in Equation 1 and the nature of refining is evaluated by the specific edge load, (SEL) describing the intensity of the refining impacts in [J/m or Ws/m] as shown in equation 2.

$SRE = (Pt-Pn = Pe) / (F * C)$ (**Equation 1**)

$SEL = (Pt-Pn = Pe) / (Zr * Zst * l * n = L * n = Ls)$ (**Equation 2**)

Where:	SRE	is specific refining energy [kWh/bdmt]
	SEL	is specific edge load [J/m]
	Pt	total absorbed refining power (refiner load) [kW]
	Pn	no-load power (idling power) [kW]
	Pe	effective refining power (net power) [kW]
	F	flow [Tph]
	C	consistency [%]

Zr, Zst	number of rotor and stator bars
l	common contact length of opposite bars [km]
L	cutting edge length [km/rev]
n	rotation speed [1/s]
Ls	cutting speed of bars [kW/rev]

The specific edge load is a measure of the energy expended per unit length of bar crossings. It only describes the amount of net energy transferred by a one meter long bar edge crossing to the pulp.

Aspects ignored in this calculation are, net energy input during one pass, refining consistency, width of the bars, number of fibres stapling on the bar edges, condition of the refiner plates and gap clearance. It only considers the length of the bar edges and assumes that the refining result is independent of all other factors described above. This theory is commonly used worldwide because of its simplicity and ease of use (Lumiainen, 2000).

Attempts have been made at extending the SEL and SEC theories to account for additional variables. The approaches include the development of the Specific surface load [SSL] (Lumiainen, 2000) where the impact of bar width on the refining intensity was considered.

In 1977, Lieder and Nissan estimated directly the number and intensity of impacts on fibres during refining. Recently, Kerekes extended that further in the C-factor theory where factors such as the fibre characteristics, consistency and plate geometry were included to determine the probability of fibre impact during bar crossing (Kerekes *et al*, 1993). C-factor analysis is perhaps the most rigorous and comprehensive theory developed to date and has been applied to a variety of refiner geometries including the disk, conical and PFI mill (Waterhouse, 1997).

In 1994, using a "single bar refiner" Martinez and Kerekes experimentally measured the shear and normal forces on an individual fibre floc during a single bar crossing. It was reported that the energy per fibre per impact was of the order of that predicted by the C-factor (Kerekes, et al 2002).

Other studies (Batchelor, *et al,* 2006), investigated a means to estimate the occurrence of fibre trapping on the bar edges. In the study, refining power was measured as a function of the actual gap between the rotor and stator over a consistency range of 1% to 6%. They concluded that the fraction of the refiner bars that trap the fibres is proportional to the pulp consistency. A reduced pulp consistency resulted in a reduction in bar coverage, reduced fibre trapping and increased the harshness of the refining of the fibres.

The classical SEL theory was challenged (Joris and Roux, 2005) with regards to the angular parameters on the refiner plates. This was based on the belief that the SEL theory did not accurately relate the refiner plate geometry to the actual fibre shortening and freeness development in the refiner. Using a 12" single disc pilot refiner several trials were conducted and a new parameter was introduced, the "reference specific edge load" [SEL_0].

The calculation for reference specific edge load included the bar and groove width of the plates, the peripheral speed, the net power and the outer plate diameter but excluded the contentious bar angle. Using this new theory a mathematical model was derived to accurately predict fibre shortening and freeness development. The reference specific edge load still does not account for the other important refining variables such as consistency, fibre properties and plate gap. Based on the reasoning provided by Joris and Roux, 2005, it is the opinion of the author that the reference specific edge load is more accurate than the classical SEL and will be used as a basis of the experiments that follow.

For a Single disc refiner: $SEL_0 = 3(a_s+b_s)(a_r+b_r) / 2\pi V_p(1-k^3) \times (P_{eff} / R_o)$ (**Equation 3**)

For a double disc refiner: $SEL_0 = 3 \times P_{eff}.(a_s+b_s)(a_r+b_r) / 8\pi^2 V_p. \times (R_o^3 - R_i^3)$ (**Equation 4**)

Where:

a_s+b_s = Bar width and groove width of the stator

a_r+b_r = Bar width and groove width of the rotor

V_p = Rotational speed of the rotor

k = Ratio of the inner and outer diameter of the plates

P_{eff} = Effective refining power (total load – no-load power)

R_o = Outer plate diameter

R_i = Inner plate diameter

To account for the angular parameters, a second parameter is introduced by Joris and Roux, termed the effective cutting angle. This value is quoted separately from the reference specific edge load to provide more detail on the cutting effect induced by a change in the bar angle

$\gamma_{eff} = \sqrt{}(\alpha + \beta + \theta)^2 + \theta^2/3$ (**Equation 5**)

Where:

α = Bar angle of the rotor
β = Bar angle of the stator
θ = Sectorial angle of the repeating plate design

The higher the effective cutting angle (γ_{eff}) the lower the cutting effect under the same reference specific edge load.

2.10 Heterogeneity of refining

It is difficult to define the primary refining effects on the structure of fibres since fibres themselves are heterogeneous in nature. Within any pulp there is a population of fibres which are described by their distribution in sizes (length, diameter, thickness of the cell wall, fibril angle).

A pulp is also described by the chemical composition of the cell wall and distribution of the main chemical constituents through the cell wall. Furthermore, unrefined fibres already have some structural damage in the cell wall from the preceding processes.

The refining process defined by the transfer of mechanical energy into fibres which creates the primary refining effects in the fibre, is controlled by some probability function. Due to the variable flow patterns of the pulp through the refiner and the variation in the fibres themselves the results of the primary beating effect are also heterogeneous.

It is possible to find fibres that have received practically no refining treatment and fibres that have received refining action well over the average amount. Studies have shown that only 25% of the fibres are really treated during one pass through the refiner (Dekker, 2005).

From a dynamic point of view, Joris and Roux (2005) suggested that the refining action itself was also heterogeneous and depending on the plate pattern, areas of harsh and smooth cutting effect can exist at the same time.

CHAPTER 3

3.1 Objectives

Measure and compare the fibre characteristics of selected Northern and Southern bleached Kraft samples. Highlight key differences between the samples, determine the individual refining characteristics and demonstrate that each require their own unique and well defined refining recipes to develop optimum refined pulp properties.

3.2 Hypothesis

Softwood harvested in the Northern Hemisphere has a unique set of fibre characteristics distinctly different to the softwoods harvested in the Southern Hemisphere. As a result, each requires its own specific and well defined refining treatment to yield optimum refined pulp strengths.

3.3 Materials and Methods

The three market pulp grades used in this investigation were selected based on the regions in which the trees were grown. Each sample was a mixture of softwood species with the predominant component of each being distinctly different between the three samples.

The first sample, a rich blend of Douglas fir (*Pseudotsuga menziesii*) with the balance Western hemlock (*Tsuga heterophylla*) and Balsam fir *(Abies balsamea*) was delivered from a pulp mill in Nanaimo. This mill sourced the major portion of its fibre from the interior of British Columbia in the Northern Hemisphere.

The second sample, a rich blend of black Spruce (*Picea mariana*) and Jack pine *(Pinus banksiana Lamb.)* was delivered from a pulp mill in North West Ontario, Canada also from the Northern Hemisphere.

The third sample, a blend of mostly *Pinus patula* with the balance *Pinus elliottii* was sourced from a pulp mill in Mpumalanga, South Africa in the Southern Hemisphere.

For ease of reference in this study, the three selected samples will henceforth be named by the prevalent species in the blend, namely *Pseudotsuga menziesii (P. menziesii)*, *Picea mariana* (*P. mariana*) and *Pinus patula (P. patula).*

It should be noted that it was not possible to quantify the ratio of saw mill wood chips and whole tree round-wood in each of the samples tested.

It would have been useful to access details of the exact origin of the wood because the fibre characteristics are known to vary from the pith to the bark in a tree and from the base to the tip (Naidoo, 2003). Pulp mills are often supplied with specific parts of the tree such as the tree tops which are predominantly juvenile wood or off-cuts from the outside of the tree which are mostly mature wood.

Refining studies were carried out on a pilot scale. Industrial refining and laboratory PFI refining affect pulp fibres differently. PFI refining causes internal fibrillation of the fibre and decreases fibre curl while industrial disc refiners cause much more external fibrillation, fibre damage and fibre shortening (Molin and Daniel, 2004). A laboratory scale single disc refiner was therefore used in this study to achieve a more accurate simulation of refining conditions experienced with disc refiners in the mill.

The pilot refining unit (Figure 3.1) supplied by Matech and designed at the French Paper School consisted of a 12" single disc refiner working at a fixed intensity in hydra cycle mode (batch process). A re-pulper including a pump and tank working in tandem fed the refiner. An impeller was positioned at the bottom of the tank; the velocity of the impeller was controlled according to its function (pulping or mixing) during the trial.

Figure 3.1: Pilot refiner fitted with pulper, water heater, sampling carousel and electronic cabinet

The velocity of the impeller was controlled according to the pulp slurry viscosity during the refining process to get a light pulp vortex providing for an even freeness distribution from the top to the bottom of the tank. Pulp recirculation was also included with a controlled recirculation flow. A specialized software programme maintained steady control of all the process variables using flow meters, flow control valves, temperature probes and pressure transmitters all linked to a PLC which controlled the process automatically according to pre-defined set-points (Figure 3.2)

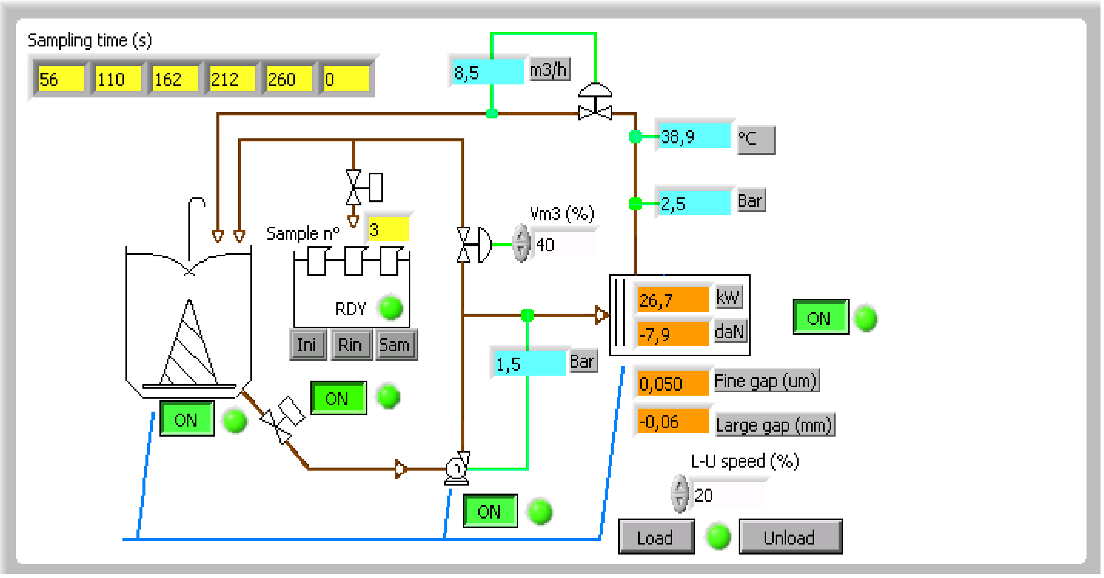


Figure 3.2: Schematic showing the process flow and instrumentation fitted to the pilot refiner

The pulping tank had a total volume of 400 liters. To start the process, a pre-determined volume of dilution water (municipal supply at room temperature with a pH of approximately 7) was added to the pulping tank, the agitator was then started followed by the addition of the pulp sample. A 10 Kg (bone dry) unrefined pulp sample was manually fed to the top of the tank to achieve a refining consistency of 35 g/l. The slurry was agitated in the repulper for a period of 20 minutes before refining.

The inlet pressure to the refiner was kept constant at 1.5 bars throughout the trials under a constant pulp flow of 8.5 m^3/h. Pulp samples were delivered to a carousel containing sampling beakers and samples were collected at timed intervals according to the calculated specific energy which had been applied to the pulp. A 4 liter sample volume was taken within a very short period of 4 seconds at moments well determined and calculated by the computer.

The refiner was connected to a 50 kW motor turning at 1430 rpm. The no-load power (power required to turn the rotor) was automatically captured at the beginning of each trial by running the refiner with the plates backed out under normal pulp flow conditions. The no-load power ranged between 14 kW and 15 kW.

The programme referenced the actual measured no-load power at the start of each trial and added additional energy to reach the required refining intensity. The intensity was fixed throughout the trial according to the load set-point which was maintained by adjusting the refining gap between the rotor and stator. The effective energy applied to the pulp slurry was increased by passing the pulp through the refiner several times in a "hydra-cycle" mode. More detail on the final formula used by the process computer to determine the refining intensity (SEL) is given below.

$$SEL_0 = \frac{C_1 \times P_{eff} \times C_2 \times 6}{5014.07} \text{ (Ws/m)}$$

with :

P_{eff} = kW (net power)
C_1 = 1 for SW and HW

C_2 = 100 for SW
= 36 for HW

The coefficients C_1 and C_2 come from the general formula computed with rotational speed and plate geometry as detailed in Equation 3 on page 18:

One standard set of softwood refiner plates (Figures 3.3 and 3.4) was fitted to the refiner and was used for all the comparative refining evaluations. The full disc 12” plates were made of stainless steel and had a classical design with a 3 mm bar width, 3 mm groove width, 4mm bar height and a 5 degree bar angle.

Figure 3.3: 12” Single disc pilot refiner

Figure 3.4: Standard 3/3/4 SW plates used in the evaluation

The MorFi fibre analyser (MORFI LAB01 supplied by Tech-pap) was used to determine the fibre morphology of the pulp samples (Figure 3.5). All samples were tested in triplicate and the average figure used for comparative purposes. The MorFi unit consists of a measuring cell, hydraulic pump and an electrical system. The pulp is analysed at two consistencies: 30 mg/l and 300 mg/l. The optical resolution is set at 10 µm. MorFi is used to determine morphological characteristics of fibres, shives and fine elements through size criteria.

A fibre is classified as being: 200 µm < fibre length < 10 000 µm
5 µm < fibre width < 75 µm

A shive is any element whose width is above the maximum width of the fibres, i.e. 75 µm.

A fine element is any object whose pulp dimensions are lower than those of the fibres:

Fines length	< 200 µm
Fines width	< 5 µm

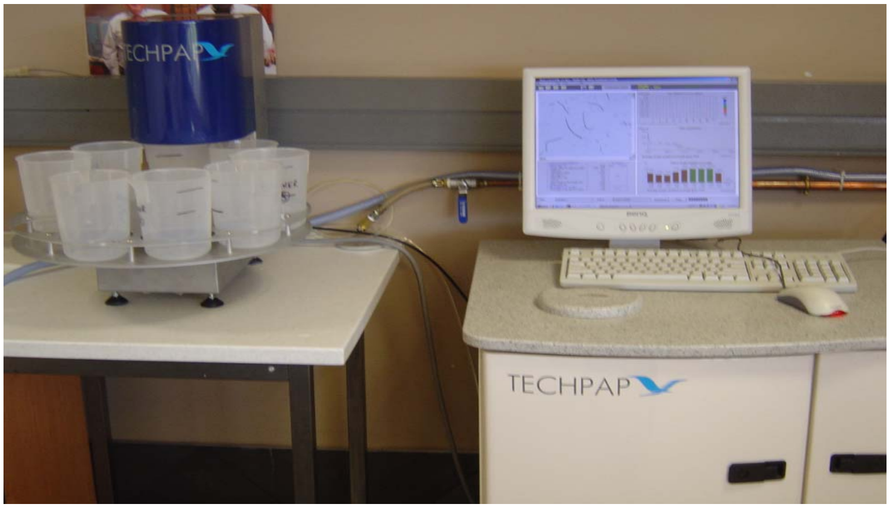


Figure 3.5: MorFi-lab used to determine the fibre characteristics

The MorFi WT (Figure 3.6) was used to measure the cell wall thickness of the fibres. The system included a measurement cell and hydraulics circuit and a PC with an interface screen, keyboard and mouse. Pulp is hydraulically transferred from the sample to the measuring cell and a special opto-electronic system based on a CCD camera (resolution 1 µm) takes successive images of the solution.

To achieve accurate measurements on such a small scale and to account for the depth of field constraint, the analysis is operated on fibres laid on a reference plain (refer to the grid shown in Figure 3.6). The pulp analyses deliver a report on the average wall thickness and the wall thickness distribution in microns. The final results are calculated from the combined analyses from a series of images of fibres. Each image includes several fibres that are measured on numerous points to get a representative sample. For this study results were based on 100000 measurements per sample.

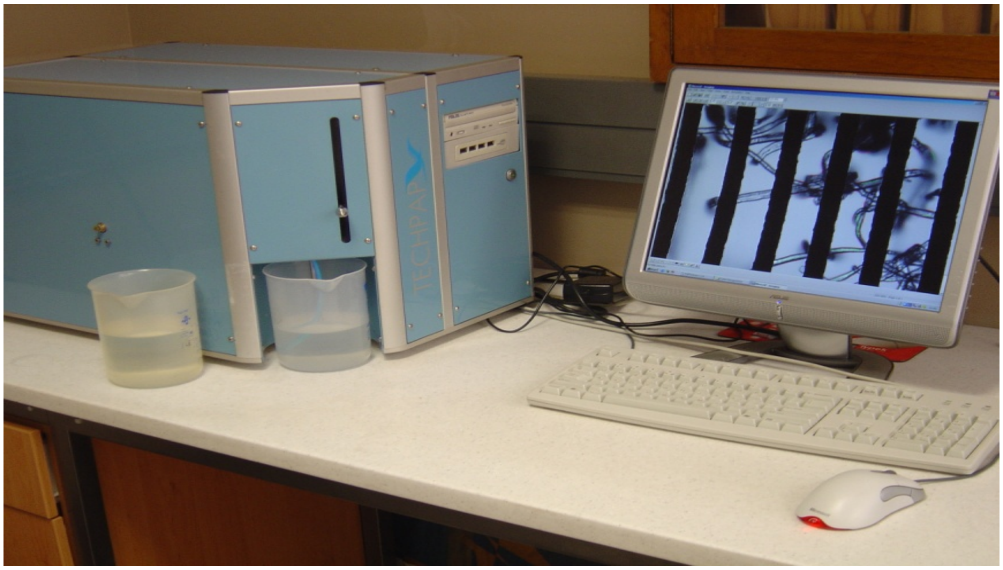


Figure 3.6: MorFi WT – Instrument used to measure the cell wall thickness

The Pulmac Z-Span 3000 was used to determine the individual fibre strength of the fibres. The equipment (Figure 3.7) included an automatic hand sheet former making six 60 gsm hand-sheets on a batch basis. The hand-sheets were then weighed to ensure a constant weight. Three of the hand sheets were transferred to the tester feed tray where they are wetted with reagent water using a sponge and roller before testing.

The testing instrument used two jaws to clamp fibres at a zero gap. The wet zero-span tensile strength measures the tensile strength at the moment of tensile failure of wet fibres; the result is reported in Newton's per centimeter and is used to assess the tensile strength of individual fibres in their length direction when wet. Fibre strength is measured by averaging 12 wet zero-span tensile tests and correcting the resulting average number in newtons/cm^2 to 60 grams per square metre.

FS = Avg. of 12 Wet zero spans * (Actual Basis Weight / Target Basis Weight)

For the Z-span wet test, the TAPPI T 273 test method was followed.

Figure 3.7: Pulmac automatic sheet former (left) and the wet zero span tester used to measure the fibre strength and bonding index of fibres

Freeness measurements were performed using the Mutek DFR. This is a dynamic measurement device which calculates the weight of water draining from a pulp sample through a wire mesh per unit time. The instrument reports a wetness result in Schopper Riegler (°SR) as well as a calculated Canadian standard freeness (CSF) result.

Hand-sheets were made to a 75 gsm conditioned grammage using a Rapid Kothen hand-sheet maker. Hand-sheets were dried and conditioned overnight to approximately 6% moisture (70 gsm bone dry) before testing the strength properties.

The refined and unrefined tear properties were measured in the lab according to ISO method 1974. Results were reported in units of mN and referenced against the grammage to give a more accurate tear index in mN.m^2/g. The grammage of the hand-sheet was measured according to ISO method 536 and reported in units of g/m^2.

The refined and unrefined tensile properties were measured according to ISO 1924-3. Results were reported in kN/m but were also referenced against the grammage for a more accurate tensile index reported in Nm/g.

CHAPTER 4

4.1 Characterizing the fibre morphology of *P. patula, P. mariana* and *P. menziesii*

Pulp samples are known to be heterogeneous in nature and are therefore best described using a population distribution rather than a single average value. Fibre length distributions of the unrefined *P. menziesii, P. mariana* and *P. patula* are provided in Figure 4.1.

P. mariana from the Northern Hemisphere had the highest percentage of short fibres and lowest percentage of long fibres. *P. menziesii* and *P. patula* had similar length distributions for the short fibre fractions but *P. patula* has the highest percentage of long fibres. *P. menziesii* exhibited the narrowest length distribution and was therefore the least heterogeneous (in terms of fibre length) of the three samples.

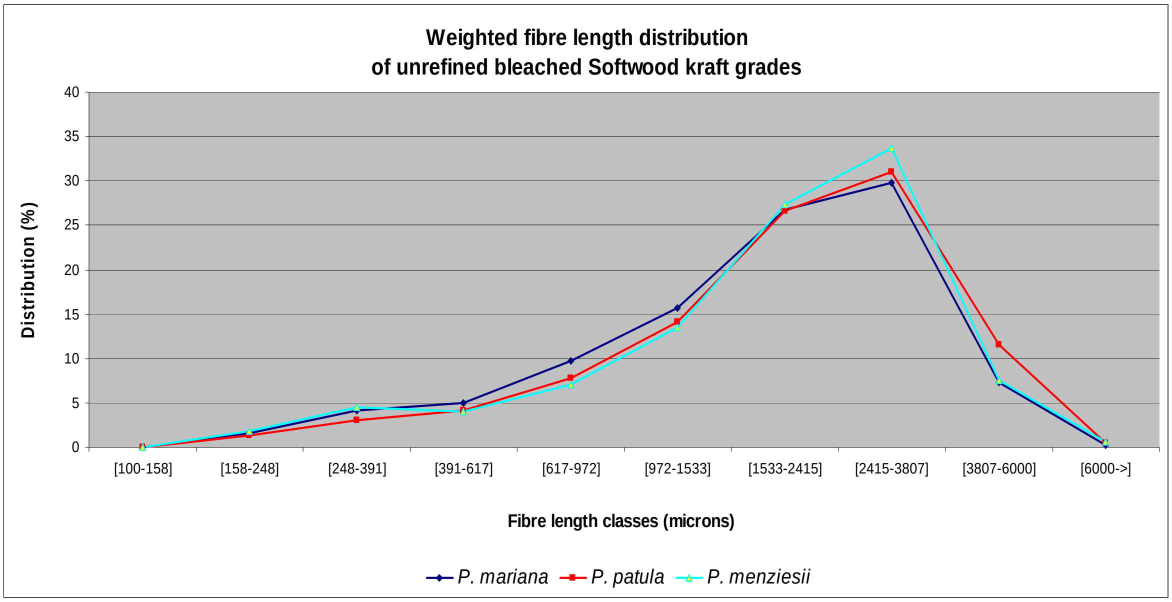


Figure 4.1: Comparative fibre length distributions of *P. menziesii, P. mariana* and *P. patula*

The relative fibre width measurements (Figure 4.2) also demonstrated a heterogeneous distribution in all the pulp samples tested. There is a clear differentiation in fibre width trends between all three samples.

The two Northern Hemisphere samples had different fibre width distributions but followed a similar pattern with the *P. menziesii* having a greater proportion of wider fibres. *P. patula* had the widest distribution and differed from the other two pulp samples with significantly wider fibres.

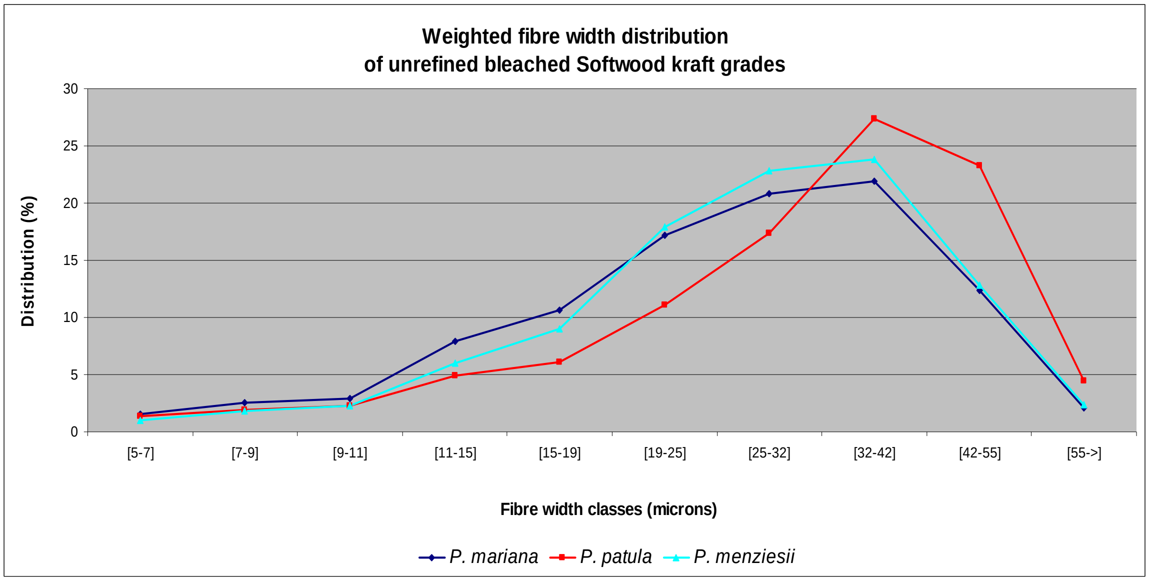


Figure 4.2: Comparative fibre width distributions of *P. menziesii, P. mariana* and *P. patula*

P. menziesii and *P. mariana* pulp samples were similar with regards to their distribution of cell wall thickness (Figure 4.3) however; *P. patula* displayed a greater heterogeneity with a significantly lower percentage of fibres in the 3 µm range and a higher percentage of fibres with a higher wall thickness in the 4-6 µm range.

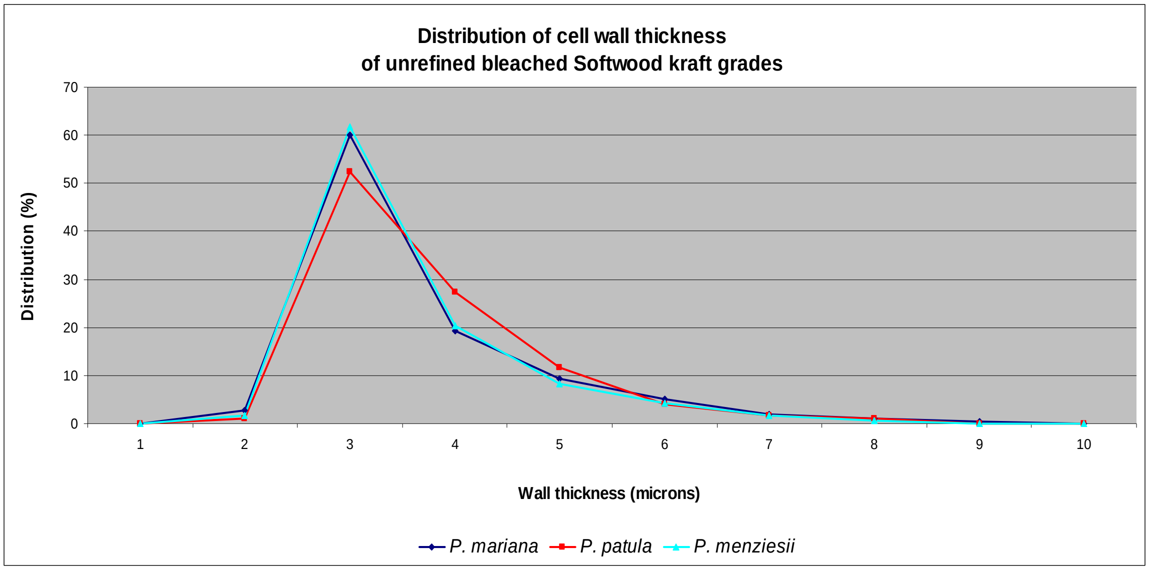


Figure 4.3: Comparative distributions of cell wall thickness for *P. menziesii, P. mariana* and *P. patula*

To gain more detail and understanding of the relative difference in the fibre characteristics of the pulp samples, separate wood samples of the three predominant species were sourced (discs collected at breast height of tree) for anatomy and densitometry tests. It must be noted that these wood samples were not from the exact same pulp samples analyzed in the refining study, the pulp samples were from a blend of this specific species and other softwood species.

Comparative anatomy measurements on the three wood samples revealed *P. patula* had the greatest variation in all the fibre characteristics measured from the pith to the bark of the tree (1 mm increments) and between the earlywood and latewood fractions. Test results on the wood samples compared well with the MorFi fibre distributions on the pulp samples because both measurements indicated that *P. patula* had a relatively large fibre width (Figures 4.2 and 4.4).

In general, all three samples follow a trend of increasing fibre widths from the pith to halfway between the pith and the bark, thereafter the fibre width stabilized around a fixed mean to the outer diameter of the tree. It was however evident that the variance in fibre width between the earlywood (high fibre width peak) and latewood (low fibre width) fractions was significantly higher with the *P. patula* during the mature wood growth period.

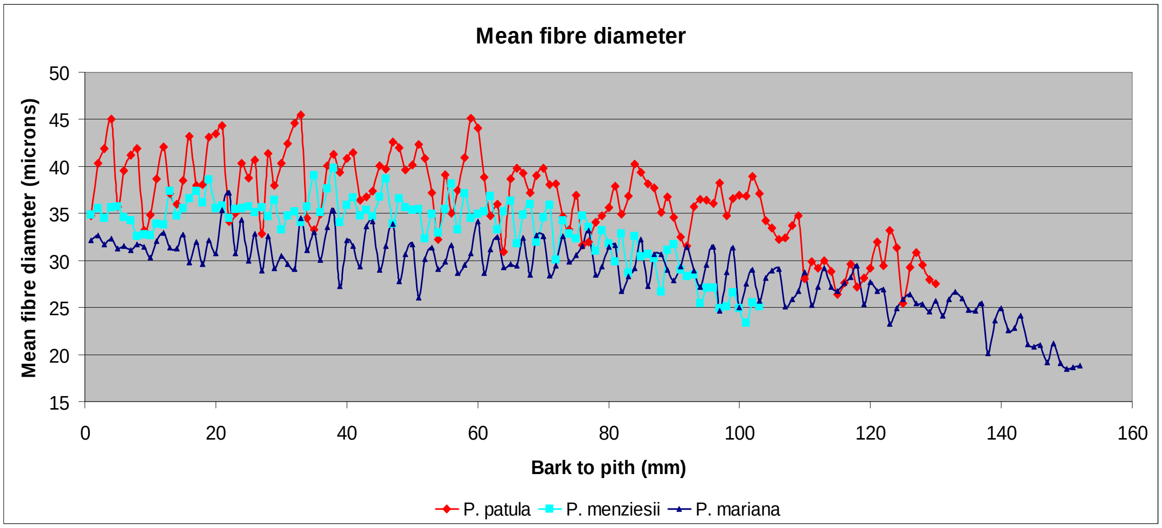


Figure 4.4: Fibre width distributions (bark to pith) of the three bleached softwood species taken from wood samples collected at breast height.

Cell wall thickness (Figure 4.5) increased from pith to bark. Compared to the two Northern wood samples, the Southern *P. patula* had a uniform wall thickness close to the pith indicative of juvenile wood with a high ratio of earlywood. *P. mariana* and *P. menziesii* samples exhibited a high frequency of consistent cyclical increases and decreases in the wall thickness from the pith to the bark as the tree produced earlywood (small wall thickness) and latewood (large wall thickness). This suggested that overall, the two Northern samples had a higher latewood content than *P. patula.*

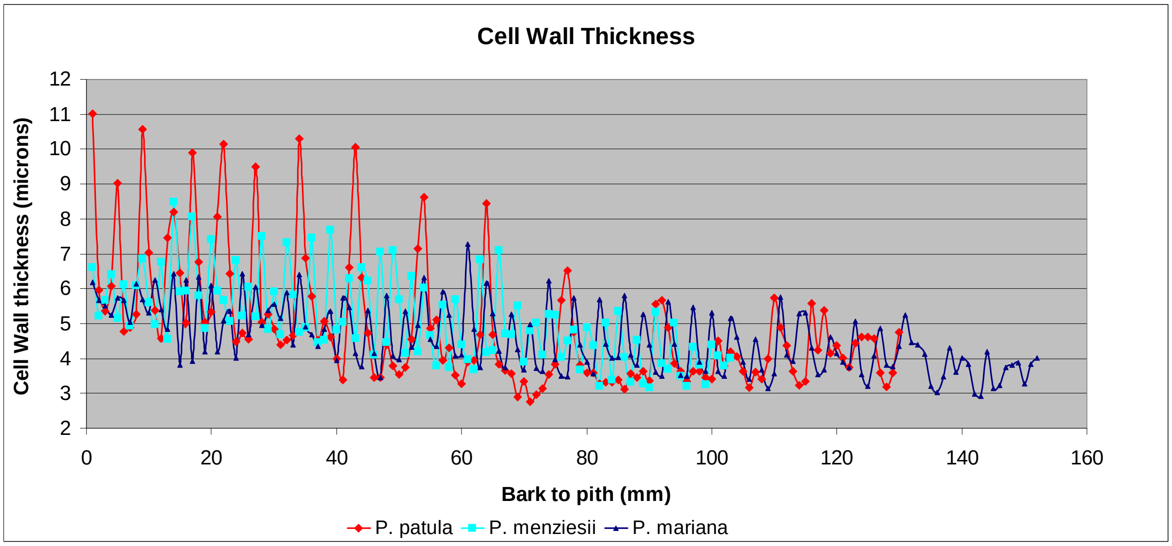


Figure 4.5: Cell wall thickness distributions (bark to pith) of the three bleached softwood species taken from wood samples collected at breast height.

Compared to the Northern samples, the fibre characteristics of *P. patula* during mature wood formation was significantly more heterogeneous with a wide range of wall thicknesses and lumen diameters. On the outside of the tree, the peaks in the wall thickness of the *P. patula* were much higher than that of the two Northern species. This finding was also noted in fibre morphology tests on the respective pulp samples where *P. patula* contained a higher proportion of thicker cell walls (Figure 4.3). Furthermore, as the cell wall thickness of the *P. patula* doubled during latewood formation, the fibre width decreased significantly and the lumen width halved, the combination of these characteristics during latewood formation resulted in a very stiff fibre, highly resistant to fibre collapse.

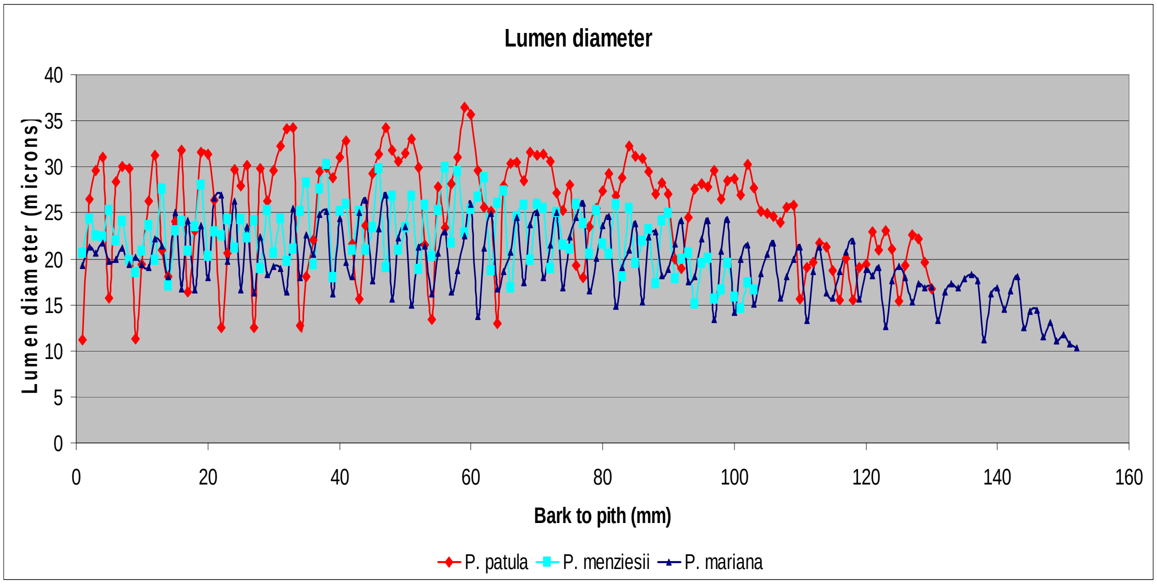


Figure 4.6: Lumen diameter (bark to pith) of the three bleached softwood species taken from wood samples collected at breast height.

There was an abrupt change to mature wood formation in the *P. patula*. The Northern *P. mariana* and *P. menziesii* had a more gradual transition from juvenile to mature wood. *P. menziesii* had the most cyclical growing characteristics with the highest frequency of peaks in wall thickness. This was consistent with the characteristics of an older tree having a higher number of latewood rings. In general, the Northern softwoods had more latewood but the difference in fibre characteristics between the earlywood and latewood was significantly less than that of the *P. patula*. Northern latewood fibres were not as coarse and "stiff" as the Southern *P. patula*.

Figure 4.7 highlights the relative development of key fibre characteristics of *P. patula* during the entire growth period. There was a marked change in the fibre characteristics between year 10 and 11 of its growth period, indicating the change from juvenile to mature wood formation. This was characterized by a significant increase in the cell wall thickness and an equally significant decrease in the lumen diameter (50% reduction) and fibre width (20% reduction). This was followed by a sharp decrease in the wall thickness together with an increase in the lumen diameter and fibre width. The frequency of these excursions increased from pith to bark through the transition from juvenile to mature wood. These results correlate well with Naidu's findings in 2003 (Figure 2.3).

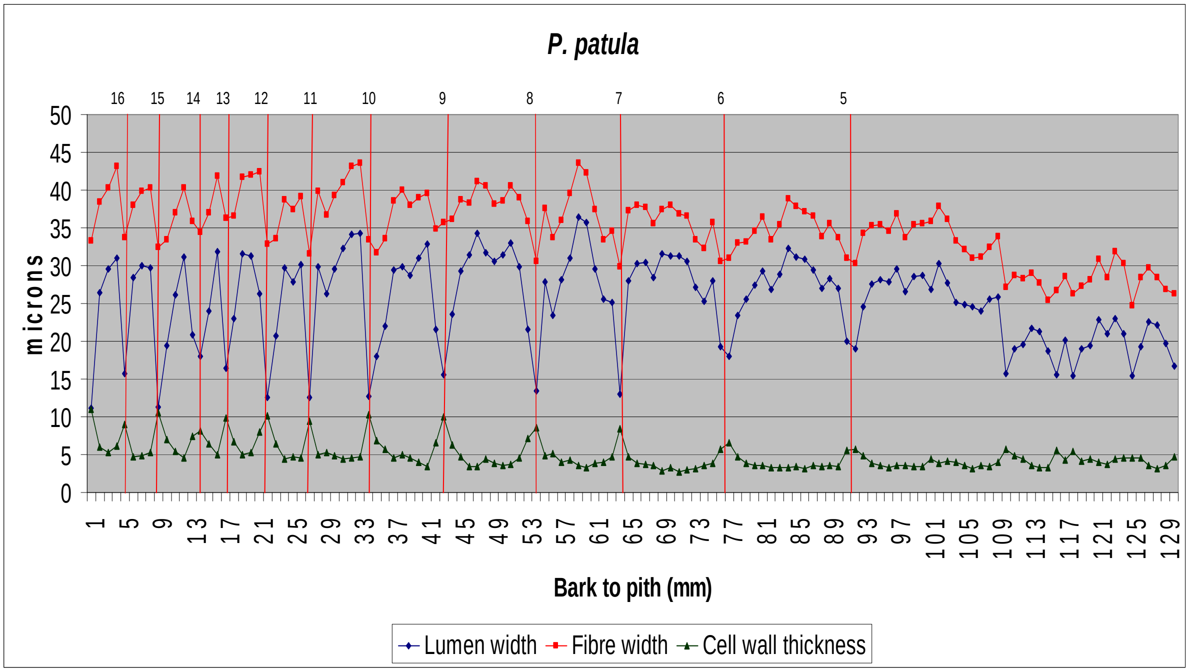


Figure 4.7: Anatomy measurements from pith to bark taken from a *P. patula* wood sample collected at breast height (red vertical lines indicate latewood growth and age of tree)

The vastly different fibre characteristics noted with the *P. patula* from the inner to outer diameter of the tree (Figure 4.7) will result in differing refining characteristics. Fibres collected from the outer diameter will have a higher average coarseness and will offer a greater resilience to refining than those from the inner diameter. This highlights the importance of knowing the ratio of saw mill chips (fibre from outer diameter of the tree) to whole tree or round-wood in a pulp sample.

The extreme heterogeneity of the *P. patula* makes fractionation an attractive option with the potential to yield two distinctly different pulp streams. One with coarse latewood fibres for good tear development and the other accept stream with finer, collapsible fibres for tensile development.

During mature wood formation in the earlywood growth period, the fibre width and lumen diameter of the *P. patula* are considerably larger than the two Northern species. This distinctive fibre characteristic aids refining making it easier for the penetration of liquids (Brit & Kenneth, 1970) and promotes fibre collapsibility, ultimately resulting in improved fibre bonding characteristics. However, during latewood formation (minority portion of the total sample), *P. patula* fibres have the smallest lumen width relative to the two Northern samples.

Results of fibre measurements showed, *P. patula* had a significantly higher average coarseness (Figure 4.8). This was explained by the large wall thickness and smaller lumen formation in the mature wood during latewood growth mentioned earlier.

The MorFi coarseness results for the Northern *P. mariana* and *P. menziesii* were similar to each other but significantly lower than the *P. patula* most likely due to less variation in the fibre properties during mature wood formation.

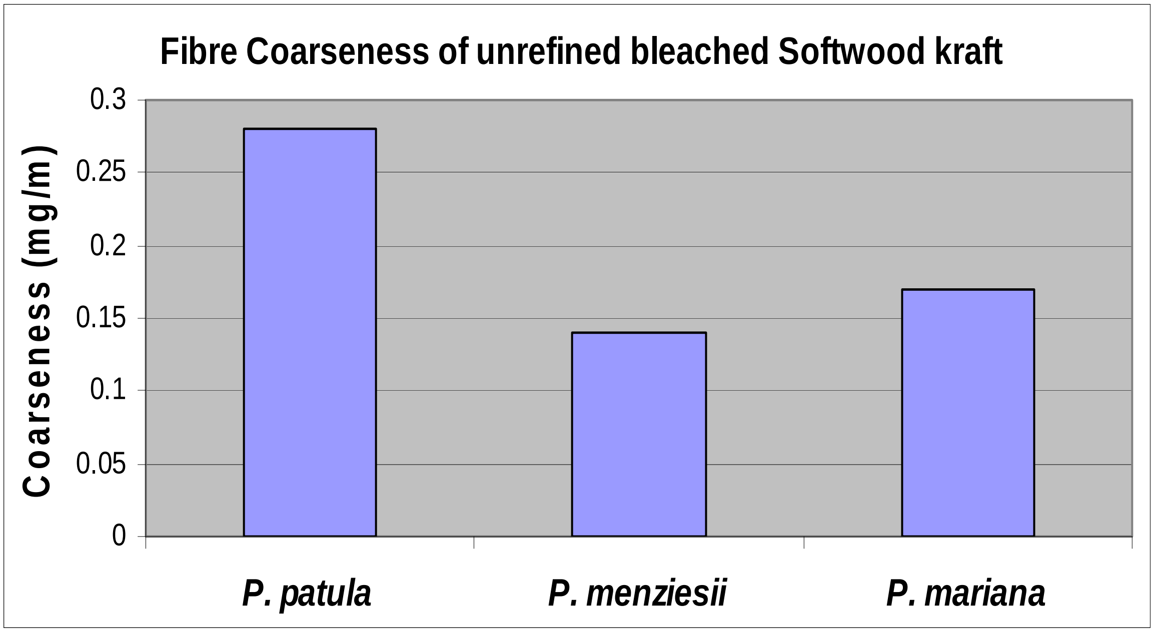


Figure 4.8: Comparative fibre coarseness for the unrefined *P. menziesii, P. mariana* and *P. patula*

The MorFi fibre coarseness results of the pulp samples was in agreement with the densitometry test results on the respective wood samples and correlated with the number of fibres per gram of pulp (Table 4.1).

The impact of fewer fibres per gram will have a negative effect on the final sheet strength as there will be fewer fibres available for bonding per unit area.

Table 4.1: Number of fibres per gram of the unrefined *P. menziesii,P. mariana* and *P. patula*

	Number of fibres per gram of pulp Number (10^6/g)
P. patula	3.7
P. menziesii	5.7
P. mariana	4.6

Gamma –ray densitometry tests were performed on wood samples for the three species at 1mm intervals from bark to pith. The results clearly indicated the Southern *P. patula* had a low and consistent density close to the pith (Figure 4.9).

As was noted with the cell wall thickness (Figure 4.5), density measurements on *P. patula* had significant peaks of very high densities (in excess of 0.9 g/cm^3) during latewood growth from the middle to the outer diameter of the tree. The Northern *P. mariana* and *P. menziesii* also had annual peaks of a lower wood density (0.7 g/cm^3) from the pith to the bark but proportionally there was a higher latewood content than the *P. patula*.

The difference in growth rate could also be seen because the *P. patula* was only 16 years old and had a larger radius than the *P. menziesii* which was over 40 years old.

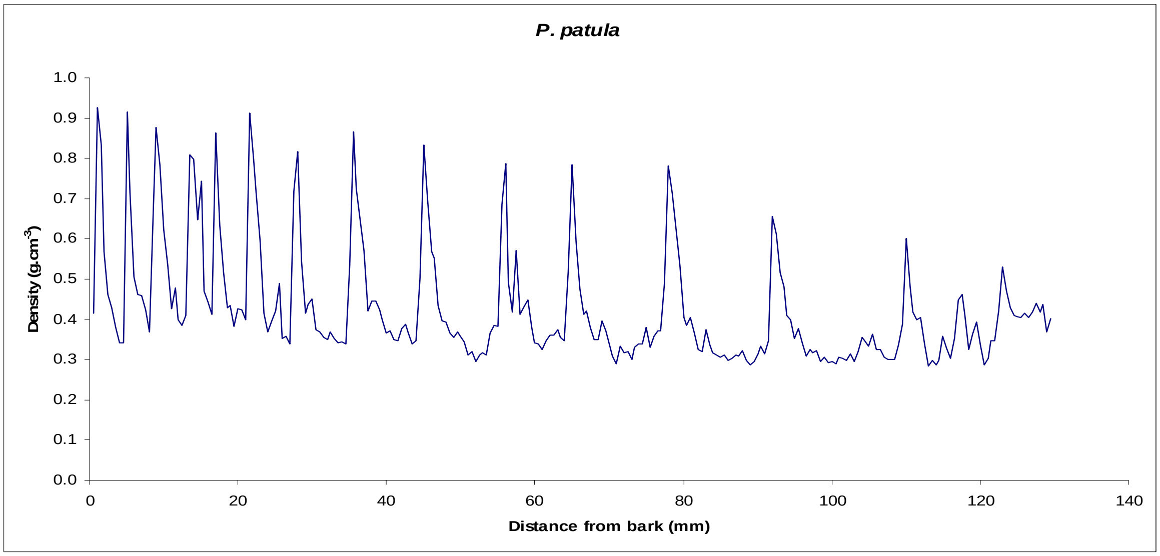


Figure 4.9: Densitometry tests on a *P. patula* wood sample taken at breast height.

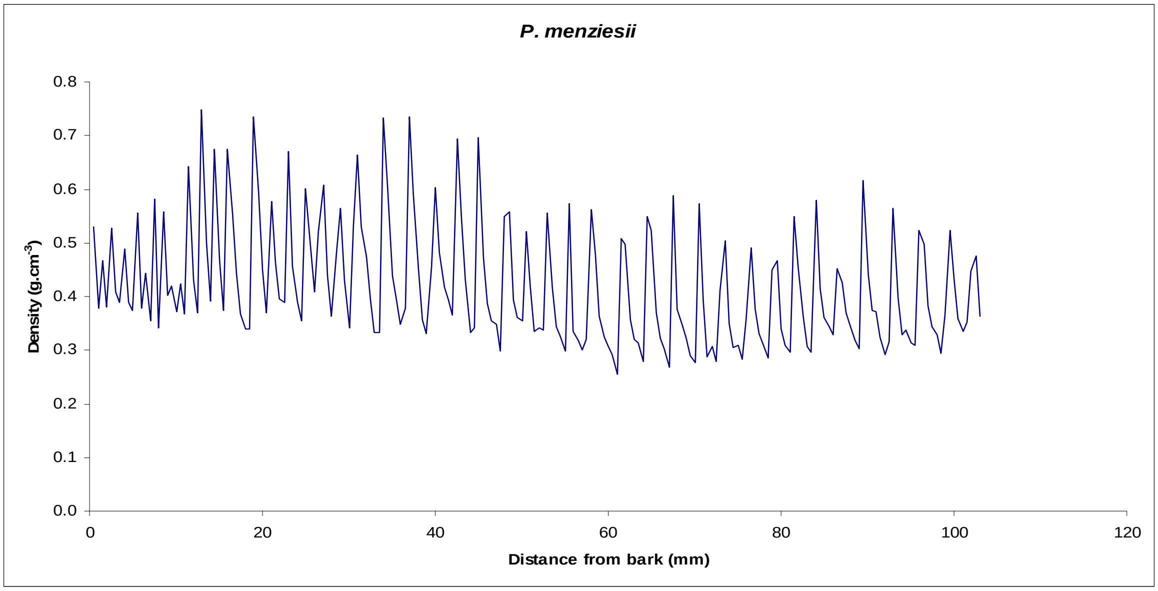


Figure 4.10: Densitometry tests on a *P. menziesii* wood sample taken at breast height.

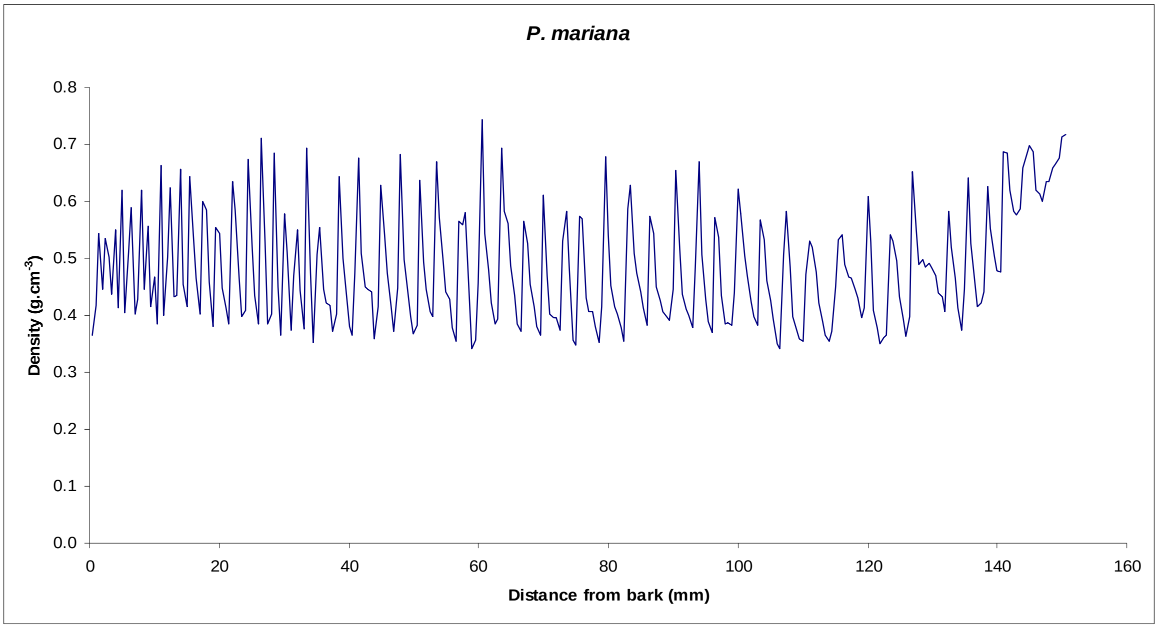


Figure 4.11: Densitometry tests on a *P. mariana wood* sample taken at breast height.

In this investigation, a fines particle was defined as an element having a length less than 200 µm. During the paper sheet-forming process the fines particles fill the voids between fibres reducing the drainage and porosity of the sheet. In dryer limited paper-machines a high fines content is likely to reduce the production capacity as the machine has to run slower to dry the sheet to the required solids content.

P. patula had the highest fines area of the three softwood species (Figure 4.12). Table 4.2 suggests that these fines particles were also shorter than those of the *P. mariana* and *P. menziesii*.

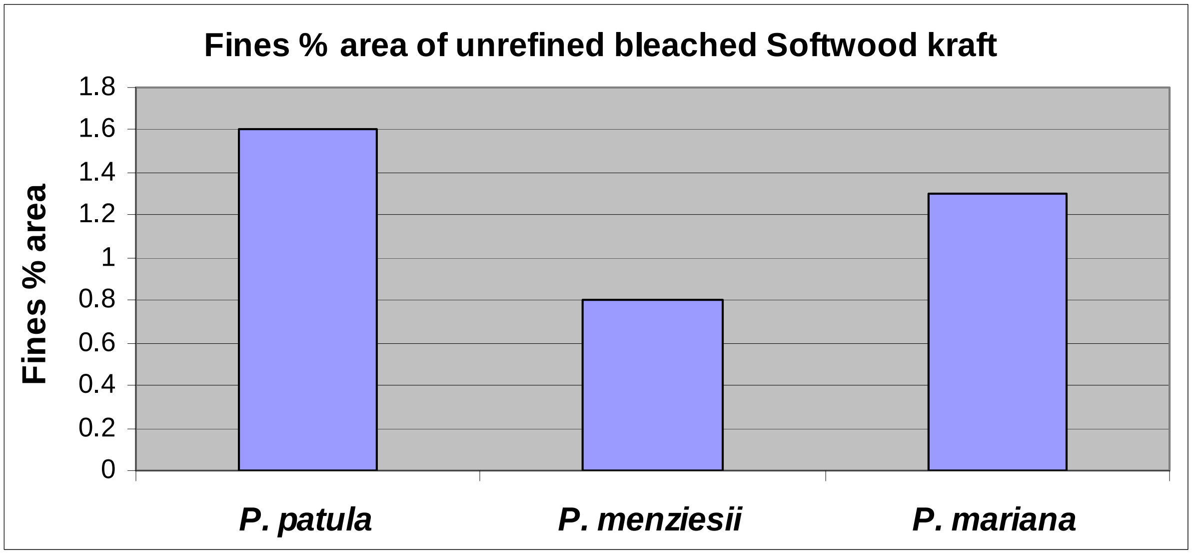


Figure 4.12: Comparative Number of fines for the *P. menziesii, P. mariana* and *P. patula*

Table 4.2: Comparative fines length for the unrefined *P. menziesii, P. mariana* and *P. patula*

	Average fines length
	(Microns)
P. patula	45.5
P. menziesii	54.5
P. mariana	49.0

The fibre strength (measured by Pulmac) of the Southern *P. patula* appeared to be lower than that of the *P. menziesii* and *P. mariana (*Figure 4.13*)*. Factors known to influence the Pulmac fibre strength measurements include fibre coarseness, number of fibres per gram (Cowan, 1994), cell wall thickness, ratio of earlywood to latewood and the micro fibril angle in the S2 layer (Paavilainen, 1993).

Compared to the Northern samples, *P. patula* had a significantly higher coarseness and fewer numbers of fibres per gram. According to Cowan (1994), Pulmac fibre strength results are highly dependant on the number of fibres per gram. This was accounted for by referencing the fibre strength relative to the coarseness (Table 4.3). Using this approach reversed the initial ranking and resulted in *P. patula* having increased fibre strength significantly higher than that of the *P. menziesii* and *P. mariana* which were very similar.

The micro fibril angle was not measured in this investigation, however, the *P. mariana* and *P. menziesii* appeared to have a higher frequency of latewood content in the wood densitometry tests (Figures 4.10 and 4.11). Latewood has a lower micro fibril angle in the S2 layer and as such has higher fibre strength (Biermann, 1996).

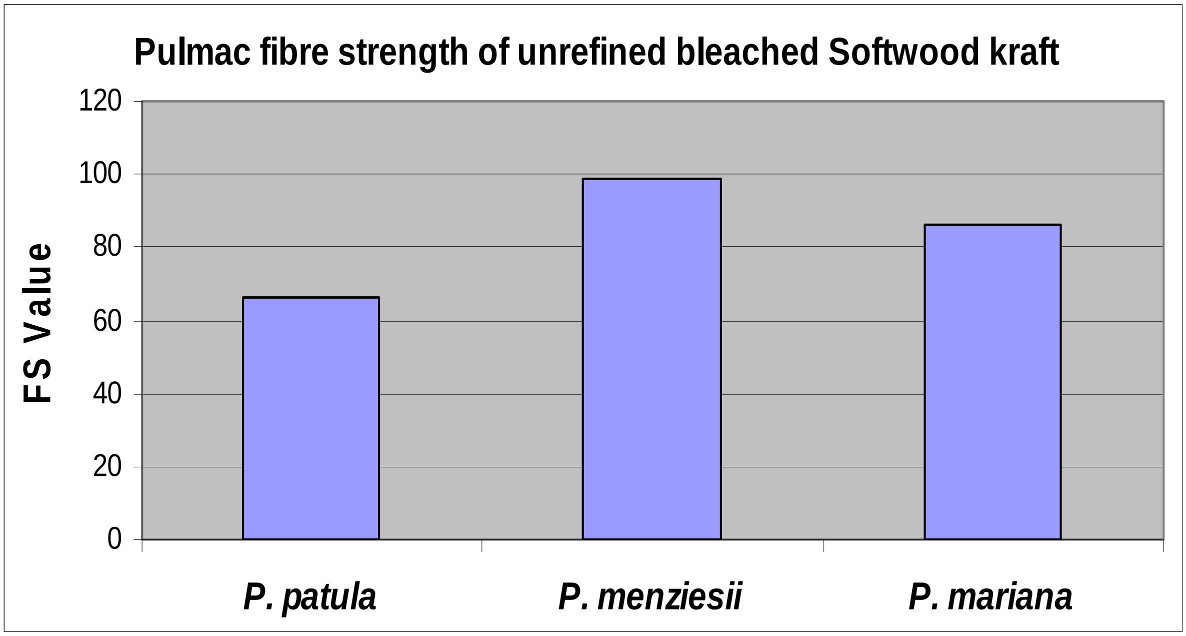


Figure 4.13: Comparative fibre strength for the *P. menziesii, P. mariana* and *P. patula*

Table 4.3: Pulmac Fibre Strength measurements relative to fibre coarseness and the number of fibres per gram of pulp

	Coarseness	Fibres/gram	Avg. FS No.	Relative Coarseness	Relative FS No.
	(mg/m)	(10^6/g)	(N/cm)	(mg/m)	(N/cm)
P. menziesii	0.14	5.7	98.9	1.0	98.9
P. mariana	0.17	4.6	86.1	1.2	104.5
P. patula	0.28	3.7	66.5	2.0	133.0

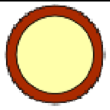
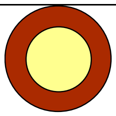
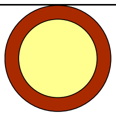
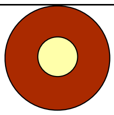
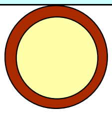
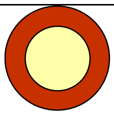
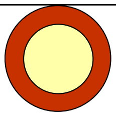
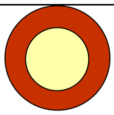
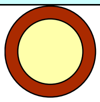
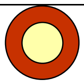
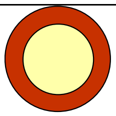
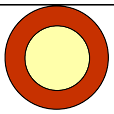
Table 4.4: Comparative average MorFi fibre characteristics of *P. menziesii, P. mariana* and *P. patula* after repulping

			P. patula	*P. menziesii*	*P. mariana*
Avg. fibre length	**(L)**	**(µm)**	2119	1976	1870
Avg. fibre width	**(D)**	**(µm)**	26.9	27.1	25.3
Avg. wall thickness	**(w)**	**(µm)**	3.40	3.67	3.65
Avg. Lumen Width	**(d)**	**(µm)**	20.1	19.7	18.0

The average fibre dimensions measured by the Morfi are presented in table 4.4 but as it has been shown that the *P. patula* is extremely heterogeneous the use of averages is meaningless.

P. patula is a coarse, wide fibre with a large average lumen width. However, the actual fibre dimensions from latewood growth during mature wood formation is not fully realized in the representation of average fibre characteristics due to the high proportion of juvenile wood which contains mostly earlywood. This is highlighted in table 4.5 which provides a visual representation of the differences in the fibre dimensions of the three samples between earlywood and latewood and between juvenile and mature wood growth.

Table 4.5: Comparative fibre dimensions during tree growth

Specie	Age	Season	Width	Wall thickness	Lumen width	Relative Dimension
P. patula	Juvenile	Early	35.6	3.64	28.3	
		Late	30.3	5.67	18.9	
	Mature	Early	42.0	5.33	31.3	
		Late	32.8	10.14	12.6	
P. menziesii	Juvenile	Early	31.2	3.16	24.9	
		Late	28.5	5.32	17.9	
	Mature	Early	33.8	5.66	22.5	
		Late	34.8	6.80	21.2	
P. mariana	Juvenile	Early	24.6	3.50	17.7	
		Late	19.8	4.30	11.2	
	Mature	Early	32.2	5.20	21.7	
		Late	31.2	5.70	19.70	

CHAPTER 5

5.1 Comparative Refining characteristics of *P. patula, P. mariana* and *P. menziesii*

During industrial pulp refining, the degree of refining is usually adjusted according to a specified freeness target measured at the outlet of the refiner. This refined pulp freeness relates to the drainage rate of the pulp and is, in turn, a measure of how quickly the pulp dewaters when transferred from the head-box onto the paper machine forming section.

With refining, fines are generated which tend to fill the voids between the inter-fibre bonds thereby restricting the drainage. Refining also causes fibre swelling which increases the relative bonded area and reduces the freeness.

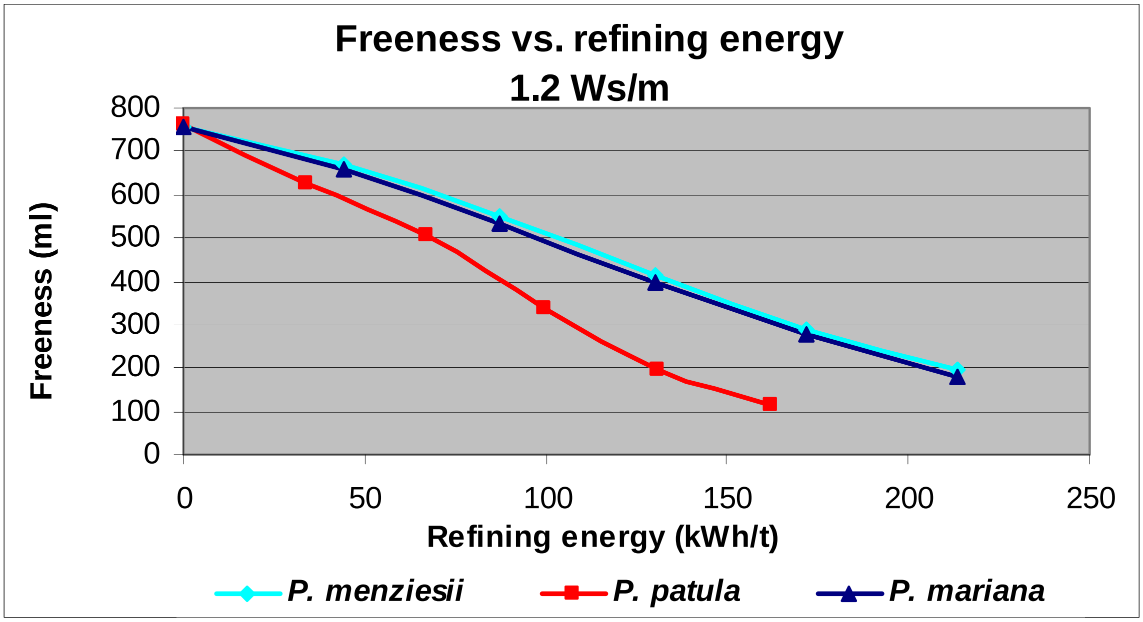


Figure 5.1: The effect of refining energy on the freeness development of *P. menziesii, P. mariana* and *P. patula* at a fixed refining intensity of 1.2 Ws/m

Data collected from the 12” single disc refiner at a fixed reference specific edge load (SEL_O) of 1.2 Ws/m revealed that *P. patula* was easier to refine and developed a comparatively steep drop in the freeness as the refining energy was increased (Figure 5.1).

The fast freeness development could have been caused by a number of factors. The first being the relatively small number of fibres per gram of pulp (Table 4.1). The applied refining load and intensity was calculated on the flow of the pulp in tons per hour and did not consider how many fibres were present in that specific volume. This implied that when a fixed load was applied to a pulp with coarse fibres there was a higher force on fewer fibres as opposed to that same load being applied to a pulp with a low coarseness having a greater number of fibres with each fibre receiving a smaller portion of the total load and intensity. *P. patula* also had a relatively high percentage of juvenile earlywood with a small wall thickness and large lumen width (Table 4.3). These characteristics made it easier for the penetration of liquids and subsequent fibre swelling and internal fibrillation. Furthermore, *P. patula* had a large fibre width providing for a greater likelihood of receiving a refining impact.

The two Northern species differed significantly from the *P. patula* but between them had a similar trend demonstrating a more gradual drop in the freeness. This was easily understood when comparing the relative fibre dimensions (Table 4.5) of the three samples.

Using an equivalent refining intensity, *P. patula* reached a freeness of 450 CSF using a refining load of 80 kWh/t, whereas *P. menziesii* and *P. mariana* required a considerably higher refining load of approximately 120 kWh/t and 115 kWh/t respectively to achieve the same refined freeness of 450 CSF.

The energy required to develop the fibres of a specific pulp grade is an important parameter when considering rising energy costs in a tough economic climate.

In Europe, energy costs are high, (equivalent in Rand terms to approximately R0.35/kWh on average) compared to South Africa (approximately R0.09/kWh on average) where energy is relatively cheap but in short supply. Table 5.1 shows the relative cost to develop the three different pulp grades in both Europe and South Africa to a constant freeness. As an example, the approximate cost of refining 12 dry tons per hour of each pulp grade through a 42” double disc refiner was specified.

Table 5.1: South African and European energy costs to refine each of the three species to a freeness of 450 CSF applying a refining intensity of 1.2 Ws/m

		P. patula	*P. menziesii*	*P. mariana*
Required energy (To achieve 450 csf)	kWh/t	80	120	115
No-load power of 42" refiner	kW	250	250	250
Effective power applied to fibres	kW	960	1440	1380
Total power	Total kW	1210	1690	1630
Cost to refine in Europe (R0.35/kwh)	R m/pa	3.71	5.18	5.00
Cost to refine in SA (R0.09/Kwh)	R m/pa	0.95	1.33	1.29

The Southern grown *P. patula* required on average 35%-50% less refining energy to achieve a specific freeness. The Northern *P. menziesii* and *P. mariana* differed from the Southern *P. patula* requiring a higher refining energy at the early stages of refining to reduce the freeness (Figure 5.2).

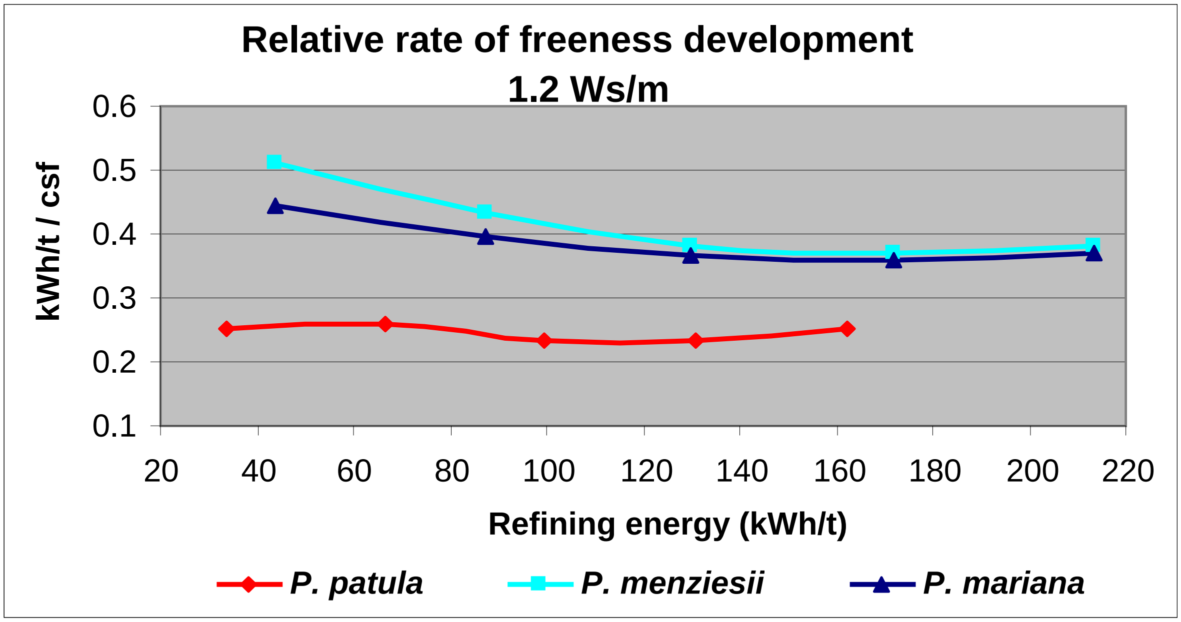


Figure 5.2: The relative rate of freeness development of *P. menziesii, P. mariana* and *P. patula* at a fixed refining intensity of 1.2 Ws/m

The higher energy requirement corresponded with the number of fibres per gram (Table 4.1) and smaller average lumen width (Table 4.3). The relative refined freeness trends were also in agreement with the fines % area (Figure 5.3) of the samples when refined.

The comparatively low fines area of the *P. menziesii* could be attributed to a higher proportion of juvenile latewood growth and possibly a lower effective energy and applied intensity (total energy distributed over a greater number of fibres).

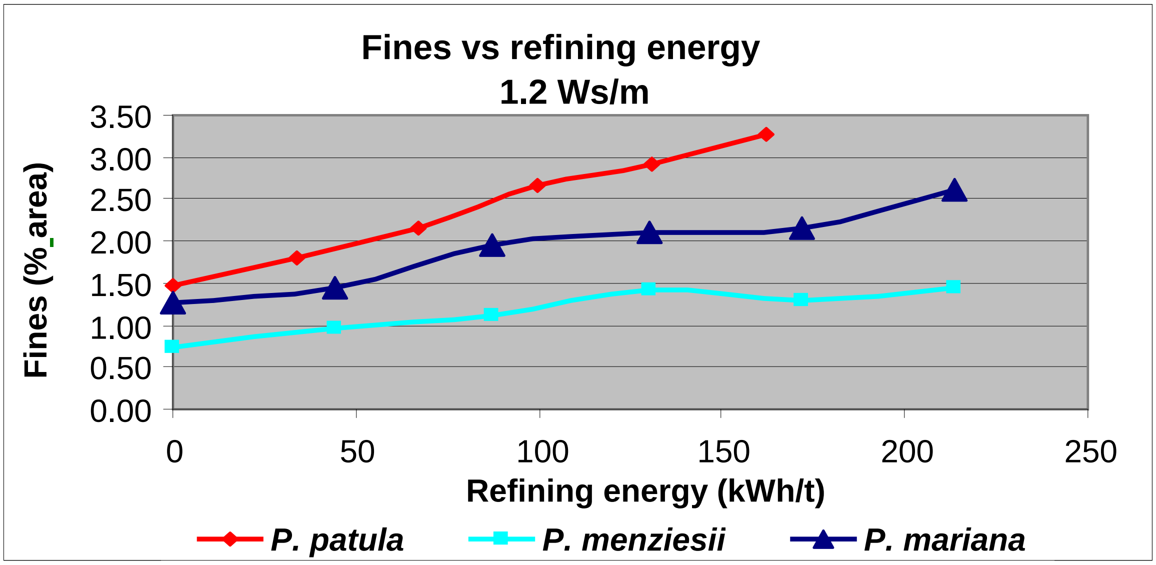


Figure 5.3: Refining vs. fines generation of *P. patula, P. menziesii* and *P. mariana* at a fixed intensity of 1.2 Ws/m

When the three samples were refined, the average weighted fibre length of the *P. patula* was reduced at a faster rate than the *P. menziesii* and *P. mariana* (Figure 5.4).

Initially, in its unrefined state, the *P. patula* had the longest fibre length but when refined using 50 kWh/t at a low intensity of 1.2 Ws/m the *P. patula* had the shortest comparative average weighted fibre length. The rate of decrease in fibre length appeared to increase above an SRE of about 75 kWh/t. The characteristic ease with which the *P. patula* fibres were shortened was in agreement with the theory that the fibres were exposed to a higher effective intensity than that applied to the *P. menziesii* and *P. mariana*.

There may have been a specific contribution from the coarser *P. patula* latewood fibres from the small mature wood portion of the tree which were stiffer (high wall thickness and small lumen) having a higher propensity for fibre cutting. The effect of refining on the relative fibre length distributions of the three samples is clearly seen in Figures 5.5 to 5.7. The refined *P. patula* fibres have a distinctly different fibre length distribution after refining to a 500 CSF freeness with clear signs of fibre cutting. The longer fibres appear to be most affected by the fibre cutting effect.

Refined *P. mariana* fibres also differ in length distribution after refining to a 500 csf freeness but to a lesser degree than the *P. patula*. The fibre length distribution of the *P. menziesii* before and after refining is similar.

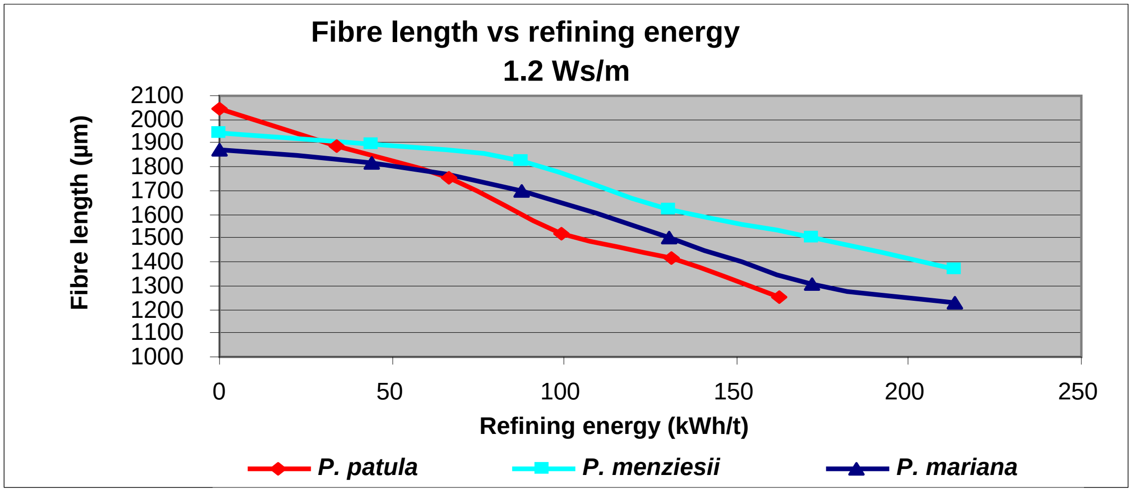


Figure 5.4: Refining vs. average weighted fibre length of *P. patula, P. menziesii* and *P. mariana* at a fixed intensity of 1.2 Ws/m

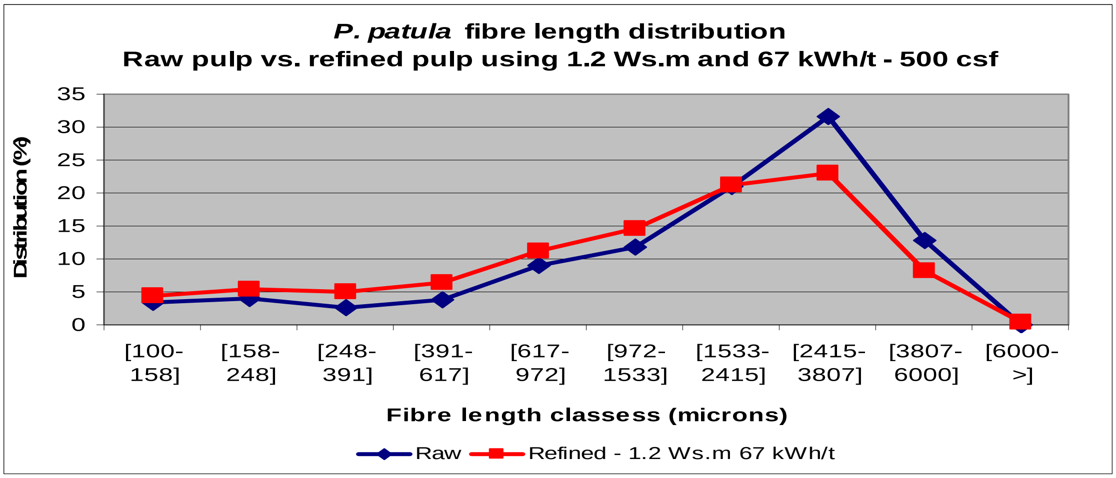


Figure 5.5: Effect of refining on the fibre length distribution of *P. patula*

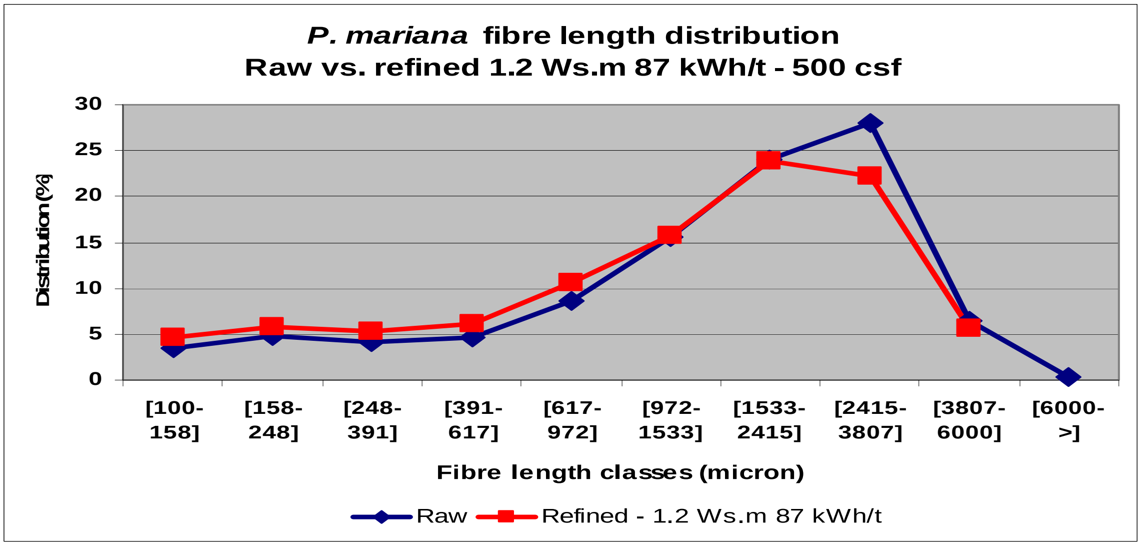


Figure 5.6: Effect of refining on the fibre length distribution of *P. mariana*

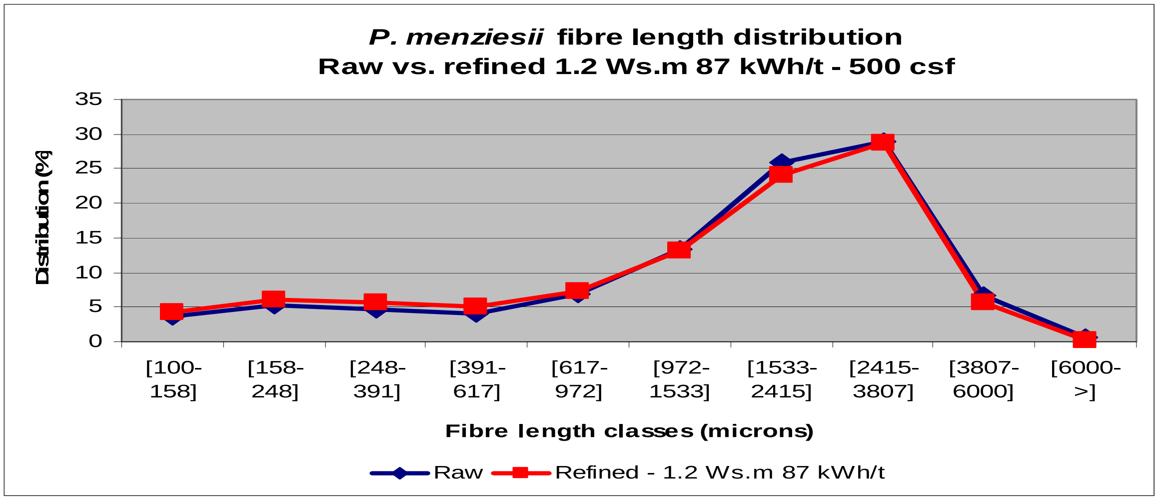


Figure 5.7: Effect of refining on the fibre length distribution of *P. menziesii*

Refining at the selected 1.2 Ws.m intensity to a 500 CSF freeness did not have a significant effect on the fibre width of the three samples tested (Figures 5.8 – 5.10)

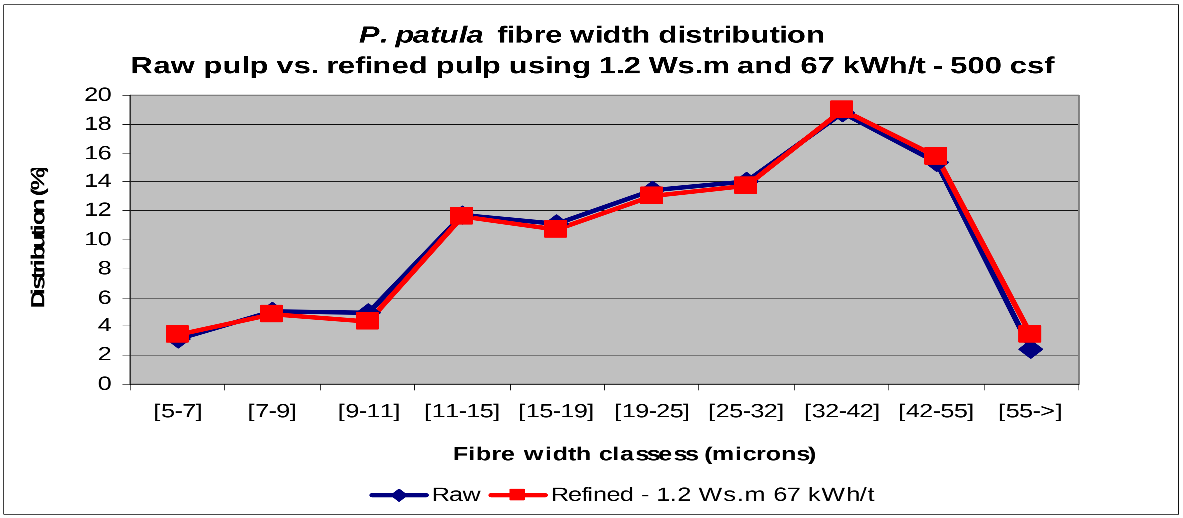


Figure 5.8: Effect of refining on the fibre width distribution of *P. patula*

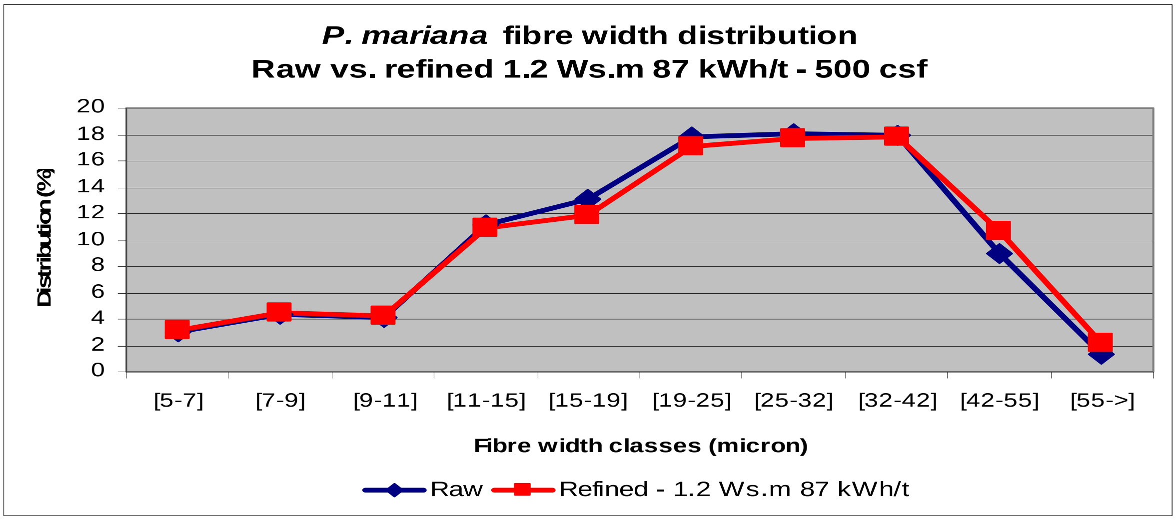


Figure 5.9: Effect of refining on the fibre width distribution of *P. mariana*

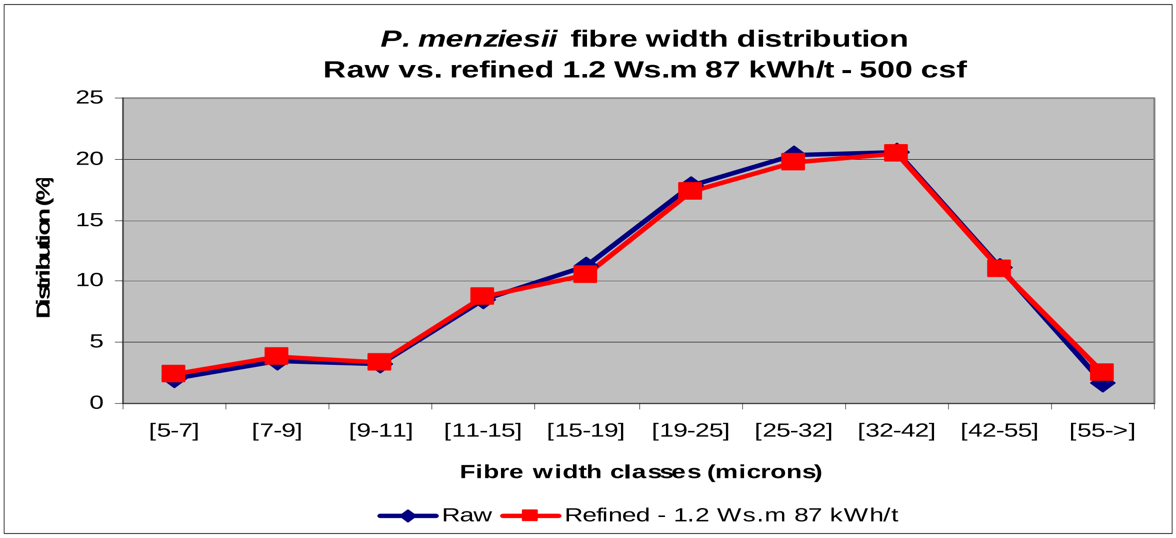


Figure 5.10: Effect of refining on the fibre width distribution of *P. menziesii*

Another distinguishing characteristic between the three samples was the average fibre curl (Figure 5.11) as measured by the MorFi fibre analyzer. The unrefined *P. patula* had an initial curl significantly higher than that of the unrefined Northern, *P. menziesii* and *P. mariana*. When refined, the curl was reduced in all three samples, but, *P. patula* had the largest loss in curl and ended up with the straightest fibres after refining.

The higher apparent flexibility of the *P. patula* fibres most likely emanated from the juvenile earlywood growth. *P. menziesii* and *P. mariana* showed similar curl characteristics which were significantly different to that of the Southern *P. patula*. The general loss in curl (Figure 5.11) with refining was in agreement with previous studies which correlated with an increased tensile (Figure 5.12) and reduced tear result, Figure 5.14 (Wang, 2007).

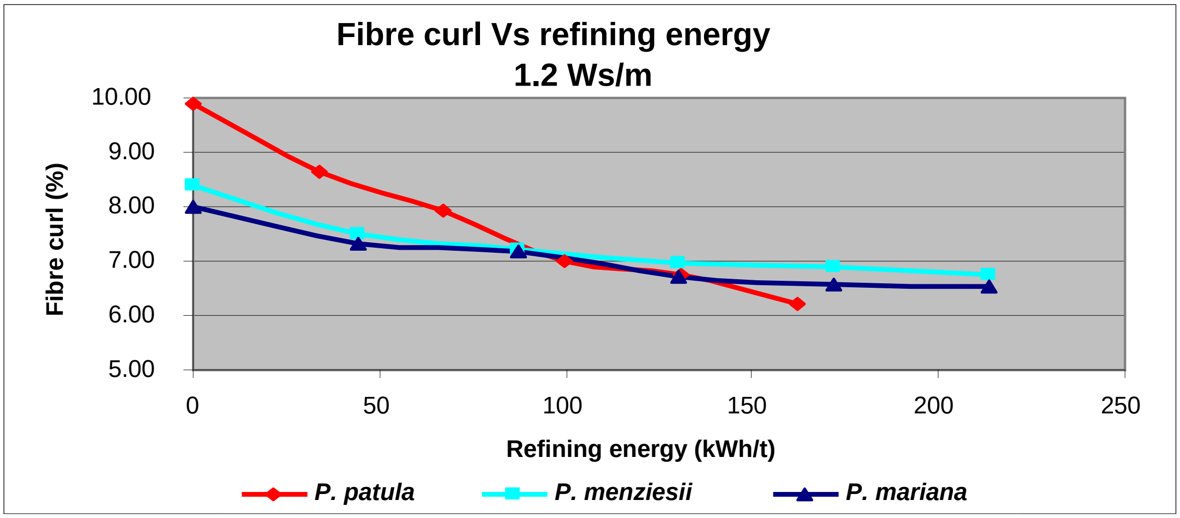


Figure 5.11: Refining vs. fibre curl of *P. patula, P. menziesii* and *P. mariana* at a fixed intensity of 1.2 Ws/m

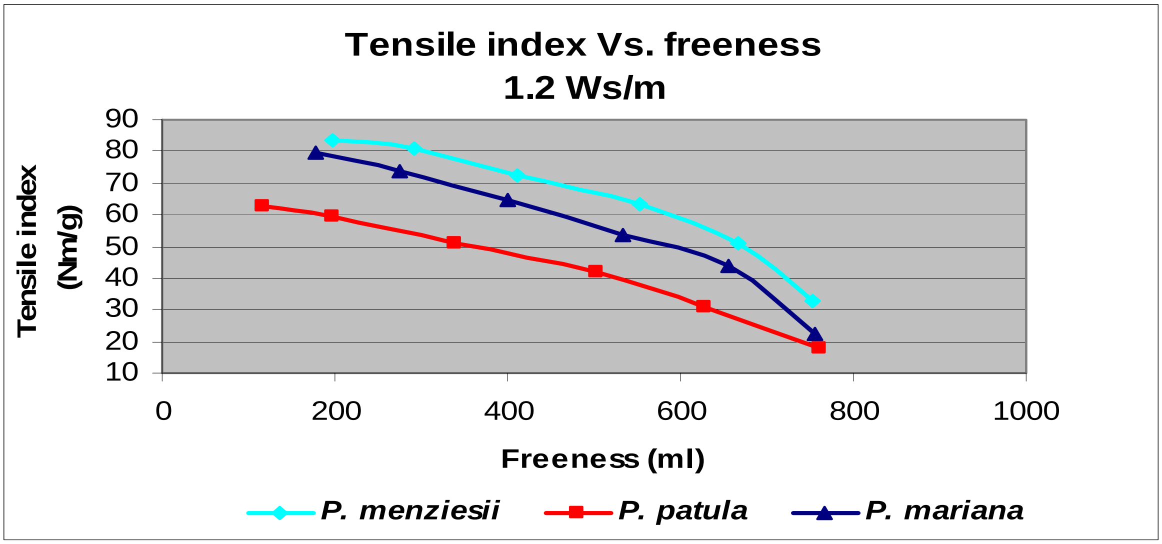


Figure 5.12: Refining curve of tensile index vs. freeness of *P. patula, P. menziesii* and *P. mariana* at a fixed intensity of 1.2 Ws/m

In terms of tensile properties, there appeared to be a correlation with the relative coarseness and number of fibres per gram. *P. patula* had a significantly higher coarseness and relatively small number of fibres per gram giving the lowest tensile result compared to the *P. menziesii* which had the lowest coarseness and highest number of fibres providing for the highest unrefined tensile index and the highest refined tensile gain (Figure 5.13).

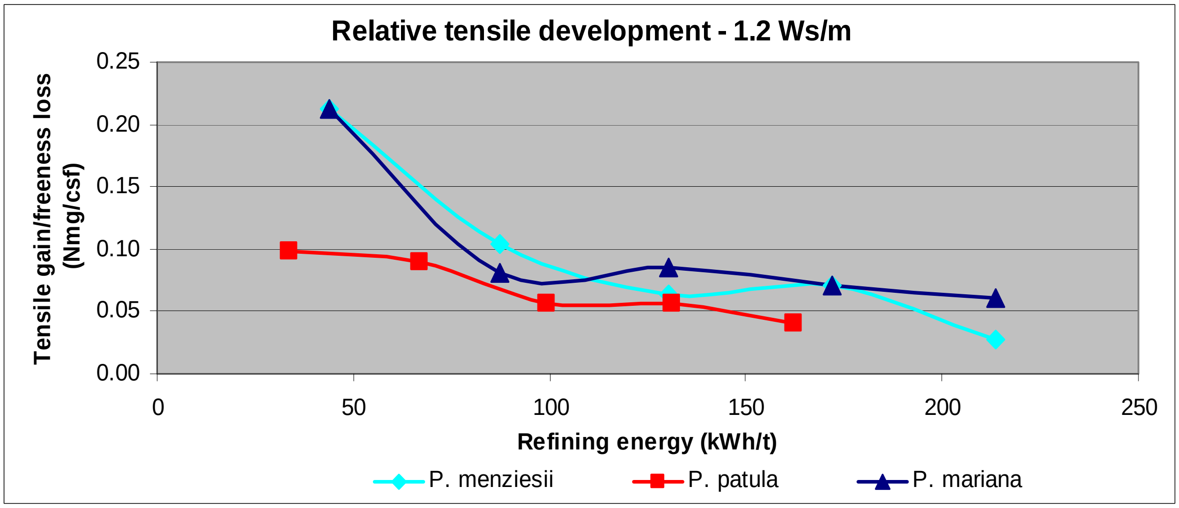


Figure 5.13: Relative tensile development of *P. patula, P. menziesii* and *P. mariana* at a fixed intensity of 1.2 Ws/m

For these three pulps, the relative tensile development in Figures 5.12 and 5.13 is likely to be dependant on fibre bonding. Although some of the *P. patula* fibres were good for bonding (earlywood fibres) (Figure 4.13) it would appear that there was simply not enough of these fibres to carry and distribute a tensile load. Furthermore, the extreme coarseness of the latewood fibres may disrupt the bonding matrix.

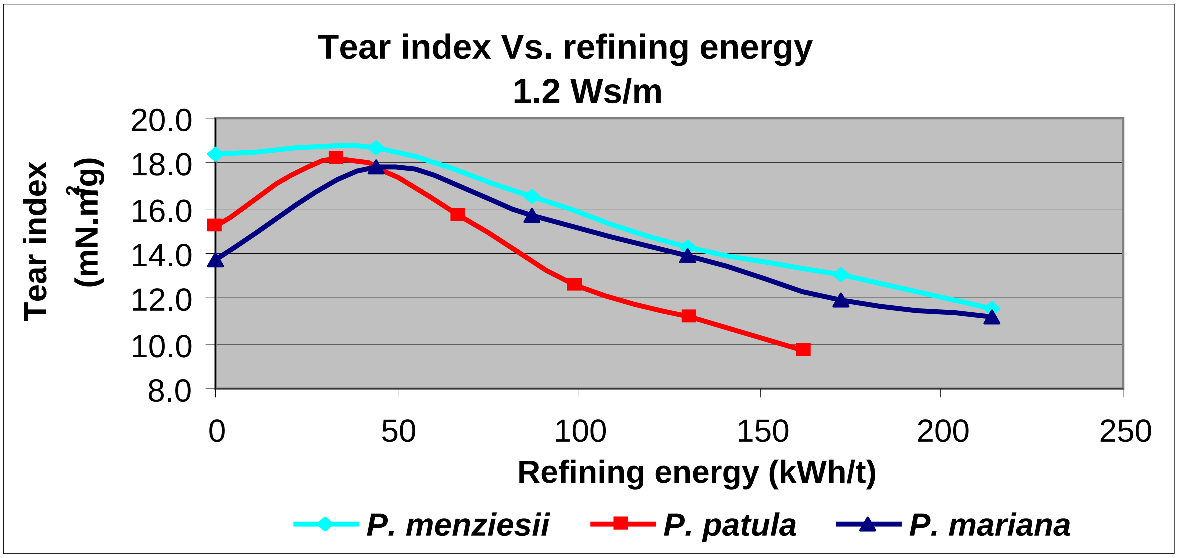


Figure 5.14: Refining curve of tear index vs. refining energy of *P. menziesii, P. mariana* and *P. patula* at a fixed intensity of 1.2 Ws/m.

Figure 5.14 shows that the three samples were able to achieve a similar optimum tear result. With *P. patula,* optimum tear development was achieved at a lower refining energy. Coarse, strong fibres contribute to a high tear.

P. patula had a low percentage of latewood during Juvenile wood growth and a fewer number of coarse fibres than the Northern species which had a higher frequency of latewood formation during juvenile wood growth. *P. patula* latewood fibres were extremely coarse during mature wood formation but, *P. patula* sampled here was felled shortly after the transition to mature wood and as such contained a relatively small proportion of coarse fibres.

The relative rate at which the *P. patula* reached optimum tear development as well as the faster rate of tear loss may be attributed to the actual number of coarse fibres relative to the Northern species. The impact of fibre cutting and the significant loss of fibre length relative to the two Northern samples is also an important factor to consider when comparing the relative tear trends. The two Northern samples with a similar average wall thickness and coarseness had a similar tear development.

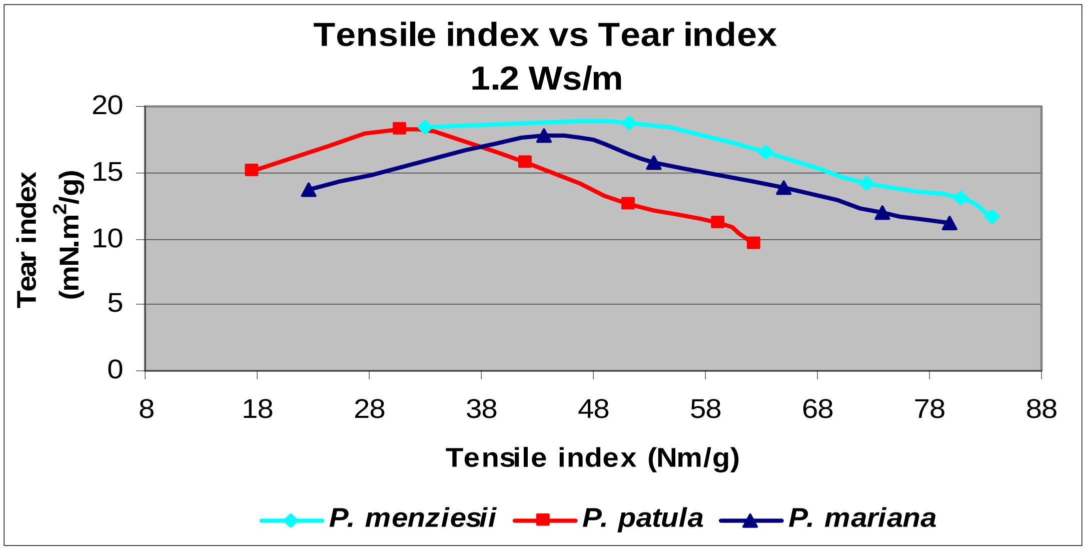


Figure 5.15: Refining curve of tensile index vs. tear index of *P. menziesii, P. mariana* and *P. patula* at *a* fixed intensity of 1.2 Ws/m.

With refining optimization projects there is always a compromise between the tear and tensile result (Figure 5.15). Ideally both the tear and tensile should be as high as possible however each one of these two properties is developed at the expense of the other.

P. patula developed a slightly higher tear but lower tensile than the *P. mariana.* It is possible to develop *P. patula* to a similar tear as the other two Northern samples but not tensile. This is in agreement with Horn's findings (1974) that suggested fibres with a higher coarseness are able to deliver a higher tear result and fibres with a lower coarseness and subsequently containing a higher number of fibres are able to deliver a higher tensile.

It must however be noted that this analogy is based on fibre characteristics deemed to be most influential on the tear and tensile result however, other fibre characteristics such as the micro fibril angle not measured in this report are also likely to play a role in the development of these properties.

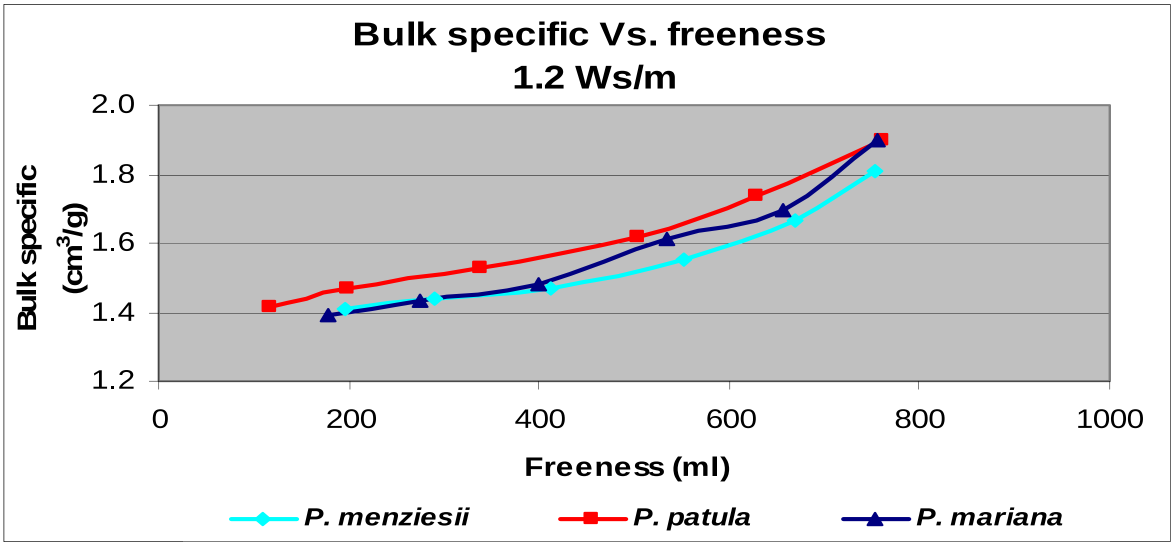


Figure 5.16: Refining curve of Bulk vs. freeness of *P. menziesii, P. mariana* and *P. patula* at a fixed intensity of 1.2 Ws/m.

During refining, the bulk of a pulp sheet reduces as the fibres collapse, increasing the sheet density, this is demonstrated in Figure 5.16.

P. patula exhibited the highest bulk of the three samples analyzed. A higher bulk implies a lower degree of fibre compaction. This may be explained by noting that the Southern *P. patula* sample had the largest coarseness of the 3 samples.

CHAPTER 6

6.1 Establishing optimized refining conditions for the three samples

The initial set of test results discussed in CHAPTER 3 highlighted a significant difference in the raw fibre characteristics of the three samples. The refining results presented in CHAPTER 4 showed the unique fibre morphology of each pulp sample plays a vital role in determining how that specific fibre responds to a refining treatment.

The aim of this chapter was to match the raw fibre characteristics with a custom set of refining conditions to yield optimum refined pulp properties.

Due consideration was given to the energy requirements and the final refined freeness as this had a direct impact on the economics and runnability of most paper-machines. On the basis of local practice and for the purposes of this study a refined freeness of 450 CSF was selected as a reference point to monitor the optimum tear and tensile development.

6.2. Establishing optimized refining parameters for *P. patula*

Anatomy results on the wood samples and MorFi results on the pulp samples showed *P. patula* contained some very coarse fibres with a relatively small number of fibres per gram of pulp. The application of a standard refining programme on this unique pulp with fewer fibres resulted in a higher effective intensity. This was demonstrated with a high tendency towards fines generation and a rapidly reduced freeness (Figure 6.1) at unusually low refining loads. The rate at which the fines generation and fibre cutting occurred was highly dependant on the energy and intensity of the refining action.

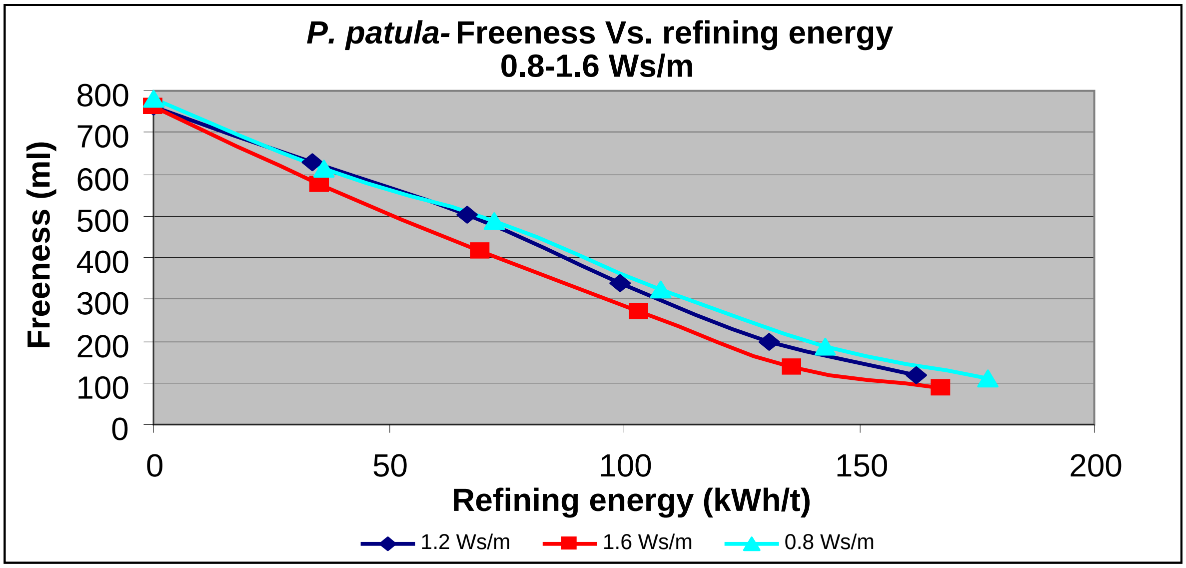


Figure 6.1: Freeness development of the *P. patula* as a function of the refining energy and intensity

Reducing the intensity from 1.6 Ws/m to 0.8 Ws/m produced a "brushing" action. The lower intensity appeared to preserve the fibre strength and increase the fibre bonding producing an improved tensile result at a higher freeness (Figure 6.2). When refining softwoods, low intensity refining is usually unsuitable due to the high fibre strength and an increased refining energy is required to meet the freeness target. This is a severe limitation considering the current and ever increasing cost of energy.

With the Southern *P. patula* species, there are significantly fewer fibres per gram of pulp and so less refining energy and intensity is required to develop them. Reducing the refining intensity for *P. patula* from 1.6 Ws/m to 0.8 Ws/m required only 20 kWh/t of additional energy to meet the 450 CSF freeness target but there was a 20% increase in the refined tensile result from 42 Nm/g to 50 Nm/g (Figure 6.2). This is an appealing option when considering the current cost of energy.

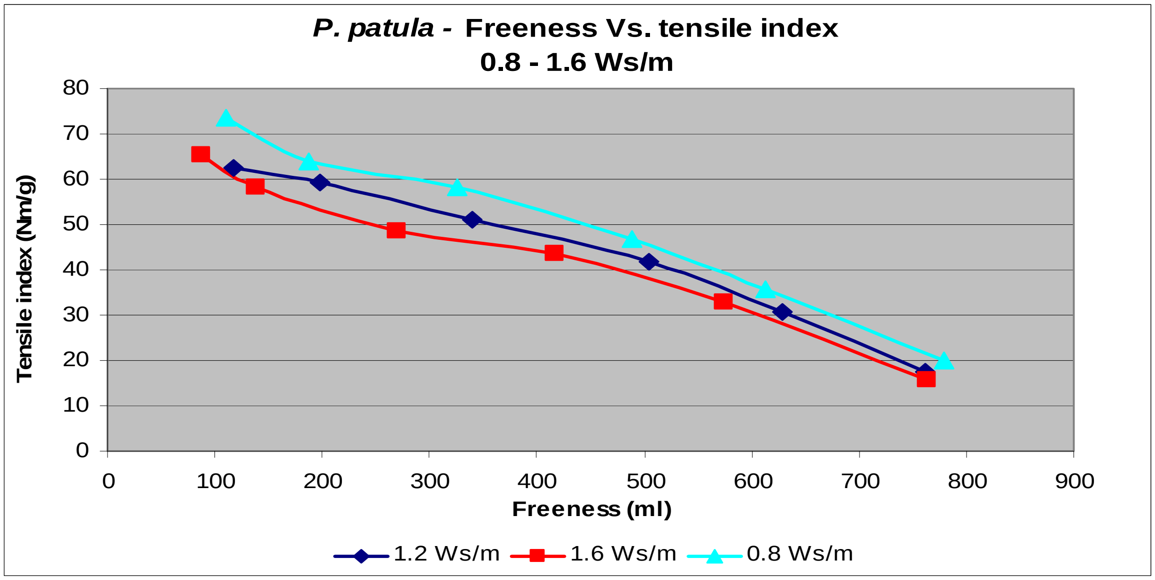


Figure 6.2: Refined freeness vs. tensile index of the *P. patula* at various refining intensities.

To develop the tensile index, the optimum refining intensity for this specific *P. patula* sample was in the region of 0.8 Ws/m. To refine to a 450 CSF freeness target a refining load of 80 kWh/t would be required.

To develop the tear index a higher refining intensity of 1.6 Ws/m was most suitable; to reach the maximum tear index at a 450 CSF freeness a refining load of approximately 60 kWh/t was required. A higher tear result could be achieved at a higher freeness using only 35 kWh/t.

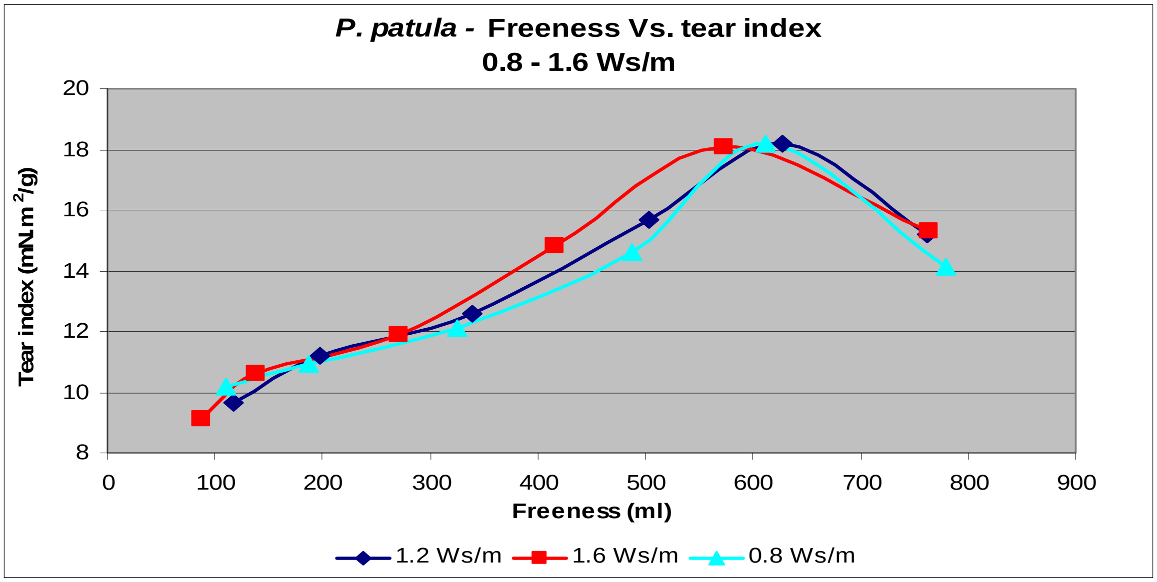


Figure 6.3: Refined freeness vs. tear index of the *P. patula* at various refining intensities.

It was clear that the refining intensity had a significant impact on the strength properties and freeness development of *P. patula*. The optimum intensity was dependant on the specific properties being targeted. For instance, to develop good tensile strength with the *P. patula* species, a low intensity of 0.8Ws/m was most appropriate, however, to develop tear, a higher intensity of 1.6 Ws/m was required. These intensities were relatively low for a softwood species and the reason is most likely due to the fewer fibres per gram.

Without considering the freeness development, the tear and tensile relationship is a good indicator when looking to optimize refining conditions because it is targeting the ideal point between fibrillating and collapsing the fibre with minimum fibre shortening. Figure 6.4 summarizes the effects of refining *P. patula*.

In the early stages of refining there was an increase in the tear and tensile indexes up until a load of approximately 35 kWh/t (equivalent to a range of approximately 570 CSF - 630 CSF). As the refining load was increased beyond this point the tear index decreased sharply and the tensile index continued to increase. Using a low intensity of 0.8 Ws/m provided the highest tensile for a given tear index.

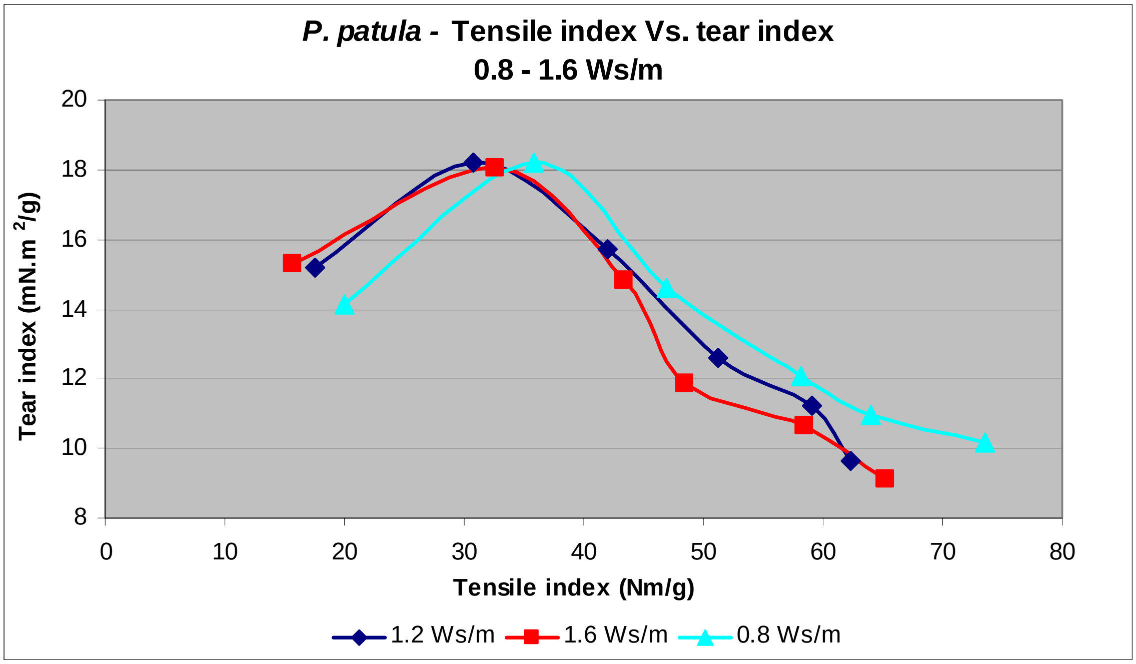


Figure 6.4: tensile index vs. tear index of the *P. patula* at various refining intensities.

6.3. Establishing optimized refining parameters for *P. mariana*

The fibre dimensions of the *P. mariana* fall between that of the P. *patula* and *P. menziesii* but are more closely associated to the *P. menziesii. P. mariana* had the smallest average fibre width of the 3 samples with a higher number of fibres per gram and had a significantly lower average lumen width than the *P. patula* suggesting that it would be more difficult to refine with a comparatively slower freeness development.

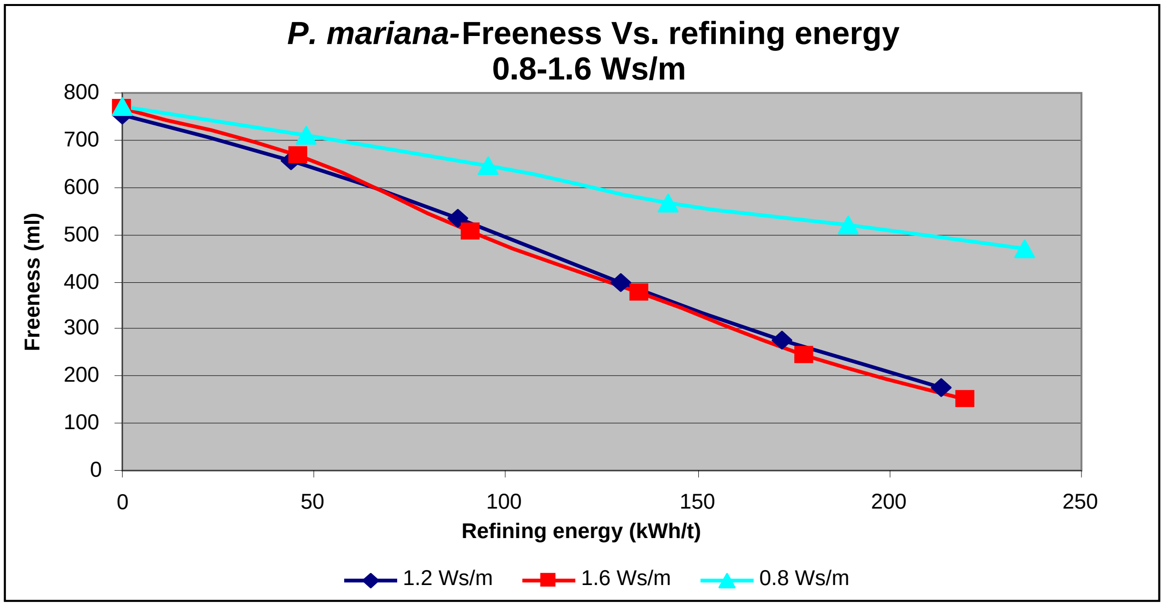


Figure 6.5: Freeness development of the *P. mariana* as a function of the refining energy and intensity

Figure 6.5 confirmed that *P. mariana* was definitely more resilient to refining than the *P. patula* requiring a higher energy and intensity to reach the 450 CSF freeness target. The low intensity of 0.8 Ws/m did not provide the required force to break down and hydrate the cell walls at an acceptable energy level.

The freeness target was reached at the higher intensity levels using 1.2 Ws/m and 1.6 Ws/m with both showing a similar freeness trend. To achieve the 450 CSF target, 110 kWh/t was required at 1.6 Ws/m, this was considerably higher than the *P. patula* which required only 60 kWh/t at an intensity of 1.6 Ws/m or 80 kWh/t at 0.8Ws/m.

Figure 6.6 indicated that the *P. mariana* did develop a higher tensile (62 Nm/g) than the *P. patula* (50 Nm/g) at a freeness of 450 CSF but required a higher intensity of 1.6 Ws/m and 30 kWh/t more energy.

In this assessment, the 0.8 Ws/m low intensity trial on the *P. mariana* sample did not have enough energy (240 kWh/t +) to attain the 450 CSF target but did show better tensile development at the higher freeness's when compared to the 1.2 and 1.6 Ws/m trials. To achieve this low intensity, high energy condition in the mill requires several refiners running in series. This is a costly option not easily justified in the current economic climate.

With *P. mariana,* the tensile at higher freeness (600 CSF) is already the same as for *P. patula* at 450 CSF and therefore a better option for the papermaker. For the purposes of this study however, all pulps were referenced at a standard refined freeness of 450 CSF. The 1.2 Ws/m and 1.6 Ws/m *P. mariana* trials had trends that were almost identical to each other. With this pulp grade a further trial at a higher intensity of 2.0 – 2.5 Ws/m may have provided better insight into the refining characteristics of this fibre but this went beyond the scope and experimental design of this project

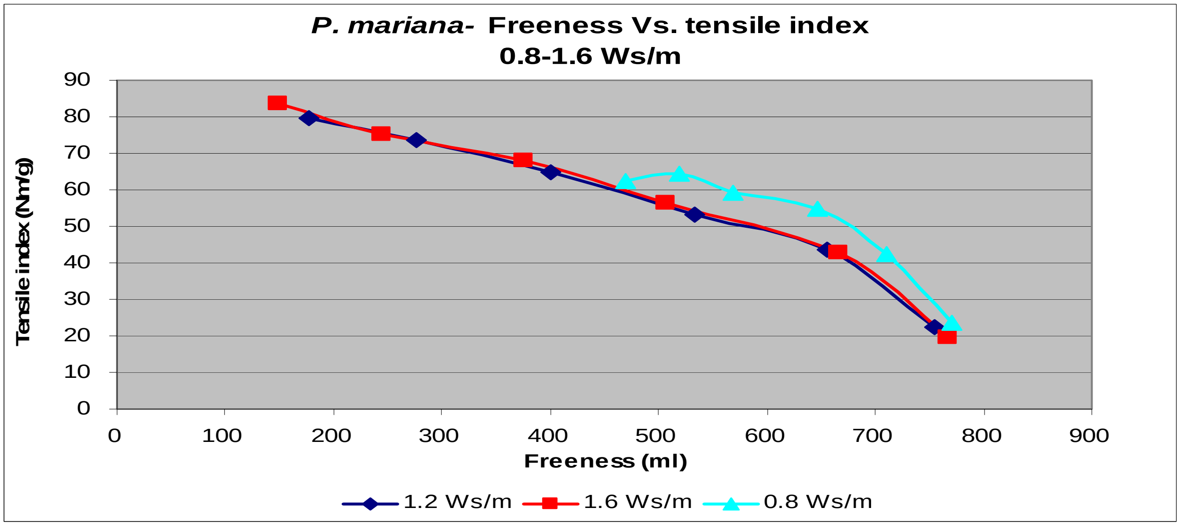


Figure 6.6: Refined freeness vs. tensile index of the *P. mariana* at various refining intensities.

As noted with the *P. patula,* a high intensity of 1.6 Ws/m was best suited to develop tear with the *P. mariana* (Figure 6.6) , to reach the maximum tear index at a 450 CSF freeness a refining energy of approximately 110 kWh/t was required. Compared to the *P. patula*, the *P. mariana* was less sensitive to the selected intensities when developing the tear and tensile, this was most likely due to the *P. mariana* having more fibres per gram. The *P. patula* developed a higher tear (16.2 $mN.m^2/g$) than the *P. mariana* (15.2 $mN.m^2/g$) at the 450 CSF freeness target using 50 kWh/t less energy.

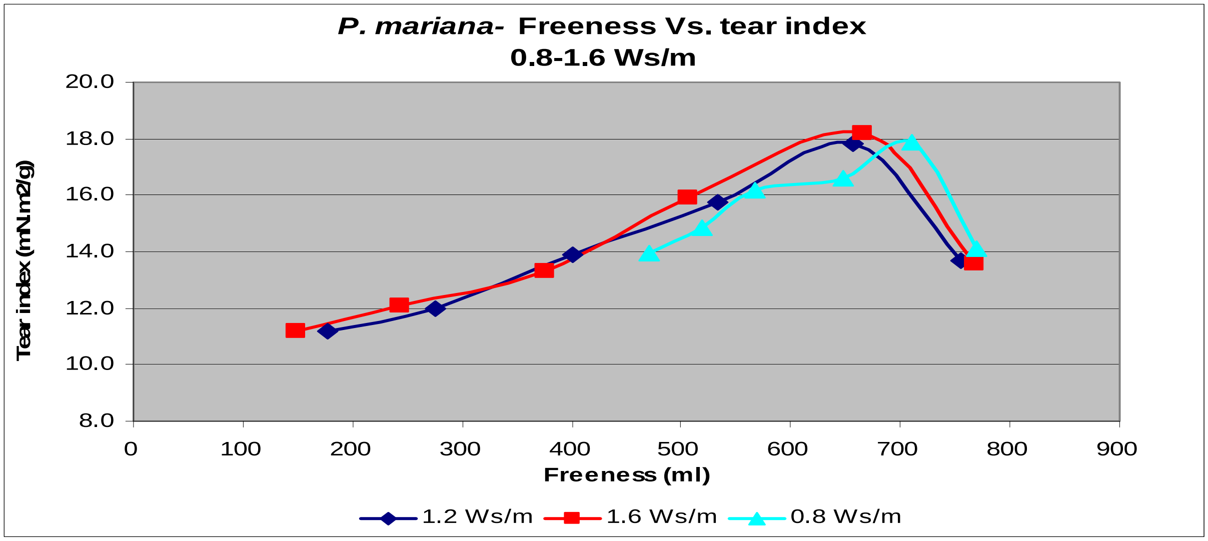


Figure 6.7: Refined tear index vs. freeness of the *P. mariana* at various refining intensities.

The *P. mariana* tear / tensile relationship (Figure 6.8) indicated that the high intensity 1.6 Ws/m trial was best, providing for the maximum tensile at a given tear. The low intensity 0.8 Ws/m trial also provided good strength development but is not economically feasible due to the high amount of costly refining energy required to reduce the freeness to the set target.

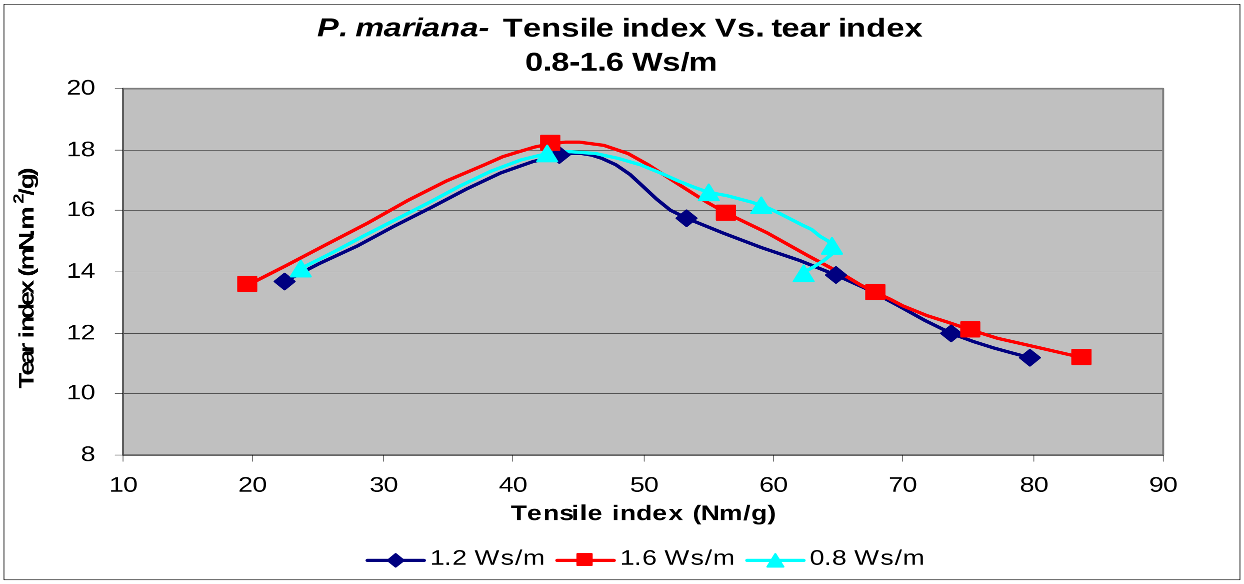


Figure 6.8: Refined freeness vs. tear index of the *P. mariana* at various refining intensities.

6.4. Establishing optimized refining parameters for *P. menziesii*

Of the three samples evaluated, the *P. menziesii* had the lowest average coarseness, highest number of fibres per gram and a thick cell wall. These fibre dimensions resulted in a fibre that was more resilient to refining, requiring a high energy and intensity to develop the greater number of fibres and reduce the freeness (figure 6.9).

At the higher intensities of 1.2 Ws/m and 1.6 Ws/m the freeness curves were close to each other and very similar to that of the *P. mariana* requiring approximately 120 kWh/t to reach the 450 CSF target. With low intensity refining at 0.8 Ws/m the energy requirement increased to 175 kWh/t to achieve the same 450 CSF target. This was lower than the *P. mariana* (240 kWh/t) but more than double that required by the *P. patula* (80 kWh/t).

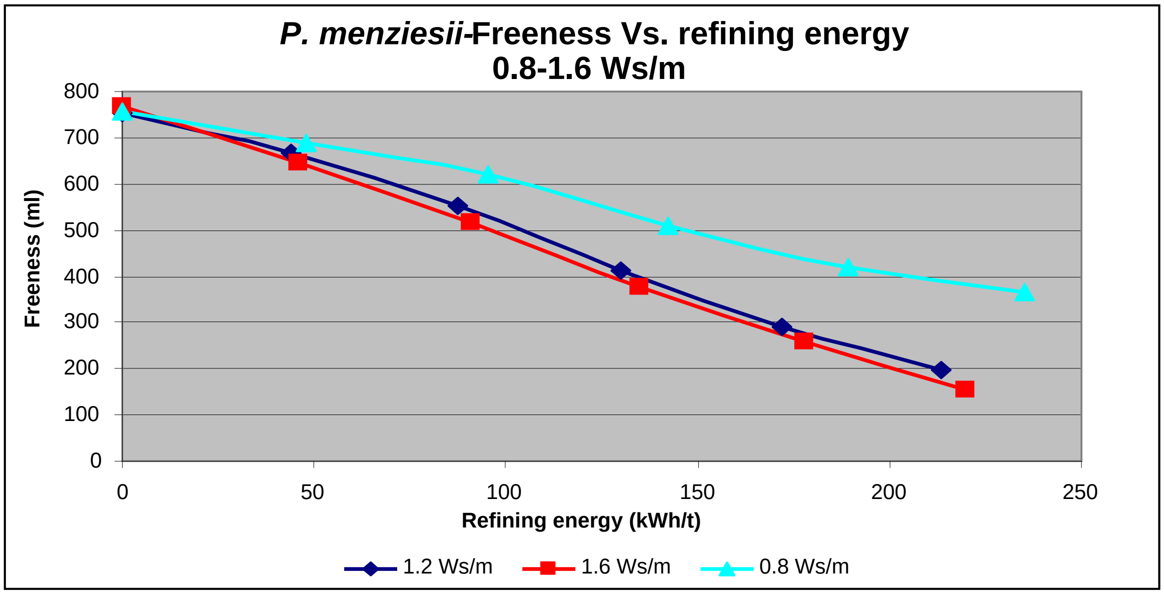


Figure 6.9: Refining energy vs. freeness of the *P. menziesii* at various refining intensities.

The *P. menziesii* had the highest unrefined tensile and developed the highest refined tensile of all 3 samples at the 450 CSF target. Once again, as with the *P. mariana*, the 1.2 and 1.6 Ws/m trials showed similar tensile trends with a significant shift when moving to the 0.8 Ws/m intensity. The low intensity trial exhibited the highest tensile result at the expense of a high refining energy (Figure 6.10). The difference in the refined tensile between the low intensity and high intensity trial was only 7 % but the difference in the refining energy to achieve the tensile gain was a significant

70 kWh/t which is not easily justified. There was very little difference in the refined tensile with the 1.2 Ws/ and 1.6 Ws/m trials (1.5%) but the 1.6 Ws/m trial required 10 kWh/t less energy to get to the freeness target. With due consideration to both energy costs and fibre development a refining intensity of 1.6 Ws/m using 110 kWh/t provided the best set of conditions to match the required freeness target and achieve good tensile development.

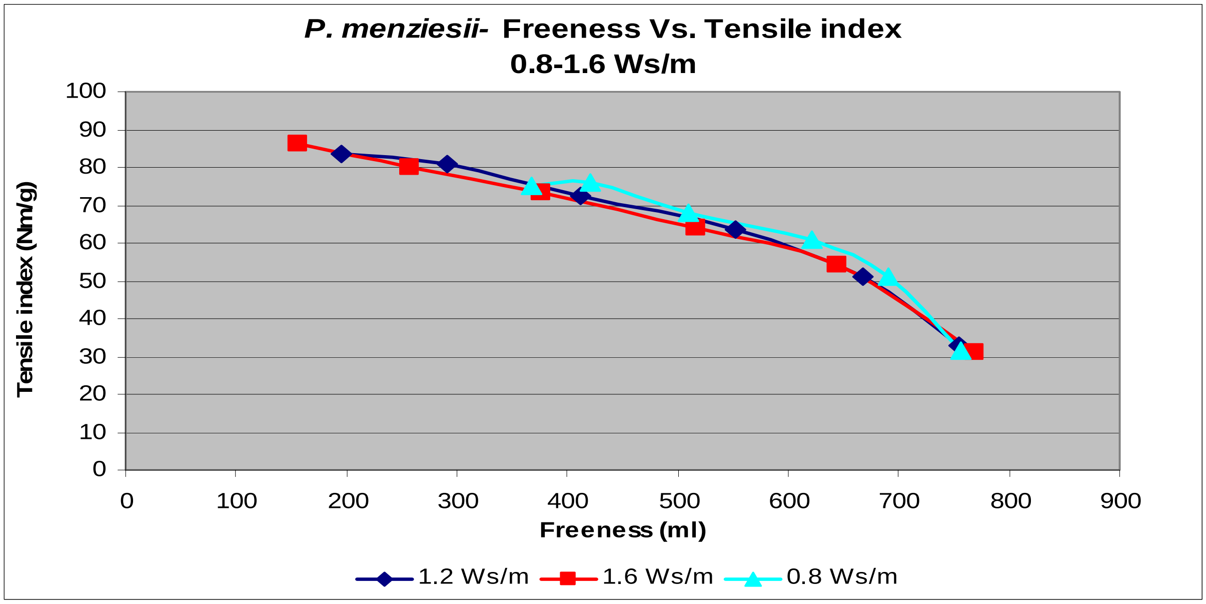


Figure 6.10: Refined freeness vs. tensile index of the *P. menziesii* at various refining intensities.

The *P. menziesii* was not very sensitive to the selected refining intensities. All three of the intensities evaluated followed a similar trend in the tear and tensile development. This was most likely due to the higher number of fibres per gram of pulp. As with the *P. mariana*, a greater range of intensities may have presented a wider spread in the trends.

Excluding the low intensity 0.8 Ws/m trial (due to the high energy requirement), the 1.2 Ws/m trial delivered a slightly higher tear (2%) than the 1.6 Ws/m trial (Figure 6.11) but required 10 kWh/t more energy achieve the 450 CSF target. With rising energy costs the optimum set of refining conditions will probably favor the 1.6 Ws/m intensity as the additional 2% tear is not likely to add any significant benefit. The *P. menziesii* developed a slightly lower tear (14.9 mN.m^2/g) than the *P. mariana* at the 450 CSF target using the same refining energy and intensity.

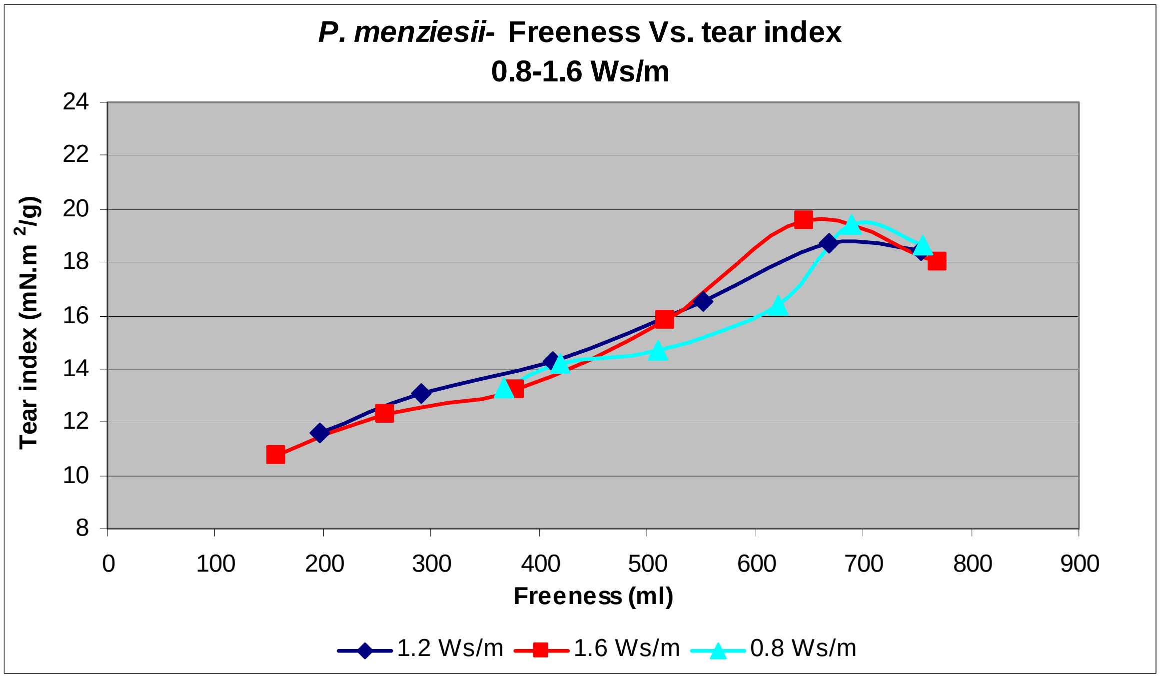


Figure 6.11: Refined freeness vs. tear index of the *P. menziesii* at various refining intensities.

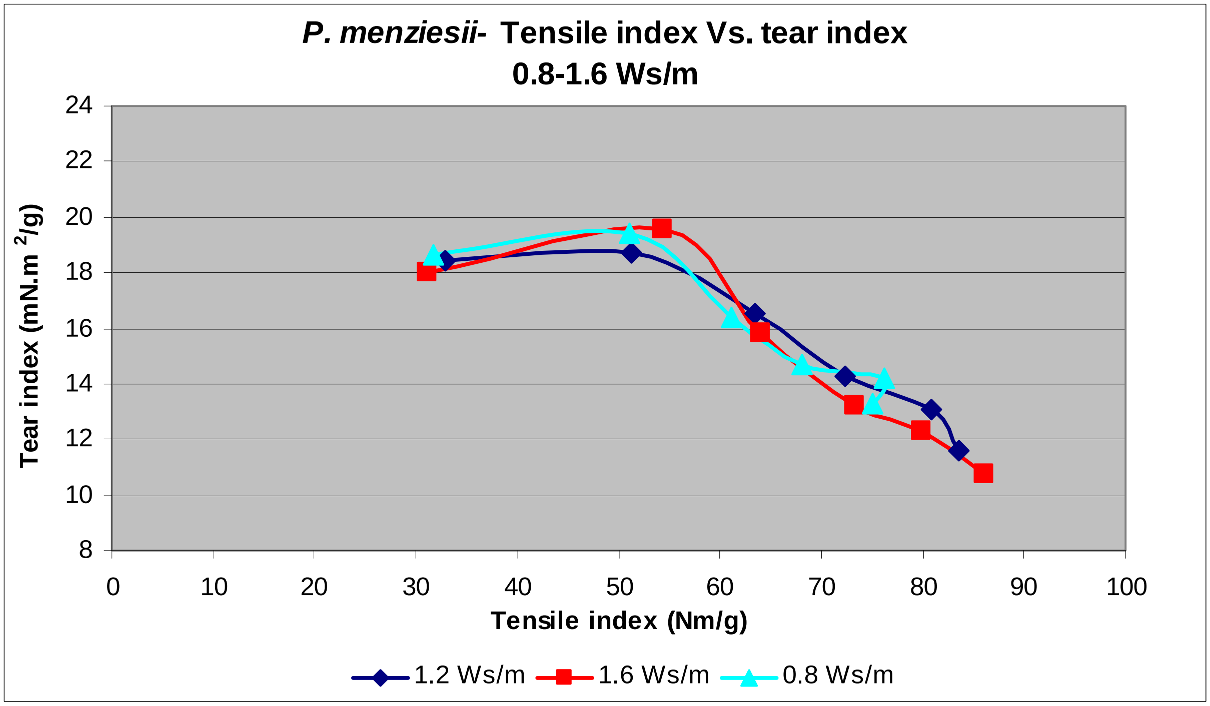


Figure 6.12: Refined tensile index vs. tear index of the *P. menziesii* at various refining intensities.

6.5. Summary of optimized refining parameters for *P. patula, P. mariana* and *P. menziesii*

Table 6.1 summarizes the effects of refining energy and intensity on the tear and tensile development of the three pulp samples. The highlighted blocks provide a comparison of optimum conditions and relative refining energy costs.

Table 6.1: Summary of refined properties for *P. patula*, *P. mariana* and *P. menziesii at* a 450 CSF freeness

Intensity			***P. patula***	***P. menziesii***	***P. mariana***
O.8 Ws/m	**Energy**	kWh/t	80	172	240
	Cost	R m pa	0.95	1.82	2.47
	Tensile	Nm/g	50	74	62
	Tear	mNm^2/g	14	14.4	14
1.2 Ws/m	**Energy**	kWh/t	80	120	115
	Cost	R m pa	0.95	1.33	1.29
	Tensile	Nm/g	46	70	62
	Tear	mNm^2/g	14.5	14.9	14.8
1.6 Ws/m	**Energy**	kWh/t	60	108	115
	Cost	R m pa	0.76	1.22	1.29
	Tensile	Nm/g	42	68	62
	Tear	mNm^2/g	15.5	14.4	15

Scanning electron micrographs (SEM) were taken from hand-sheets made from each of the refined samples at an approximate freeness of 450 CSF (Figures 6.13 – 6.18).

SEM images confirmed *P. patula* contained fewer fibres for a given area. The *P. patula* fibres were also extremely heterogeneous containing both flat, collapsed fibres and rigid fibres. The fibres that resisted collapse increased the bulk of the sheet and created voids which reduced the fibre/fibre contact points. Images of the two Northern species revealed a greater number of fibres per unit area and a more homogenous distribution in fibre characteristics. Cross section images showed most of the Northern fibres were collapsed and very "flat" in nature promoting an increased surface area for adjacent fibre/fibre bonds thereby supporting a higher tensile strength when compared to *P. patula*.

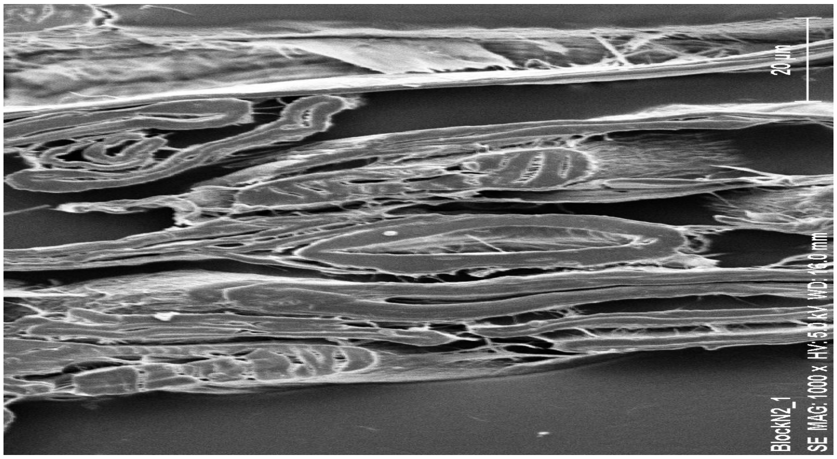


Figure 6.13 SEM Cross section of a handsheet made from refined *P. patula*

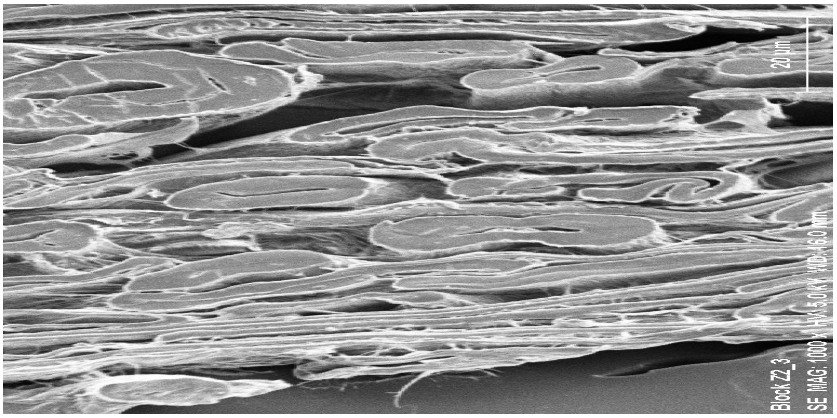


Figure 6.14 SEM Cross section of a handsheet made from refined *P. menziesii*

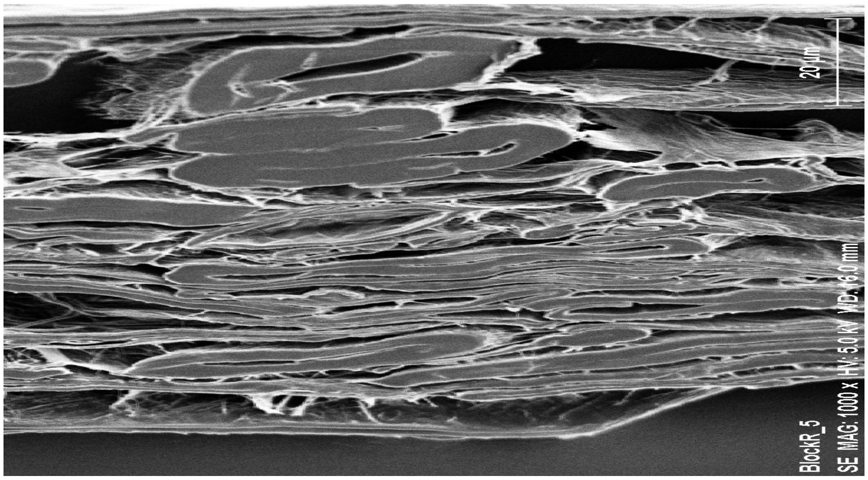


Figure 6.15 SEM Cross section of a handsheet made from refined *P. mariana*

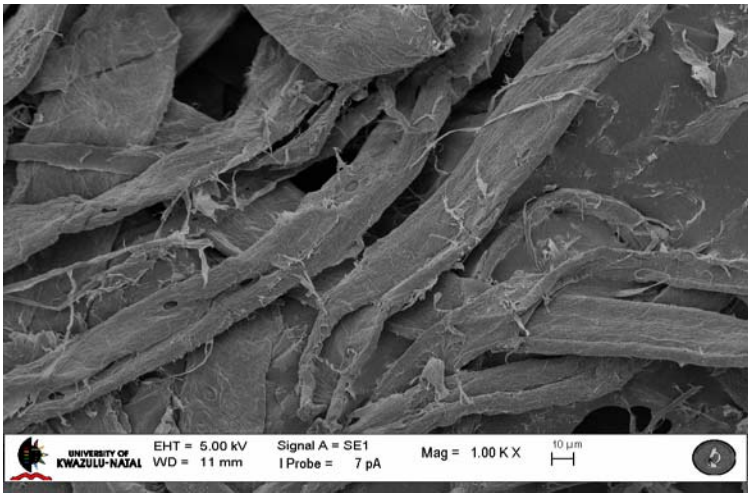


Figure 6.16 SEM surface image of a handsheet made from refined *P. patula*

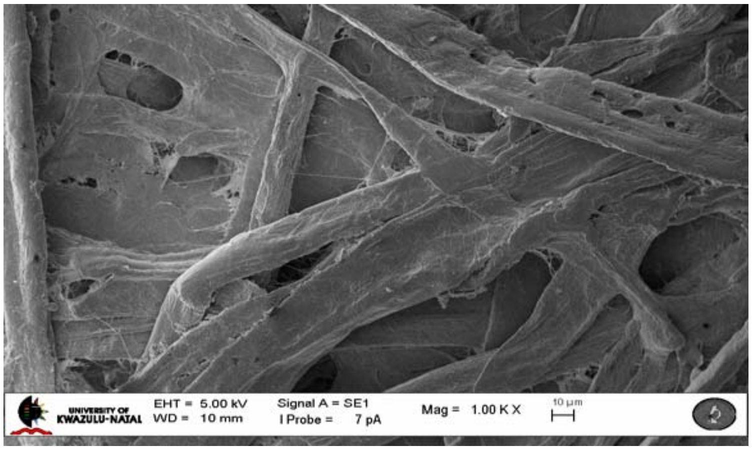


Figure 6.17 SEM surface image of a handsheet made from refined *P. menziesii*

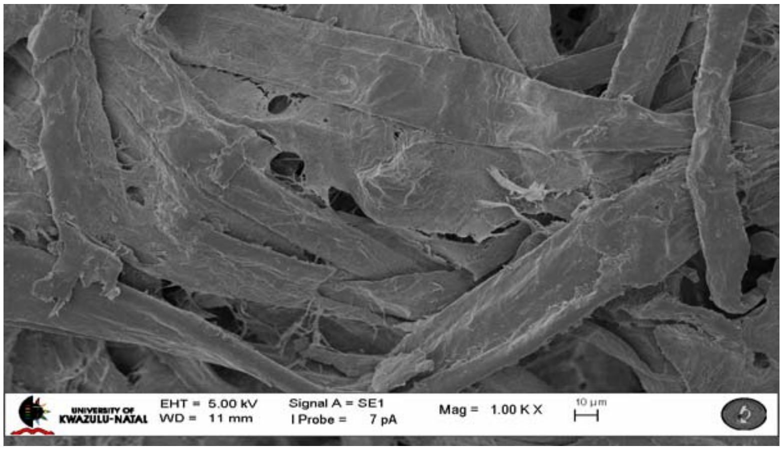


Figure 6.18 SEM surface image of a handsheet made from refined *P. mariana*

CHAPTER 7

7.1 Summary and Conclusions:

The selected Northern and Southern softwood samples were heterogeneous in nature with each exhibiting a unique set of fibre characteristics. *P. patula* demonstrated the highest degree of heterogeneity with a wide variation in fibre characteristics both between earlywood and latewood formation and between juvenile and mature wood growth. This suggested that a *P. patula* pulp sample produced from the inner core of the tree will differ significantly (in refining response and strength development) to *P. patula* pulp produced from wood chips sourced from the outer core of the tree. The pulping of whole tree *P. patula* therefore contains a mix of fibres with exceptionally wide ranging morphologies. These unique characteristics make *P. patula* an ideal candidate for fractionation studies. Appropriate treatment of the fractionated streams could enhance both the tear and tensile properties of the *P. patula* sample.

Anatomical measurements on wood samples of the respective wood species showed *P. patula* had the longest fibre length with a relatively large width and lumen diameter. As expected, with all three wood samples there was clear evidence of increasing fibre width and cell wall thickness from the pith to bark, indicating increased latewood formation with tree age. Results from Densitometry tests on the wood samples also showed an increasing frequency of high density peaks from the pith to the bark, confirming increased latewood formation.

The fibre morphology and densitometry trends noted with *P. patula,* was particularly unique and significantly different to the two Northern samples. In the early stages of tree growth, during juvenile wood formation, *P. patula* had few high density peaks (relative to the high frequency of high density peaks noted with the two Northern samples) suggesting a comparatively low proportion of latewood growth. As the *P. patula* aged and entered into mature wood formation there was a marked increase in the frequency of high density peaks, indicative of increased latewood growth.

Fibre characteristics also differed significantly for *P. patula* in the transition between earlywood and latewood formation. Extreme changes in fibre width, density and cell wall thickness were evident. The cell wall thickness peaks of the *P. patula* during mature wood formation were significantly higher than the two Northern samples.

Comparative fibre morphology studies on the three pulp samples showed the unrefined, Southern *P. patula* pulp sample contained fibres that were significantly wider and slightly longer than the Northern *P. mariana* and *P. menziesii* samples. The thicker fibre widths meant that the *P. patula* had a relatively high coarseness and fewer fibres per gram of pulp.

The Northern *P. mariana* and *P. menziesii* pulp samples showed similar distributions in cell wall thickness but differed to the Southern *P. patula* sample which exhibited a significantly higher cell wall thickness during latewood formation.

The Northern hemisphere pulps had the highest Pulmac fibre strength. However, when corrected for differences in fibre frequency per gram of pulp, *P. patula* had the highest fibre strength. *P. patula* had the highest number of fines particles which were also the shortest in length.

To monitor and compare the individual refining characteristics of the three samples, one standard refining programme was selected and applied to all by means of a 12"single disc pilot refiner.

When refined, *P. patula* differed significantly to the two Northern samples, because of a fast freeness development at a relatively low energy input. This phenomenon was attributed to the relatively small number of fibres per gram of *P. patula* pulp which was equivalent to a higher refining energy and intensity. *P. patula* also had the widest average lumen width emanating from the high percentage of earlywood fibres.

The Northern *P. menziesii* and *P. mariana* had very similar fibre dimensions with a lower average coarseness and higher number of fibres per gram. Both these Northern pulps showed more resilience to refining whereas the *P. patula* was more sensitive and susceptible to fibre cutting and fines generation.

In its unrefined state, *P. patula* exhibited the highest fibre curl but after refining had the straightest fibres showing signs of relatively high fibre flexibility, most likely due to the high percentage of earlywood fibres.

P. menziesii and *P. mariana* had the highest unrefined tensile index and developed the highest tensile gain in the early stages of refining. *P. patula* developed less tensile with refining.

Considering *P. patula* had the highest fibre strength but developed the lowest relative tensile could be related to the coarse fibres. The extremely coarse *P. patula* latewood fibres produced during mature wood growth are rigid and resist collapse, interfering with adjacent fibre to fibre bonding of the earlywood fibres. This, together with the relatively small number of fibres per gram results in a pulp with a low bonded area and reduced tensile potential. It could be said, that the final refined tensile properties of *P. patula* is only as strong as the weakest link in the fibre network which in this case appears to be the presence of coarse fibres

All three samples had an initial increase in refined tear index at a low energy input followed by a reduction in tear as the refining energy was increased. *P. patula* delivered a high refined tear index but also demonstrated the greatest loss in tear at high refining energy levels, a phenomenon most likely related to the coarse fibres.

P. patula with its coarse fibres also provided for the highest refined bulk index. Of the three samples, *P. patula* had the longest average fibre length which is likely to have contributed to better tear results.

In general, results confirmed that there were significant differences in the fibre morphology of the raw samples both between the three different species and between the two Hemispheres. Results from the comparative refining study also provided evidence that the fibre characteristics dictate the manner in which a fibre responds to refining which in turn determines the relative contribution to specific refined pulp properties.

The final stage of the study focused on the identification of an optimum set of refining parameters for each of the three samples. Optimum conditions were based on the refining parameters that delivered the best tear and tensile result at a refined freeness of 450 ml CSF.

Southern *P. patula* delivered optimum refined strength properties using a relatively low specific energy and low intensity refining. The two Northern samples required both a higher refining energy and intensity to develop the fibres to the optimum strength potential. A hand-sheet study of the refined pulps generated from ideal refining conditions on each sample showed that the Southern *P.*

patula delivered a high refined tear index but did not have the potential to develop the refined tensile properties achieved with the Northern samples.

It was also noted that the selection of a suitable refining programme was highly dependant on that specific pulp grade and the refined properties being targeted. For example, when refining *P. patula* to achieve maximum tear, a refined freeness of 575 ml CSF is optimum using a refining load of only 35 kWh/t and a high intensity of 1.6 Ws/m. When targeting an optimum tensile result the optimum refining parameters are vastly different, the *P. patula* should be refined with a higher energy ranging from 70-100 kWh/t (depending on the low freeness limit of the paper-machine) using a low intensity of 0.8 Ws.m. Similar findings were observed with the Northern samples however the optimum refining conditions differed significantly to the *P. patula*.

In general, the findings suggested the refining parameters should be carefully selected according to the pulp being refined and the strength properties required for the specific end product.

7.2 Recommendations

From the results analyzed in this investigation it is recommended that further studies focus on the fractionation of *P. patula* and the benefits associated with subsequent refining of the separated streams. Furthermore, valuable insight may also be gained through a similar investigation comparing the refining characteristics of the same species grown in both the Northern and Southern Hemispheres.

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Appendix 1 – Refining results at 1.2 Ws/m

P. menziesii		**1.2 Ws/m**					
	kWh/t	**0**	**44**	**87**	**130**	**172**	**214**
Freeness	**ml**	754	668	552	412	291	196
Grammage(Cond)	**Gsm**	75.5	73.7	76.2	77.2	76.1	76.4
Grammage(B.D)	**Gsm**	70.6	68.8	71.1	72.1	71.0	71.3
Moisture	**%**	6.46	6.61	6.64	6.66	6.77	6.64
Bulk Specific	**cm³/g**	1.81	1.67	1.55	1.47	1.44	1.41
Tear Index	**mN.m²/g**	18.4	18.7	16.5	14.3	13.1	11.6
Tensile Index	**Nm/g**	33.0	51.3	63.4	72.4	80.9	83.5
P. patula		**1.2 Ws/m**					
	kWh/t	**0**	**33.8**	**66.8**	**99.3**	**131**	**162.1**
Freeness	**ml**	762	628	504	339	198	117
Grammage(Cond)	**Gsm**	75.1	74.1	72.7	72.4	73.9	73.9
Grammage(B.D)	**Gsm**	70.4	69.4	68.1	67.8	69.2	69.2
Moisture	**%**	6.31	6.32	6.31	6.35	6.30	6.40
Bulk Specific	**cm³/g**	1.90	1.74	1.62	1.53	1.47	1.42
Tear Index	**mN.m²/g**	15.2	18.2	15.7	12.6	11.2	9.7
Tensile Index	**Nm/g**	17.57	30.79	41.96	51.24	59.14	62.37
P. mariana		**1.2 Ws/m**					
	kWh/t	**0**	**44**	**87**	**130**	**172**	**214**
Freeness	**ml**	755	656	534	400	276	177
Grammage(Cond)	**Gsm**	74.8	74.8	76.6	77.0	77.2	76.9
Grammage(B.D)	**Gsm**	70.1	70.0	71.8	72.1	72.3	72.0
Moisture	**%**	6.30	6.37	6.32	6.32	6.31	6.37
Bulk Specific	**cm³/g**	1.90	1.70	1.61	1.48	1.43	1.39
Tear Index	**mN.m²/g**	13.7	17.8	15.7	13.9	12.0	11.2
Tensile Index	**Nm/g**	22.50	43.60	53.4	64.9	73.70	79.70

Appendix 2 – Refining results at 0.8 Ws/m

P. menziesii		**0.8 Ws/m**					
	kWh/t	**0**	**48**	**95**	**142**	**189**	**235**
Freeness	**ml**	756	690	621	510	420	367
Grammage(Cond)	**Gsm**	75.8	75.9	75.4	77.1	75.1	75.4
Grammage(B.D)	**Gsm**	70.8	70.9	70.4	72.1	70.0	70.3
Moisture	**%**	6.70	6.55	6.63	6.38	6.72	6.85
Bulk Specific	**cm³/g**	1.81	1.64	1.60	1.52	1.47	1.43
Tear Index	**mN.m²/g**	18.6	19.4	16.4	14.7	14.2	13.3
Tensile Index	**Nm/g**	31.8	51.1	61.0	68.0	76.2	75.0
P. patula		**0.8 Ws/m**					
	kWh/t	**0**	**36.3**	**72.3**	**107.8**	**142.8**	**177.4**
Freeness	**ml**	780	612	488	325	187	110
Grammage(Cond)	**Gsm**	73.8	75.4	73.1	75.4	76.7	75.3
Grammage(B.D)	**Gsm**	69.1	70.6	68.4	70.6	71.7	70.4
Moisture	**%**	6.32	6.44	6.45	6.46	6.48	6.47
Bulk Specific	**cm³/g**	1.90	1.72	1.59	1.51	1.43	1.37
Tear Index	**mN.m²/g**	14.1	18.2	14.6	12.1	10.9	10.2
Tensile Index	**Nm/g**	19.93	35.80	46.94	58.19	64.06	73.58
P. mariana		**0.8 Ws/m**					
	kWh/t	**0**	**48**	**95**	**142**	**189**	**235**
Freeness	**ml**	770	710	647	568	519	470
Grammage(Cond)	**Gsm**	75.0	74.1	73.7	74.6	73.3	74.2
Grammage(B.D)	**Gsm**	69.9	69.1	68.8	69.6	68.4	69.2
Moisture	**%**	6.83	6.80	6.64	6.69	6.70	6.64
Bulk Specific	**cm³/g**	1.90	1.73	1.66	1.57	1.53	1.48
Tear Index	**mN.m²/g**	14.1	17.9	16.6	16.2	14.9	14.0
Tensile Index	**Nm/g**	23.60	42.60	55	59.1	64.50	62.30

Appendix 3 – Refining results at 1.6 Ws/m

P. menziesii		**1.6 Ws/m**					
	kWh/t	**0**	**46**	**91**	**135**	**178**	**220**
Freeness	**ml**	769	645	517	377	258	156
Grammage(Cond)	**Gsm**	74.4	73.4	77.0	76.4	74.7	75.5
Grammage(B.D)	**Gsm**	69.5	68.7	72.1	71.6	70.1	70.6
Moisture	**%**	6.60	6.44	6.38	6.25	6.21	6.51
Bulk Specific	**cm³/g**	1.74	1.63	1.52	1.45	1.42	1.39
Tear Index	**mN.m²/g**	18.0	19.5	15.8	13.2	12.3	10.7
Tensile Index	**Nm/g**	31.1	54.3	64.0	73.3	79.9	86.1
P. patula		**1.6 Ws/m**					
	kWh/t	**0**	**35.3**	**69.7**	**103.2**	**135.8**	**167.5**
Freeness	**ml**	763	574	416	270	138	87
Grammage(Cond)	**Gsm**	76.0	73.4	74.2	75.2	74.0	76.8
Grammage(B.D)	**Gsm**	71.0	68.7	69.4	70.3	70.7	71.8
Moisture	**%**	6.48	6.44	6.49	6.49	4.44	6.47
Bulk Specific	**cm³/g**	1.90	1.71	1.64	1.54	1.46	1.36
Tear Index	**mN.m²/g**	15.3	18.1	14.8	11.9	10.6	9.1
Tensile Index	**Nm/g**	15.66	32.69	43.30	48.42	58.38	65.24
P. mariana		**1.6 Ws/m**					
	kWh/t	**0**	**46**	**91**	**135**	**178**	**220**
Freeness	**ml**	767	666	506	375	244	149
Grammage(Cond)	**Gsm**	75.1	73.8	75.2	74.2	76.7	75.3
Grammage(B.D)	**Gsm**	70.2	69.2	70.5	69.5	71.9	70.6
Moisture	**%**	6.43	6.22	6.30	6.32	6.24	6.18
Bulk Specific	**cm³/g**	1.95	1.68	1.64	1.46	1.42	1.33
Tear Index	**mN.m²/g**	13.6	18.2	15.9	13.3	12.1	11.2
Tensile Index	**Nm/g**	19.70	43.00	56.5	67.9	75.20	83.80

Appendix 4 – Average MorFi results on pilot refined *P. patula* pulp samples

	Energy	Fibre Length	Fibre Width	Wall thickness	Coarseness	Fines	Kink	Curl
Intensity	**kWh/t**	**µm**	**µm**	**µm**	**mg/m**	**%**	**%**	**%**
0.8 Ws.m	0	2119	26.9	3.40	0.28	1.5	36	9.6
	36	1920	27.2	3.23	0.28	1.9	29	8.3
	72	1833	27.8	3.23	0.22	2.1	22	7.5
	108	1579	27.6	3.16	0.21	2.4	20	7.0
	143	1435	27.2	3.16	0.20	3.0	18	6.7
	177	1248	27.0	3.18	0.19	3.2	17	6.6
1.2 Ws.m	0	2119	26.9	3.38	0.28	1.5	36	9.6
	34	1891	27.4	3.42	0.24	1.8	30.1	8.6
	67	1754	27.6	3.38	0.24	2.2	26.1	7.9
	99	1517	27.5	3.42	0.24	2.7	22.0	7.0
	131	1419	27.5	3.30	0.20	2.9	18.4	6.8
	162	1249	27.0	3.43	0.29	3.3	16.9	6.2
1.6 Ws.m	0	2119	26.9	3.40	0.28	1.8	36	9.6
	35	1815	27.4	3.55	0.24	1.9	28.0	8.1
	70	1628	27.5	3.48	0.21	2.3	22.3	7.3
	103	1408	27.6	3.53	0.20	2.9	19.0	6.9
	136	1231	27.1	3.48	0.18	3.2	17.4	6.5
	168	1054	26.7	3.23	0.19	3.9	16.7	6.3

Appendix 5 – Average MorFi results on pilot refined *P. menziesii* pulp samples

	Energy	Fibre Length	Fibre Width	Wall thickness	Coarseness	Fines	Kink	Curl
Intensity	**kWh/t**	**µm**	**µm**	**µm**	**mg/m**	**%**	**%**	**%**
0.8 Ws.m	0	1976	27.43	3.671	0.14	0.8	25.4	8.12
	48	1897	27.3	3.690	0.15	1.05	20.9	7.34
	95	1865	27.43	3.59	0.13	0.96	18.2	7.09
	142	1832	27.63	3.49	0.12	0.93	16.9	7.26
	189	1691	27.47	3.45	0.14	1.19	15.7	6.81
	235	1668	27.57	3.46	0.14	1.15	14.9	6.76
1.2 Ws.m	0	1976	27.43	3.671	0.14	0.8	25.4	8.12
	44	1894	27.33	3.700	0.12	0.98	21.4	7.49
	87	1828	27.3	3.567	0.13	1.11	18.8	7.22
	130	1617	27.47	3.394	0.13	1.42	16.5	6.97
	172	1501	27.5	3.4	0.12	1.29	16	6.89
	214	1369	27.23	3.413	0.13	1.44	15.4	6.76
1.6 Ws.m	0	1976	27.43	3.671	0.14	0.8	25.4	8.12
	46	1919	27.33	3.862	0.14	1.07	20.4	7.41
	91	1708	27.27	3.811	0.13	1.26	18.1	7.04
	135	1593	27.2	3.46	0.12	1.38	16.5	6.82
	178	1432	27.4	3.31	0.13	1.52	16.3	6.72
	220	1332	27.45	3.169	0.13	1.83	15.1	6.94

Appendix 6 – Average MorFi results on pilot refined *P. mariana* pulp samples

	Energy	Fibre Length	Fibre Width	wall thickness	Coarseness	Fines	Kink	Curl
Intensity	**kWh/t**	**µm**	**µm**	**µm**	**mg/m**	**%**	**%**	**%**
0.8 Ws.m	0	1870	25.3	3.75	0.17	1.34	28.6	8.1
	48	1821	25.3	3.82	0.17	1.56	23.3	7.36
	95	1797	25.7	3.69	0.17	1.57	20.4	7.00
	142	1763	26.2	3.43	0.15	1.58	19.1	7.00
	189	1699	26.3	3.18	0.16	1.58	17.6	6.85
	235	1623	25.8	3.17	0.17	1.69	16.4	6.74
1.2 Ws.m	0	1870	25.3	3.28	0.17	1.34	28.6	8.1
	44	1819	25.6	3.24	0.16	1.44	22.8	7.33
	87	1696	25.8	3.02	0.16	1.96	19.9	7.19
	130	1500	26	3.24	0.15	2.11	17.7	6.73
	172	1309	26.1	3.13	0.15	2.16	17.6	6.58
	214	1230	26.3	2.88	0.14	2.61	16.5	6.53
1.6 Ws.m	0	1870	25.3	3.65	0.16	1.34	28.6	8.1
	46	1727	26.2	3.46	0.15	1.59	23.3	7.43
	91	1630	26.1	3.43	0.14	1.83	20.2	7.07
	135	1487	26.1	3.3	0.14	2.21	17.7	6.73
	178	1306	25.9	3.07	0.14	2.33	17.4	6.73
	220	1180	25.9	3	0.13	2.74	16.6	6.71