THE IMPACT OF LOW CONSISTENCY REFINING OF EUCALYPTUS SPECIES ON THE FIBRE MORPHOLOGY AND STRENGTH PROPERTIES OF PULP.

by

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ABSTRACT

It is a well-known fact that the selection of the raw material and how it is further treated within the stock preparation system has a major affect on the quality of paper obtained. While the pulp selection is important for a good product, the refining treatment received by that pulp is the determining factor for the properties of the product. It is for these reasons that it is interesting and beneficial to study the pulp quality and refining results. The focus of this research work was to study the behaviour of selected clones of Eucalyptus materials from different site indices under different refining conditions. Poor and good sites were investigated. The strength properties of the resulting refined pulp were investigated.

The project was conducted in three phases with the focus of the project being phase 3. The work began with refining of commercial Eucalyptus pulp obtained from Mondi Richards Bay (phase 1). The objective here was to get an understanding of the influence of the various parameters affecting refining. This knowledge could then be used on a more focused research program on the well defined pulps with limited refining variables being considered. The results indicated that of the three variables investigated (i.e. stock flow rate, stock consistency and refiner speed of rotation) the parameter speed of rotation gave the most repeatable results when varied and also resulted in the largest range of refining intensity (SEL) achievable compared to the variation of the other two parameters. It was decided that the work on the different pulps investigated in phase 3 would be carried out using the parameter speed of rotation to vary the SEL and multiple passes through the refiner to vary the specific refining energy (SRE).

A comparison between the refining characteristic of bleached and unbleached pulp was carried out (phase 2). It was seen that there were differences in the refining characteristics between bleached and unbleached pulp. These differences however, occurred in a predictable manner. This indicated that with further investigations on the differences in refining characteristics, it would be possible to extend the results obtained from refining studies using unbleached pulp to what can be expected from the refining of bleached pulp.

Phase 3 of the project considered the refining of different pulps. Two different clones of *Eucalyptus* (GU A380 and GC G438) each from two site indices (good and poor), were selected to provide raw materials having different wood anatomy. These were pulped under similar cooking conditions using the kraft pulping process. The kappa numbers were in the range of 18 to 21. The refining trials were then conducted to determine how the different

pulps affected the refining process and also how the refining process affected the pulp properties. Refining was carried out at three different refiner speeds. It was seen that for the overall results SRE was a good predictor of all the pulp properties measured except for the tear. The pulp fibre length was able to predict the tear best. It was seen that refining higher intensities reduced the SRE required to obtain a pulp freeness of 400 ml.

PREFACE

The experimental work described in this dissertation was carried out at the Forestry and Forest Products Research Centre, University of Kwazulu Natal-CSIR, Durban. The author was registered with the School of Chemical Engineering at the University of Kwazulu Natal, Durban from March 2003 to May 2005. Professor Philip Turner, director of the Forestry and Forest Products Research Centre, CSIR and Mr Iain Kerr, University of Kwazulu Natal, Durban, supervised this work.

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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LIST OF ABBREVIATIONS

• 100SRE	At a SRE of 100 kWh/t
• 400csf	At a freeness of 400 ml
• A.A	Active Alkalinity
• ANOVA	Analysis of variance
• CEL	Cutting edge length in m/revolution
• CSF	Canadian Standard Freeness
• CSIR	Council for Scientific and Industrial Research
• CWT	Cell wall thickness in micron
• DBH	Diameter at breast height in cm
• FD	Fibre diameter in microns
• *ffp*	Forestry and forest products
• FL	Fibre length in mm
• GC	Refers to the Eucalyptus GC G438 clone
• GCG	Refers to the GC clone from the good site
• GCP	Refers to the GC clone from the poor site
• GU	Refers to the Eucalyptus GU A380 clones
• GUG	Refers to the GU clone from the good site
• GUP	Refers to the GU clone from the poor site
• i-Coarse	Initial pulp coarseness in mg/m
• i-Collaps	Initial pulp fibre collapsibility
• i-CWT	Initial pulp cell wall thickness (micron)
• i-CWT/LD	Ratio of initial pulp cell wall thickness to initial pulp lumen diameter
• i-FD	Initial pulp fibre diameter (micron)
• i-FD/CWT	Ratio of initial pulp fibre diameter to initial pulp cell wall thickness
• i-FD/LD	Ratio of initial pulp fibre diameter to initial pulp lumen diameter
• i-fines	Initial pulp fines content (%)
• i-FL	Initial pulp fibre length in mm
• i-FL/FD	Ratio of initial pulp fibre length to initial pulp fibre diameter
• i-LD	Initial pulp lumen diameter (micron)

- i-Muhlsteph — Initial pulp muhlsteph ratio
- i-Runkel — Initial pulp Runkel ratio
- LC — Low-consistency
- LD — Lumen diameter in micron
- Ls — Bar edge crossings or cutting speeds in m/s
- M — Fibre flow rate in bone dry tons/hour
- P — Gross refiner power in kW
- P*net* — Net effective power in kW
- P*o* — No-load power in kW
- r — correlation coefficient
- R^2 — The adjusted R^2 (see glossary)
- SD — Standard deviation
- SEL — Specific Edge Load (Refining intensity in Ws/m)
- SRE — Specific refining energy in kWh/t
- TEA — Tensile energy absorbed in J/m^2
- w-Coarse — Wood fibre coarseness in mg/m
- w-Collaps — Wood fibre collapsibility
- WCWT — Wood cell wall thickness in micron
- WFD — Wood fibre diameter in micron
- WLD — Wood lumen diameter in micron
- w-Runkel — Runkel ratio for wood fibres
- Z-span — Zero-span tensile strength in kN/m

GLOSSARY

Adjusted R^2 A goodness-of-fit measure in multiple regression analysis that penalizes additional explanatory variables by using a degrees of freedom adjustment in estimating the error variance.

Bark The outer covering of stems and branches of trees.

Basis Weight Basis weight is the weight in grams of a single sheet of area one square meter.

Beater This refers to the equipment used for beating or refining pulps.

Beating This is the mechanical treatment of fibres to increase surface area and flexibility of pulp fibres. This promotes bonding when dried.

Bone Dry This is the term that refers to the moisture-free conditions of paper.

Breaking Length This refers to the theoretical length of a uniform width of paper which, when suspended by one end, would break by its own weight.

Bulk The thickness of a sheet of paper. Units are μm

Bursting Strength The resistance of paper to rupture as measured by the hydrostatic pressure required to burst it when a uniformly distributed and increasing pressure is applied to one of its side.

Cellulose Fibre An elongated, tapering, thick walled cellular unit, which is the main structural component of woody plants. Fibres in the plants are cemented together by lignin.

Chemical Pulp Pulp obtained from the chemical cooking or digestion of wood or other plant material.

Chipper The machine that converts wood logs into chips.

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

Cooking This is the process whereby the raw material reacts with chemicals under elevated pressure and temperature to soften and/or remove lignin to separate fibres.

Correlation coefficient (r) A measure of the closeness of the relationship between two variables. The value of r ranges from -1 to +1. As r approaches +1, the more positive the relationship. An r value of 0 indicates no relationship. Negative r values indicate an inverse relationship

Delignification The removal of lignin during the chemical pulping process.

Digester This refers to the reaction vessel in which the cooking process takes place

External fibbrillation Partial detachment of fibrils from the outer layer of a fibre.

Fibre Coarseness Weight per unit length of fibre.

Fibrils Thread-like elements unraveled from the walls of native cellulose fibres in papermaking by the action of refiners.

Fines Small fibre particles defined arbitrarily by classification.

Formation Physical distribution and orientation of fibres and other solid constituents in the structure of a sheet of paper that affects its appearance and other physical properties.

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

Handsheet Circular sheet which is formed on a fine screen from a pulp suspension of fibres.

Hardwood Wood from trees of angiosperms, usually with broad leaves. Hardwoods grow faster than softwoods but have shorter fibres compared to softwoods.

Internal fibrillation This refers to the loosening of internal bonds within a fibre.

Kappa Number This is a measure of residual lignin in pulp.

Kraft Pulp Pulp obtained using the Kraft pulping process. In this process chemical pulping is achieved by the using solutions of sodium hydroxide and sodium sulphide.

Lignin A complex constituent of the wood that cement the cellulose fibres together.

Moisture Content The amount of moisture in paper, pulp, or wood chips.

No-load power To simply just rotate the refiner plates against the stock flow will require some energy. This energy is referred to as the no-load power.

Oven-Dry see bone dry

Paper A sheet that is formed on a fine screen from a suspension of pulp fibres.

Papermaking The process whereby pulp fibres in solution at very low consistency undergo a series of dewatering stages and results in the formation of a sheet of fibres (paper) on a wire screen.

Pith The central part of stems or branches of trees.

Pulp A suspension of cellulose fibres in water produced by either the chemical or mechanical treatment of wood.

Pulping see cooking. The terms cooking and pulping are used interchangeably

Refiner Equipment used to mechanically treat fibres

Refining Refining refers to the process where fibres are subjected to a mechanical action in order to develop their properties optimally with respect to the products being made.

Refining Intensity This refers to the rate at which the effective refining energy is applied. The units are Ws/m

Rejects The fibre bundles that do not go through the 200 μm mesh screens.

Relative Humidity The amount of water vapor present in the air as compared to the maximum potential amount.

Screened pulp yield The yield after uncooked fibre bundles, bark and dirt are removed through 200μm mesh screens, expressed as a percentage of oven dry mass of pulp per unit oven-dry mass of wood.

Sheet Density This is the reciprocal of bulk and is derived by dividing bulk by the basis weight of the handsheet.

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

Softwood Wood obtained from gymnosperms, such as pines, spruces and hemlocks. This type of wood imparts the strength properties to the paper.

Specific refining energy This refers to the amount of effective energy applied per unit weight of pulp. The units are kWh/t

Tear Strength A measure of how likely a paper will continue to tear once started.

Tensile Strength A measure of how likely a paper is to break when pulled at opposite ends or the resistant property of a sheet to stress.

Washing A process of separating spent cooking or bleaching chemicals from pulp fibres.

Yield Ratio of product output and raw material input, expressed in percentage.

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Chapter 1

Introduction and Aims

1.1 Introduction

When considering the manufacture of pulp and paper, it is a well-known fact that the selection of wood and how it is further treated within the stock preparation system has a major affect on the quality of paper obtained. While the pulp selection is important for a good product, the refining treatment received by pulp is a key determinant of the properties of the end product. Historically, the raw materials tended to be long fibres (softwoods) and thus most beating was designed not only to develop fibres but also to reduce fibre length. The treatment of long fibres (softwood fibres) is significantly different to the treatment of short fibres (hardwood fibres), which are being used in larger quantities than in the past. Modern refining practices can produce fine paper from a 100% hardwood furnish and most contain at least 70-90% (Baker 1995).

Due to the fine fibre morphology in relation to other common pulping species, *Eucalyptus* pulps (hardwood pulps) gives good values for opacity, bulk, porosity and sheet formation. The advantages of its use as raw material not only relates to good printing grades but also physical strengths reach the level of the best hardwoods and even though *Eucalyptus* is a short fibre, its mechanical characteristics, after refining, can approach those of long fibres. This allows the incorporation of higher percentages of this type of pulp, which can generally be produced at lower cost than those of softwoods, thus providing an additional economic incentive to use hardwoods to the maximum extent possible (Soini *et al* 1998).

1.2 Aims

Before commencing with the refining trials on four different pulps, to investigate the aim of this project, two other investigations had to be considered. These were considered as two other objectives in the study. The first was an investigation on selected refiner parameters. This was carried out in order to decide on conditions that were used when refining the different pulps. The second investigation was a comparison between the refining characteristics of bleached and unbleached pulp. This was done to see whether differences in the refining characteristics between these two pulps occurred in a predictable manner. After completion of these two objectives the aim of the project was considered in phase three. The aim of this project was to investigate the

differences in refining characteristics of pulps from *Eucalyptus* species that have different fibre morphological characteristics.

Chapter 2

Literature review

2.1 Background

Paper is a fibre product in which fibres are bonded together. The basic material of paper is cellulose (Bolam 1965). There are many possible sources of this cellulose fibre but the most important is wood. Cellulose fibres have the useful property of swelling in the presence of water. The fibres act as their own cement if they are soaked in water and allowed to dry in close contact with one another. In papermaking, a suspension of cellulose fibres in water is poured onto a wire sieve. Most of the water drains through, leaving a layer of fibres that bonds together as it dries to form a coherent sheet (Bolam 1965).

Amongst other things, the properties of the paper are dependent on the properties of the bonds formed between the fibres. In the formation of paper, the fibres are brought into contact with each other and in the subsequent operations the bonds are formed which give the web mechanical strength. The properties of the web are dependent on the size of the contact area and the strength of the bond formed. Since the bonds are formed between the fibre surfaces, one of the basic factors that determines the degree of bonding is the total free surface area of the fibres which are available for bonding. The beating or refining process is in essence a development process. The process modifies the physical structure of the papermaking fibres by subjecting them to repeated strain (Martinez *et al.* 1994). Thus with proper refining it is possible to increase the degree of bonding and hence improve certain strength properties of the paper.

Different types of fibres require different types of refining treatment. The refining treatment of long softwood fibres for example is harsher than the refining treatment of the comparatively shorter hardwood (eg *Eucalypts*) fibres (Baker 1994). Due to the fine fibre morphology in relation to other common pulping species, *Eucalyptus* pulps result in good sheet formation and good values for sheet properties such as opacity, bulk and porosity (Soini *et al.* 1998). However, the advantage of its use as a raw material not only relates to good printing grades. Its physical strengths can reach the level of the best hardwoods and even though *Eucalyptus* is a short fibre, its mechanical characteristics, if refined properly, can approach those of long fibres (Baker 1994, Soini *et al.* 1998). This would allow the incorporation of higher percentages of this type of pulp, which can generally be produced at lower cost than those of softwoods, thus providing an

economic incentive to use this hardwood to the maximum extent possible (Soini *et al* 1998). Modern refining practices can produce fine paper from a 100% hardwood furnish and most contain at least 70-90% (Baker 1995).

2.2 Different types of wood

Botanically, woods have been classified into two major groups; softwoods and hardwoods (Britt 1970, Smook 1992). The structural features of hardwoods and softwoods differ substantially and as a result the way these woods are processed differ accordingly. Softwood fibres are relatively long in comparison to hardwoods. It has become a general practice among papermakers to use long (softwood) fibres - due to their good mechanical properties - to give the paper web better machine runnability during the manufacturing process and the end product higher strength properties. The application of short (hardwood) fibre pulps, typically ranging at lower strength potentials relative to softwood fibres, are used in most cases for the improvement of surface characteristics of the finished sheet. Consequently the relevance of short fibres particularly relates to the production of wood-free printing and writing papers where the optical appearance matters most. Due to differences in fibre characteristics between hardwoods and softwoods, the refining treatment that they require is different.

The anatomy of *eucalyptus* fibres, is given by spindle shaped cells with abundant bordered pits. In general fibre length, diameter and wall thickness, as well as vessel diameter increase with age while vessel frequency decreases. In a literature review by Muneri (Muneri 1994), it was found that eucalypt fibres generally range from less than 1mm to about 1.5mm in length with diameters of about 15 to 25μm. Vessel elements are generally shorter than fibres but of larger diameters. It was stated that vessel elements range from 80 to 180 μm and occupy 10 to 20% of the wood volume. The differences in fibre length between woods formed at different ages are greater than those between the woods of different species. The basic wood density is regarded as one of the main determinants of pulping of *Eucalyptus species* and papermaking properties. (Hillis *et al.* 1978, Bamber 1985).

2.2.1 Wood and fibre characteristics and papermaking

The role of the raw material is very important. The paper grade being produced is what determines the specific types of raw materials to be used so as to ensure that a superior quality product at a competitive value is obtained. The suitability of the fibres with respect to certain

desired characteristics must be considered along with the economical factors such as availability of wood supply and production costs.

In considering wood as a source of fibre for the production of pulp and paper, two factors must be taken into account.

- The yield of fibre per given volume or weight of wood (particularly in the chemical processes).
- The quality of the resulting fibre.

The first factor mentioned is dependent on the characteristics of the wood prior to pulping and the process employed in its conversion into pulp. The second factor is mainly a result of morphological features of the individual fibres and their modifications brought about by the methods of conversion (example, refining to improve strength properties). The quality of the resulting fibres depends on the wood structure, that is, the type of cells present in a given wood, the morphological characteristics of the individual cells and to a lesser degree on the chemical composition of the cell wall material. Some of the fibre variables responsible for determining the physical characteristics of pulp and paper are:

- Fibre cell wall thickness
- Fibre length
- Fibre strength
- Fibre conformability
- Fibre coarseness

2.2.1.1 Fiber cell wall thickness

The fibre wall thickness affects the pulp yield. It is one of the most important factors influencing the characteristics of the resulting pulp and paper products. The fibre wall thickness can be used as a measure of the fibre quality and there is a good correlation between the wall thickness and pulp fibre strength properties (Xu *et al.* 1997). It has been shown (Alexander *et al.* 1968, Smook 1992, Britt 1970, Peel 1999) that thin walled fibres results in the formation of sheets with high tensile strength, elastic modulus, burst strength, and fold. They tend to collapse during formation to give paper of high density. The thick walled fibres do not collapse readily like thin walled fibres and are known to give high bulk, tear strength and porosity but low burst strength, tensile strength and fold. Fibre-wall damage and plasticization are the major consequences of the

refining or beating process. Work by Alexander and Marton indicated that this results in an increased wet fibre flexibility (Alexander *et al.* 1968). This is believed to be the single most important effect of beating.

2.2.1.2 Fibre length

A minimum length is required for interfibre bonding. Paper made from fibres that are too short have insufficient common bonding area between fibres. This leads to points of weakness for stress transfer within the sheet and the paper will be low in strength. The morphological ratio of fibre length/fibre diameter (FL/FD) has been explored and it was pointed out that FL/FD correlates mainly with the tearing resistance (Alexander *et al.* 1968). In the work done by Alexander and Marton, it was found that longer fibres don't necessarily produce stronger sheets (Alexander *et al.* 1968). When beaten or refined the long fibres are shortened and the possibility of entanglement progressively decreases and the sheet tensile strength can be more efficiently developed since the fibres contribute more effectively. It was also seen that the shorter the fibres the faster their response to refining action (Alexander *et al.* 1968).

2.2.1.3 Fibre strength

The relationship between tensile strength of the individual fibres and the shear strength of the fibre-to-fibre bonds is what determines the ultimate failure of the paper. The main problem in evaluating the contribution of individual fibres to strength and other properties quantitatively has been attributed to the technical difficulties encountered in designing meaningful strength tests of single wood cells. However the zero span tensile strength tests can be used to obtain the intrinsic strength values of fibres in paper. It was noted that fibre breakage was as prevalent as bond breakage in certain types of well-bonded paper. When a well bonded, closely packed sheet is ruptured in tension, fibres lying across the rupture line are broken. However if a poorly bonded sheet is stressed in tension then provided the fibre strength is adequate, it will be seen that the bond breakage is responsible for failure. Therefore fibre strength is important to paper strength in well-bonded sheets (Britt 1970).

2.2.1.4 Fibre conformability

Fibre conformability refers to the flexibility and collapsibility of the fibres. It is dependent on cross-dimensional fibre properties and on the elasticity of the cell wall (Paavilainen 1993). Fibre flexibility refers to the axial conformation of fibres while fibre collapsibility refers to vertical

conformation of fibres, towards the fibre axis (Paavilainen 1989 & 1991). Fibres with a higher degree of conformability will have superior strength properties compared to fibres with low conformability

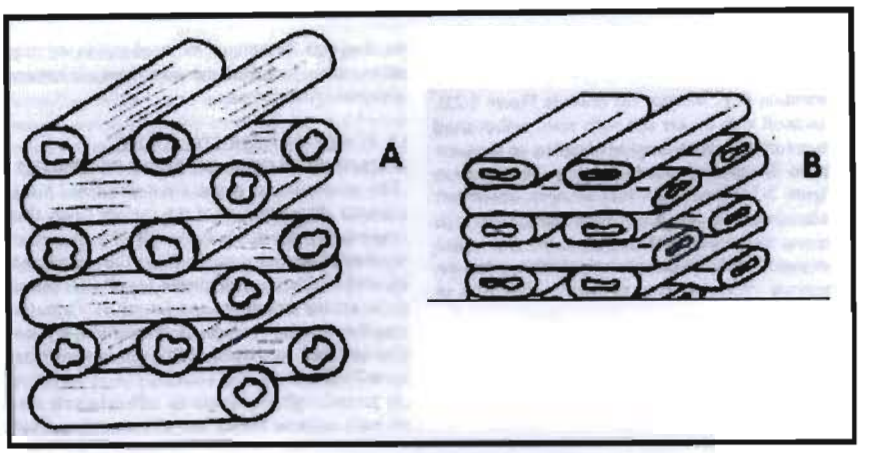


Figure 2.1: Diagram showing collapsibility of fibres (Smook 1992)

2.2.1.5 Fibre coarseness

Fibre coarseness is defined as mass of oven-dry material per unit length of fibre. Fibre coarseness varies considerably between softwoods and between hardwood species (Muneri 1994). In the literature review by Muneri, it was stated that within eucalypts, since the fibres have similar external dimensions, fibre coarseness would be correlated with fibre wall thickness.

2.2.1.6 Wood density

The wood density is a measure of the amount of wood substance per unit volume (Malan *et al.*1991). It is a complex wood property and represents a combination of characteristics. It is affected by - the thickness of the cell walls; the diameter of cells; the chemical content (cellulose, hemicelluloses, lignin, extractives) of the wood and the ratio between earlywood and latewood. It affects the yield of wood fibre per m^3 of wood in pulp production. It was seen that a low-density wood would have inferior strength and produce less wood fibre per unit volume than a high-density wood (Mary *et al.* 2001).

2.3 Fibre morphology and paper strength properties

Strength is a very important property because paper is often used under conditions where it must withstand considerable stress. According to Casey (1981), paper strength is a vague term and the particular property desired by specific paper grades needs to be carefully specified. There are many strength tests made on paper and the most common tests carried out are bursting strength, tearing resistance, tensile strength, folding endurance and stiffness. None of these is a fundamental measurement but rather a combination of factors such as flexibility, bonding strength, and fibre strength (Casey 1981). These factors are dependent on the type of fibres, the length and thickness of the fibres, the flexibility of the individual fibres, the number of bonds, and the strength of individual bonds amongst others as listed by Casey (1981). Dinwoodie (1965) gives a thorough review on the relationships between pulp strength properties and fibre morphology.

The comprehensive analysis carried out by Dinwoodie indicated that the three principal factors controlling paper strength are (Alexander *et al.* 1968, Dinwoodie 1965):

- Cell-wall thickness – this influences both the fibre flexibility and bonding
- Fibre length – important since a minimum bonded length is required
- Fibre strength – this limits the sheet strength

2.4 Fibre treatment – refining or beating

Pulp as it comes from the pulp mill is not satisfactory for the manufacture of paper. The fibres may be long and their surface characteristics may be such that they result in poor formation and paper of inferior properties (Calkin 1957, Casey 1952, Britt 1970). Fibres are subjected to a mechanical action in order to develop their properties optimally with respect to the products being made (Grant 1961, Baker 1991, Casey 1952). This process is referred to as beating or refining. The beating or refining process is in essence a development process, in as much as each fibre is capable of a certain potential. How the fibre is treated (i.e. refining or beating) determines to what extent that latent potential is realised and at what cost (Britt 1970). The process modifies the physical structure of the papermaking fibres by subjecting them to repeated strain (Martinez *et al.* 1994). Refining straightens fibres and causes both internal and external fibrillation (Stoere *et al.* 2001).

While the terms beating and refining are often used interchangeably, beating refers more precisely to the mechanical action of the rotating bars opposite a stationary bedplate on a circulating fibre suspension. The individual fibres themselves are orientated in a perpendicular arrangement to the bars (Smook 1992). While beaters are capable of performing many different types of action it has one major drawback in that it has not been adapted to continuous operation, which in this modern day with the advent of high-speed, high-production paper machines, is a necessity (Reid 1965).

Refining refers to the mechanical action carried out in a continuous conical or disc refiner. Here the fibres move parallel to the bar crossings. The objective of using either of the two is the same, i.e. to modify the pulp fibres in an optimal way so as to meet the demands of the desired product being made (Smook 1992). While the beating or refining of the pulp is one of the most important unit operations in the papermaking process, it also an energy inefficient process (Naujock 2001).

2.4.1 Refining of hardwoods

Hardwood fibres are shorter than softwood fibres and they do not require any fibre shortening during refining for the purpose of good formation. In the past it has been used as a filler pulp with little refining treatment. The trend now is to develop these fibres to their maximum potential and this requires a gentle treatment (0.5-1.0Ws/m) because since the fibres are already short they do not require fibre cutting thus only fibrillation of the fibres is required. It has been noticed that for hardwoods like eucalyptus, the tear strength increases with increasing refining (Soini *et al.* 1998, Baker 1995). Thus according to Baker (1995), fairly high specific energy inputs of up to 150 kWh/ton) can be used to develop strength. For hardwood chemical pulp Lumiainen (1995) suggested that specific energy inputs should be between 25-80 kWh/ton and intensities between 0.3-1.5 Ws/m. However it was also noted that while these figures are typical for unrefined fibres, variations can be considerably large as the physical dimensions of fibres and the refining resistance vary quite significantly (Lumiainen 1995, Kibblewhite 1994).

2.5 Refiner construction & operation

2.5.1 Principal Features of refiners and beaters

Batch – operated beaters were originated from stamping mills in the 1600's. They are still in use in the production of specialty paper grades. Figure 2.2 (Peel 1999) shows a Hollander beater. This was one of the first pieces of refining equipment. The initial machine made use of a rotor containing blades/bars, which operated opposite a stator, which also contained blades/bars (Reid 1965, Calkin 1957, Grant 1961). The appearance of these machines has changed a lot but the basic principle of operation still exists (Bolam 1965). As the pulp is circulated by the action of the roll, the fibres are subjected to a rather violent compression and shearing action at high speeds between bars of the bedplate. Depending on the application, chemical pulps are beaten for up to several hours before being discharged from the beater (Peel 1999).

The modern refiner, which was developed from the beater, has a similar mechanical action to that of the beater however the refiner operates continuously on the supplied stock. So the desired structural changes to the fibres must be achieved in one pass between pairs of plates or in multiple passes between pairs of plates in one machine or in multiple passes through refiners in series (Peel 1999, Reid 1965). The conical and disc refiners have almost completely replaced the beaters in the stock preparation systems due to their better efficiency in fibre development and their more compact design (Kocurek 1992). Also the beaters have not adapted to a continuous operation (Calkin 1957).

2.5.2 Types of refiners

There are two major types of refiners that are in use (Smook 1992, Peel 1999, Kocurek 1992):

- Conical refiners
- Disc Refiners

These can be further divided into low-angle and wide-angle conical refiners and even single and double disc refiners (Brecht 1967). This study makes use of a disc refiner and only this type of refiner is discussed further.

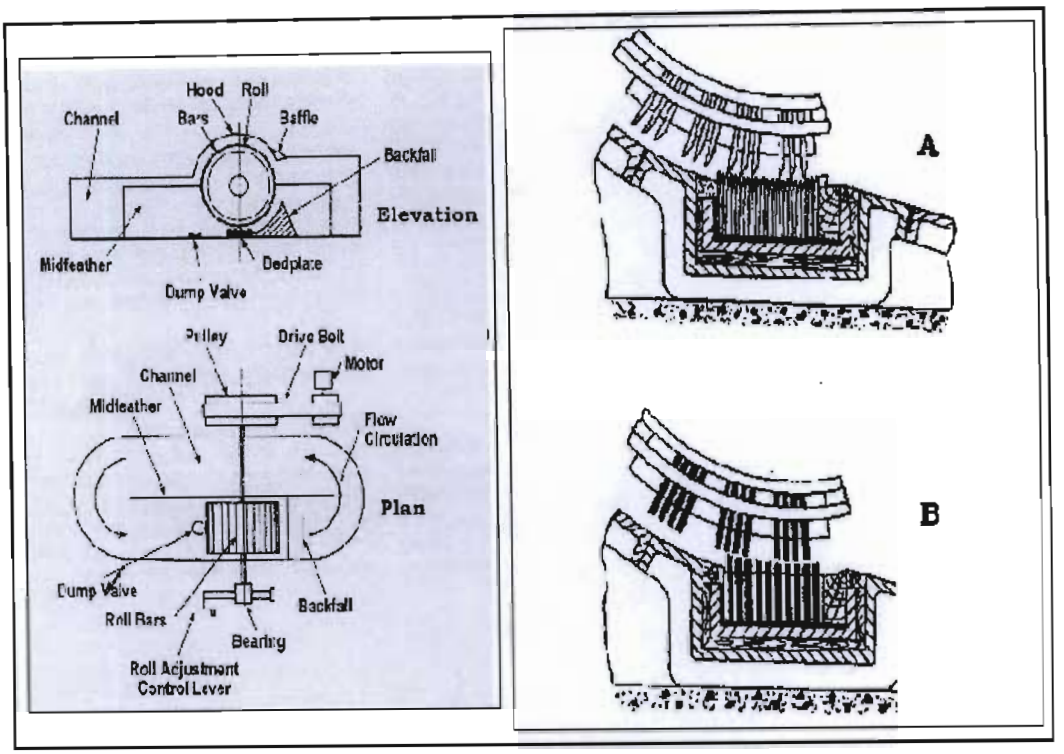


Figure 2.2: A Hollander beater (Peel 1999)

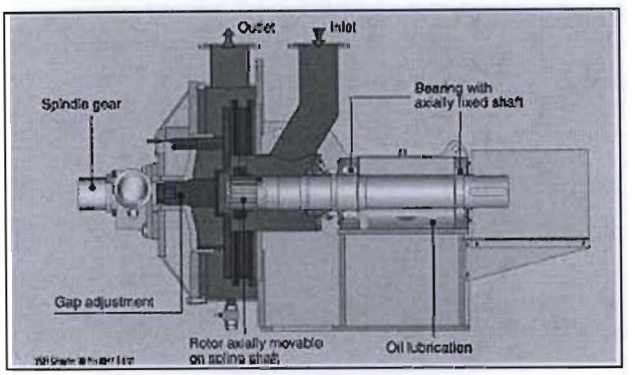


Figure 2.3 Cross section of double disc refiner (Sigl *et al.* 2001)

2.5.2.1 Features of disc refiners

Pairs of opposing discs are located so that one disc rotates with respect to the other. This is achieved by fixing one disc to remain stationary while the other rotates or alternatively both discs can be made to rotate at either different speeds or in opposite directions (Casey 1952, Peel 1999) The refiner plates are essentially flat and bear special grooved designs. During the operation of the refiner, the discs are positioned so that the bar surfaces are separated by fractions of a

millimeter. The diameters of commercial refiners usually range from 400 – 2000 mm and the bars are typically between 3 and 8 mm wide (Peel 1999). The stock is usually pumped to the eye of the refiner at a consistency between 2 – 5 % (Calkin 1957, Peel 1999). From here it flows radially outwards between the plates. Refiners usually operate as pump-through machines. A backpressure ensures that the gap between the plates is full. The residence time is then determined by the flow rate of stock entering the refiner. For some refiners that operate with an open discharge (i.e. atmospheric discharge), the gap between the plates cannot be maintained full of stock so the residence time depends not only on the flow rate of stock entering but on other conditions as well (Peel 1999).

Disc refiners are more recent than conical refiners and are available in a wide variety of designs and disc patterns. The refiner plates are parallel to each other. Three basic types exist;

1. Rotating disc opposite a stationary disc
2. Two opposing rotating discs.
3. A double sided rotating disc positioned between two stationary discs

The double-disc refiner offers a greater efficiency than the standard conical refiners do. This is because it has a lower no-load energy consumption (section 2.7 explains what the no load power is). It also has a greater potential for fibre treatment due to its two internal zones. The two zones allow for higher energy input per refiner for a given refining intensity (SEL).

2.5.2.2 Disc refiner plates

The plates for the disc refiners comprise a variety of bars, which are cast onto a base plate. The configuration of these bars is important in achieving specific refining effects. Figure 2.4 shows some common plate patterns (Sharpe *et al.* 1988). Studies of the refiner fillings or plate designs showed that these variables could modify the edge effect (Fahay 1970) (Section 2.7 discusses the refining theories). Coarser patterns will provide higher intensity action which is more suitable for fibre shortening whilst the finer patterns are better suited for strength development (Smook 1992).

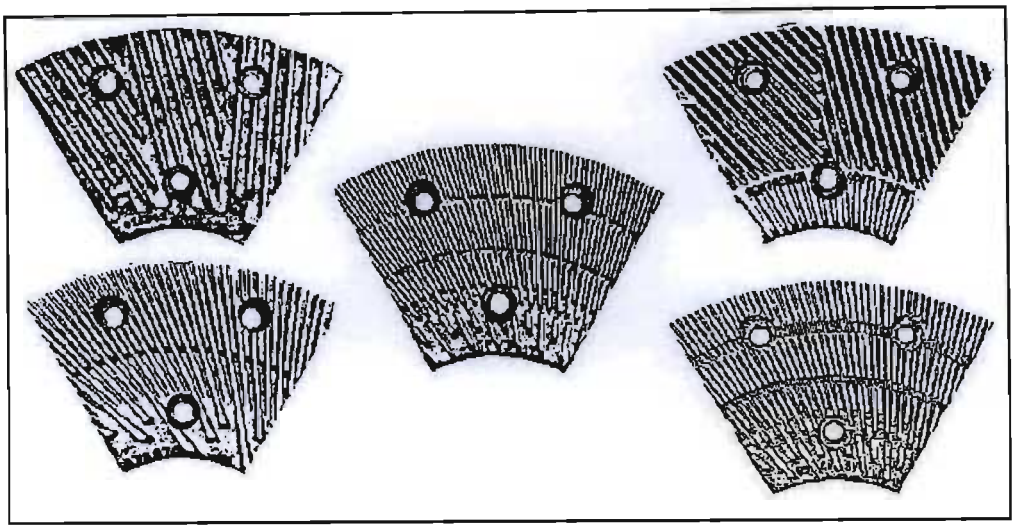


Figure 2.4: Typical Refiner plate patterns (Sharpe *et al.* 1988)

2.6 Refiner hydraulics

The design of the refiner plates is important in that it decides the type of refining action (i.e. cutting or fibrillation). The grooves between rotor and stator bars have two functions. Firstly they provide the bar edges and surfaces necessary for the refining action and they also transport the fibres through the refiner (Hietanen *et al.* 1990, Kocurek 1992). Refiners need to have sufficient hydraulic capacity and this is taken care of by the grooves between rotor and stator bars (Hietanen *et al.* 1990).

Investigations about the movement of fibres in a refiner have been carried out. There is a substantial build-up of pulp fibres on the refiner tackle (Fox *et al.* 1982). The accumulation of the fibres will depend on the size of the fibres, the stock consistency and the speed of the bar relative to the stock.

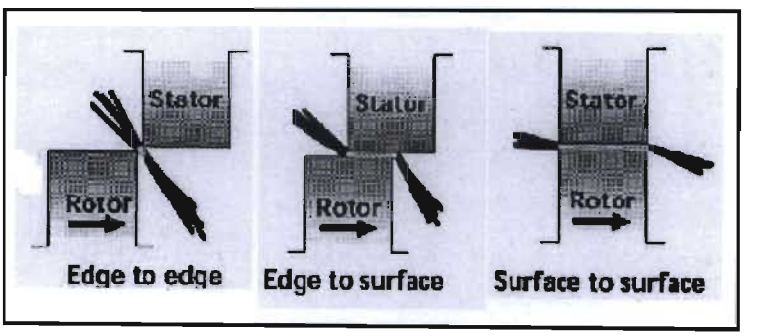


Figure 2.5: Different phases of refining (Lumiainen 1995)

It was seen (Fox *et al.* 1982), that from just a 3% pulp suspension the collection of fibres on the bar could be such that the local consistency in that area reaches consistencies of about 12% thus a considerable thickening of the stock may occur within the refiner. All the refining cannot be done in the time it takes for the leading edges of the bars to cross each other. Figure 2.5 above shows schematically what happens inside a refiner. The refining starts when the leading edges of the rotor bars approach the leading edges of the stator bars (edge-to-edge phase). When this happens the fibre flocs are compressed and receive a strong impact. This leads to most of the water being compressed out of the floc. Next both leading edges slide along the fibre and press it against the flat bar surfaces. Most of the refining is carried out during this stage. This phase continues until the leading bar edges reach the trailing edges of the opposite bar. When the rotor bars move across the stator bars, there are strong vortex flows formed in the grooves between bars and the fibres are released and re-absorb water. The process just described describes just a single refining impact, the whole length of the impact is dependent on the width of the bars. (Lumiainen 1995, Kocurek 1992, Smook 1992, Lumiainen 1991, Fahay 1970)

The energy split between the phases is highly dependent on the plate pattern while the refining outcome itself depends on the energy distribution between phases. If most of the energy is used in the edge –to-edge phase then the fibres will experience a cutting type of action while if most of the energy is consumed in the other phases then the fibres are more likely to be fibrillated (Lumiainen 1991).

2.7 Refining theory

The alteration/modification of the fibre characteristics is achieved by employing both hydraulic and mechanical forces. The fibres experience a twisting, rolling and tensional action between the bars and in the grooves and channels of the refiner. This action subjects the fibres to shear stresses. The bending, crushing, and pulling/pushing actions on the fibre clumps, while caught between the bar-to-bar surfaces are responsible for the normal stresses that are imposed on the fibres. (Smook 1992)

Recently the refining process has been described by process and equipment parameters with the focus being on the energy usage. The knowledge of how this energy is utilised is essential in understanding the refining process (Baker 1995, Lumiainen 1991).

In examining the performance of a refining system there are two factors of primary importance. These are:

- The net specific energy (SRE)
- Refining intensity (SEL)

The first factor refers to the amount of effective energy applied per unit weight of pulp, while the second refers to the rate at which this energy is applied. While the first factor can be precisely and easily measured, the intensity with which the fibres are hit poses a little difficulty in its evaluation. To aid in the evaluation of this, a term called the "Specific Edge Load' is commonly used. This factor is computed by dividing the net power by the total length of bar edges which make contact with the stock per unit time. (Lumiainen 1991, Smook 1992, Lumiainen 1995)

2.7.1 Refining intensity

The amount of energy that is absorbed by the pulp is a critical factor affecting the changes that occur in the pulp properties but another significant thing to consider is the manner in which the work is carried out. To achieve a greater amount of fibrillation as opposed to fibre cutting, which is desirable in the development of fibre properties, refining will have to be carried out at lower intensities. What this basically means, is that for a fixed amount of energy that will be applied to the pulp in a refiner, the fibre treatment will be more optimal if this energy is applied gradually in steps as opposed to applying this same amount of energy in a concentrated fashion. Unfortunately this gradual application of the energy in low consistency refining usually means that multiple refiners will have to be used in series (Ortner *et al.* 1999, Smook 1992). This was seen experimentally when it was observed that conducting refining with three refiners in series instead of only two gave better strength properties (Ortner *et al.* 1999).

In an extensive study by Brecht and Siewert it was found that the SEL is a good measure of refiner performance (Brecht 1967, Kocurek 1992.). In tests where the net energy, speed of rotation and the length of the bars were varied, the same beating results were obtained if the variables were used such that a relatively constant SEL was used (Brecht 1967, Kocurek 1992). Also when using different types of refiners the same refining result will be obtained if operated at the same SEL. Thus it was implied that the SRE and the SEL defines the results that will be obtained from refining a given pulp. The bar widths, number of bars, average contact area, speed of rotation, stock consistency, and volumetric flow rate had little influence on the refining except for the influence that it had within the SRE and SEL parameters (Kocurek 1992). This is in

accordance with modern refining theories. In the process of formulating the Specific Edge load Theory Brecht and Siewert had demonstrated that an Escher Wyss pilot plant refiner could be compared with different types of mill refiners. They showed that for the same conditions of net power and energy, different types of refiners gave similar fibre treatment (Baker 1991, Volkan *et al.* 1994).

2.7.2 Transfer of energy during refining

The energy is actually transferred to the fibre in three phases (Smook 1992).

1. *The edge-to-edge phase*- here the flocs of fibre trapped between the bar edges receives a strong impact over a short length of the fibres.
2. *The edge-to-surface phase*-here a brushing action is imparted as the leading edges of both the rotor and stator bar presses the fibres against the flat bar surfaces.
3. *The surface-to-surface phase*- after the leading edges reach the trailing edges of the opposite bars the fibres undergo a further gliding action. This phase continues until the rotor bar clears the trailing edge of the stator bar.

Parameters such as the sharpness of the bars, the width of the bars and grooves, and the roughness of the bar surfaces influences the energy split between the three phases. Fibre cutting or shortening is associated with energy consumption in the first phase while energy consumption in the second and third phase is associated with fibrillation of the fibres.

2.7.3 The specific edge load theory

(Peel 1999, Smook 1992, Kocurek 1992, Baker 1995, Lumiainen 1995)

This theory involves an empirical measurement of refining action as the type (or intensity) of refining, the amount (or extent) of treatment and the energy consumed in the process. The refining action is a balance between the total net energy applied, the number of impacts on the fibres and the intensity of those impacts. The power consumed by the refiner is made up of two components:

- The idling (or no-load) power consumption.
- The power applied to the stock.

It stands to reason that to simply just rotate the unit against the stock flow will require some energy. This energy is referred to as the no-load power. The amount required will vary with type of refiner. The net energy applied to stock is the gross energy less the no load energy requirement.

The no load power consumption is given by

$$P_o = K.N^3.D^5 \qquad \text{----(1)}$$

(Peel 1999) Where,

- P_o is the no-load power in kW
- K is a constant, which depends on the refiner plate.
- N is the refiner speed in revolutions per minute (rpm)
- D is the plate diameter in m.

The net power is given by (Peel 1999)

$$P_{net} = P - P_o \qquad \text{-----(2)}$$

Where,

- P_{net} is the net power in kW
- P is the gross refiner power in kW.

The bar edge length is the total intersecting length of the rotor and stator bars. The product of the bar edge length and the refiner speed provides the rates of the bar-edge crossings. The intensity of the refining is then calculated by dividing the net refining power by the rate of bar-edge crossings (Peel 1999, Lumiainen 1995).

$$L_s = C_{el}.N.(1/60) \qquad \text{-----(3)}$$

Where,

- L_s is the bar edge crossings or cutting speed in m/s.
- C_{el} is the cutting edge length in m/rev. This parameter is defined by the manufacturer. To calculate the C_{el} (Lumiainen 1995):

$$C_{el} = Z_r \times Z_s \times l \qquad \text{----(4)}$$

Z_r & Z_s are the number of rotor and stator bars respectively

l is the length of the bar

The 1/60 is a conversion factor to convert the units of N from rpm to rps (revolutions per second) Then the rate at which the energy is applied is given by (Peel 1999, Baker 1995, Lumiainen 1995):

$$SEL = P_{net}/L_s \qquad \text{-----(5)}$$

Where, SEL is the Specific Edge Load in Ws/m. The beating result in terms of fibre shortening or fibrillation is determined by the SEL (Lundin *et al.* 1999). A high SEL value denotes a tendency to result in fibre shortening or cutting while lower values are associated with fibrillation i.e. good refining response (Baker C.F. 1995). This would imply that the longer softwood fibres should be refined at higher refining intensities to result in fibre shortening for good formation whereas the shorter hardwood fibres should be refined at lower intensities to preserve its length thus not resulting in a decrease in strength properties resulting from fibres being cut.

And the amount of effective energy applied per unit weight of pulp is given by (Peel 1999, Baker 1995, Kocurek 1992, Lumiainen 1995):

$$SRE = P_{net}/M \qquad \text{------(6)}$$

Where,

- SRE is the Specific Refining Energy in kWh/ton
- M is the fibre flow rate in dry tons/hour.

Equations 5 and 6 are related through a term, which may be defined as the specific number of impacts (N_i)

$$N_i = L_s/M \qquad \text{-----(7)}$$

The result of the beating is considered to be greatly dependent on the number of impacts on the fibres (Lundin *et al.* 1999). These formulae are used to visualise the refining process and are not exact mathematical expressions (Baker 1995). Considering equations 5 & 6 it can be seen that the more important refining variables that need to be considered are the: - Refiner Power (kW), No-load Power (kW), the plate design-since it influences the cutting speed, the speed of rotation, the consistency of the stock and the volumetric flow rate (Baker 1995).

The number and length of bars in the refiner plate in combination with the speed of rotation determines the ability of that refiner to either fibrillate or cut efficiently (Baker 1995). The Specific edge load theory does not consider the bar width. It considers only the length of the bar

edges and assumes that the beating result is independent of the bar width (Lumiainen 1995, Lumiainen 1991).

New theories such as the specific surface load theory, the reference specific edge load theory and the c-factor theory have been developed which focus on the severity of impacts received by the fibres. However the Specific Edge Load theory is still the most widely accepted and because of its ease of application it is the most widely used (Baker 1995, Lundin *et al.* 1999). Theories that neglect the effect of bar width should be used carefully. They work quite precisely if applied to a given plate pattern but do not provide an adequate comparison of different plate patterns (Lumiainen 1991). That is for studies that considers only variations in process variables in a refiner which uses the same plate the Specific Edge Load Theory can be used.

2.8 Variables affecting refining

A simple theory of mechanical treatment of pulp fibres has not been developed. The reason for this is that the subject is very complex. As indicated by Fahey even if one were to ignore the paper properties, the variables that are involved include those related to raw materials, equipment and the process (Fahay 1970). Some of the variables that influence the refining process are given in table 2.1.

Table 2.1: Variables affecting the Refining Process (Smook 1992, Kocurek 1992, Fahay 1970)

Raw Materials	Equipment Characteristics	Process variables
wood species pulping method degree of pulping bleaching treatment prior processing fibre length distribution fibre coarseness earlywood/latewood ratio chemical composition	bar size and shape area of bars and grooves depth of grooves presence or absence of dams materials of construction wear patterns bar angles speed of rotation	temperature pH consistency additives pretreatments production rate applied energy

2.8.1 Effect of raw materials

Different pulps have different refining requirements. There are many contributions to the heterogeneity of wood pulps as they are sent to the paper machine. Wood properties are influenced by a number of factors, which include their genetic factors and site conditions (Fahay 1970, Muneri *et al.* 1998). The site condition is influenced by the climate, altitude and soil condition. Environmental variation is known to influence most tree species and it can be expected that the wood, pulp and papermaking properties are similarly affected. The majority of pulp mills use wood of a number of different species from different sites and very little is known about the effects of the growing environment on pulp and paper properties (Clarke *et al.* 1999). With a strong genetic influence environmental effects can be exploited by matching species or genotype to sites

The type of cooking and degree of bleaching also affect the refining requirements. In general pulps produced by the Kraft process have a larger energy requirement than sulphite pulps. Bleached pulps are usually easier to refine than unbleached pulps (Blechschmidt *et al.*2000, Smook 1992). Pulps containing larger percentages of hemicellulose are more easily refined. The hemicellulose has a large affinity for water thus swelling is promoted which promotes fibrillation (Smook 1992).

2.8.2 Effect of equipment parameters

With regards to the fillings or plate patterns, plates with narrower bars give a lower intensity refining than plates with wider bars. The lower intensity refining results in a less fibre shortening than pulp refined at higher intensities (Kocurek 1992). The configuration of the plate or filling is the controlling factor in the strength development of the pulp and for this reason both conical and disc refiners can be made to operate such that similar results are obtained. The geometrical configuration will impose some restrictions though. Although conical and disc refiners can be made to give similar results it was observed by Ortner, in mill scale refining trials that a modern conical refiner was found to give better and more homogeneous overall refining result compared to a conventional disc refiner (Ortner *et al.* 1999).

Table 2.2: Requirements for refiner plates for low intensity refining (Sigl *et al.* 2001)

	Advantage	Limit
Bar width ↓	• **CEL ↑** • **Refiner efficiency ↑**	• **Plate material** • **Cutting effect**
Groove width ↓	• **CEL ↑** • **Refiner efficiency ↑**	• **Plugging** • **Throughput**
Bar height ↓	• **No-load power ↓**	• **Lifetime** • **Plate material** • **Throughput**

For table 2.2, the arrows can be read as in the following example. Plates with smaller bar width, would have a higher CEL and higher refining efficiency than plates with larger bar width. The limiting factors would be the plate material, which depending on the strength of the material would limit how narrow the bar can be made. Also, too narrow bars would result in increased fibre cutting.

2.8.3 Effect of process variables

The substantial process parameters are stock flow rate, pulp consistency, temperature, pressure and pH value. Both flow rate and consistency are dictated by production rate and existing pumps respectively, whereas temperature, pressure and pH value are determined by the process system.

2.8.3.1 pH

Higher pH levels (>7) promotes faster beating. At these high alkalinities the fibres absorb more water and thus swell more. The fibres become less compact and thus are less susceptible to cutting action thus fibrillation is promoted. Refining in acidic medium usually results in more fiber cutting and fines generation (Hietanen *et al.* 1990, Smook 1992).

2.8.3.2 Consistency

Generally higher consistencies are better since there is increased fibre-to-fibre contact and this results in less cutting (Smook 1992, Kocurek 1992, Fahay 1970). The homogeneity of refining also increases (Hietanen *et al.* 1990). From tests carried out in a laboratory beater at constant conditions of temperature bar clearance and rotor speed but consistencies varying from 1.1% to 2%, it was seen that handsheets made from pulps beaten at higher consistencies were more elastic and had more internal bonded areas, as indicated by the z-directional tensile strength, thus indicating greater fibre collapse (Brown 1968). Typically, consistencies in low-consistency (LC) refining range from 3.0 - 5.0 %. The LC-range is normally limited by conventional pumps that

can operate up to consistencies of 6 %. Often refining takes place at around 4 %, which allows an unproblematic operation for most of the pump types (usually centrifugal pumps) used in the paper industry (Naujock 1995; Paulapuro 2000).

2.8.3.3 Refiner speed

It was found, that higher disc speeds provides a lower refining intensity for the same throughput and will thus result in a superior fibre development (Smook 1992, Fahay 1970). According to Reid (1965), at any production rate, an increase in refiner speed would result in a proportional increase of bar-edge impacts received by the pulp. This type of treatment would result in a less intense type of refining action received by each fibre thus resulting in less cutting action for any level of freeness drop (Reid 1965). The disadvantage is that at these higher rotational speeds there is a larger wastage of energy because the no-load energy requirement increases by the cube of the rotor speed (Smook 1992). In a study by Brecht, it was seen that pulp refined at higher speeds of revolution was treated more rapidly than pulp refined at lower speeds of rotation (Brecht 1967). That is for the same specific refining energy the pulp treated at higher speeds of rotation would result in a pulp having lower freeness than a pulp treated at lower speeds. The speed of rotation also has an influence on the residence time of the fibres in the refiner. As expected from theory it was shown that lower rotational speeds resulted in longer residence times in the refining zone (Senger *et al.* 1998).

2.8.3.4 Temperature

The effect of temperature on pulp refining is related to fibre swelling, which is reduced at higher temperatures and thus should be kept below 45 °C (Reeves *et al.* 1996). According to Baker (2003) the increase in temperature over the normal range of refining is low enough so as not to have a significant effect on the refining process (Baker 2003, Hietanen *et al.* 1990).

2.8.3.5 Refining gap

There is a direct relationship between the refining gap and the intensity of refining (Hietanen *et al.* 1990, Sharpe *et al.* 1988). Reduced refining gap reduces the open area between the plates and thus the throughput capability while increasing the pulp development. However the clearance between the plates should remain above some minimum amount in order to avoid fibre cutting (Sharpe *et al.* 1988).

2.9 Effect of refining

2.9.1 Effect of refining on fibres

Fibres are basically long hollow cylinders and depending on its origin (i.e. softwoods or hardwoods), they vary in length, diameter, cell wall thickness and flexibility (Kocurek 1992). Figure 2.6 shows a typical woo cell.

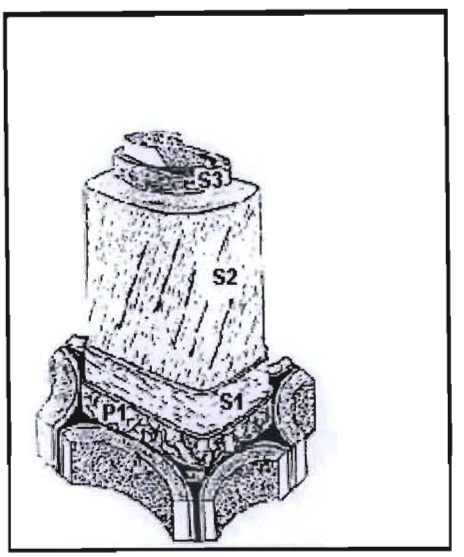


Figure 2.6: A typical cellulose fibre (Sjostrom 1981)

The middle lamella containing approximately 70-90% of the total lignin separates the individual fibres (Kocurek 1992). The fibres have different lengths and the cross-sectional area is about one hundredth of their length. The fibre wall is made up of several layers:

- An outer primary wall (P1)
- The inner secondary wall-which is actually made up of 3 components itself (i.e. S1, S2, S3)

Inside the fibre is an empty space called the lumen. The secondary wall is rich in cellulose and is considered to be the main body of the fibre (Kocurek 1992). Cellulose in fibres exists in the form of microfibrils, which are predominantly crystalline in nature, but they are thought to have small areas of disorder (Fahay 1970).

Three types of action can occur during the refining process (Reid 1965, Lumiainen 1991, Sharpe *et al.* 1988):

Cutting or shortening: this refers to the rupturing of the fibre in a plane perpendicular to its longitudinal axis leaving two or more fibres shorter in length but with same diameter as original fibre

Splitting: this refers to the rupturing of the fibre in a plane parallel to its longitudinal axis leaving two or more fibres ideally with the same length as original fibre but smaller in diameter.

Bruising: this refers to the internal crushing and flexing of the fibre with ideally no change in fibre length but with a reduction in diameter.

The cutting of fibres is most often considered to be undesirable as it contributes to a slower drainage and a reduction in strength. However the cutting of fibres always occurs to some extent during refining. Nevertheless this shortening of fibres is sometimes desired in certain applications as the shorter fibres promotes good sheet formation or maybe needed to control the drainage on the paper machine. As the refining proceeds it will be noted that the drainability of the pulp reduces rapidly. That is the pulp drains more slowly and the pulp is described as being less free (Smook 1992, Peel 1999).

Table 2.3 shows the major effect of refining on the fibres (Casey 1952, Smook 1992, Fahay 1970, Hietanen *et al.* 1990).

Although the primary wall is permeable it doesn't swell and thus hinders the fibre as a whole to swell (Smook 1992, Casey 1952). Upon the partial removal of the primary wall and also the S1 layer of the secondary wall, the S2 layer of the secondary wall is exposed and water is absorbed into the molecular structure (Smook 1992, Kocurek 1992). The ensuing loosening of the internal structure promotes fibre swelling and this leaves the fibre soft and flexible. This is referred to as internal fibrillation and is regarded as the most important primary effect of refining following the removal of the primary wall. The further refining action, which follows, is referred to as the external fibrillation. This involves the loosening of the fibrils and raising of the finer microfibrils on the surfaces of the fibres. This produces a very large increase in surface area for the beaten fibres (Smook 1992). Hietanen and Ebeling discuss the effects of refining on fibres in more detail (Hietanen *et al.* 1990).

Table 2.3: The primary and secondary effects of refining

Primary Effects
• Partial removal of the primary wall and the formation of fibre debris or fines
• Penetration of water into the cell wall (a.k.a bruising/swelling)
• Breaking of some intra-fibre bonds and the subsequent replacement by water-fibre hydrogen bonds
• Increased fibre flexibility
• External fibrillation and foliation
• Fibre shortening
Secondary effects
• Fractures in the cell wall
• Fibre stretching and/or compression
• Partial solubilization of surface hemicellulose into gels
• Straightening of the fibre at low consistency
• Curling of the fibre at high consistency

As the refining progresses, the fibres become more flexible and the cell walls collapse into the lumens. This results in the fibres becoming ribbon-like and they now boast good conformability. Figure 2.7 shows visually the difference between refined and unrefined pulp fibres.

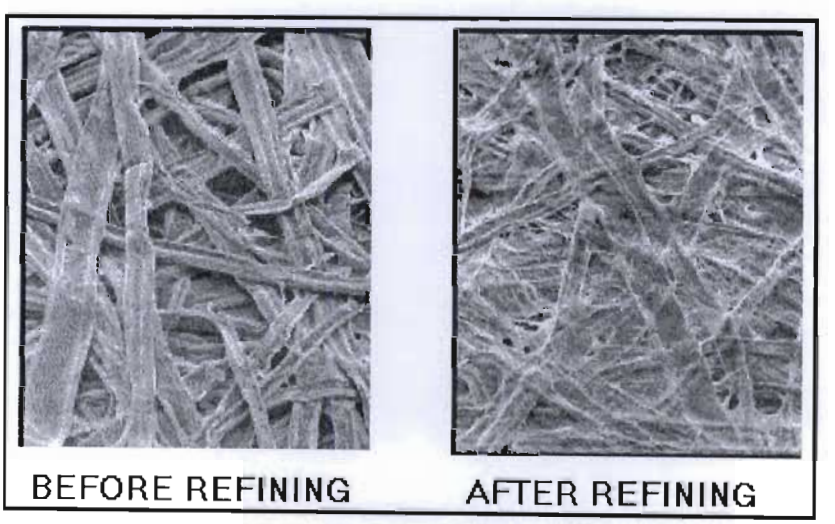


Figure 2.7: Difference between unrefined and refined pulp

It is known that beating or refining is used to develop the strength of the pulp. Several theories have been put forward with regards to the mechanisms of the strength development (Page 1985). Different authors have different views as to how beating increases the tensile strength of paper. Page (1985) suggested that most of these theories couldn't completely explain why this happens and proposed a new mechanism of strength development. He proposed that unbeaten fibres of dried pulp contains crimps and kinks that are produced in the pulping or bleaching plant and are set into fibres by drying. These crimps and kinks are incapable of transmitting load, resulting in a poor tensile strength in unbeaten sheets. Beating or refining increases swelling and applies tensile stress, which results in the straightening of fibres. This improves the stress distribution and the tensile strength is improved. Page (1985) suggests that this mechanism is responsible for the increase in tensile strength that occurs as a result of beating.

According to Britt (1970), the loosening of the concentric layers of the fibres is considered to be the most important effect. It was suggested that the strength increase brought about by beating depends on the increase of fibre flexibility and plasticity during beating. After formation, pressing and drying, this results in increased interfibre bonding and a denser and more transparent sheet (Britt 1970).

2.9.2 Effects of refining on pulp properties

The resultant changes that occur due to refining are ultimately what the papermaker is particularly interested in. The refining conditions can be varied greatly to produce different combinations of pulp properties. It was seen from investigations carried out by Volkan (1994) that the change in any physical property for a given pulp could be correlated with two parameters. For the specific edge load theory these two parameters are the SRE and the SEL.

The actual response of any pulp furnish to refining is dependent on the initial fibre properties, the refiner parameters and the operating conditions (Casey 1952, Smook 1992, Kocurek 1992). It was seen that pulp quality differences present in the unrefined stock are generally retained throughout the refining process (Kibblewhite 1994). The refining process changes the properties of the resultant sheet such that they are all affected but while increased refining may result in an increased value of one desired property (for example tensile strength) it may decrease another desired property (for example tear strength). Thus the final properties of the paper or board products will have to be a proper balance of the desired properties (Kocurek 1992, Casey 1952).

The extent of the refining is measured by standard drainage tests. The most commonly used drainage tests are the Canadian Standard Freeness (CSF) and the Schopper Riegler wetness (°SR). Freeness is a measure of the readiness with which water drains freely from a pulp. There is a direct relationship between refining and freeness. By describing various sheet properties in terms of freeness makes the information less dependent on the type of refiner employed in the refining (Grant 1961, Peel 1999, Kocurek 1992, Calkin 1957, Stephenson 1952). Kibblewhite concluded that the pulp freeness – strength property relations can be very different depending on the furnish composition, refining stock concentration and specific edge load and either separate or mixed refining (Kibblewhite 1994).

The freeness of the stock decreases with increased refining and the resultant paper sheet becomes more dense and with reduced porosity, increased opacity and decreased dimensional stability. Tear strength always decreases with refining. This is because the tear strength is dependent on the strength of the individual fibres and during beating the individual fibres are made weaker. The other strength properties will increase as they are dependent on the degree of bonding between fibres and refining increases the surface area available for bonding thus as refining progresses there is improved inter-fibre bonding (Grant 1961, Smook 1992, Casey 1952)
Kibblewhite observed that the same effects are obtained when furnish components are refined separately or co-refined (Kibblewhite 1994). However he also saw that separate refining required the least energy and developed the highest tensile strengths at a given freeness value.

According to work by Alexander *et al* (1968), sheet density was a reliable measure of inter-fibre bonding. Mechanical and optical properties of paper varied in a logical manner with sheet density if the sheet density could be taken as a direct indicator of the degree of bonding. However it was also noted that even though the variation of paper properties with sheet density is reproducible and fundamental, it is not the only criterion for characterising sheet. For a given pulp and set of forming conditions (i.e. refining and wet pressing) it was found that there was an optimum sheet density beyond which the fibres were so damaged as to lower the sheet strength. Once this point was reached it was pointless in continuing a refining treatment to try and achieve greater bonding (Alexander *et al.* 1968).

Chapter 3

Material and Methods

3.1 Introduction

Refiners are expensive machines to operate and their impact on the paper quality is very significant. The fibre development in a refiner is dependent on the specific refining energy and on the intensity with which the energy is applied. There are many different ways that this energy can be varied using the various refining variables.

3.2 Equipment

A Bauer 8-inch single disc laboratory refiner was used to carry out all the refining trials in this project. This refiner was equipped with a variable speed drive. The plate design chosen for the investigations was similar to one that was used at Mondi Richards Bay mill (a local mill) with the exception of the groove depth. Table 3.1 gives the pattern details.

Table 3.1: Pattern specification for lab refining application (Mugler 2002b)

Number of sectors		18
Master groove width	[mm]	10
Bar width	[mm]	2
Groove width	[mm]	2
Groove depth	[mm]	3
CEL - clockwise	[km/rev]	0.251430
CEL - anti-clockwise	[km/rev]	0.279009
Material		Stainless steel

The general principle of the stock feeding operation rig followed the one for changeover chest refining. The rig consisted of 2 agitated stock tanks (each tank has a 400 litre capacity) in which the pulp suspension was stored before and after passing through the refiner. Four air-actuated valves performed the automated changeover between tanks. A progressive cavity pump (or Mono pump), was used to transport the stock between chests. The flow was monitored via an electro-magnetic flow meter that was integrated into the pressurized piping section between the refiner outlet and the backpressure valve. A manually operated sampling point was fitted into the

atmospheric pressure section before the stock is transported to the second storage tank. Figure 3.1 illustrates the set-up of the refining rig.

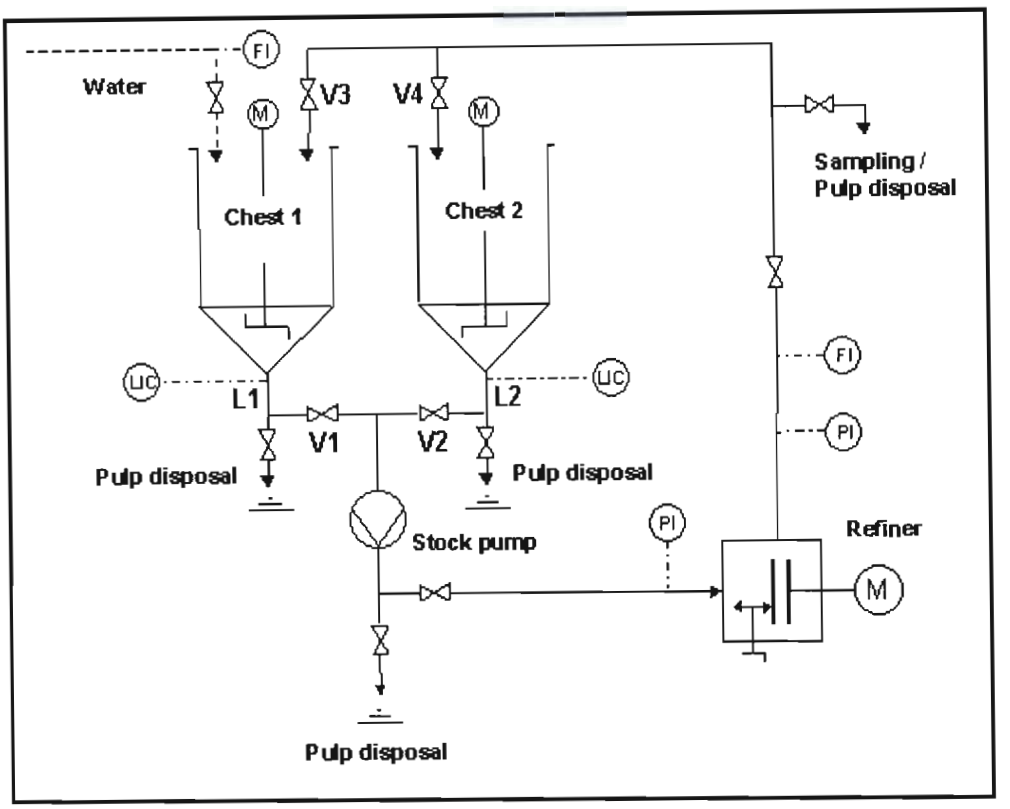


Figure 3.1: Layout of the refiner set-up

3.3 Refining theory used

The specific edge load theory is still the most widely accepted concept in full-scale refining of low consistency pulp. Due to its simplicity, the specific edge load theory was used for the energy quantification of the lab refining (Smook 1992, Peel 1999). According to Lumianen, theories that neglect the effect of bar width- should be used carefully. They work quite precisely if applied to a given plate pattern but do not provide an adequate comparison of different plate patterns (Lumiainen 1991). For studies that consider only variations in process variables in a refiner which uses the same plate the Specific Edge Load Theory can be used.

Brecht and Siewert demonstrated that an Escher Wyss pilot plant refiner could be compared with different types of mill refiners and that for the same conditions of net power and energy, different types of refiners gave similar fibre treatment (Baker 1991, Volkan *et al* 1994). In their extensive study it was found that the SEL is a good measure of refiner performance (Brecht 1967, Kocurek 1992). In tests where the net energy, speed of rotation and the length of the bars were varied, the same beating results were obtained if the variables were used such that a relatively constant SEL was used (Brecht 1967, Kocurek 1992)

3.4 Variation of refiner parameters (Phase 1)

The purpose of this phase was to determine the influence of the various process and machine parameters on the refining of *Eucalyptus* fibres in general. The objective being that this knowledge could then be used on a more focused research program on well-defined pulps with limited refining variables being considered. The pulp used in phase 1 was unbleached *Eucalyptus* pulp, which was obtained from Mondi Richards Bay (a local pulp mill). This pulp was a mixture of different *eucalyptus* species (about 80% *Eucalyptus grandis*). The pulp was sampled from a point just before the first bleaching stage. It was collected at a consistency of 27% and stored in a cold room at 4°C.

By considering the equations used in the specific edge load theory (Baker 1995), it was determined that the more important refining variables to be considered included:

- Net refining power (kW),
- the plate design-since it influences the cutting speed,
- the speed of rotation,
- the consistency of the stock and
- the volumetric flow rate

Table 3.2 shows the parameters that were investigated during phase 1 and also the ranges that were used for each parameter. Other parameters (e.g. temperature and pH) were kept constant. The pump limited the upper limit for the range of consistencies in the system. It could not handle higher consistencies and stalled each time an attempt was made at using a 5% consistency.

Table 3.2 Refiner variables investigated and the range considered

Parameter	Parameter range
Consistency	2.5 ; **3** ; 4 ; 4.75 %
Flow rate	0.6 ; **1** ; 1.5 ; 2 l/s
Speed of Rotation	1500 ; 1750 ; 2000 ; **2200** rpm

The values shown in bold are the values that were held constant for each of the other two parameters while one of these three parameters were varied. That is for example, while investigating the effect of consistency, the flow rate was maintained at 1 l/s and rotational speed at 2200rpm. When investigating other variables a 3% consistency was used. Each point was investigated in triplicate. A refiner gap clearance of 25 micron was used for all the trials. If the refiner gap clearance is to be investigated then a more sophisticated refiner system would be needed.

3.4.1 Samples

From each refining trial a sample was taken from the sampling point indicated in figure 3.1. These samples collected were spin-dried for 5 minutes each and stored in the cold room at 4°C. The moisture content of the spin-dried samples were determined before any testing of the pulp properties was done. The samples were tested to determine the pulp freeness and handsheets were made using the standard Tappi method (T205 sp-95) to determine the pulp strength properties. Table 3.3 shows the tests that were carried out on the pulp samples and the standard Tappi method that was used to test them.

Table 3.3: Properties tested and standard test method used

Canadian Standard Freeness (CSF)	T 227 om-94
Tensile strength	T494 om-88
Tear strength	T414 om-88
Bursting strength	T403 om-91

3.4.2 Analysis of results obtained

Graphs were plotted showing the average property values with standard errors (See section 4.2). Of the 3 different methods used to vary the refining energy, it was determined which method yielded the largest range in SEL and produced the lowest overall standard errors. Also for all the parameters used to vary the refining energy, the results were studied to determine which point within that parameter produced the most repeatable results. This was done by considering the standard errors at each point. A principal component analysis was carried out to see which of the three parameters was of greatest importance. The outcomes of this phase were used to decide on refining conditions used in phase 3 of this project.

3.5 Comparison between refining of bleached and unbleached pulp (Phase 2)

The quality of the pulp is changed when it is bleached and this affects the refining process. The overall focus of the research project involved unbleached pulp due to difficulties in producing sufficient bleached pulp that would be required for refining in a laboratory environment. However since refining is normally done on bleached pulp, it was decided that a comparison should be made between bleached and unbleached pulp to determine any differences in refining characteristic between the two pulps.

The unbleached pulp used in this phase of the project was the same pulp that was used in the first phase. Unrefined bleached *eucalyptus* pulp was obtained from Mondi Merebank, which gets this bleached pulp from Mondi Richards Bay. The refining for this phase of the project was carried out in stages by multiple passes through the refiner. All refining variables were held constant at the values shown in table 3.4. The specific refining energy (SRE) is a cumulative property, i.e. if the SRE for a single pass through the refiner is x, and the SRE for the second pass through the refiner is y, then the total SRE after the two stages is $x + y$. The refining intensity is not cumulative however and thus remains constant over all stages of refining.

Table 3.4: Refining conditions used for comparison

Stock consistency	(%)	4.5
Stock flow rate	(l/s)	1.2
refining gap	(micron)	25
Speed of rotation	(rpm)	2200
Number of stages		6

Samples were taken after each stage of refining including samples of unrefined pulp. The trials were carried out in triplicate. The samples taken were tested as mentioned in section 3.4.1. Results are shown in section 5.2.

3.5.1 Analysis of results obtained

Graphs showing average property value per stage of refining and standard errors are presented. The properties of both pulps were interpolated at a series of fixed SRE values and a series of fixed freeness values along the range considered. A one-way analysis of variance (ANOVA) was carried out to check for differences between the two pulps at different SRE and freeness values.

3.6 Refining trials of four different *eucalyptus* pulps (phase 3)

The starting characteristics of an unrefined pulp and its further treatment during refining, has a major effect on the quality of paper obtained. While the pulp selection is important for a good product, the refining treatment received by that pulp is of equal importance for the properties of the end product. It is for these reasons that it is interesting and beneficial to study the effect of refining on pulp of different qualities. The focus of phase 3 of this research work was to study the behavior of different types of pulps under different refining conditions and the testing of the resultant pulp to determine if recommendations can be made about how to refine wood of different characteristics in industrial processes.

Two different clones of *eucalyptus* each from two different site qualities (good and poor) were selected to provide a variation in the wood anatomy of the raw material. Grzeskowiak *et al.* (2000) showed that the GU A380 and GC G438 clones offered different characteristics that could meet the required criteria of the project.

3.6.1 Field Sampling

GU A380 and GC G438 clones, each from poor and good site qualities were identified for sampling. Site quality was based on site index measurements. The table below highlights the key characteristics of the compartments used. The sampling was conducted in April 2004.

Table 3.5: Characteristics of the 4 compartments

Species	GU A380	GU A380	GC G438	GC G438
Plantation	Kwambo Timbers	Palmridge	Mavuya	Palmridge
Age (years)	9	9	7	7
Site Index	26.6	17.8	28.5	19.0
Mean DBH (cm)	20.8	16.9	18.9	11.0
SD DBH (cm)	2.2	1.4	1.5	1.1
Mean Total Height (m)	30.0	20.4	27.4	19.4
SD Total Height (m)	1.5	0.9	0.9	0.9

Ten trees were felled from each compartment and two sets of samples were taken from each tree (see figure3.2). The diameter of the ten trees at 1.5m (breast height) from the base was measured together with the total tree height. The samples used for the wood density and anatomy measurement took the form of a 2cm thick disc taken at breast height. The samples taken for pulping and refining consisted of two 1.5m billets taken from either side of the 2cm disc. Thus 20 billets were obtained for each compartment. These 20 billets from a single compartment were pooled together and used to provide enough pulp for the refining trials. The billets were debarked in the compartments and samples were appropriately labeled before leaving each compartment.

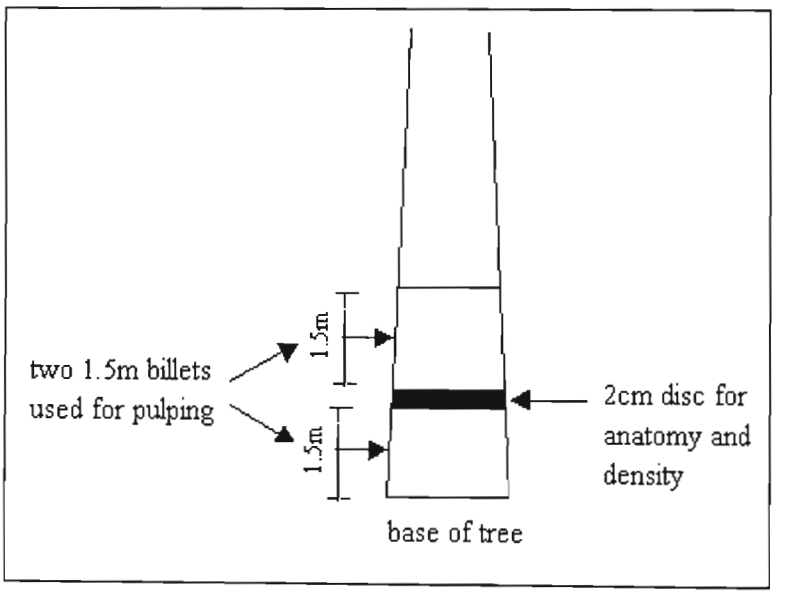


Figure 3.2: Samples taken from each tree

In total for the four compartments, forty discs and 80 billets were transported back to the *ffp* Research center.

3.6.2 Wood Anatomy and Density

The 2cm thick disc samples were used to determine the wood density, and anatomical properties. A 2cm block from pith to bark was cut from each disc. From this 2cm block, a 2.5mm thick strip from pith to bark was cut which was used for image analysis. This strip was immersed in a beaker of water until it was sectioned and slides prepared. The remainder of the 2cm block was prepared for the density measurement. This will be discussed shortly in section 3.6.2.2.

3.6.2.1 Anatomy

The wood anatomical properties were measured using image analysis techniques. Using a sliding microtome, samples were cut from pith to bark from the strips that were immersed in the beaker of water. The unbroken transverse sections obtained were placed on a glass slide and wetted with 99.9% ethanol. The ethanol provides a good medium for the viewing of the cells through the light microscope. According to Naidu (2003), wetting the samples with ethanol prevents evaporative shrinkage of cells, which would result in imprecise measurements. A cover slip was placed over the samples to prevent curling of the sample. Using a research microscope with fluorescent light together with a Leica image analysis system and digital camera, measurements of the anatomical properties were made systematically from pith to bark. Each strip had to be analysed twice. This was necessary because of the different magnifications required to measure the fibre and vessel properties. The first time was for the measurement of the fibre properties at 200 times magnification and a second time for the measurement of vessel properties at 50 times magnification. The anatomical properties measured were

- fibre cell wall thickness
- fibre diameter
- lumen diameter
- vessel diameter
- vessel percentage
- vessel frequency.

3.6.2.2 Density

The remaining portion from the 2cm block of wood was cut to 2.5mm thickness using a specially designed saw. This strip was conditioned to constant moisture content in a conditioning room set at 23 °C and 50% relative humidity before carrying out the density measurements. The density measurements were carried out using a gamma ray densitometer. The samples were scanned at 0.5mm intervals from pith to bark. Wood extractives were not removed thus the density measured was the unextracted density.

3.6.2.3 Analysis of Anatomical properties and Density

The properties measured for each sample gives the profile of that property along the strip from pith to bark. In order to compare the properties, weighted mean values were calculated by multiplying each property value by the area measured, then adding all these together and dividing by the sum of the areas measured. The equation below was used.

$$WMX = \frac{\sum_{i=1}^{n} x_i A_i}{\sum_{i=1}^{n} A_i}$$

Where, x_i = Property measured

A_i = Area of the i^{th} ring

n = The total number of measurements made fom pith to bark

WMX = weighted mean property

Using a one-way analysis of variance (ANOVA) at the 95% confidence level, the results obtained were analysed to check for variation of wood physical properties amongst the four compartments used. As already mentioned, the two different clones from poor and good sites were chosen to provide this variation. The Duncan multiple range test was carried out to test for homogeneity. Data analysis was carried out using Microsoft Excel and the statistical package Statgraphics. Results can be seen in section 6.1.

3.6.3 Pulping

The 20 billets from each compartment were chipped together for pulping purposes. Thus there were four batches of chips that represented the four compartments investigated. The chipping was done in an industrial mill chipper at Sappi Saiccor. The chips were screened using vibratory screens to remove oversized and undersized chips. The screened chips were then left to air-dry before commencing with pulping. Representative samples of the air-dried chips from each of the four compartments were used to determine the moisture content of the compartment. The moisture content was determined by measuring the mass of chips before and after drying the chips in an oven set at a temperature of 105°C for 24 hours. The moisture content was calculated as the ratio of the mass of water evaporated in the oven to the mass of chips before being placed in the oven.

The Kraft pulping process was used. Table 3.6 below shows the Kraft cooking conditions used.

Table 3.6: Kraft cooking conditions used

A.A charge (expressed as % Na2O):	18%
Sulphidity	25%
Liquor-to-wood ratio:	4.5:1
Time to 170°C	90 min
Cooking time at 170°C	50 min
H factor	892

The reason for using 20 billets per compartment was that a large quantity of pulp was required for the refining trials. The pulping was carried out in an electrically heated rotating batch digester. This digester's capacity was such that it could pulp only 800g of oven dried chips at a time. Thus in order to produce sufficient pulp for the refining trials approximately 80 cooks had to be done per compartment. Thus in total for four compartments 320 cooks were done.

Only the average results of the pulping, i.e. the kappa number, screened pulp yield, rejects, and total pulp yield will be presented. All the pulp produced from the 80 cooks for each of the four compartments was divided into 9 batches each. Results are shown in section 6.2.

3.6.4 Refining

It was decided from the results of phase 1 reported in section 4, that the most appropriate method of varying the refining energy when refining the four different clones, was to use multiple passes through the refiner to vary the SRE and to use different speeds of rotation to vary the SEL. Three different speeds were used to provide 3 different refining intensities that could be compared. All trials were carried out in triplicate therefore 9 batches of pulp were required per compartment. Table 3.7 shows the refining parameters used when refining the pulp from the four compartments.

Table 3.7: Refiner parameters used during refining of clones

stock flow rate	1 litre/s
refiner gap	25 micron
stock consistency	3%
speed of rotation	750 : 1500 : 2200 rpm

For refining carried out at 1500 rpm and 2200 rpm, 6 stages of refining were carried out (i.e. 6 passes through the refiner). Samples of pulp were taken after each stage of refining as well as a sample of the unrefined pulp. For refining carried out at 750 rpm the SRE per pass was low so 25 stages of refining was carried out. This time samples were collected after stages 1, 5, 10, 15, 20 and 25 as well as a sample of the unrefined pulp. Pulp samples collected from the refining trials were tested as outlined in section 3.4.1.

3.6.4.1 Analysis of results obtained

A sub sample from each sample collected was sent to Mondi Richards Bay for fibre morphology analysis. This was done using a Fibre Lab Analyser manufactured by Metso. The initial pulp fibre morphology was obtained from the unrefined pulp samples. The results obtained for this initial pulp fibre property were analysed for differences, using a one-way ANOVA at the 95% confidence level. The Duncan multiple range test was used to check for homogeneity.

The results were compared in three ways. Firstly the overall strength properties were considered to look at the development of the pulp properties with refining. Results of this are shown in section 6.3. The results were then compared at a constant SRE of 100 kWh/t. This showed the pulp properties after the same level of refining treatment. The results for this are shown in section 6.4. The results were then compared at a constant freeness of 400 ml. Industry is generally

interested in pulp having freeness values in this range. When the results are compared in this way the impact of the different quality pulps on the refining process itself was seen in terms of how much of refining is needed to achieve this freeness level. Results for this are shown in section 6.5.

Correlations between initial wood physical properties and pulp strength properties as well as correlations between initial pulp strength properties were determined to try to see what drives the different pulp strength properties. Principal component analyses were carried out to determine which variables could account for most of the differences in the results and thus reduce the number of variables that would be used in the multiple regression analysis and also avoid any autocorrelations. Multiple regression analysis was carried out to try and predict pulp strength properties. By using one-way ANOVA's at the 95% confidence level, results compared at constant SRE and constant freeness were analysed for differences due to different pulp qualities as well differences due to the three different refining speeds used.

Chapter 4

Results and discussion for the variation of refining variables

4.1 Introduction

This chapter deals with the investigations of the impact of refining variables as defined in section 3.4. The reason for doing this was to gain an understanding of how these variables influence the refining outcome. Upon completion of this phase a suitable parameter would be chosen to continue further investigations in phase 3 of this project.

4.2 Results and Discussion

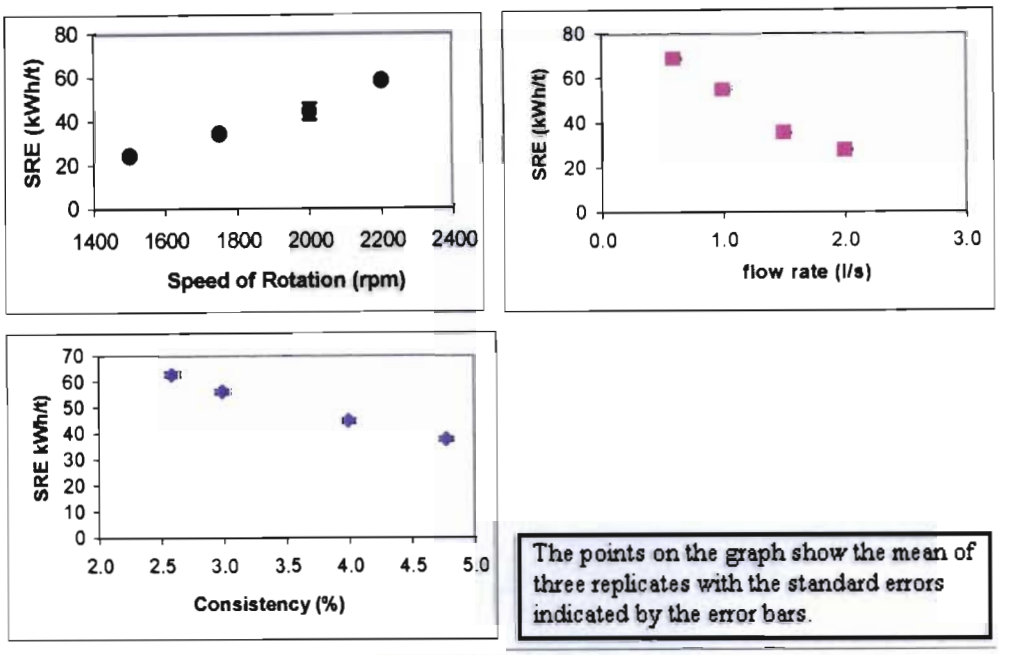
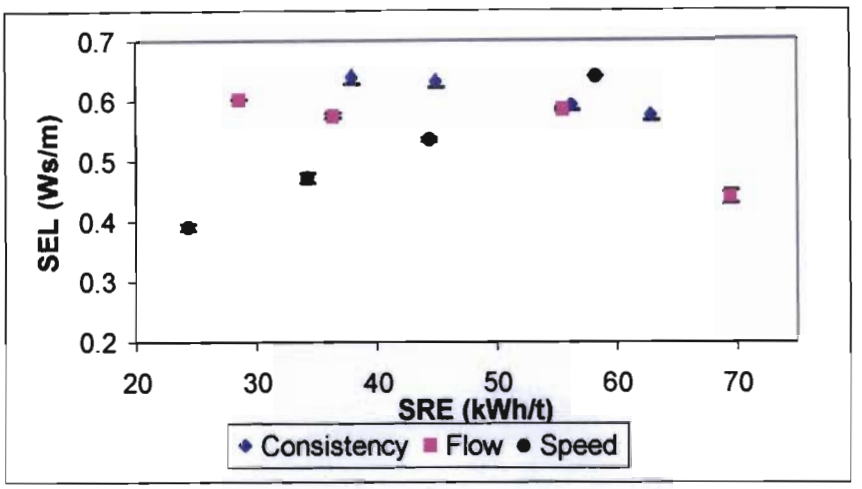


Figure 4.1: Graph of specific refining energy versus parameter varied

Figure 4.1 shows how the specific refining energy (SRE) changes as one of the parameters is varied while maintaining the other parameters constant. As the flow rate and consistency decreased, there was an increase in the refining energy. With increasing speed of rotation, there was an increase in refining energy. These trends are expected as will be explained shortly.



The points on the graph show the mean of three replicates with the standard errors indicated by the error bars.

Figure 4.2: Relationship between refining intensity (SEL) and specific refining energy (SRE)

Figure 4.2 shows the relationship between the refining intensity (SEL) and the specific refining energy (SRE). Three different methods were used to vary the amount of refining energy and it can be seen in figure 4.2 that each methods gave rise to a different relationship between SRE and SEL.

When varying the amount of SRE by changing the consistency of the refining stock it was observed that as the stock consistency was decreased, the SRE increased and the calculated SEL decreased. The stock flow rate followed the same trend i.e. as the flow rate decreased the specific refining energy increased and the refining intensity decreased. With increasing speed of rotation an increase in both SRE and SEL was observed.

Table4.1: Table showing range of SEL with variation of each parameter

	Consistency	Flow rate	Speed
Highest SEL (Ws/m)	0.64	0.60	0.64
Lowest SEL (Ws/m)	0.57	0.44	0.39
ratio of highest to lowest	1.11	1.37	1.63

Varying the stock consistency led to minimal changes in refining intensity with increasing refining energy (the highest SEL was only 11% greater than the lowest SEL). It was noted that a change in flow rate from 2 l/s down to 1 l/s, led to a small change in SEL (only 5% difference).

However, a large change in SEL was observed when the flow rate was reduced to 0.6 l/s. With the variation of speed of rotation it can be seen in table 4.1 that the SEL range was relatively larger than for when varying stock consistency or flow rate.

An understanding as to why these variables relate to the SRE and SEL the way they do can be obtained by looking at the way the SRE and SEL are obtained.

$$SRE = \frac{P_{net}}{fibre\ flowrate} = \frac{P_{net}}{(consistency)x(stock\ flowrate)}$$

$$SEL = \frac{P_{net}}{cutting\ speed} = \frac{P_{net}}{(Speed of\ rotation)x(Cutting\ edge\ length)}$$

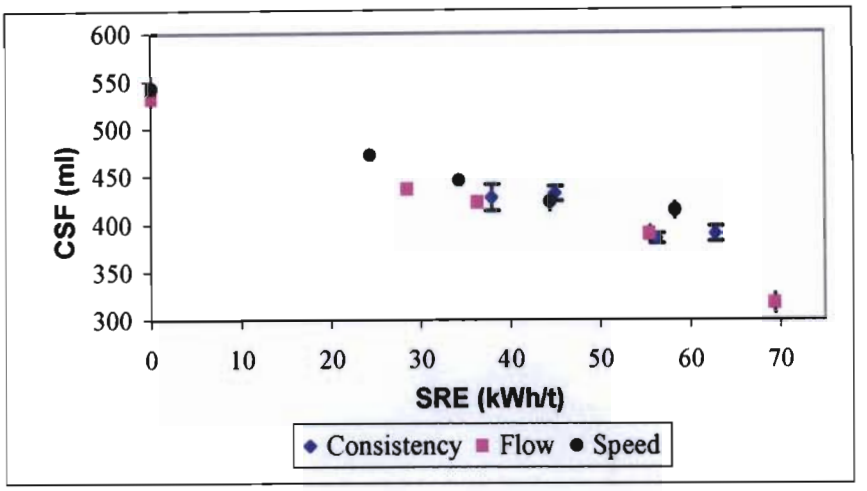
The cutting edge length depends on the refiner plate patterns and for a given set of plates this is a constant. Thus in terms of this study where the same plate was used throughout the SEL only changes when the speed of rotation changes or the net power changes. The net power changes as any of the refining conditions changes.

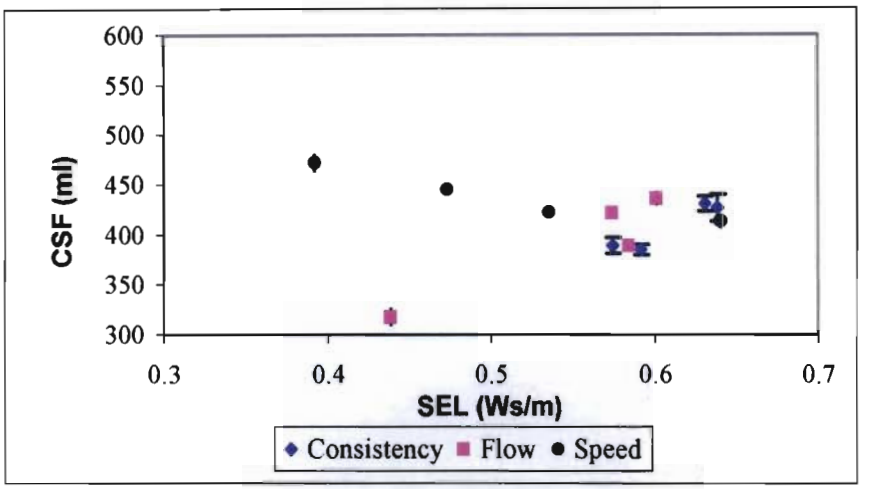
As the stock consistency changed the net power changed only slightly therefore the SEL didn't change a lot. However the fibre flow rate changed a lot therefore the SRE changed a lot more than the SEL. As the consistency decreased the net power was also observed to decrease very slightly and this is what resulted in a decrease in SEL. At the same time due to the lower consistency at fixed stock flow rate the fibre flow rate decreased therefore the refining energy was distributed to less fibres leading to an increase in SRE. The same explanation applies as the stock flow rate was decreased while keeping other variables constant. The exception here is the case of a stock flow rate of 0.6 l/s where the net power was observed to be low compared to the net power observed at flow rates of 1, 1.5 and 2 l/s.

When the speed of rotation was increased both the SRE and the SEL increased. The net power is proportional to the cube of the speed so as the speed increases, so does the net power. The SRE increases as a result of this net power. Even though the cutting speed increased the SEL was observed to increase. This is because for the refiner used the net power increased by a larger amount than the cutting speed as the speed was increased.

In other studies (Reid 1965), it has been observed that as the speed of rotation increased the refining intensity decreased. It was noted that in these studies larger refiners were used. The size of the refiner would influence the magnitude of the cutting edge length. It is very likely that this parameter is the reason for this study showing an increase in SEL with increasing speed while in other studies it has been observed to be different. The cutting speed depends on both the speed of rotation and the cutting edge length. The larger refiners used in the other studies mentioned would have had larger cutting edge lengths compared to the refiner used in this study. Thus for large cutting edge lengths the product of speed and cutting edge length probably increases by a larger amount for an increase in speed than the net power increase.

Figure 4.3 shows the relationship between the freeness of the pulp and SRE. It was observed that the freeness correlates very well with SRE. Freeness was observed to decrease as the specific refining energy was increased. With larger specific refining energies the fibres are treated more and become more collapsible. This causes the fibres to pack more closely together and thus hinder the drainability of the pulp. Also with increased refining the amount of fines which are produced increases and with increased fines the fibre mat produced as the pulp drains becomes less porous and the resistance to drainage of the water increases resulting in decreased freeness as refining progresses. The results show that even though different refining treatments were used, the freeness of the pulp was similar at the same SRE. The lowest standard errors were observed when the variation of speed of rotation was used to vary the SRE.





The points on the graph show the mean of three replicates with the standard errors indicated by the error bars.

Figure 4.3: Relationship between freeness and SRE and SEL

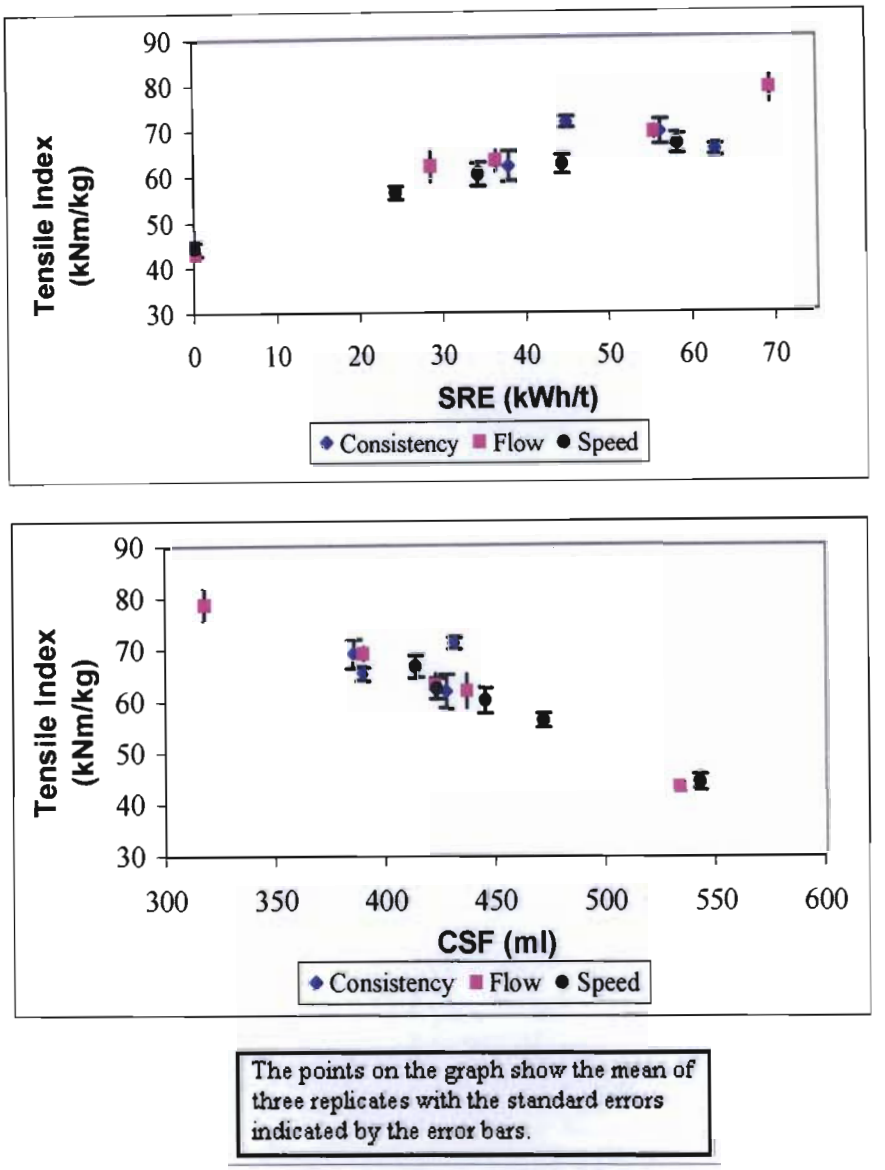
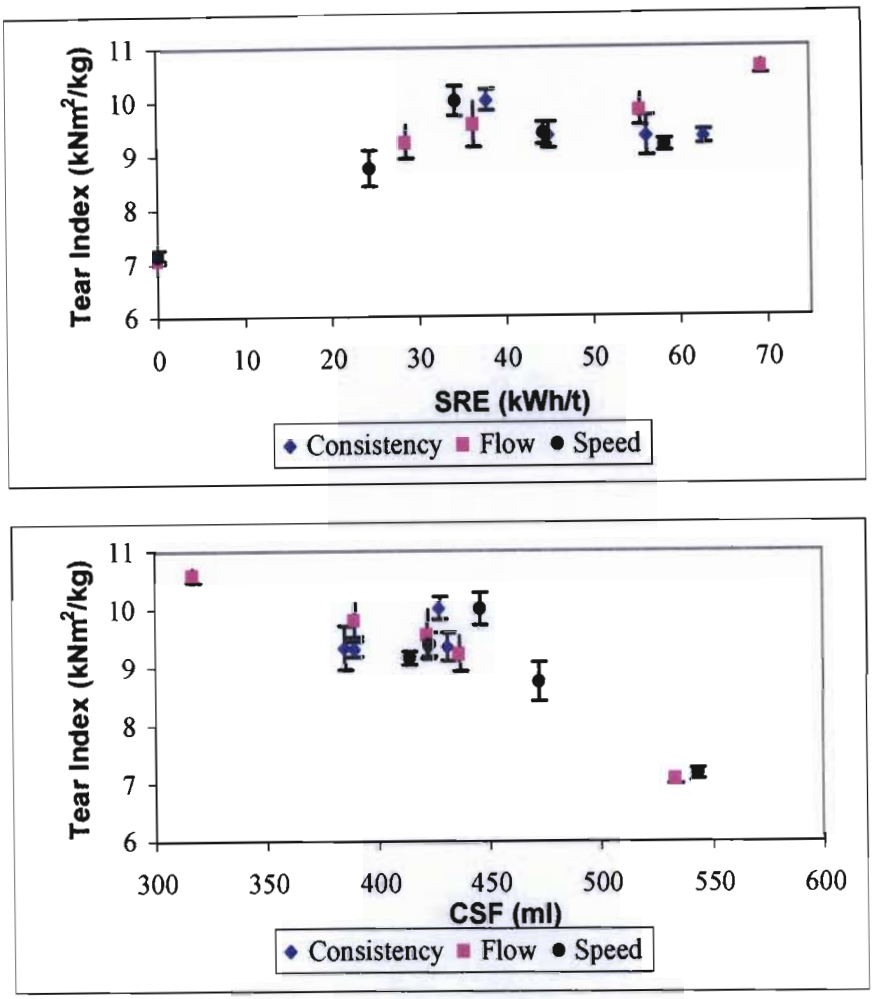


Figure 4.4: Relationship between tensile index and SRE, freeness

There was a good correlation between tensile index and SRE. The tensile index was observed to increase as the specific refining energy increased. The tensile strength is dependent on the bonds between fibres. Refining results in an increase in surface area of the fibres and this allows for increased bonding between fibres. Britt (1970), pointed out that it is believed that the interfibre bonding is the predominant factor in tensile strength while the fibre strength plays a secondary role. The refining action causes the fibres to swell by increasing the imbibition of water as the fibre surface is ruptured and fibrillated. The fibres become more flexible and are better able to mat and contact neighbouring fibres. It can also be seen in figure 4.4 that the freeness correlates very well with the tensile index. It was also noted, that of the different methods used to vary the

SRE, that the results obtained for the variation of the parameter speed of rotation resulted in the lowest standard errors for the tensile strength. This was also noted with all other properties measured.



The points on the graph show the mean of three replicates with the standard errors indicated by the error bars.

Figure 4.5: Relationship between tear index and SRE, freeness

Tear index (figure 4.5), showed an initial increase in tear strength up to about 35-45 kWh/t thereafter with continued refining the tear strength deteriorates. The exception to this trend, are the results from the variation of flow rate where the tear index is still high at a SRE of 69.4 kWh/t. Casey (1981) mentioned that stretch is a factor in the initial tearing resistance of paper.

This might contribute to the high tear strength achieved when refining at 0.6 l/s. It can be seen in figure 4.8 that the refining at 0.6 l/s resulted in sheets with the highest stretch (3.5%).

Fibre length and interfibre bonding are both important factors contributing to the tearing resistance of paper. It is believed that long fibres result in higher tear strength and the reason for this is because longer fibres distribute the stress over a greater area and over more fibres and more bonds than short fibres. Thus with shorter fibres the stress is concentrated over a smaller area (Britt 1970). With a low degree of interfibre bonding, fibres are able to pull apart easily and this results in a low tear strength. As the amount of interfibre bonding increases the fibres do not pull apart as easily and tear strength increases. The tear strength increases to a maximum and then decreases (Britt 1970). Refining increases the surface area to improve interfibre bonding and this is what results in an initial increase in tear strength with refining. However the refining process cuts the fibre and decreases the fibre strength and as a result of this the tear strength increases to a maximum beyond which point further refining lowers the fibre strength too much and the tear strength starts to deteriorate.

The work involved in tearing a paper is made up of two components (Casey 1981). These are the work involved in pulling fibres out of the paper and the work involved in rupturing fibres. According to Casey (1981), for paper made from unrefined pulp, the tearing resistance is made up mostly of work involved in overcoming the frictional resistance of the fibres being pulled from the paper. Casey goes on to mention that, after slight refining, interfibre bonding is increased and the tear strength increases due to increased frictional resistance in pulling the fibres out of the paper. However with increased refining the fibres do not slip past one another easily and as a result of this there is an increase in the number of fibres that are ruptured in tension. When this happens, tearing becomes more of shearing action rather than a pulling one. Since the work involved in rupturing a fibre is much less than the energy involved in pulling a fibre out of the paper, the energy required to tear the paper decreases. What this implies is that with increased refining the cohesion of the sheet increases and this concentrates the tearing force over a smaller area and because of this lower tear strength values are obtained.

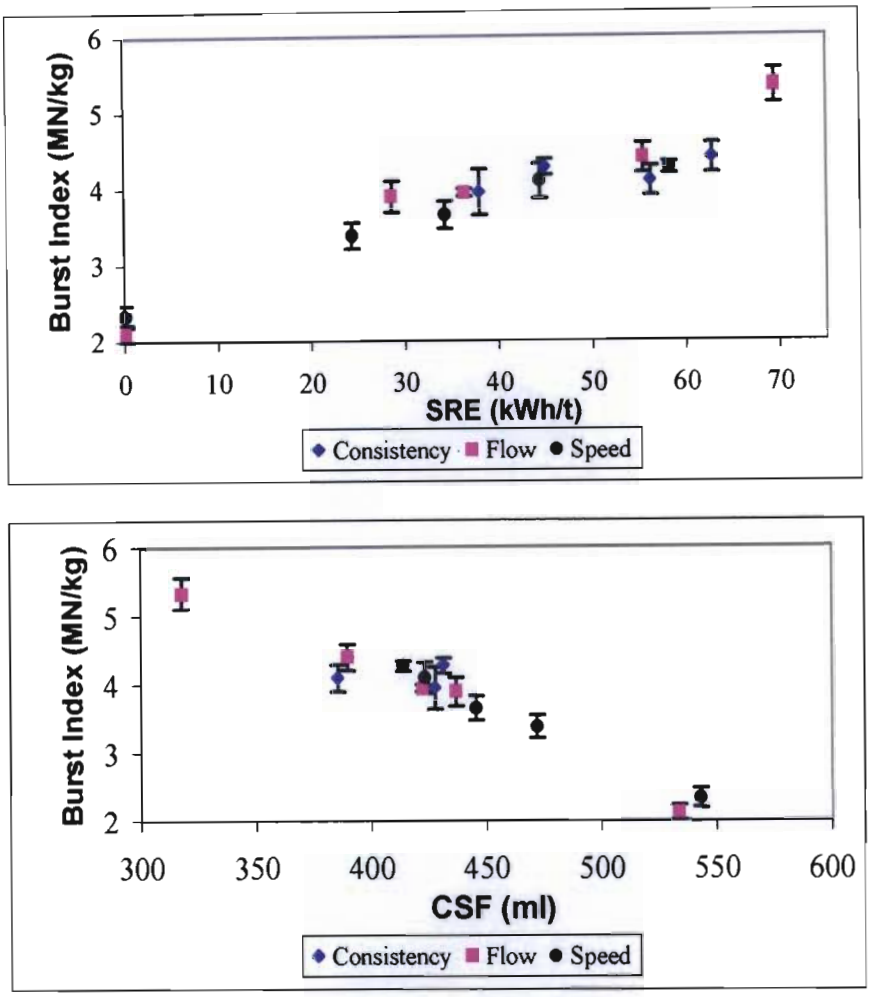
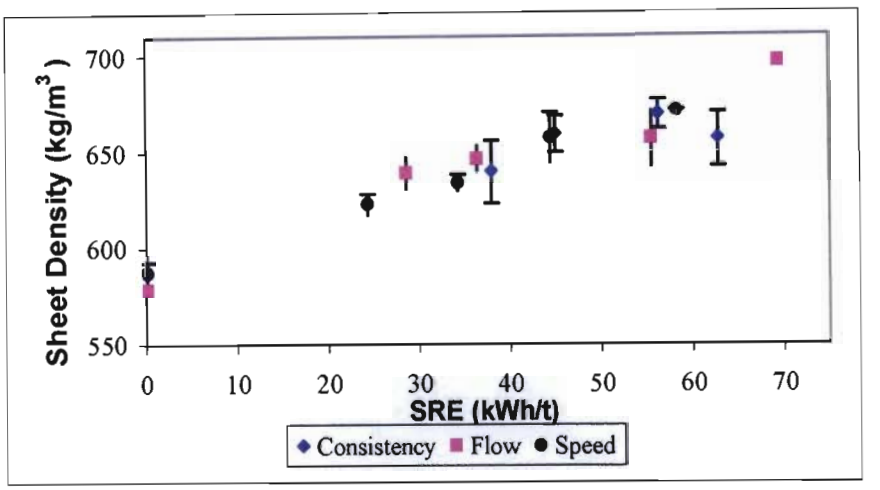
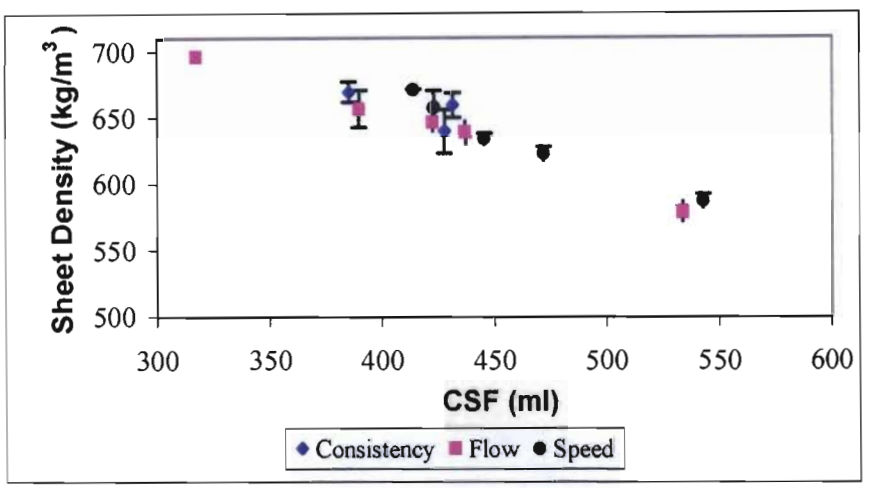


Figure 4.6: Relationship between burst index and SRE, freeness

The burst index increases with increasing SRE (figure 4.6). At a fixed SRE or freeness there were no marked differences in burst strength amongst the different methods used to vary the SRE. The development of the burst strength occurs in a similar manner as the tensile strength. The reasons for the observed increase in burst strength with refining are thought to be the same as mentioned for tensile strength (Britt 1970). Increased fibre lengths produce higher burst strength however the amount of interfibre bonding has a greater affect on the burst strength. According to Casey (1981), the bursting strength is complex function of tensile strength and stretch. While burst strength increases with refining over most of the range, some loss in burst strength can occur with excessive refining. Casey attributes the loss in burst strength with excessive refining to the

disintegration of the fibre and also states that part of the loss could be accounted for by a loss in stretch.





The points on the graph show the mean of three replicates with the standard errors indicated by the error bars.

Figure 4.7: Relationship between sheet density and SRE, freeness and SEL

The sheet density was observed to increase with increasing SRE (figure 4.7). With increased refining the fibres become more conformable and are able to pack more closely together. In addition, fines are produced which fill up any voids and increase the sheet density. At a fixed SRE, all refining treatments resulted in pulps which produce similar sheet densities.

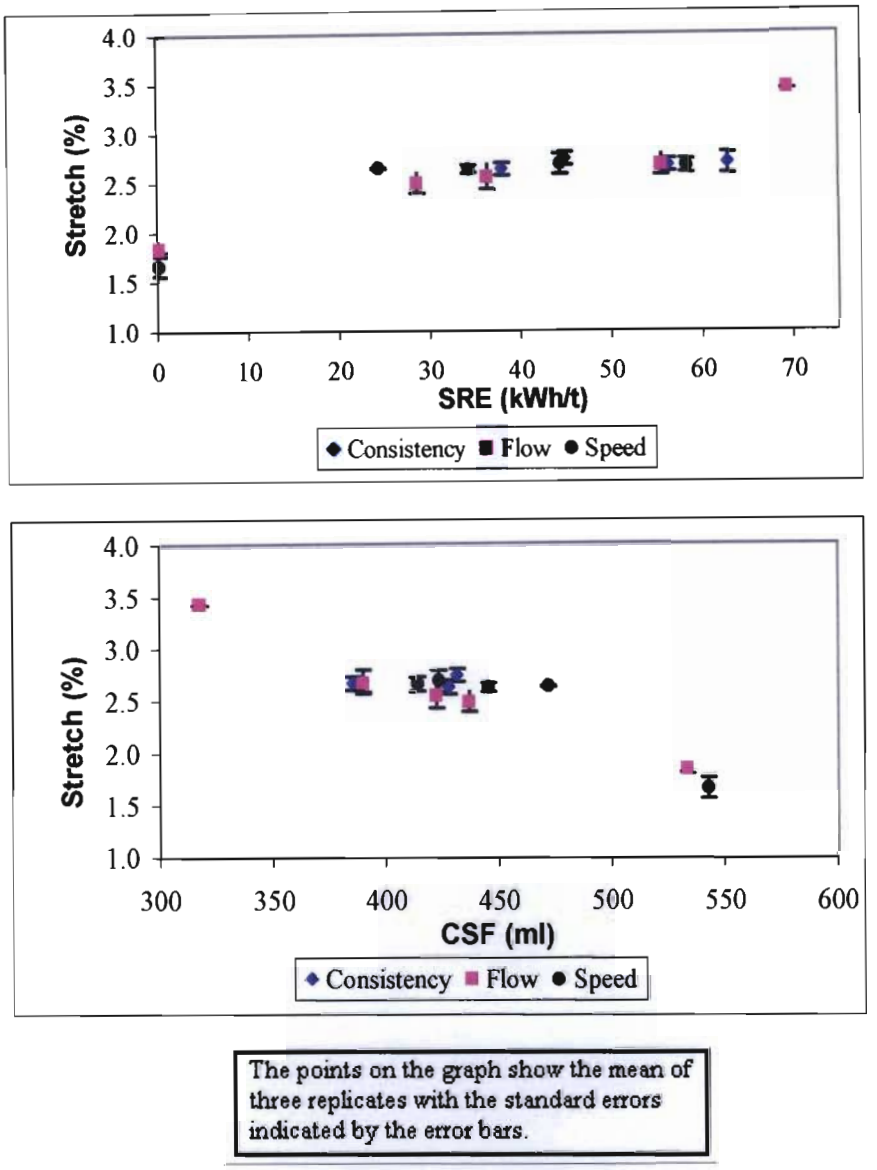
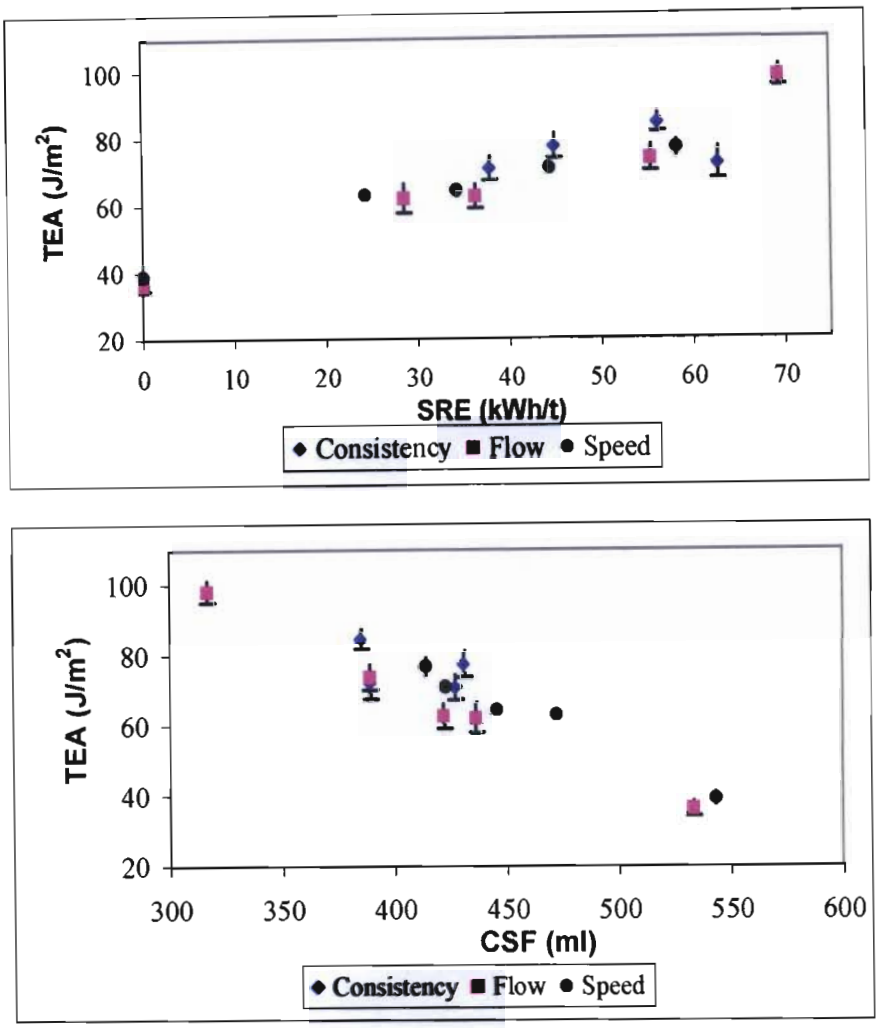


Figure 4.8: Relationship between stretch and SRE, freeness

Stretch is the amount of elongation that the sheet undergoes under tensile stress. With the variation of flow rate and speed of rotation, it was seen (figure 4.8) that there was an increase in stretch in the sheets produced from the refined pulps compared to the stretch of the unrefined pulp. In the case of variation of speed of rotation the stretch did not change with SRE. For the variation of flow rate, the stretch increased continuously with SRE. The highest stretch obtained was about 3.5% for the flow rate of 0.6 l/s. In the case where variation of consistency used to vary the SRE, there was no change in stretch with SRE. The stretch values were the same as when using speed of rotation to vary the SRE. Some of the factors that influence stretch are fibre elasticity and strength, sheet density and formation (Britt 1970). Refining results in sheets with

higher density and better formation. According to Britt (1970), the stretch of normal paper generally does not exceed 5%.



The points on the graph show the mean of three replicates with the standard errors indicated by the error bars.

Figure 4.9: Relationship between TEA and SRE, freeness

The tensile energy absorbed (TEA), is a very important measure of the strength of paper. The TEA increases with increasing refining energy (figure 4.9). At the same SRE all methods seem to give the same TEA. The TEA combines the tensile strength with stretch and is a measure of the toughness of the paper (Casey 1981). The reasons for an increase in TEA with refining are probably the same the reasons for an increase in tensile strength and stretch with refining.

Table 4.2: Regression models for prediction of pulp properties

Property	p-value	R^2	Equation
Freeness	<0.0001	88.18	Freeness = 533.519 - 2.60344*x*SRE
Tensile strength	<0.0001	78.95	Tensile strength = 45.7071 + 0.424599*x*SRE
Tear strength	<0.0001	69.41	$Tear = 7.2784 + 0.3348\sqrt{SRE}$
Burst strength	<0.0001	82.2	Burst strength = 2.41039 + 0.0369253*x*SRE
Sheet Density	<0.0001	77.33	Sheet density = 587.813 + 1.42043*x*SRE
Stretch	<0.0001	70.2	Stretch = 1.90717 + 0.0168779*x*SRE
TEA	<0.0001	80.61	TEA = 40.4422 + 0.702391*x*SRE

A principal component analysis showed that of the three variables varied, the parameter speed of rotation was more important. Table 4.2 shows the result of a multiple regression analysis. The SRE and SEL were used to try and predict the pulp properties. It was seen that the SRE alone resulted in good predictions of the pulp properties.

4.3 Summary of findings

- The SRE is the main determinant in predicting pulp strength properties.
- The results obtained from varying the parameter speed of rotation had the largest range in SEL and had the smallest standard errors. A principal component analysis showed this parameter to have a larger weighting than the other two variables used to vary the refining energy. Therefore this parameter was used in phase 3 of this project to provide a variation in refining intensity when refining the different pulps.
- Within each parameter investigated the following points had the lowest standard errors for the freeness and were chosen to be held constant in phase 3 of the project
    - Flow rate 1 l/s
    - Consistency 3 %
- It was seen that the control of flow rate led to good development of tear strength compared to the other methods used to control the SRE. This could have important implications if the results are confirmed with more testing. This is something worth exploring in future projects.

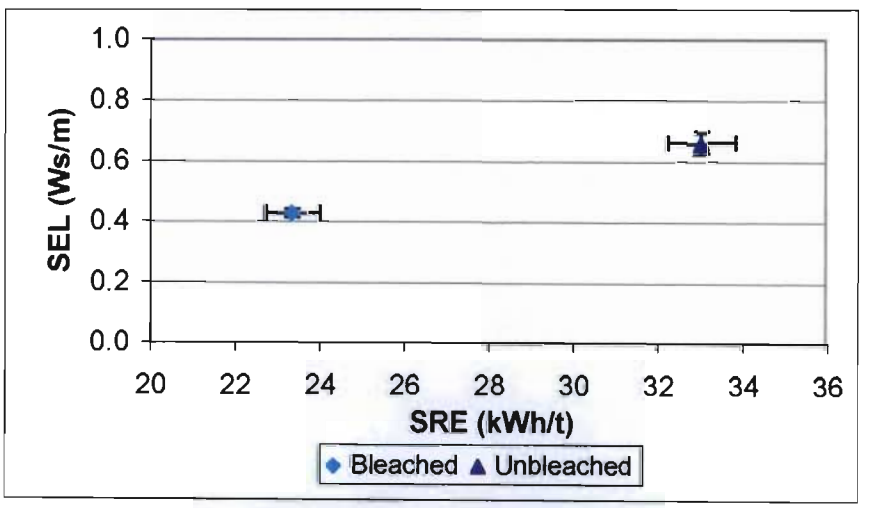
Chapter 5

Results and discussion for the comparison of refining between bleached and unbleached pulp

5.1 Introduction

Refining is normally done on bleached pulp in industry. The bleaching process changes the properties of the pulp. This is due to the removal of more lignin from the fibres which results in the fibres becoming more flexible than fibres of unbleached pulp. As a result of the extra delignification of the bleached pulp certain fibre strength properties may deteriorate. The project considers the refining of unbleached *eucalyptus* pulp due to the difficulties involved in producing sufficient quantities of bleached pulp that would be required for refining trials in a lab environment. This chapter deals with investigations regarding the comparison of refining of bleached and unbleached eucalyptus pulps.

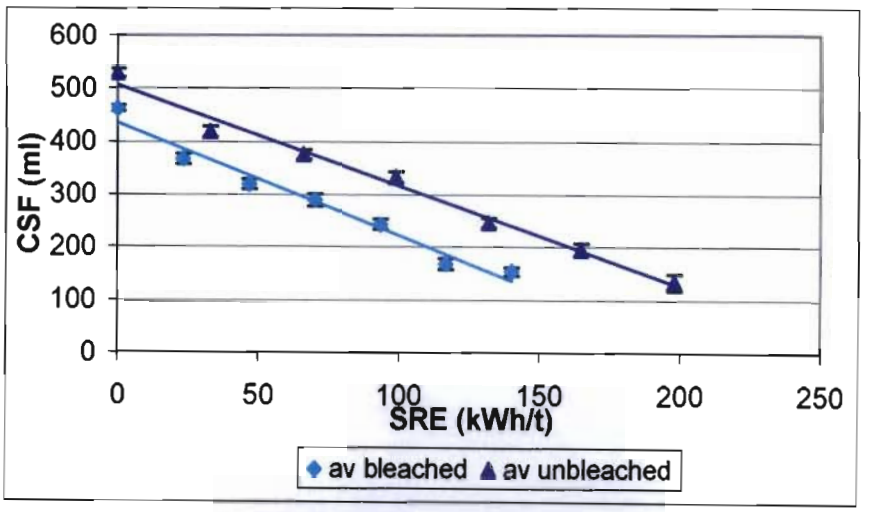
5.2 Results and discussion



The points on the graph show the mean of three replicates with the standard errors indicated by the error bars.

Figure 5.1: Absorbed energy differences for refining of bleached and unbleached pulp

Figure 5.1 shows specific refining energy and refining intensity observed for a single pass through the refiner during the refining of the bleached and unbleached pulp. It can be seen that when all the parameters, i.e. flow rate, refining gap, consistency and speed of rotation, are fixed and different pulps are used (in this case bleached and unbleached pulp), the energy characteristics are different. It can be seen that the unbleached pulp offers a greater resistance to the action of the refiner and thus a larger amount of power is used when all other refiner variables are fixed. Unbleached pulp has a higher lignin content compared to bleached pulp. Fibres with higher lignin content will be less flexible and this is what contributes to unbleached pulp having a higher resistance to the refining action.



The points on the graph show the mean of three replicates with the standard errors indicated by the error bars.

Figure 5.2: Relationship between freeness and SRE for bleached and unbleached pulp

Figure 5.2 shows the results observed for how freeness changed for both pulps at increased levels of refining. It can be seen that at a fixed specific refining energy there is a significant difference between the freeness of the two pulps throughout the range considered. This was confirmed by an analysis of variance test being carried out and table 5.1 below shows the results.

Table 5.1: ANOVA table for freeness at constant SRE

SRE	0	25	50	75	100	125	140
p-value	0.0008	0.0005	0.0005	0.0007	0.0011	0.0018	0.0023

The lower freeness of the bleached pulp is a result of the higher flexibility of the fibres due to the lower lignin content as compared to the fibres in the unbleached pulp. This greater flexibility of the bleached fibres allows them to pack more closely than the more rigid unbleached fibres and thus offer a greater filtration resistance. The refining treatment increases the flexibility of both fibres and this contributes the decrease in freeness observed with increased refining treatment. Also contributing the decrease in freeness will be the production of fines during refining. The fines fill up voids between fibres thus increasing the drainage resistance.

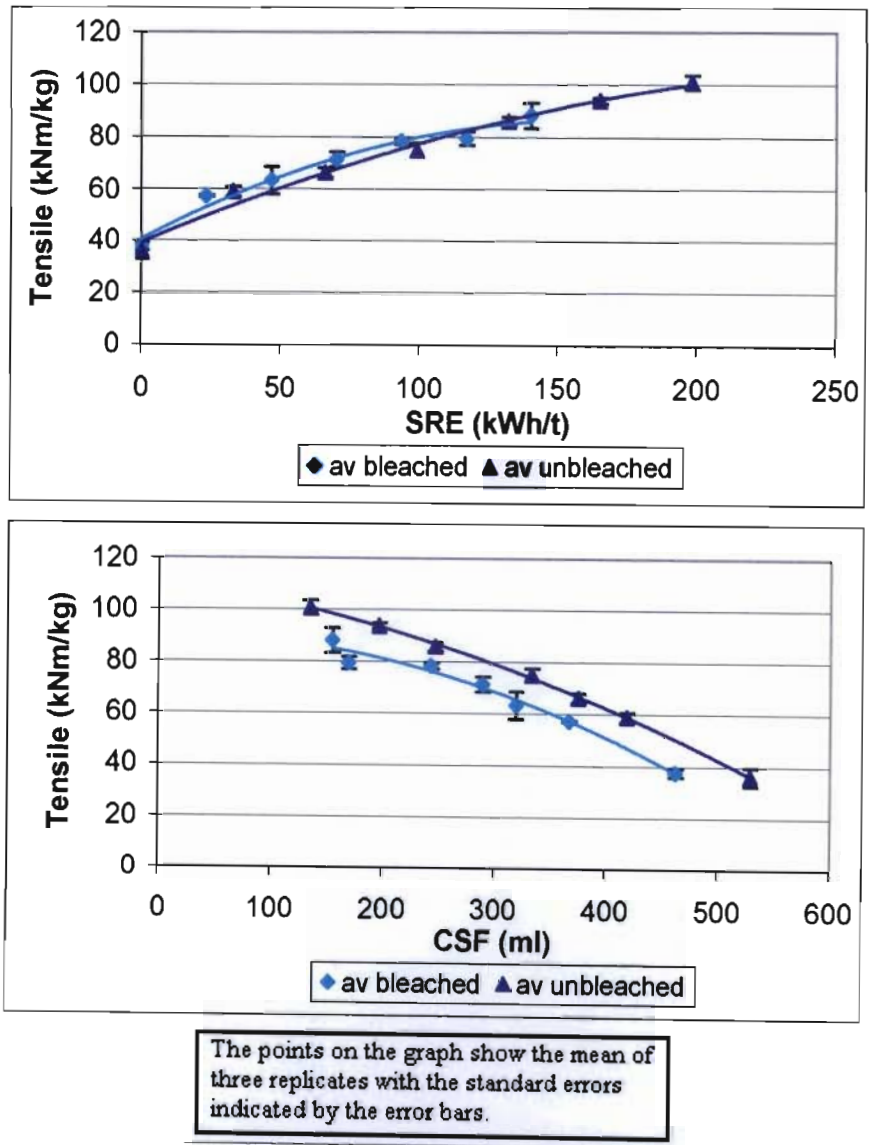


Figure 5.3: Relationship between tensile index, SRE and freeness for bleached and unbleached pulp

It was observed that at a fixed specific refining energy there were no significant differences between the tensile index of the bleached and unbleached pulp (table 5.2). However when compared at constant freeness significant differences were observed for the two pulps. The tensile index is significantly higher for the unbleached pulp compared to the bleached pulp at constant freeness. Reasons why the tensile index increases with refining have already been discussed in section 4.2

Table 5.2: ANOVA results for tensile index at constant SRE and constant freeness

SRE	0	25	50	75	100	125	140
p-value	0.9470	0.7023	0.4341	0.2846	0.2961	0.3174	0.3323
Freeness	150	200	250	300	350	400	
p-value	0.0184	0.0101	0.0064	0.0068	0.0135	0.0330	

Figure 5.4 shows the results observed for the relationships between tear index and SRE and tear index and freeness. The trend for both pulps showed an initial increase in tear index with increased refining up to a maximum and thereafter starts to decrease. The reason why the tear index behaves in this manner has been discussed in section 4.2. The maximum tear strength occurs at a SRE of between 65-70 kWh/t and from the figure it appears that the tear strength for the unbleached pulp is higher. This difference is not significant however, as can be seen from the results from an analysis of variance at constant SRE in table 5.3 below.

The tear strength graphs cross each other at a freeness of about 325 ml. For freeness values above 325 ml the unbleached pulp appears to have a higher tear strength value than the bleached pulp and for freeness values below 325 ml it appears that the bleached pulp has higher tear strength values. These differences are not significant however as can be seen in table 5.3.

Table 5.3: ANOVA results for tear index at constant SRE and constant freeness

SRE	0	25	50	75	100	125	140
p-values	0.7854	0.7817	0.6221	0.6190	0.6421	0.7384	0.8818
Freeness	150	200	250	300	350	400	
p-values	0.1291	0.2062	0.4022	0.8285	0.4762	0.1678	

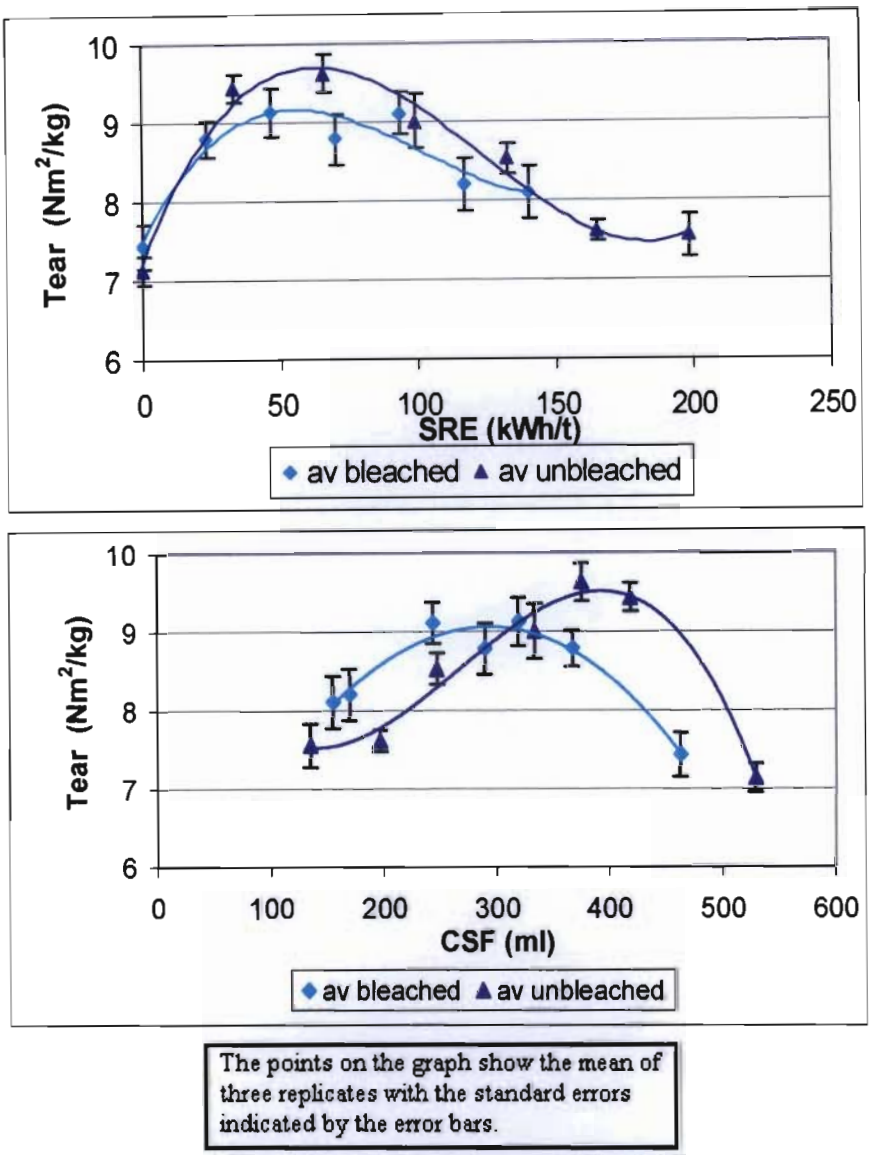
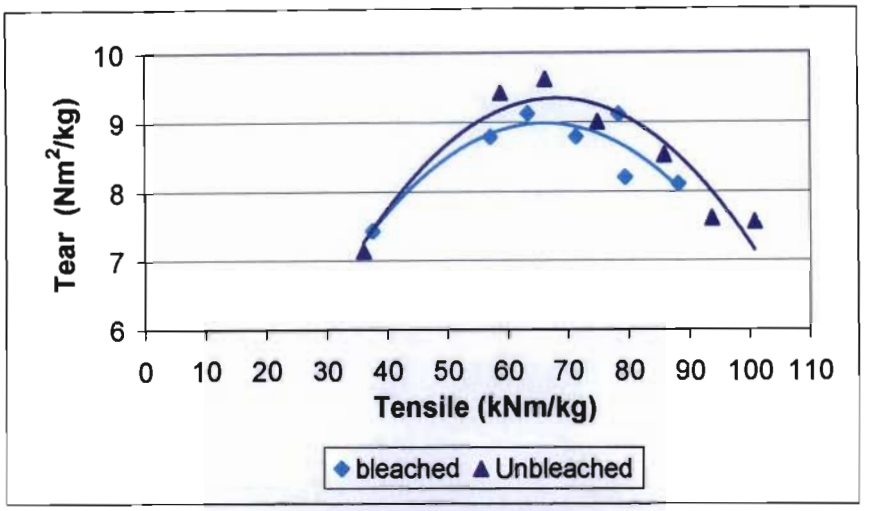


Figure 5.4: Relationship between tear index, SRE and freeness for bleached and unbleached pulp

Figure 5.5 shows the relationship between tear strength and tensile strength. Generally it is desired to optimise both these properties. However, while, the tensile strength increases with increasing refining the tear strength only increases initially and thereafter starts to decrease. Thus the strength of paper would be a compromise between properties depending on the strength requirements of a given paper grade. Figure 5.5 shows that for both bleached and unbleached pulp the maximum tear strength occurs at a tensile index of 70 kNm/kg.



The points on the graph show the mean of three replicates with the standard errors indicated by the error bars.

Figure 5.5: Relationship between tear index and tensile index for bleached and unbleached pulp

Figure 5.6 shows the relationship between Burst Index and SRE and Burst Index and Freeness for both bleached and unbleached pulp. It can be observed that the Burst Index increases with increased refining. The reason for this increase is discussed in section 4.2. An analysis of variance (Table 5.4) shows that in the early parts of the refining there was no significant difference in burst strength between the bleached and unbleached pulp at constant SRE. However with increased refining (50-140 kWh/t) there were significant differences in burst strength between bleached and unbleached pulp at constant SRE. At constant freeness there are no significant differences in burst strength between the two pulps below a freeness of 350 ml.

Table 5.4: ANOVA results for burst index at constant SRE and constant freeness

SRE	0	25	50	75	100	125	140
p-values	0.9134	0.2353	0.0443	0.0289	0.0298	0.0328	0.0347
Freeness	150	200	250	300	350	400	
p-values	0.4140	0.2728	0.1553	0.0804	0.0459	0.0367	

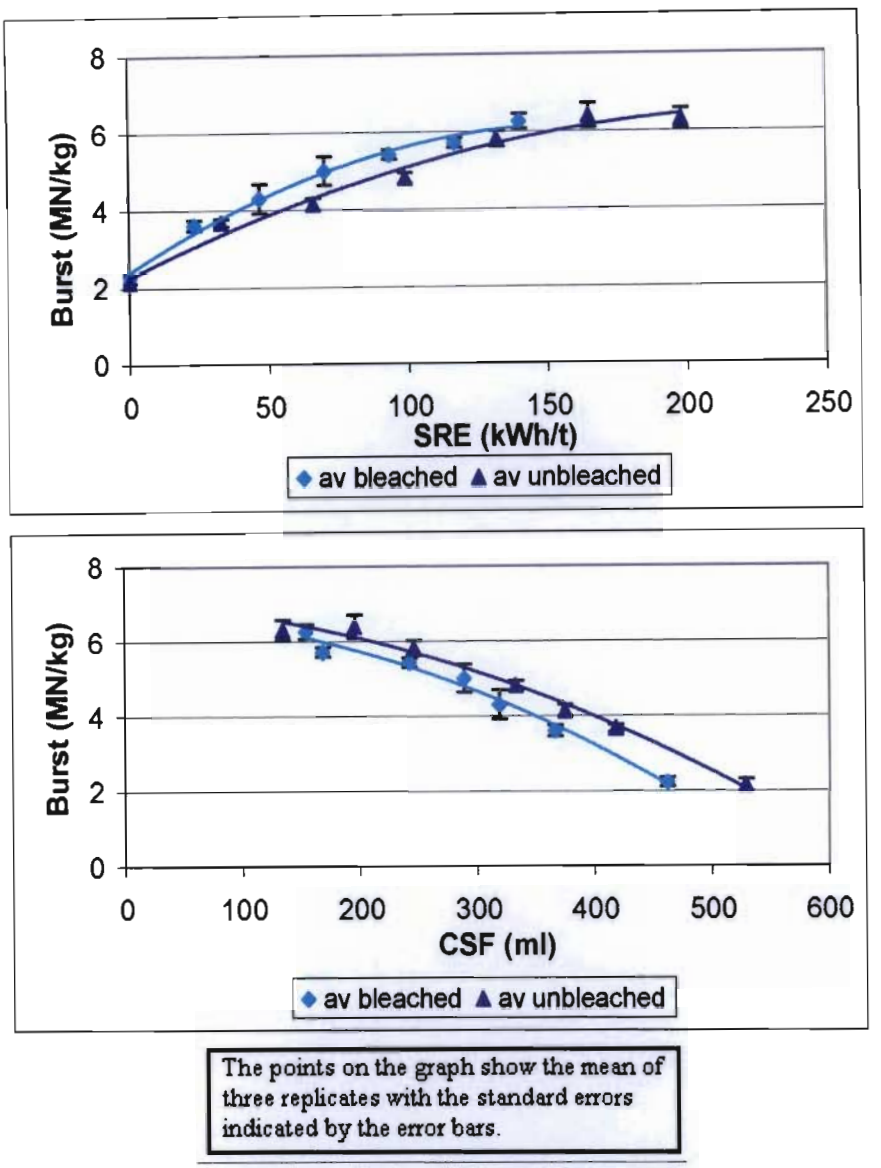
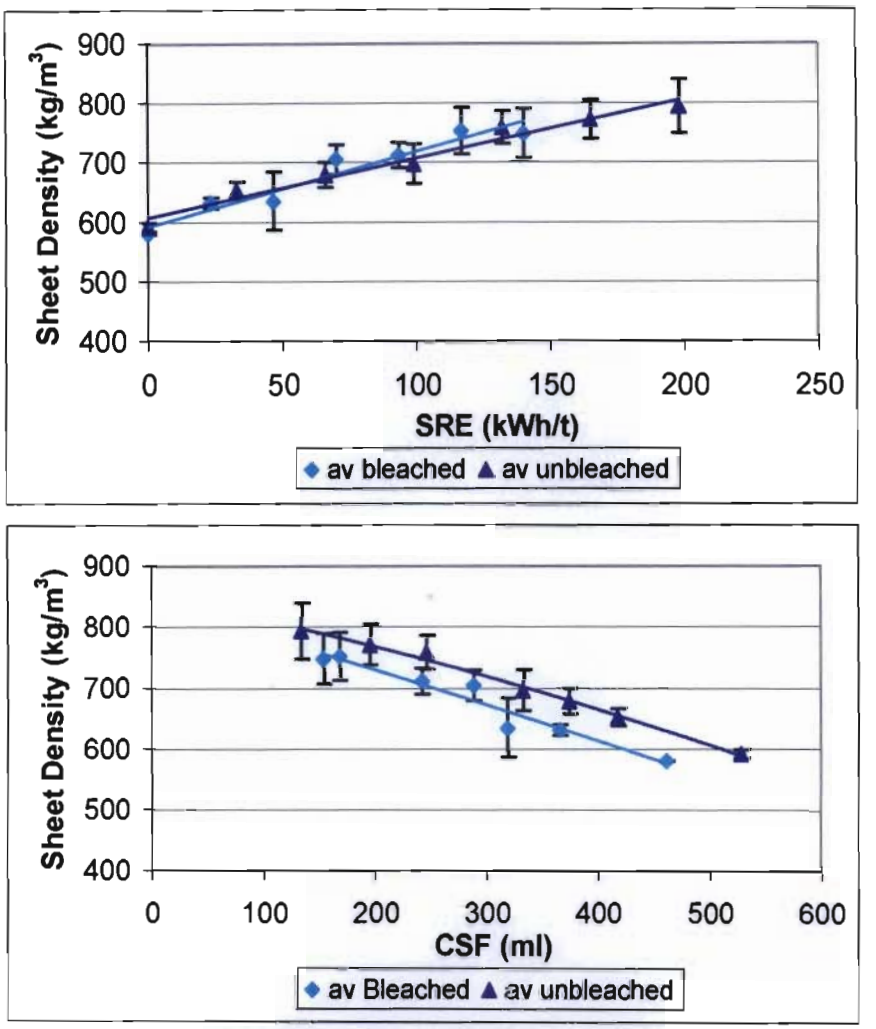


Figure 5.6: Relationship between burst index, SRE and freeness for bleached and unbleached pulp

It can be seen in figure 5.7 that at a fixed specific refining energy there is no difference in average sheet density from the bleached and unbleached pulp. At constant freeness the unbleached pulp has a higher average sheet density compared to the bleached pulp however from an analysis of variance it can be seen (table 5.5 below) that there were no significant differences at the 95% confidence level.

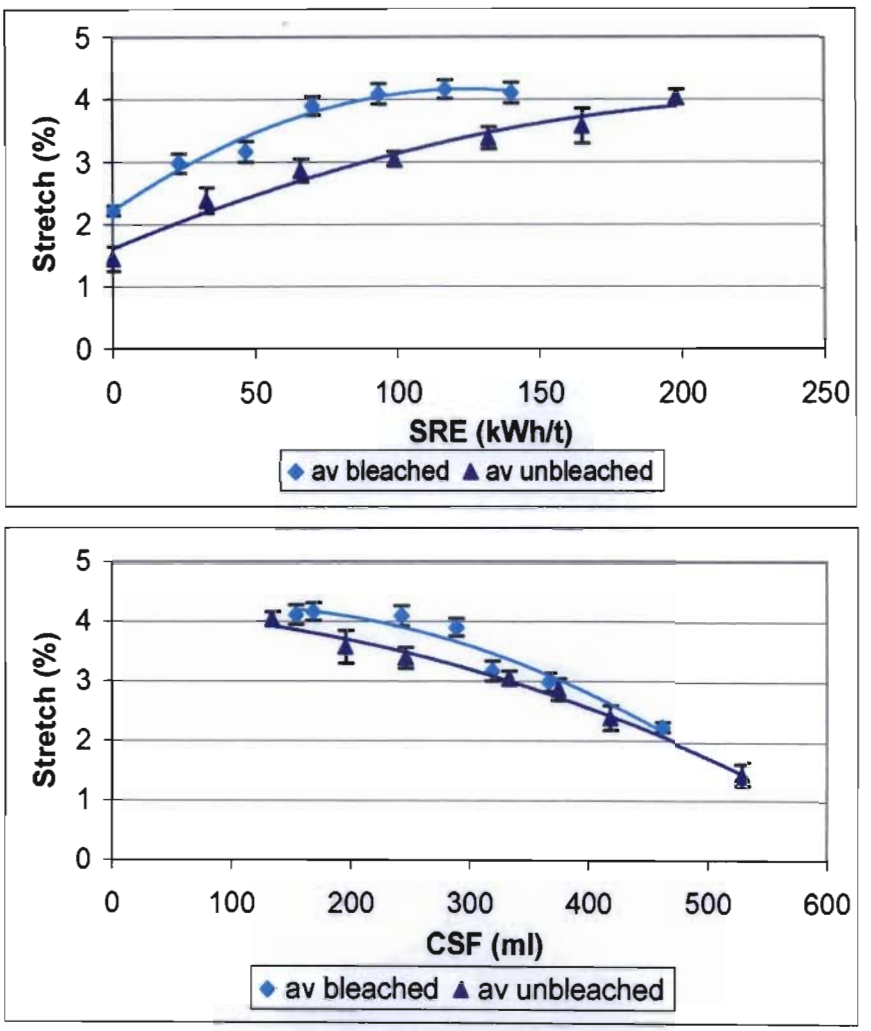


The points on the graph show the mean of three replicates with the standard errors indicated by the error bars.

Figure 5.7: Relationship between sheet density, SRE and Freeness for bleached and unbleached pulp

Table 5.5: ANOVA results for sheet density at constant SRE and constant freeness

SRE	0	25	50	75	100	125	140
p-values	0.3269	0.6566	0.9114	0.9334	0.8374	0.7742	0.7460
Freeness	150	200	250	300	350	400	
p-values	0.5458	0.4625	0.3660	0.2595	0.1539	0.0695	



The points on the graph show the mean of three replicates with the standard errors indicated by the error bars.

Figure 5.8: Relationship between stretch, SRE and freeness for bleached and unbleached pulp

It was observed that at constant SRE there were significant differences in stretch for the bleached and unbleached pulp at the 95% confidence level (Table 5.6). The stretch increases with increased levels of refining and the stretch for the bleached pulp is significantly higher than the stretch for the unbleached pulp at constant SRE. At constant freeness the average stretch for the bleached pulp is observed to be higher than for the unbleached pulp however it can be seen from an analysis of variance that the differences at constant freeness are not significant at the 95% confidence level.

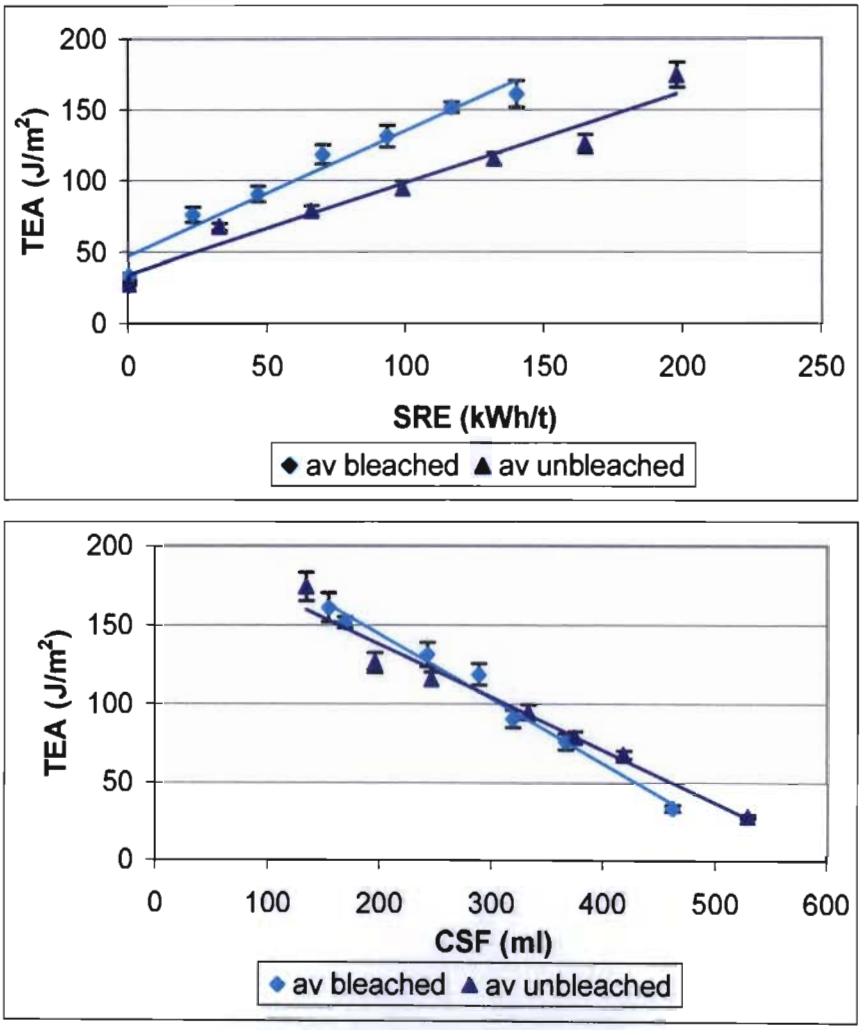
Table 5.6: ANOVA results for stretch at constant SRE and constant freeness

SRE	0	25	50	75	100	125	140
p-values	0.0209	0.0105	0.0062	0.0049	0.0050	0.0060	0.0070
Freeness	150	200	250	300	350	400	
p-values	0.1455	0.1082	0.0829	0.0743	0.0856	0.1196	

The TEA was observed to be significantly different at constant SRE at the 95% confidence level (Table 5.7). The TEA increased with increased refining and the bleached pulp had a higher TEA than the unbleached pulp. It can also be seen in figure 5.9 that there are no observable differences in TEA at constant freeness.

Table 5.7: ANOVA results for TEA at constant SRE and constant freeness

SRE	0	25	50	75	100	125	140
p-values	0.1154	0.0110	0.0008	0.0007	0.0019	0.0044	0.0062
Freeness	150	200	250	300	350	400	
p-values	0.3801	0.4798	0.6898	0.8342	0.2279	0.0625	



The points on the graph show the mean of three replicates with the standard errors indicated by the error bars.

Figure 5.9: Relationship between TEA, SRE and freeness for bleached and unbleached pulp

5.3 Summary of findings

- There are differences in the refining characteristics between bleached and unbleached *eucalyptus* pulps. The results indicate that the differences in refining characteristics occur in a predictable manner. These results indicate that it was acceptable to carry out the next phase of work on the different genetic material in an unbleached form.
- Bleached pulp requires less energy than the unbleached pulp to achieve the same level of freeness
- There were no significant differences in tensile strength of bleached and unbleached pulp at the same SRE but at the same freeness the tensile strength of the unbleached pulp was significantly higher than the tensile strength of the bleached pulp.
- The maximum tear strength of the bleached and unbleached pulp occurs at the same SRE but at different freeness values. The maximum tear strength of the unbleached pulp occurred at a higher freeness than the bleached pulp. For both pulps the maximum tear strength occurred at a tensile strength of 70 kNm/kg
- At constant SRE the average burst strength of the bleached pulp was observed to be greater than the average burst strength of the unbleached pulp. At constant freeness however the opposite was noted.
- The bleached pulp had a higher stretch than the unbleached pulp at the same SRE and also at the same freeness. However this difference was only found to be significant in the case of comparisons at the same SRE.
- The TEA was significantly higher for the bleached pulp at the same SRE however when compared at the same freeness there were no differences in TEA observed between the two pulps.

Chapter 6

Phase 3 - Investigations with four different pulps

6.1 Wood anatomy and density

The role of the raw material is very important. The paper grade being produced is what determines the specific types of raw materials to be used so as to ensure that a superior quality product at a competitive value is obtained. It is known that there exist large variations in wood properties. Amongst other factors, wood properties are known to vary with species, site quality, and age. In order to optimise the conditions of processing and to control the quality of the end products, it is important to understand the properties of the wood being processed and how they respond to pulping and the refining process

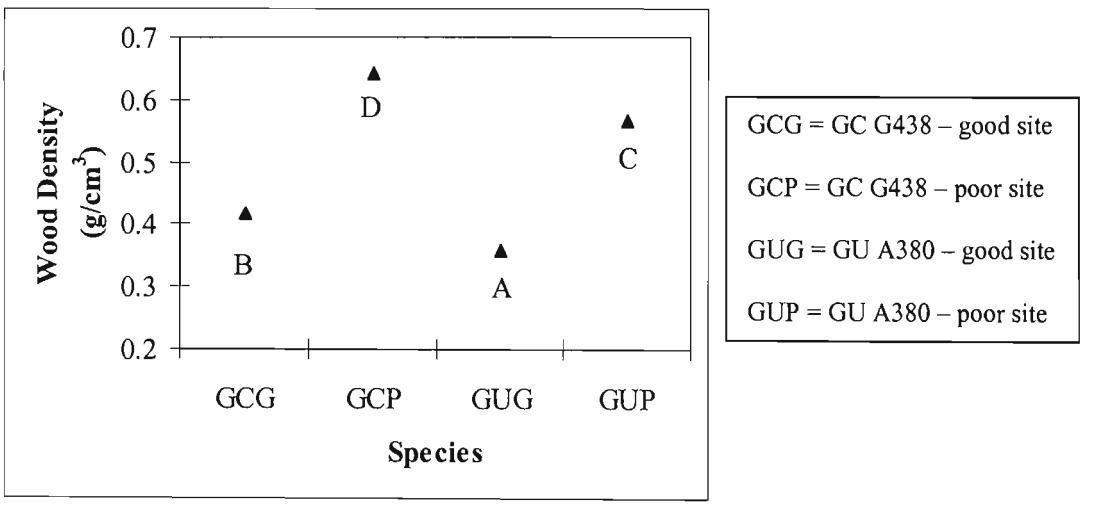
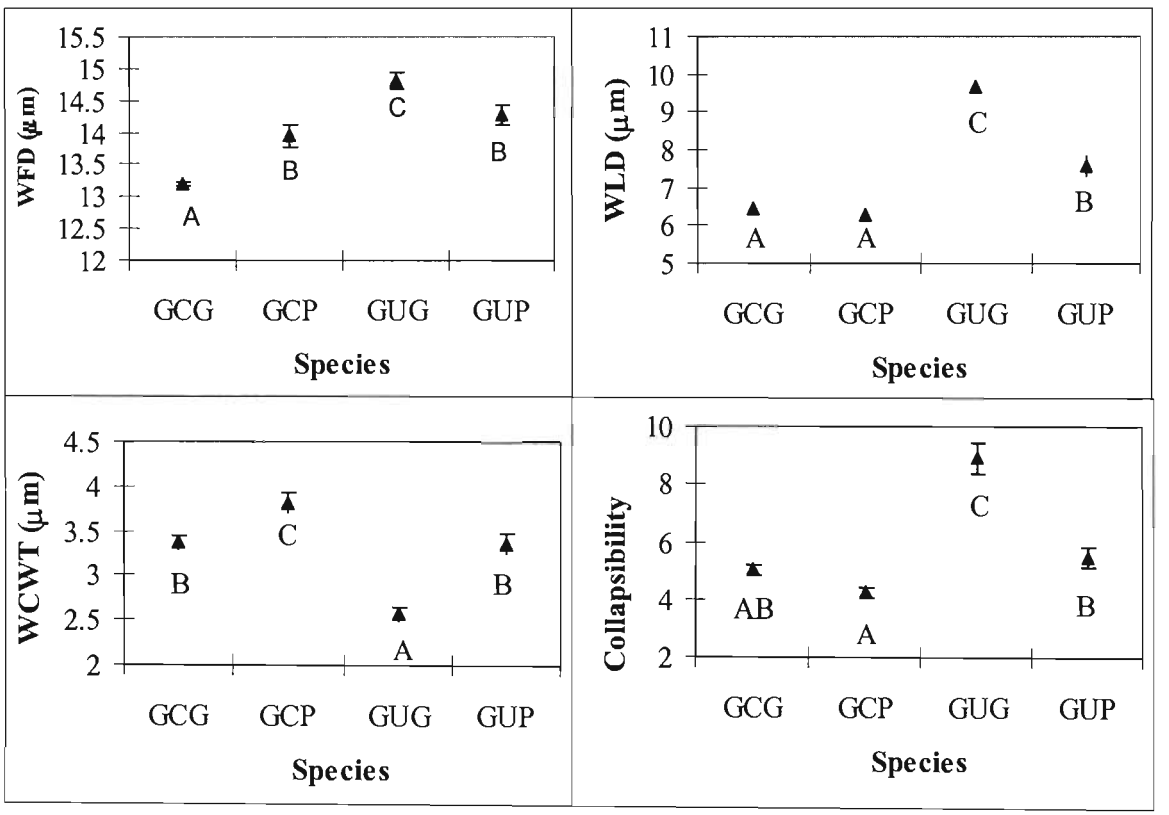


Figure 6.1: Graph of weighted mean wood density

Figure 6.1 above shows the average density for each of the four compartments. The letters (A – D) on the graph indicate the results of a Duncan multiple range test. For the Duncan test, common letters indicate that there were no significant differences between samples at the 95% confidence level. In this case it can be seen that the four compartments have significantly different densities. The largest density is 0.641g/cm^3 for GCP and this is 79% higher than the density for GUG, which is 0.358g/cm^3. At both the poor and good sites the GC clones had a higher density than the GU clones.

At the good sites the density of the GC clones (0.416 g/cm^3) is 16% higher than the density of the GU clones. At the poor sites the density of the GC clones is 13% higher than the density of the GU clones (0.568g/cm^3). For the same species, the density for GC at the poor site is 54% higher than for the GC at the good site. The density for GU at the poor site is 58% higher than for GU at the good site. This shows that for the selected material, there are greater differences in wood density due to site quality differences than differences due to different species from the same site quality.



GCG = GC G438 – good site

GCP = GC G438 – poor site

GUG = GU A380 – good site

GUP = GU A380 – poor site

Figure 6.2: Graphs of wood fibre properties

The weighted mean fibre diameter for each of the four compartments can be seen in figure 6.2. The letters A to C on the graph show the results of a Duncan multiple range test. At both sites the GU clones had a larger mean fibre diameter, however at the poor site the difference was not significant at the 95% confidence level. There were three significantly different groups at the 95% confidence level as indicated by the letters on the graph. The GUG had the largest mean fibre diameter of 14.79 microns and was 12 % larger than the mean fibre diameter of the GCG (13.18 microns).

It can be seen (figure 6.2), that there were significant differences in wood lumen diameter at the 95% confidence level. The wood lumen diameter for the GCG and GCP were similar but significantly different to the GUG and GUP. The GUG and GUP had significantly different wood lumen diameter at the two sites. The GUG had the largest wood lumen diameter of 9.66 microns and was 53% larger than the smallest wood lumen diameter from the GCP. For both species, the clones from the good sites had a larger lumen diameter than the same clones grown in the poor site, however the difference in lumen diameter was not significant at the 95% confidence level for the GC clones from both sites. It was seen that the GCG and GCP had a smaller lumen diameter than both GUG and GUP. This indicates that irrespective of site quality the GC clones had a smaller wood lumen diameter than the GU clones.

Figure 6.2 shows the weighted mean cell wall thickness for the four compartments. From the Duncan test it can be seen that there were significant differences in cell wall thickness among the four compartments at the 95% confidence level. The GCG and GCP had thicker cell walls than the GUG and GUP. The GCP had the thickest cell wall (3.82 microns) and was 49% larger than the cell wall thickness of the GUG, which had the smallest cell wall thickness.

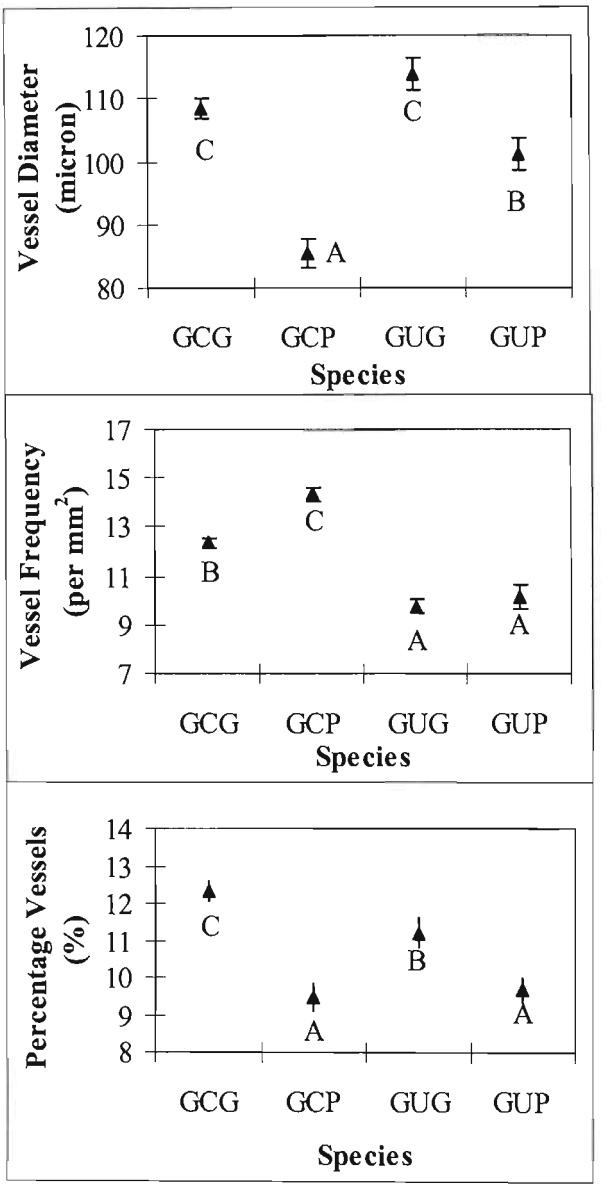
There were significant differences in wood fibre collapsibility (figure 6.2). The GUG had the highest fibre collapsibility (8.9) and was more than double the collapsibility of the GCP (4.2). The fibre collapsibility of the GUP was significantly higher than the GCP but similar to the collapsibility for the fibres from the GCG. There were no significant differences in fibre collapsibility between the GCG and GCP.

The weighted mean vessel diameter of the four compartments can be seen in figure 6.3. From the results of the Duncan test it can be seen that there were significant differences in vessel diameter between compartments at the 95 % confidence level. The largest vessel diameter was from the

GUG (113.9 microns) which was 33% larger than the GCP (85.5 microns). The difference in vessel diameter between the two clones at the good sites was not significant at the 95% confidence level.

Figure 6.3 also shows the mean percentage of vessel for the four compartments. It can be seen from the results of the Duncan test, that there was a significant difference in the vessel percentage amongst the compartments. The GCG had the highest percentage of vessels (12.3%) this being 30% larger than the GCP, which had the smallest percentage of vessels (9.5%). There was no significant difference in the percentage of vessels between the GCP and GUP.

The GCP had the highest vessel frequency of 14.3 per mm^2 (figure 6.3) being 47% higher than the vessel frequency of the GUG (9.8 per mm^2). It can be seen from the results of the Duncan test that there were significant differences in vessel frequency amongst the four compartments at the 95% confidence level. The GCG and GCP had a higher vessel frequency than the GUG and GUP. The GUG and GUP had a similar vessel frequency. For both species the clones from the poor sites had higher vessel frequency than the clones from the good sites, however this difference was only significant for the GC clones.



GCG = GC G438 – good site

GCP = GC G438 – poor site

GUG = GU A380 – good site

GUP = GU A380 – poor site

Figure 6.3: Graph showing wood vessel properties

6.2 Pulp properties

The four compartments were pulped using the Kraft pulping process. All the compartments were subjected to the same pulping conditions of being cooked for 50 minutes at the conditions mentioned in table 3.6 (section 3.6.3). The table below shows the kappa number, yield and rejects results. Work with the four clones deals with unbleached pulp.

Table 6.1: Pulping results for four compartments

Species	GC G438	GC G438	GU A380	GU A380
Site Index	good	poor	good	poor
Kappa number	20.91 ± 1.31	19.17 ± 1.95	18.10 ± 0.66	21.31± 1.65
Screened pulp yield (%)	50.08 ± 0.97	48.32 ± 1.20	51.11 ± 3.38	47.54 ± 0.90
Rejects (%)	2.04 ± 0.77	0.27 ± 0.16	1.15 ± 0.48	0.61 ± 0.28
Total pulp yield (%)	52.13 ± 1.28	48.59 ± 1.22	52.27 ± 3.45	48.15 ± 0.85

The results indicated in the table are the average results of the 80 cooks from each compartment. The 80 cooks were required to provide sufficient pulp for the refining trials. It can be seen that the GU A380 clones from the good site had the highest screened pulp yield. The GU A380 clones from the poor site had the lowest mean screened pulp yield. For both species the mean screened pulp yield for the clones from the good sites were higher than the mean screened pulp yields for the poor sites. The GU A380 clones from the poor site had the highest average kappa number of 21.31 and the GU A380 clones from the good site had the lowest average kappa number of 18.10.

6.2.1 Differences in pulp physical properties

Figure 6.4 shows the initial pulp fibre length after cooking the material from the four compartments for 50 minutes at 170°C using the Kraft pulping process. The fibre length was measured using a Fibre Lab Analyser at the Mondi Richards Bay mill. This instrument was not calibrated and as such the relative fibre lengths are being compared rather than absolute lengths. The letters A to C show the results from a Duncan test and it can be seen that there are significant differences in pulp fibre length amongst the four compartments at the 95% confidence interval. The largest pulp fibre length was 0.80 mm which is from the GCG. The shortest pulp fibre length was 0.70 mm from the GUP. There was a 14% difference in fibre length between these two

compartments. There was no significant difference in the average pulp fibre length between the GUG and the GCP.

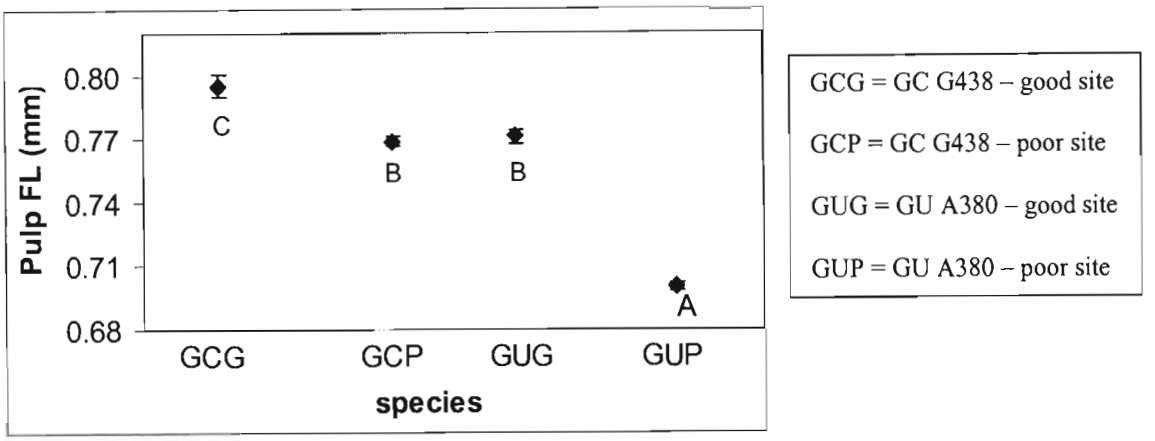
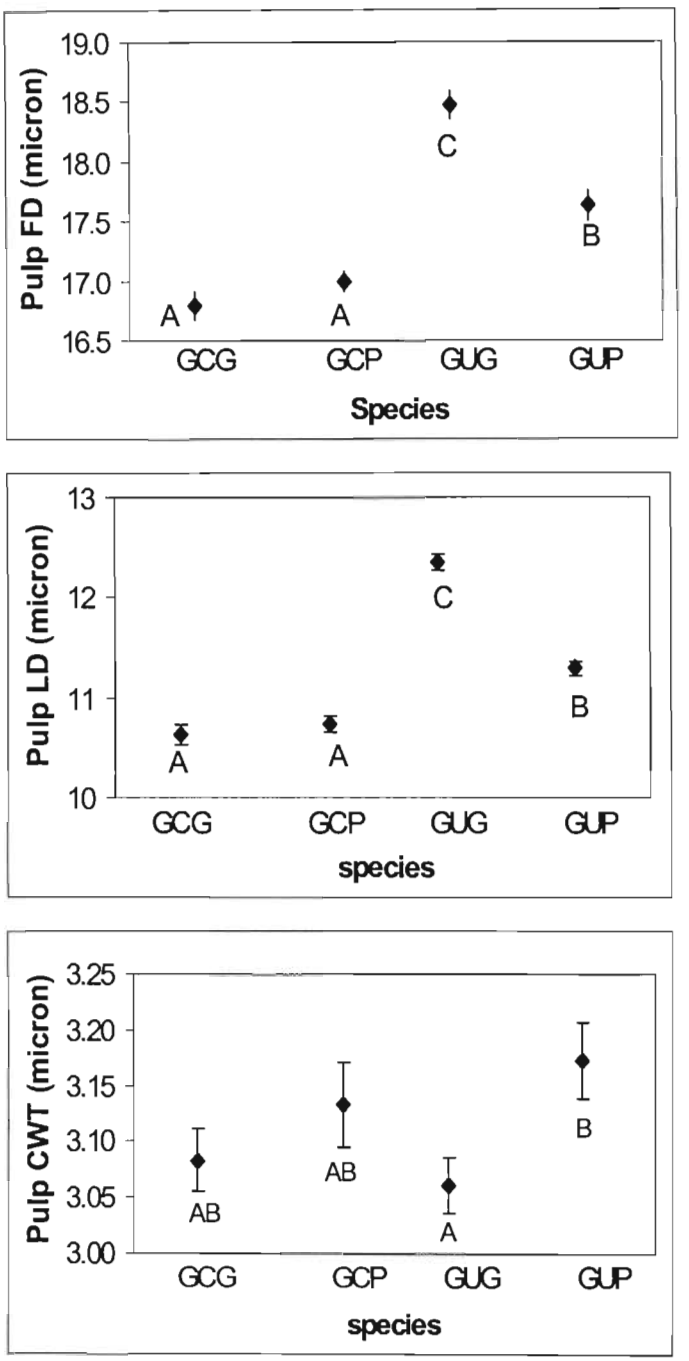


Figure 6.4: Initial pulp fibre length

The pulp fibre diameter can be seen in figure 6.5. Again it needs to be noted that the fibre diameter was measured using the fibre lab analyser at the Mondi Richards Bay mill and since the instrument was not calibrated relative fibre diameters were compared rather than absolute diameters. The GUG had the largest pulp fibre diameter (18.48micron) this was 10% larger than the smallest pulp fibre diameter (16.79micron) from the GCG. From the results of Duncan test it was seen that there were no significant differences in pulp fibre diameter for the GCG and GCP at the 95% confidence level. However, the GCG and GCP were significantly different to the GUG and GUP. The GUG and GUP were also significantly different to each other at the 95% confidence level.

The pulp cell wall thickness was also measured using the fibre lab analyser from Mondi Richards Bay and as mentioned previously since the instrument was not calibrated relative cell wall thicknesses were being compared. There were significant differences in pulp cell wall thickness between the GUG and GUP at the 95% confidence level (figure 6.5). The GUG had the thinnest cell wall thickness while the GUP had the thickest cell wall thickness. From the results of the Duncan test it was seen that the cell wall thickness of the two GC clones were comparable.



GCG = GC G438 – good site

GCP = GC G438 – poor site

GUG = GU A380 – good site

GUP = GU A380 – poor site

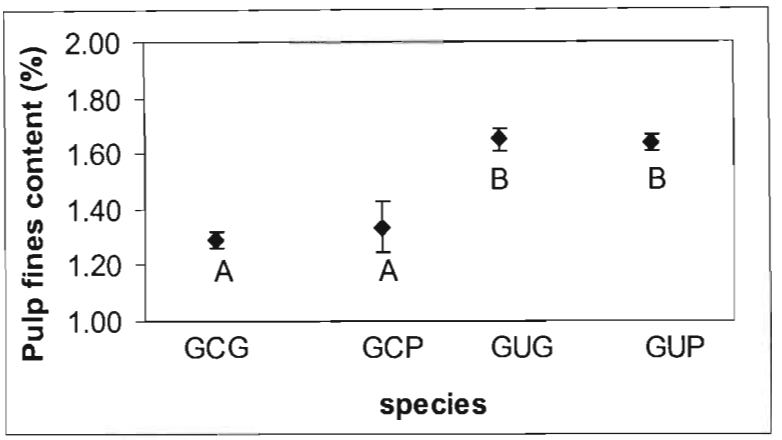
Figure 6.5: Initial pulp lumen diameter, fibre diameter and cell wall thickness

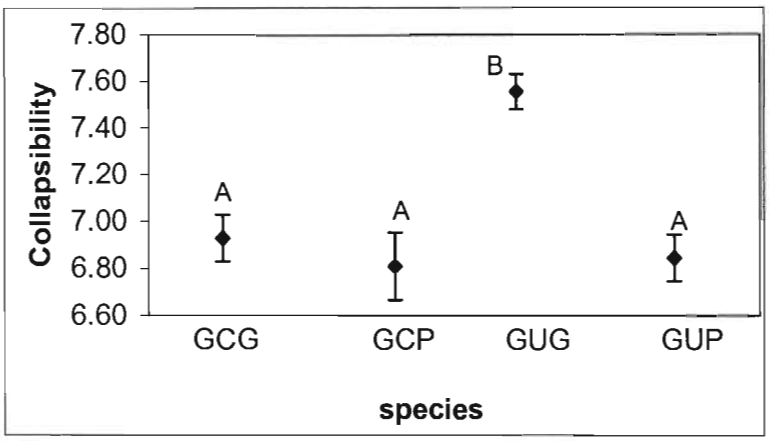
The pulp lumen diameter was calculated by subtracting twice the pulp cell wall thickness from the pulp fibre diameter. The average pulp lumen diameter (figure 6.5) ranged from 10.62 microns for the GCG to 12.36 microns for the GUG. The results from the Duncan test show that there were no significant differences in pulp lumen diameter between the GCG and GCP at the 95% confidence level. There were significant differences in pulp lumen diameter between the two GC's and the two GU's. The mean pulp lumen diameters were significantly different between the GUG and GUP.

There were significant differences in the fines content between the two different species (figure 6.6) but there were no significant differences in fines content for the same species from different sites. The GUG had the highest average fines content (1.65%). This was 28% higher than the fines content for the GCG which had the lowest fines content (1.29 %).

The pulp fibres from the GUG had the highest collapsibility (7.55) and were significantly different to the collapsibility of the fibres from the other three compartments (figure 6.6). There was an 11% difference in collapsibility between the most collapsible and least collapsible fibres. The collapsibility of the fibres from the GCG, GCP and the GUP showed no significant differences at the 95% confidence level.

There were significant differences in the initial pulp fibre coarseness (figure 6.6). The GCP had the highest coarseness (0.0545 mg/m) and this was 72% higher than the GCG, which had the lowest coarseness (0.0318 mg/m). The two poor sites had a higher coarseness than the two good sites. Coarseness has been found in many studies to be related to the cell wall thickness (Broderick *et al.* 1996) The results in this study agree with this.





GCG = GC G438 – good site

GCP = GC G438 – poor site

GUG = GU A380 – good site

GUP = GU A380 – poor site

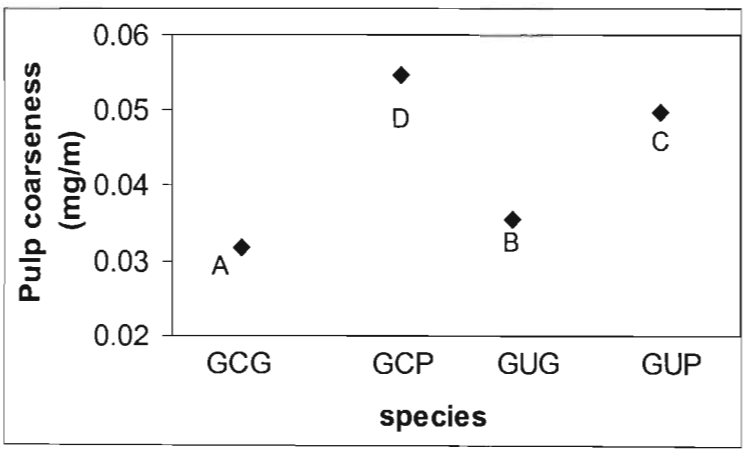


Figure 6.6: Initial pulp fines content and collapsibility

6.3 Strength properties at all refining levels

6.3.1 Introduction

This section deals with the results of all stages of refining and not at any fixed level of refining. The reason for considering the results firstly in this manner was to see how the different pulps behaved with increasing levels of refining. Analyses was carried out to determine whether a combination of the refining parameters (SRE and SEL), together with either the wood or pulp properties could be used to predict the resultant pulp properties after refining.

6.3.2 Discussion

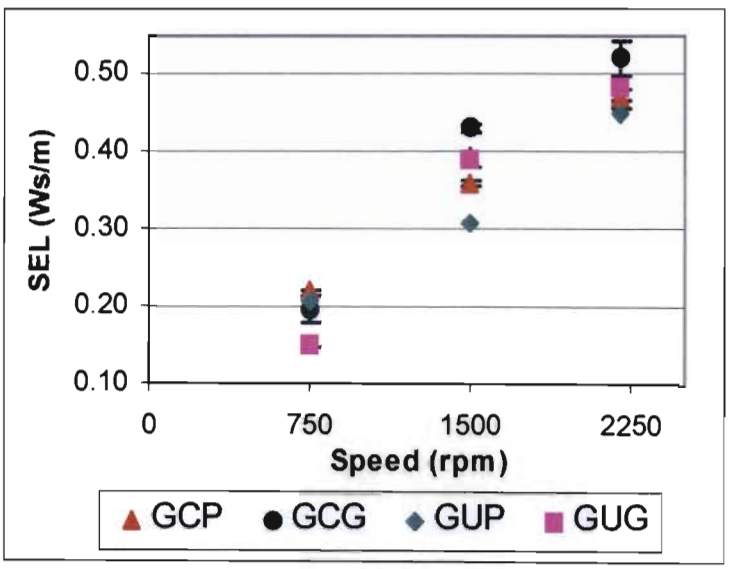


Figure 6.7: Graph of Refining Intensity (SEL) versus speed of rotation

Figure 6.7 shows the refining intensity (SEL) at each speed for each of the pulps. It was seen that at the same refining parameters the refining intensity for the different pulps were slightly different. When refining at 750 rpm, the refining intensity ranged from 0.15 Ws/m for the GUG to 0.22 Ws/m for the GCP. At 1500rpm the refining intensity ranged from 0.31 Ws/m for the GUP to 0.43 Ws/m for the GCG. At 2200 rpm the SEL ranged from 0.45 Ws/m for the GUP to 0.52 Ws/m for the GCG. The three different speeds were chosen to provide three different SEL's and this was seen. However at each speed the SEL for the four different pulps were similar though not exactly the same so in the discussions to follow, the three speeds will be used to refer to the three different refining intensities.

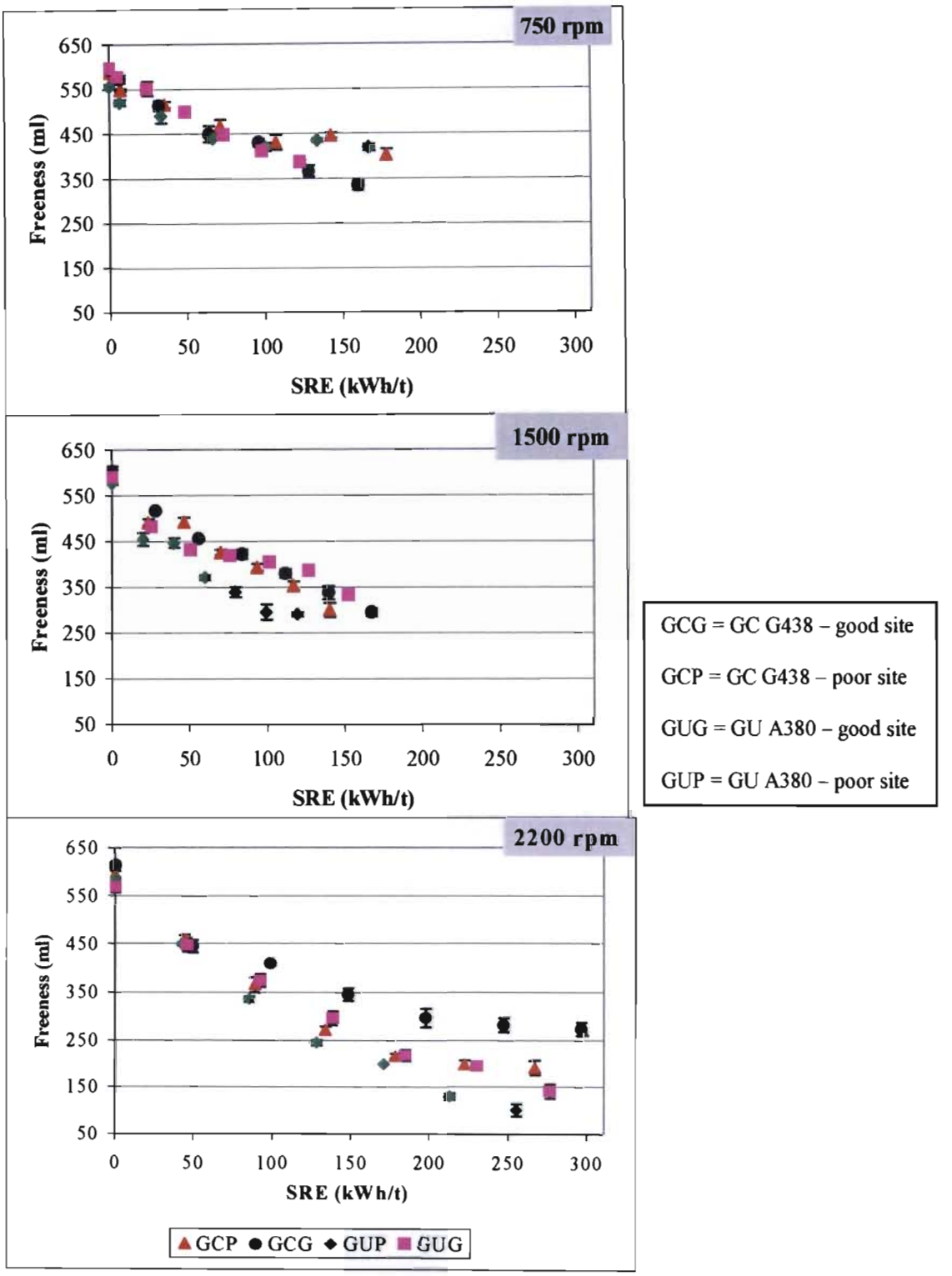


Figure 6.8: Graph of freeness versus SRE

The pulp freeness decreased with increased refining as expected (figure 6.8). The reasons for freeness decreasing with refining have already been mentioned in section 4.2. When refining at the lowest speed of 750 rpm, there were no differences in the freeness of the pulps with increased refining up to an SRE of about 100kWh/t. From this point onwards, the pulps split into two different groups with the GCP and GUP leveling of at a higher freeness than the GCG and GUG. The freeness of the GCP and GUP were about 430ml at 150kWh/t. The GCG and GUG had a freeness of 350ml at the same SRE. This shows that the GCG and GUG are more easily refined at 750 rpm. At a speed of 1500 rpm, with the exception of the GUP, there were no differences in freeness amongst the different pulps. The GUP had a lower freeness than the other three pulps. At 150kWh/t the pulps reached a freeness of about 300ml. The GUP reached a freeness of 300ml faster than the other pulps at 100kWh/t. At 2200 rpm, it was seen that with increased refining differences in pulp freeness became more noticeable. From an SRE of about 80kWh/t it was seen that the GCG had a higher freeness than the other three pulps. The GUP generally had the lowest freeness but this became most noticeable at very high refining levels. The GCP and the GUG had similar freeness levels. In considering each of the four pulps being refined with the three different speeds (Figure D5 in Appendix D shows this clearly), it was seen that the three different refining speeds (or intensities) did not have very different effects on the pulp freeness except for the GUP and GCP, which when refined at 650 rpm, initially behaved in the same way as when they were refined at the two higher speeds but with increased refining (>100 kWh/t) started to level off at a higher freeness level than when refined at the two higher speeds.

Table 6.2 shows the results of a multiple regression analysis. It was seen that pulp freeness could be predicted fairly well with a model R^2 of 88.6%. The SRE was the largest contributor to this model (80.1%). This indicates that even though there are differences in pulp physical properties, the SRE play a major role in the final freeness of the pulp.

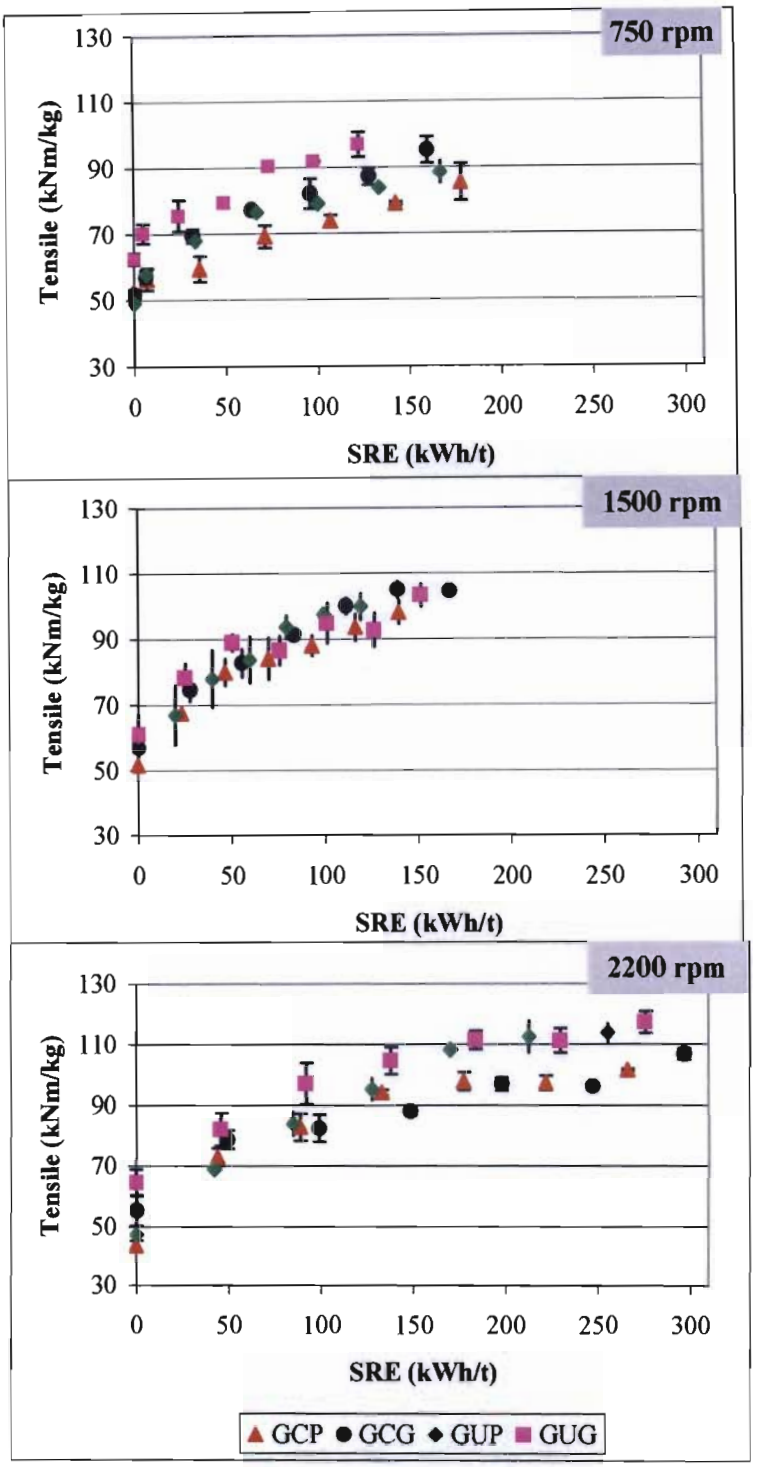
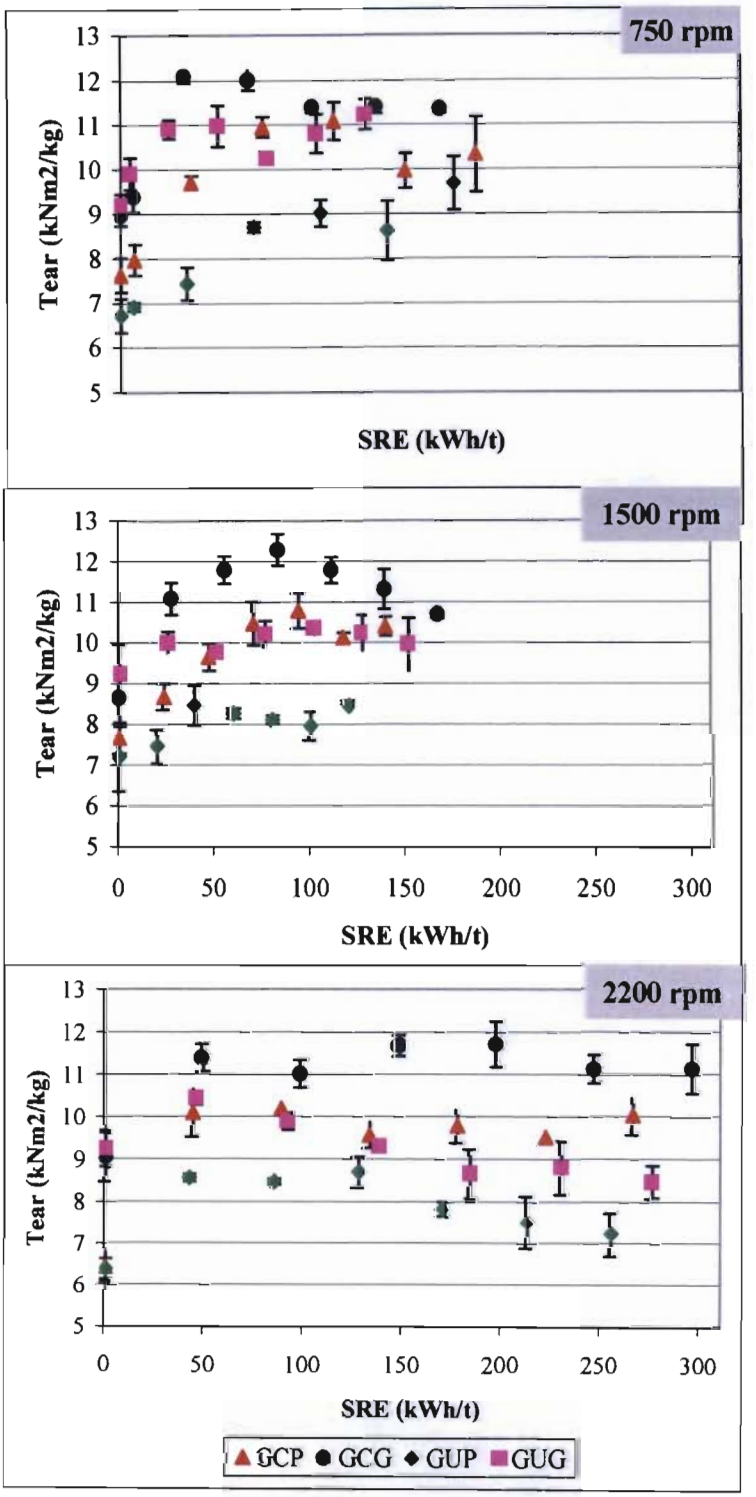


Figure 6.9: Graph of tensile index versus SRE

As expected from the literature, figure 6.9 shows that the tensile strength increased with increased refining (Smook 1992, Muneri 1994). Section 4.2 discusses why the tensile strength increases with refining. The impact of the different pulps on the tensile strength was most evident when refined at the lowest speed. At this low speed it was seen that the GUG had the highest tensile strength and the GUP had the lowest. The GCG and the GUP had similar tensile strength. When refining using a speed of 1500 rpm it was seen that the tensile strength increased with increasing SRE but the four pulps all resulted in similar tensile strength. When refining was carried out at 2200 rpm, it was seen that initially (up to about 100kWh/t) the tensile strength was not very different for the four pulps. After 100kWh/t the pulps separated into two groups. The GU clones had a higher tensile strength than the GC clones.

In considering the three different refining treatment on each of the four pulps (Figure D6 in Appendix D), it was seen that for the GUG the different refining treatments did not have different effects on the tensile strength. For the other three pulps refining at 750 rpm resulted in a slightly lower tensile strength.

From the results of multiple regression analysis (table 6.2), it was seen that tensile strength could be predicted fairly well with a model R^2 of 77.5%. The SRE contributed 67.2% to this model. This indicates that the SRE can account for 67.2% of the variation in tensile strength and is better able to predict the tensile strength than the pulp physical properties.



GCG = GC G438 – good site

GCP = GC G438 – poor site

GUG = GU A380 – good site

GUP = GU A380 – poor site

Figure 6.10: Graph of tear index versus SRE

The tear strength initially increased with increased refining up to a maximum value and thereafter started decreasing with increased refining (figure 6.10). The reason for this behaviour of tear strength with refining has already been discussed in section 4.2. At all speeds of refining the GCG generally had the highest tear strength. The GUP generally had the lowest tear strength at all speeds.

When refining at 750 rpm, the GCG reached a maximum tear strength of 12 kNm^2/kg and then with increased refining it dropped to 11.4 kNm^2/kg and seemed to stabilise at this value. The GCP and GUG both reached a maximum tear strength of 11 kNm^2/kg. At 1500 rpm, the GCG reached a maximum tear strength of 12.3 kNm^2/kg and with further refining the tear strength dropped down to 10.7 kNm^2/kg. Tear strength for the GUG and GCP peaked at about 10.5 kNm^2/kg. The GUP had the lowest tear strength and achieved a maximum of about 8.5 kNm^2/kg. When refining at 2200 rpm, for the GCG the tear strength increased compared to the unrefined pulp but it did not fluctuate much. While it did not achieve its highest tear strength as observed in the case of refining at 1500 rpm, the tear strength did not drop below 11 kNm^2/kg even with very high levels of refining. The tear strength for the GCP seemed steady between 9.5 and 10 kNm^2/kg. Thus it appears that the GCG and GCP were more resistant to fibre damage. The GUG peaked at 10.4 kNm^2/kg and thereafter the tear strength dropped with increased refining down to a tear strength of about 8.4 kNm^2/kg. The GUP peaked at 8.7 kNm^2/kg and dropped to 7.2 kNm^2/kg with increased refining. On considering the effect of the three different refining speeds on each of the four pulps, it was seen that they were not affected very differently except for the GUG. For the GUG, refining at 750 rpm seemed to give better tear strength than the when refining at the two higher speeds (Figure D7 in the appendix shows this clearly).

The initial pulp fibre length accounted for 44.3% of this variation (Table 6.2). It is believed that long fibres result in higher tear strength and the reason for this is because longer fibres distribute the stress over a greater area and over more fibres and more bonds than short fibres. Thus with shorter fibres the stress is concentrated over a smaller area (Britt 1970).

Figure 6.11 shows the tear tensile relationship. When refining at 750 rpm the maximum tear strength for the GCG, GCP, GUG and GUP occurred at a tensile strength of about 80, 72, 90 and 90 kNm/kg respectively. These occurred at freeness values of about 440, 460, 450 and 400ml

respectively. At 2200 rpm the freeness values for these clones, corresponding to the maximum tear strength were about 350, 295, 380 and 295ml respectively. Generally it is desired that the freeness be between 400 and 500 because of drainage on the paper machine.

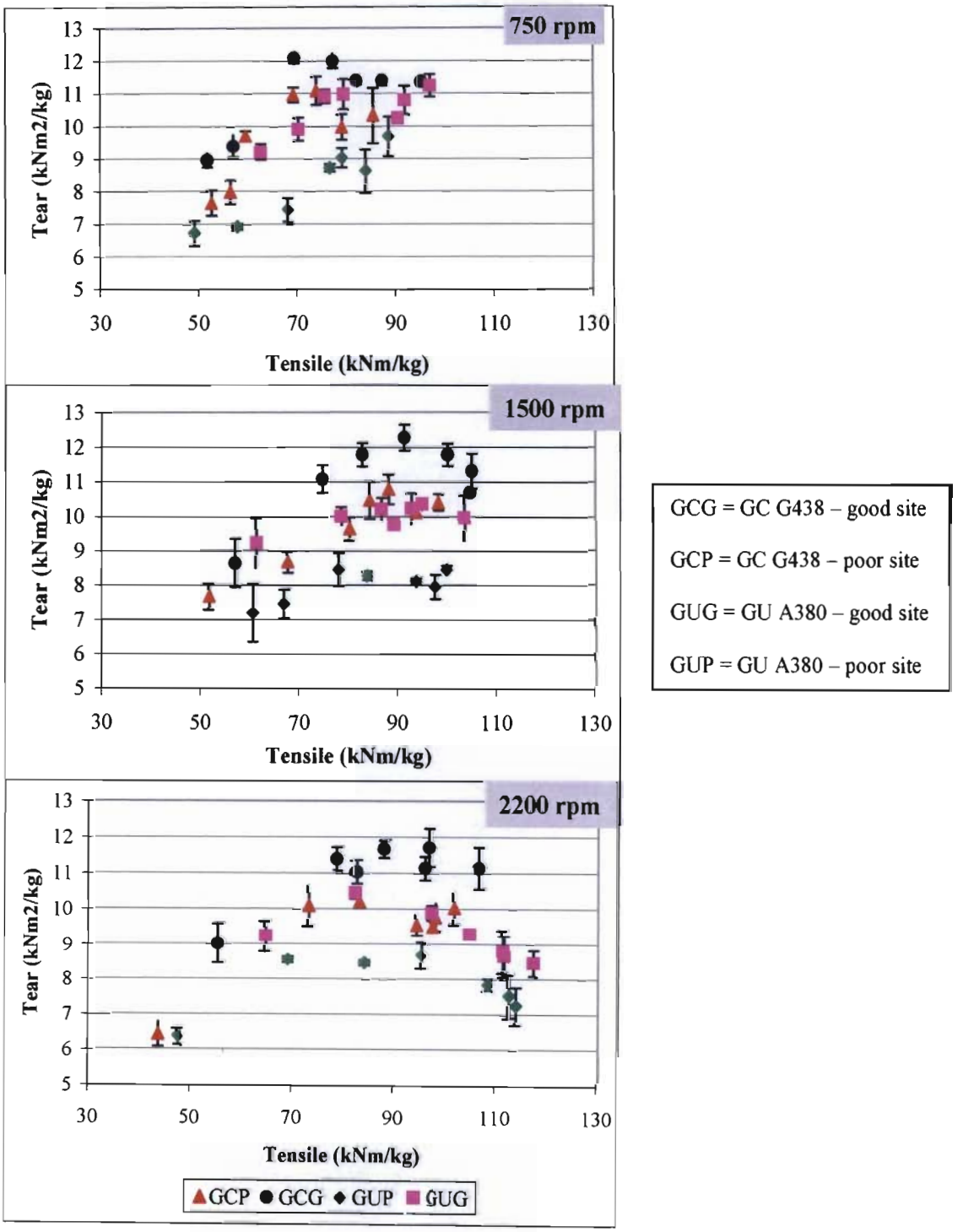
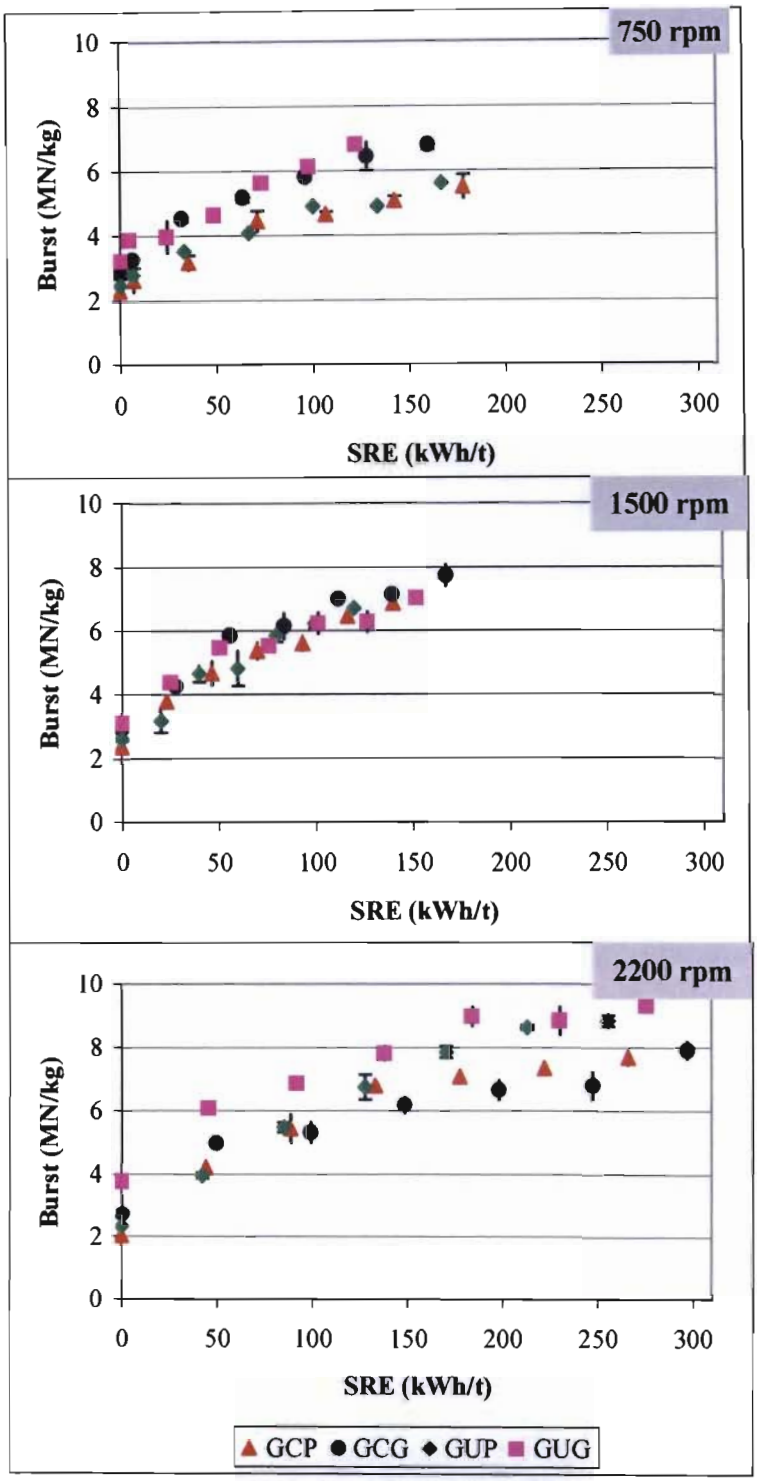


Figure 6. 11: Graph of tear strength versus tensile strength

It was seen in figure 6.12 that the burst strength increased with increased refining as expected from the literature. The reasons why the burst strength increases with refining have been mentioned in section 4.2. The development of the burst strength occurs in a similar manner as the development of the tensile strength. When refining was carried out at 750 rpm, two groups were noted. The GCG and GUG had similar burst strength and these were higher than the burst strength of the GUP and GCP, which were similar to each other. The GCG and GUG reached a maximum burst strength of about 7 MN/kg while the GCP and GUP reached a maximum burst strength of about 5.5 MN/kg. Refining at 1500 rpm resulted in the four pulps having similar burst strength. The burst strength for the GCG was approaching 8 MN/kg. When refining at 2200 rpm, it was seen that up to about 150 kWh/t the GUG had a higher burst strength than the other three pulps which had similar burst strength. For SRE levels higher than 150 kWh/t, the GUG and GUP had similar burst strength and were higher than the burst strength of the GCG and GCP, which were similar to each other. The burst strength of the GUG and GUP approached 9 MN/kg while the GCG and GCP approached 8 MN/kg.

For the GUG and GCG the three different speeds did not affect the burst strength differently (Figure D9 in Appendix D shows this clearly). For the GUP and GCP, refining at 750 rpm resulted in lower burst strength than refining at the two higher speeds.

Table 6.2 shows the results of a multiple regression analysis. It was seen that burst strength could be predicted fairly well with a model R^2 of 83.42%. The SRE was the largest contributor to this model (75.67%). This indicates that even though there are differences in pulp physical properties, the SRE can explain 75.67% of the differences in burst strength.



GCG = GC G438 – good site

GCP = GC G438 – poor site

GUG = GU A380 – good site

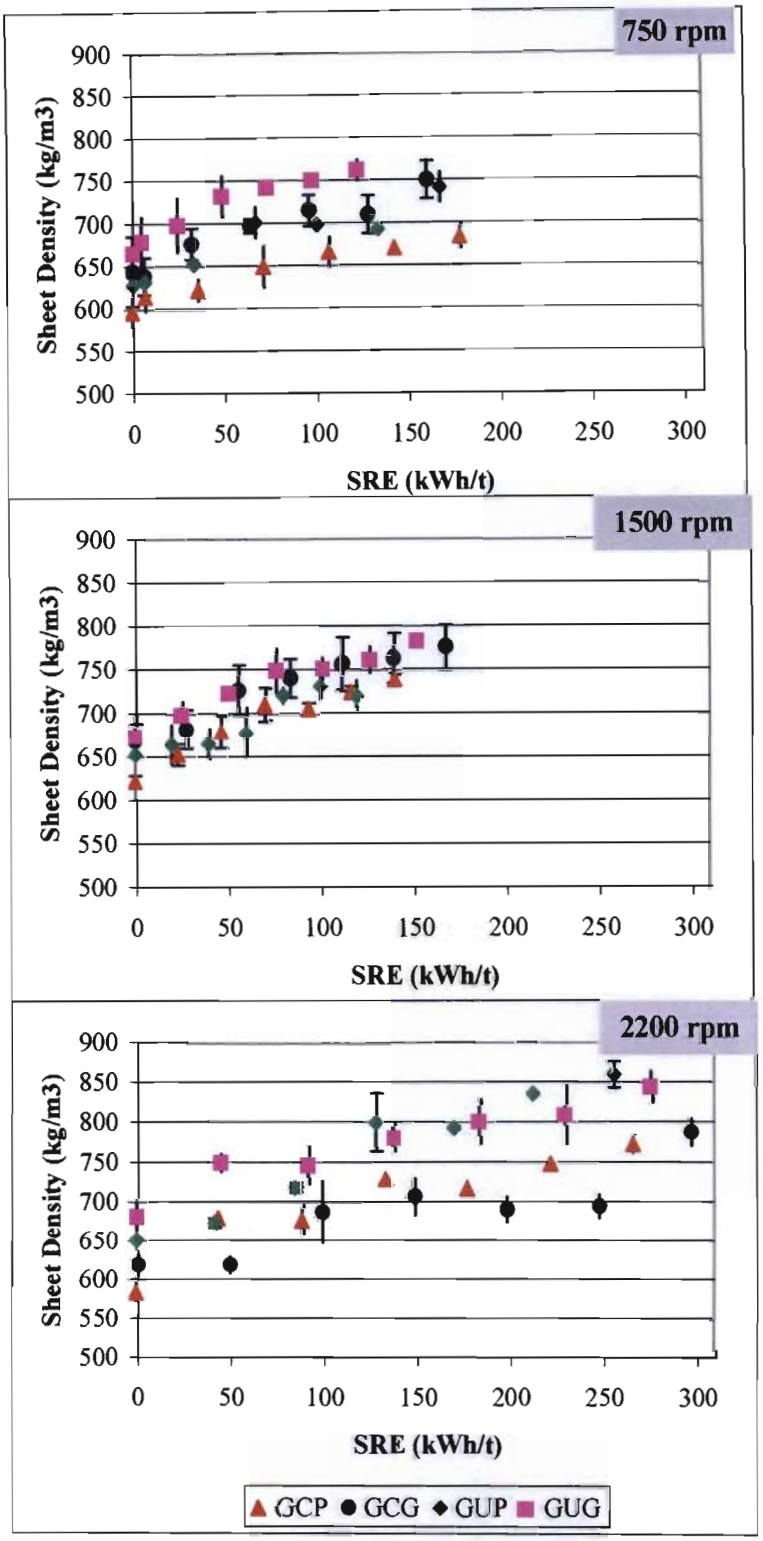
GUP = GU A380 – poor site

Figure 6. 12: Graph of burst index versus SRE

The sheet density increases with increased refining as can be seen in figure 6.13. Reasons why sheet density increases with refining have already been mentioned in section 4.2. When refining was carried out at 750 rpm it was seen that the GUG had the highest sheet density and the GCP had the lowest sheet density. The GCG and the GUP had similar sheet density. There were no differences in sheet density amongst the pulps when refined at 1500 rpm. When refining at 2200 rpm it was seen that the GUG and GUP had a higher sheet density than the GCG and GCP.

For the GUG and GUP, the three different refining speeds did not affect the sheet density very differently (figure D10 in Appendix D). For the GCP it was seen that refining at 750 rpm resulted in lower sheet densities than refining than when refining at the two higher speeds.

The results from the multiple regression analysis showed that 57.96% of the variation in sheet density could be explained by the SRE together with the initial pulp lumen diameter. The SRE accounted for 47% of the variation in this model.



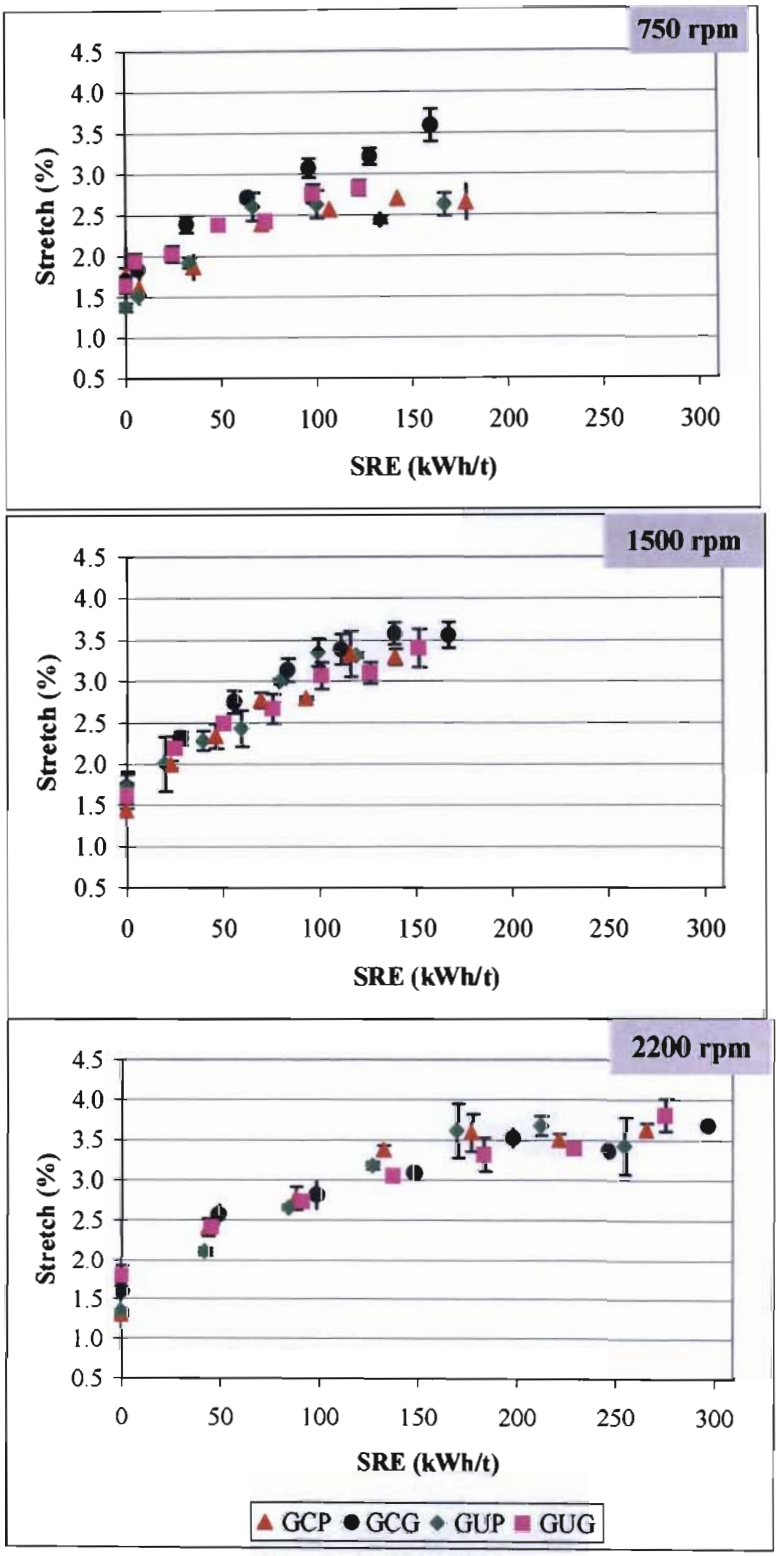
GCG = GC G438 – good site

GCP = GC G438 – poor site

GUG = GU A380 – good site

GUP = GU A380 – poor site

Figure 6.13: Graph of sheet density versus SRE



GCG = GC G438 – good site

GCP = GC G438 – poor site

GUG = GU A380 – good site

GUP = GU A380 – poor site

Figure 6.14: Graph of stretch versus SRE

Figure 6.14 shows results for stretch. When refining at 750 rpm it was seen that initially up to 100 kWh/t, the different pulps had similar stretch. Thereafter the GCG had a higher stretch reaching about 3.5% while the other three pulps levelled of at a stretch of about 2.7%. When refining at 1500 rpm all pulps had similar stretch and reached a stretch of 3.5%. There was also no difference in stretch amongst the four pulps when refined at 2200 rpm. At 2200 rpm the stretch also leveled of at 3.5%. According to Britt (1970), the stretch of normal flat paper does not usually exceed 5%. The results from the multiple regression analysis showed that overall the SRE could account for 70.32% of the variation in sheet stretch. For the GUG and GCG the three different refining treatments did not impact differently on the stretch. (Figure D11 in Appendix D shows this clearly). For the GCP and GUP when refined at 750 rpm, the stretch leveled off at a lower value than when refined at the two higher speeds.

There was an increase in TEA with increased refining (figure 6.15). For refining carried out at 750 rpm it was observed that the GCG and GUG had similar TEA and this was higher than the TEA for the GCP and GUP, which were similar. Refining at 1500 rpm gave similar TEA for the different pulps except at the high levels of refining where the GCG had a higher TEA. There were no differences in TEA observed when refining at 2200 rpm except at the very high levels of SRE. It can be seen in table 6.2 that the SRE can account for 71.8% of the overall variation in TEA. The GUG was not affected differently by the three different speeds (Figure D12 in Appendix D shows this clearly). For the GUP and GCP refining at 750 rpm resulted in lower TEA than when refining at the two higher speeds. For the GCG when refining at 1500 rpm, the TEA seemed to be higher than when refined at the other two speeds for SRE > 100 kWh/t.

When refining at 750 rpm it was seen that the zero-span tensile increased with increasing SRE (figure 6.16). While initially there appeared to be some differences in zero-span tensile it was seen that with increased refining (about (150kWh/t), the zero-span tensile for the four compartments seemed to approach the same value (about 2.25 kN/m). When refining at 1500 rpm, it was seen that the four compartments reached this same zero-span tensile with less refining (about 50 kWh/t) and this was maintained with increased refining. Differences in zero-span tensile were more evident when refining at 2200 rpm. In this case the GCG was seen to have a higher zero-span (2.5 kN/m) than the other three compartments (2 kN/m). The results obtained could not explain the overall variation in zero-span tensile.

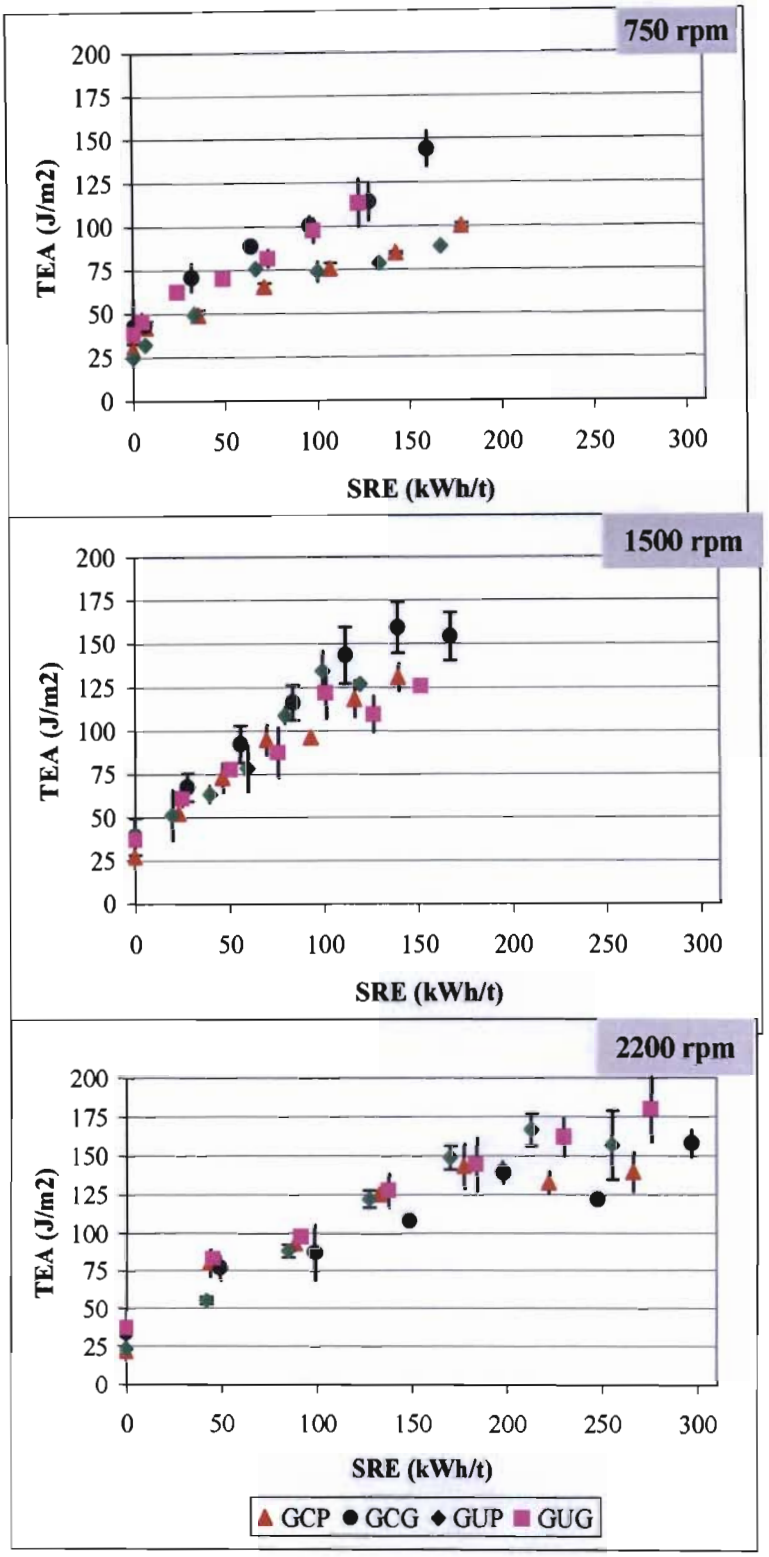
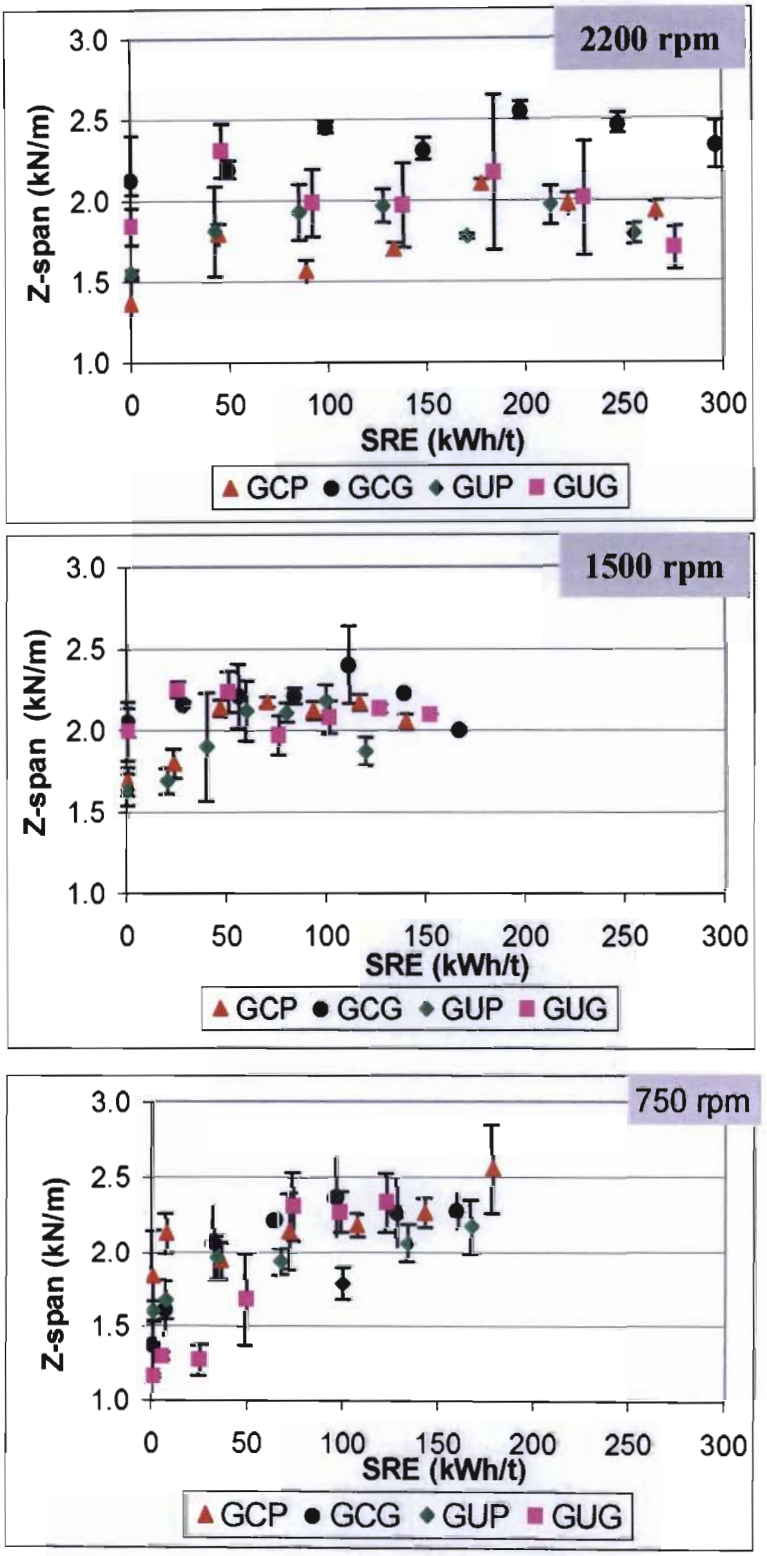


Figure 6.15: Graph of TEA versus SRE



GCG = GC G438 – good site

GCP = GC G438 – poor site

GUG = GU A380 – good site

GUP = GU A380 – poor site

Figure 6.16: Graph of Zero-span Tensile versus SRE

Table 6.2: Multiple regression results for the overall strength properties at all refining levels

	Freeness	Tensile	Tear	Burst	Sheet Density	Stretch	TEA
model R^2	85.2	72.9	44.3	80.1	47	75	75
p-value	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
Contributors to the model and their percentage contribution							
SRE	80.1	67.2	-	75.7	47	70.3	71.8
SEL	5.1	5.74	-	4.7		4.7	3.2
initial pulp FL	-	-	44.3	-	-	-	-

Table 6.2 shows the results of the multiple regression analysis. It was seen that when considering the pulp properties at increasing levels of refining rather than at a fixed condition such as constant freeness or constant sheet density, the SRE was a good predictor of the pulp properties.

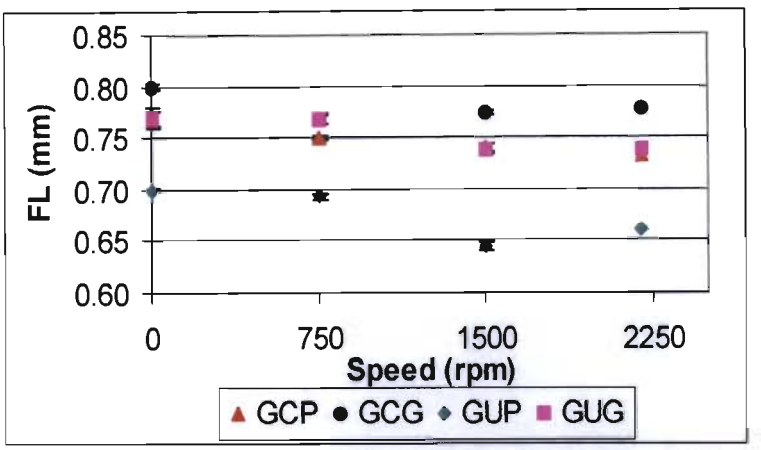
The initial pulp and wood anatomy did not come up strongly in this case and the reason for this is that while the refining process is developing the pulp properties, the initial wood or pulp anatomy for each of the pulps would be just a single value for a particular pulp and this single value cannot be used to predict a range of pulp properties that arises for that pulp after various levels of refining. The pulp anatomy after each stage of refining was also measured and using only the actual anatomy at each stage of refining in the multiple regression analysis showed that the pulp cell wall thickness was the strongest predictor for most of the pulp strength properties. (Table D11 in the Appendix D). However if the actual pulp anatomy was used together with the SRE and SEL then again the SRE proved to be the best predictor. While the pulp fibre length did not come up strongly in the multiple regression analysis for the overall results it was seen that at a compartment level the fibre length showed good relationships with most of the pulp properties. (Figures D-14 to D 17 in Appendix D).

6.4 Results at constant SRE (100kWh/t)

6.4.1 Introduction

This section considers the pulp properties of the different pulps after being refined at the same SRE. Analysing the results in this way shows the development of the pulp properties for each of the four pulps after being treated with the same amount of specific refining energy using three different speeds to apply this energy at three different rates.

6.4.2 Discussion



GCG = GC G438 – good site

GCP = GC G438 – poor site

GUG = GU A380 – good site

GUP = GU A380 – poor site

Figure 6.17: Graph of pulp fibre length for four compartments after refining with three different refiner speeds to 100 kWh/t

Figure 6.17 shows the pulp fibre length after refining at three different speeds at an SRE of 100 kWh/t for each of the four compartments. There was a slight decrease in pulp fibre length with refining. This is due to the cutting of fibres during the refining action. For the GC clones there were no significant differences in pulp fibre length with the three different refining speeds at 100 kWh/t (Table 6.8). For the GU clones the pulp fibre length was significantly higher when refined at 750 rpm as compared to refining at the two higher speeds. The reason for this is probably because of the lower intensity refining at 750rpm resulting in less fibre shortening. Table 6.3 shows the percentage decrease in fibre length relative to its original length. For the GUG there was very little change in average fibre length (0.3%) when refined using the lowest speed (lowest intensity). There was a 4% decrease in fibre length when refined at the two higher speeds. The pulp fibre length for the GUP was impacted on the most. It showed the greatest decrease in fibre

length (7.8%) when refined at a speed of 1500 rpm. When refined at a speed of 750 rpm there was only a 1% decrease in fibre length and a 5.6% decrease in fibre length when refined using a speed of 2200 rpm.

Table 6.3: Percent decrease in fibre length at 100 kWh/t using the three different refiner speeds

Speed (rpm)	GCG (%)	GCP (%)	GUG (%)	GUP (%)
2200	-2.1	-4.6	-4.2	-5.6
1500	-2.7	-3.6	-4.1	-7.8
750	-3.5	-2.5	-0.3	-1

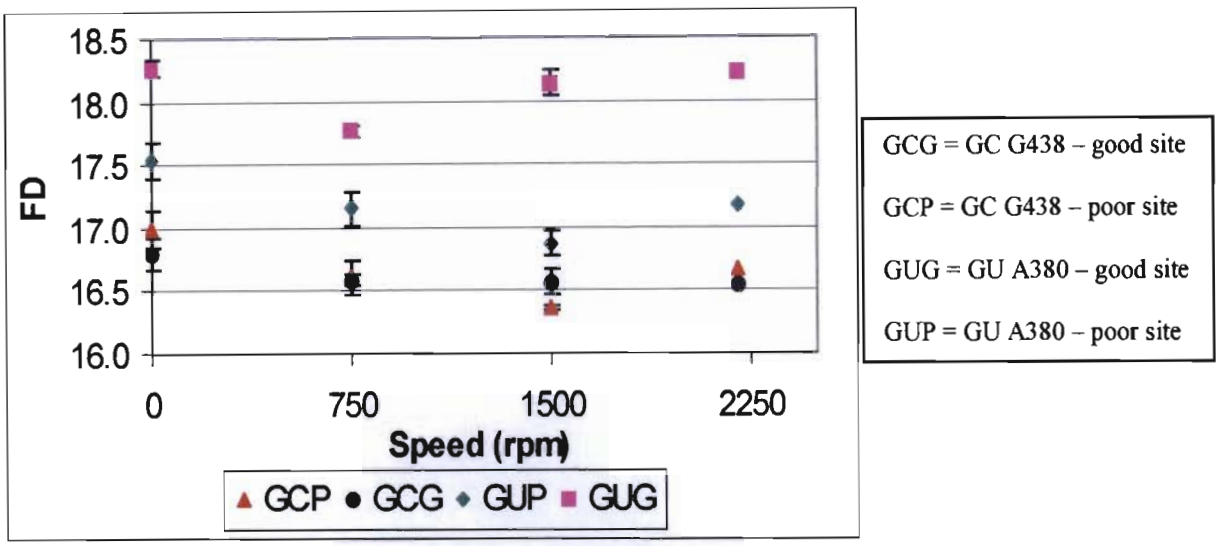


Figure 6.18: Graph of pulp fibre diameter for four compartments after refining with three different refiner speeds to 100 kWh/t

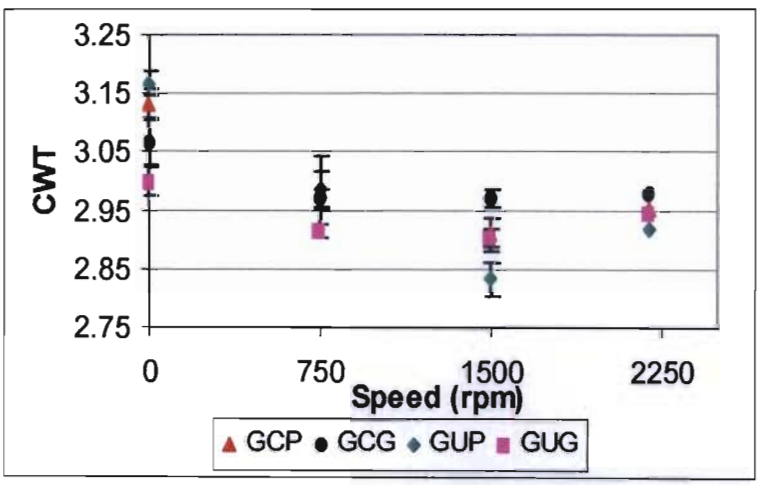
Figure 6.18 shows the fibre diameter after refining at an SRE of 100 kWh/t using three different treatments. In general the pulp fibre diameter of the refined pulp was lower than the unrefined pulp. With the exception of the GUG, there were no significant differences in pulp fibre diameter for the other three pulps when refined at the three different speeds (Table 6.8). For the GUG the pulp fibre diameter was significantly smaller when refined at 750 rpm than at the other two speeds. It is possible that fibrillation that occurs as a result of refining could affect the measurement of the fibre diameter since it can make the fibre diameter appear larger than it really is.

Table 6.4 shows the percentage decrease in fibre diameter after refining to 100kWh/t using three different speeds. It was seen that the GCG showed the smallest decrease in pulp fibre diameter. The GUP showed the largest decrease in fibre diameter (5%), this occurred when it was refined at a speed of 1500 rpm.

Table 6.4: Percent decrease in fibre diameter at 100 kWh/t using the three different refiner speeds

Speed (rpm)	GCG (%)	GCP (%)	GUG (%)	GUP (%)
2200	-1.5	-1.9	-1.4	-2.6
1500	-1.3	-3.7	-1.8	-5
750	-1.2	-2.3	-3.8	-2.7

Figure 6.19 shows the resultant pulp cell wall thickness for the four compartments after being refined using three different treatments. It can be seen that with refining there is a decrease in pulp cell wall thickness. Only the GUP showed significant differences in pulp cell wall thickness with the three different refining speeds (Table 6.8). The pulp cell wall thickness was significantly higher when refined at 750 rpm than when refined at 1500 rpm.



GCG = GC G438 – good site

GCP = GC G438 – poor site

GUG = GU A380 – good site

GUP = GU A380 – poor site

Figure 6.19: Graph of pulp cell wall thickness for four compartments after refining with three different refiner speeds to 100 kWh/t

After refining to 100kWh/t at 750, 1500 and 2200 rpm, the resultant pulp cell wall thickness decreased by 3.4, 3.6 and 3.6% respectively (Table 6.3). Again the three different treatments had the most pronounced effect on the pulp from the GUP. The percentage decrease in cell wall thickness were 5.9, 10.7 and 8% when refined at 750, 1500 and 2200 rpm respectively (Table 6.5).

Table 6.5: Percent decrease in pulp cell wall thickness at 100 kWh/t using the three different refiner speeds

Speed (rpm)	GCG (%)	GCP (%)	GUG (%)	GUP (%)
2200	-3.4	-5.8	-3.9	-8
1500	-3.6	-7.2	-5.2	-10.7
750	-3.6	-4.8	-4.8	-5.9

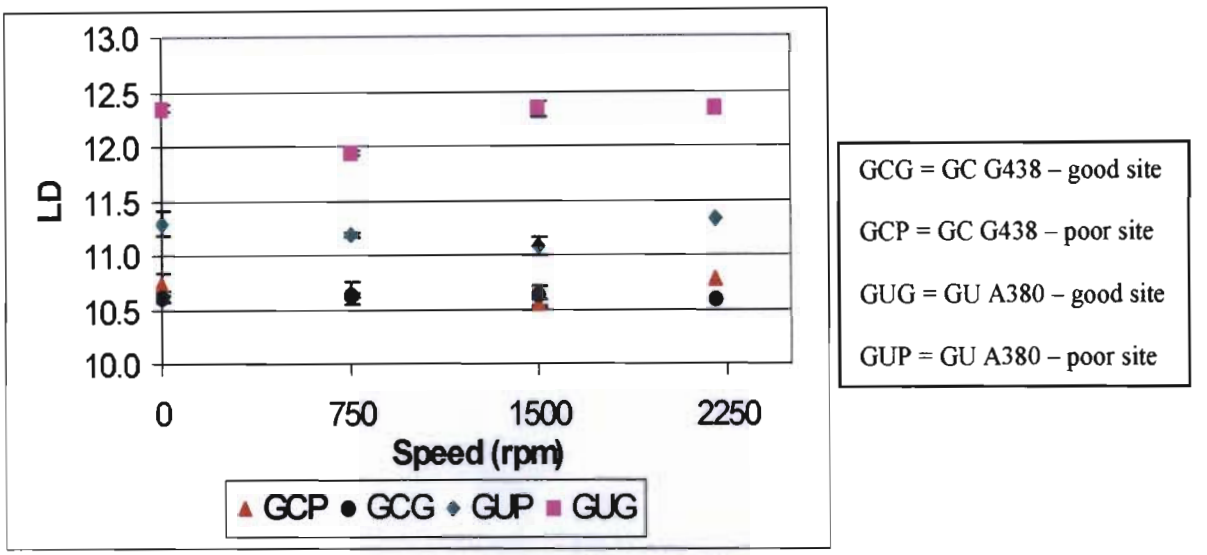


Figure 6.20: Graph of pulp lumen diameter for four compartments after refining with three different refiner speeds to 100 kWh/t

The pulp lumen diameter did not change with refining figure (6.20). This would be expected because it is the outer walls of the fibres that are affected by refining. Only the GUG had a lower lumen diameter when refined at 750 rpm compared to the unrefined pulp. The GUG maintains the highest lumen diameter, compared to the other pulps, from the unrefined state.

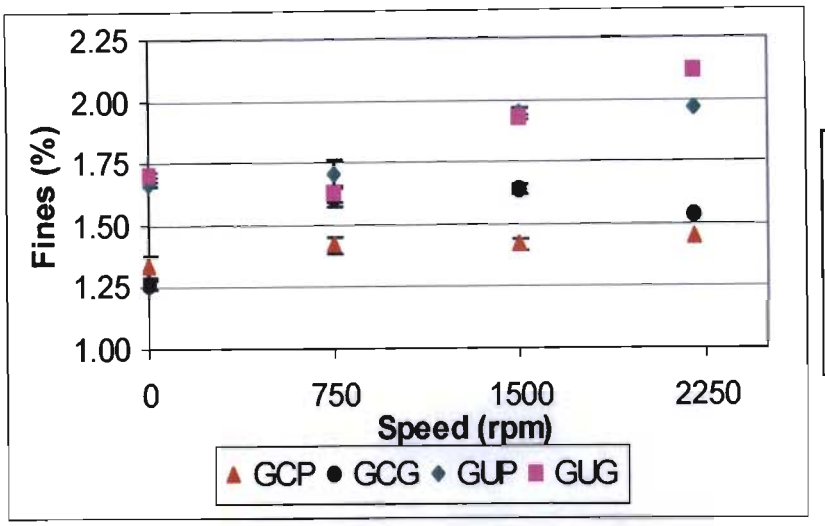


Figure 6.21: Graph of pulp fines content for four compartments after refining with three different refiner speeds to 100 kWh/t

Figure 6.21 shows that GUG and GUP had higher pulp fines content than the GCG and GCP. The results from an ANOVA and Duncan test (Tables 6.7 and 6.8), showed that there were significant differences in pulp fines content due to both, the different refining treatments and the different pulps. The highest fines content was for the GUG after being refined at 2200 rpm. At 750 rpm the GCG, GUG and GUP had similar fines content. The GCP had the lowest fines content after refining at all speeds and was effected the least by the three different treatments. Initially, the fines content for the GCG and GCP were 1.29% and 1.34% respectively. However it can be seen in table 6.6, that while the increase in fines content due to the refining treatments were low for the GCP, they were markedly higher for the GCG. This resulted in the GCP having the lowest fines content after refining, causing a change in rank in terms of which pulp had the lowest fines content before and after refining. The pulp fines content correlated negatively with the pulp fibre length ($r = -0.52$). That is the pulp fines content increases as the pulp fibre length decreases. This is because fines are produced as the fibres are cut.

Table 6.6: Percent increase in pulp fines content at 100 kWh/t using the three different refiner speeds

Speed (rpm)	GCG (%)	GCP (%)	GUG (%)	GUP (%)
2200	19	8.9	28.3	19.8
1500	27.2	6.3	17.1	18.6
750	25.1	6.2	0	4

Table 6.7: Results of Duncan multiple range test for homegeneneity across the different pulps at the same refining speed at a fixed SRE of 100kWh/t

Freeness

Speed (rpm)	GCG	GCP	GUG	GUP	p-value
750	A	B	A	AB	0.0976
1500	B	B	B	A	0.0001
2200	C	B	B	A	0.0002

TEA

Speed (rpm)	GCG	GCP	GUG	GUP	p-value
750	B	A	B	A	0.0008
1500	A	A	A	A	0.3500
2200	A	B	A	A	0.0078

Tensile

Speed (rpm)	GCG	GCP	GUG	GUP	p-value
750	B	A	C	B	0.0001
1500	A	A	A	A	0.9145
2200	A	A	B	AB	0.0456

% Fines

Speed (rpm)	GCG	GCP	GUG	GUP	p-value
750	B	A	BC	C	0.0002
1500	B	A	C	C	0.0001
2200	B	A	D	C	<0.0001

Tear

Speed (rpm)	GCG	GCP	GUG	GUP	p-value
750	C	B	B	A	<0.0001
1500	C	B	B	A	<0.0001
2200	C	B	B	A	<0.0001

FL

Speed (rpm)	GCG	GCP	GUG	GUP	p-value
750	B	B	B	A	0.0001
1500	C	B	B	A	<0.0001
2200	C	B	B	A	<0.0001

Burst

Speed (rpm)	GCG	GCP	GUG	GUP	p-value
750	B	A	B	A	<0.0001
1500	B	A	AB	B	0.0143
2200	A	AB	C	B	0.0003

FD

Speed (rpm)	GCG	GCP	GUG	GUP	p-value
750	A	A	C	B	0.0004
1500	AB	A	C	B	<0.0001
2200	A	A	C	B	<0.0001

Sheet density

Speed (rpm)	GCG	GCP	GUG	GUP	p-value
750	B	A	C	B	0.0012
1500	A	A	A	A	0.4596
2200	A	B	B	B	0.0094

CWT

Speed (rpm)	GCG	GCP	GUG	GUP	p-value
750	A	A	A	A	0.3200
1500	B	AB	AB	A	0.1280
2200	A	A	A	A	0.3800

Stretch

Speed (rpm)	GCG	GCP	GUG	GUP	p-value
750	B	A	A	A	0.0082
1500	B	A	AB	B	0.0441
2200	A	B	AB	A	0.0176

Table 6.8: Results of Duncan multiple range test for homegeneneity for each of the four pulps across the three different refining speeds at a fixed SRE of 100 kWh/t

Freeness

Speed (rpm)	GCG	GCP	GUG	GUP
750	A	C	B	B
1500	A	B	B	A
2200	A	A	A	A
p - value	0.3296	0.0006	0.0022	<0.000

TEA

Speed (rpm)	GCG	GCP	GUG	GUP
750	AB	A	A	A
1500	B	B	A	B
2200	A	C	A	B
p - value	0.0956	0.0008	0.5950	0.0017

Tensile

Speed (rpm)	GCG	GCP	GUG	GUP
750	A	A	A	A
1500	B	C	A	B
2200	A	B	A	B
p - value	0.0013	0.0007	0.6345	0.0373

% Fines

Speed (rpm)	GCG	GCP	GUG	GUP
750	AB	A	A	A
1500	B	A	B	B
2200	A	A	C	B
p - value	0.0940	0.7060	<0.000	0.0036

Tear

Speed (rpm)	GCG	GCP	GUG	GUP
750	B	B	B	B
1500	B	AB	AB	A
2200	A	A	A	AB
p - value	0.0072	0.0352	0.0123	0.1000

FL

Speed (rpm)	GCG	GCP	GUG	GUP
750	A	A	B	C
1500	A	A	A	A
2200	A	A	A	B
p - value	0.1800	0.1520	0.0260	<0.000

Burst

Speed (rpm)	GCG	GCP	GUG	GUP
750	B	A	A	A
1500	C	B	A	B
2200	A	B	B	B
p - value	0.0004	0.0056	0.0036	0.0080

FD

Speed (rpm)	GCG	GCP	GUG	GUP
750	A	A	A	A
1500	A	A	B	A
2200	A	A	B	A
p - value	0.9500	0.2390	0.0090	0.1000

Sheet density

Speed (rpm)	GCG	GCP	GUG	GUP
750	AB	A	A	A
1500	B	B	A	AB
2200	A	B	A	B
p - value	0.0587	0.0040	0.9858	0.0990

CWT

Speed (rpm)	GCG	GCP	GUG	GUP
750	A	A	A	B
1500	A	A	A	A
2200	A	A	A	AB
p - value	0.9700	0.2700	0.3300	0.0970

Stretch

Speed (rpm)	GCG	GCP	GUG	GUP
750	B	A	A	A
1500	B	A	B	B
2200	A	B	B	AB
p - value	0.0249	0.0018	0.0151	0.0904

Tables 6.7 and 6.8 show the results of an (ANOVA) and the Duncan test. The letters in the table show which groups are similar and which are different. Table 6.7 reads across the table for the four pulps at each speed and Table 6.8 reads down the table for each pulp across the three speeds. Similar letters indicate no significant differences in the property at the 95 % confidence level, while different letters indicate that there are significant differences at the 95% confidence level. The higher-ranking letters indicate a higher property value, for example, consider the freeness in Table 6.7. At 750 rpm the GCG has an A while the GCP has a B. This means that the freeness of the GCP is significantly higher than the freeness of the GCG at the 95% confidence level. The results indicated in the table are referred to while discussing the properties.

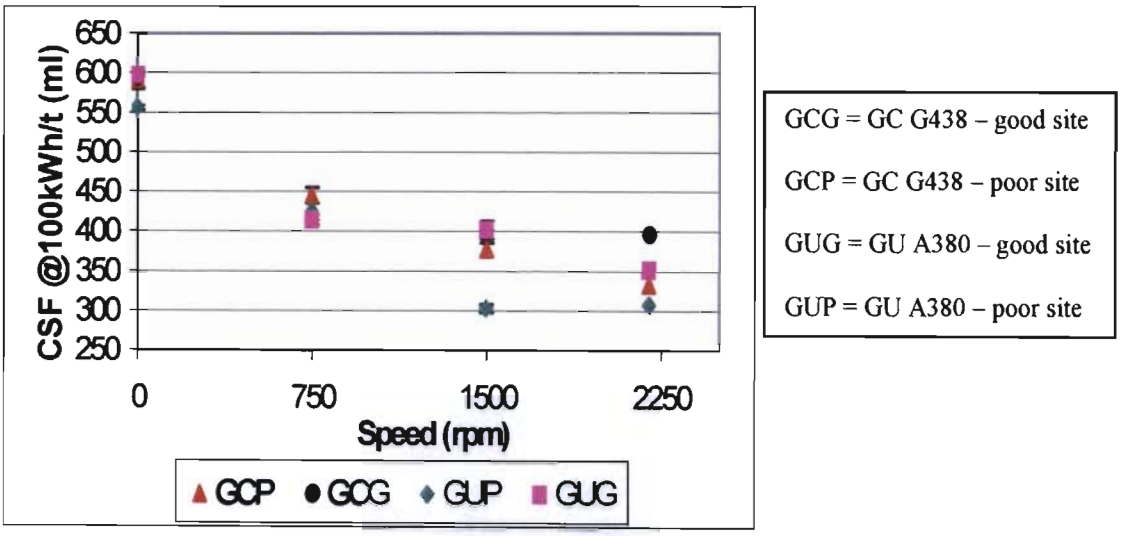


Figure 6.22: Graph of Freeness for the four compartments at an SRE of 100kWh/t using 3 different speeds

Figure 6.22 shows the freeness of the material from four different compartments after using three different types of refining speeds and refining to an SRE of 100 kWh/t. The three different treatments did not have a significant difference on the pulp freeness for the GUG (Table 6.8). It was observed that for the GCP, GUG and GUP, the pulp freeness was significantly higher when refined at 750 rpm than when refined at 2200 rpm. This is because the fibres are treated more slowly at the lowest intensity than at the higher intensity.

Industry requires the pulp freeness to be usually higher than 400 ml because of drainage constraints on the paper machine. The results indicate that if refining of these four pulps were carried out at 750 rpm to an SRE of 100 kWh/t then the freeness level does not drop to

unacceptable levels for any of the pulps. However it was seen that for refining carried out to 100 kWh/t at 1500 rpm, the two pulps from the poor site (GCP and GUP), were refined too much from an acceptable freeness point of view. When refining was carried out at 2200 rpm, the pulp is treated faster and refining to 100 kWh/t caused all the pulps except the GCG to have unacceptable freeness levels.

When refining at 2200 rpm (the highest intensity refining), the GCG were the hardest to refine and had the highest freeness (432ml) and the GUP had the lowest freeness (344ml). The GCP and the GUG had similar freeness (Table 6.7). When refining at 1500 rpm (medium intensity refining), the GCG and the GUG had similar freeness values of 401ml and 402ml respectively. The GUP had the lowest freeness (303ml). When refining at both 1500 rpm and 2200 rpm it was seen that the material from the good sites had a higher freeness than the material from the poor sites. When refining was carried out at 750 rpm it was noted that with this type of refining treatment the GCP had the highest freeness. (465ml). The freeness of the GCG and the GUG were similar (414ml and 415ml respectively).

The fibre length will influence the freeness of the pulp since shorter fibres will be able to pack more closely than longer fibres. It was noted in figure 6.16, that with the exception of the GCG, the material refined at 750 rpm had longer fibres compared to refining at the higher speeds. This might account for the higher freeness observed when refined at 750 rpm. The freeness of the pulp will also be influenced by the fines content of the pulp and pulps with higher fines content will have a lower freeness. The reason for this is that fines will fill up voids between fibres and thereby increase the resistance to the drainage of water. It will be seen in figure 6.21 that with the exception of the GCG, all the other compartments had the lowest fines content when refined at 750 rpm. For the GCG it was noted that the fines content from lowest to highest was for the pulps refined at 2200, 750 and 1500 rpm in that order. The freeness for these pulps decreased in the same order. The correlation coefficients (r), for freeness with plup fibre length and pulp fines content are 0.63 and -0.53 respectively.

The results from the multiple regression analysis showed that the initial pulp fibre length could account for most of the differences in freeness among the four pulps at an SRE of 100 kWh/t when refined at the two higher speeds (Table 6.9). The multiple regression analysis results when considering wood anatomy (Table 6.10), showed that the wood coarseness could account for some of the differences in pulp freeness.

Figure 6.23 shows the tensile index for the four compartments. It can be seen that apart from the GUG which was not affected differently by the three different treatments (Table 6.8), all the other sites showed that the tensile strength was significantly higher when refined at 1500 rpm. When refined at 1500 rpm, there were no significant differences in tensile strength among the four different pulps (Table 6.7). For refining carried out at 750 rpm and 2200 rpm significant differences in tensile strength occurred among the four pulps, with the GUG having the highest tensile strength at both speeds. At 750 rpm, the GCP had the lowest average tensile strength and at 1500 rpm the GCG had the lowest average tensile strength. To optimise tensile strength for the four pulps refining should be carried out at 1500 rpm. Also the GUG should be used in grades that require high tensile strength.

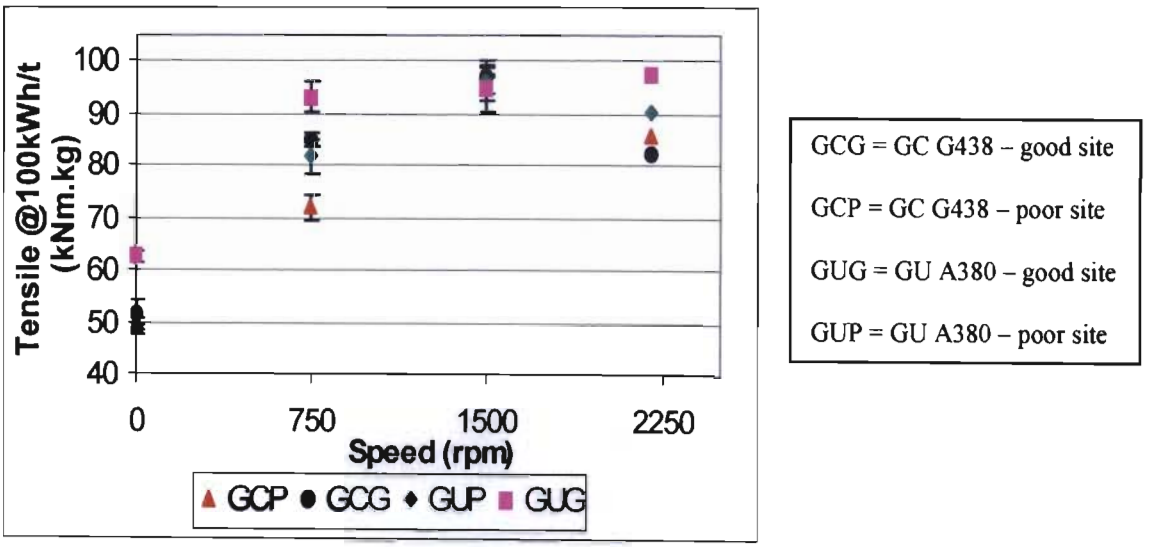


Figure 6.23: Graph of Tensile strength for the four compartments at an SRE of 100kWh/t using 3 different speeds

The tensile strength is influenced by a combined effect of several factors, one of which is the inherent bonding ability of the fibre surface. This is dependent on surface area available for bonding and strength per unit bond. The surface area of the fibres will be dependent on properties such as fibre diameter, lumen diameter and the collapsibility of the fibres. Multiple regression analysis (Tables 6.9 and 6.10), showed that at 750 rpm the initial pulp coarseness together with the initial pulp lumen diameter could be used to predict the tensile strength (R^2 = 80%). The initial pulp coarseness contributed 56.3% towards this prediction. Britt (Britt 1966) showed that less coarse fibres had a greater degree of interfibre bonding in both refined and unrefined states of

1500 rpm is recommended since there are other various advantages such as the freeness is still greater than 400 ml and tensile strength is high. For the other three pulps, to maximise tear strength, refining needs to be carried out at 750 rpm, although it needs to be noted that this treatment does not give the high tensile strength obtained when refined at the higher speeds except for the GUG where the tensile strength was high at all speeds of refining. The GUP gives very low tear strength compared to the other three pulps and this pulp should be used in grades that do not require high tear strength.

The results of analysis show a strong correlation between fibre length and tear strength (r =0.89, 0.93 and 0.93 for 750, 1500 and 2200 rpm respectively). According to Britt (1970), the explanation for longer fibres resulting in higher tear strength is that longer fibres tend to distribute the stress over a greater area, over more fibres and bonds, while with shorter fibres the stress is concentrated over a smaller area. The multiple regression analysis results show that at all speeds the initial pulp fibre length could account for most of the differences in tear strength (Table 6.9). It was seen that at all refining speeds the wood coarseness could account for about 30% of the differences in tear strength (Table 6.10). Britt (1966), saw that coarser fibres had a higher tear strength than less coarse fibres.

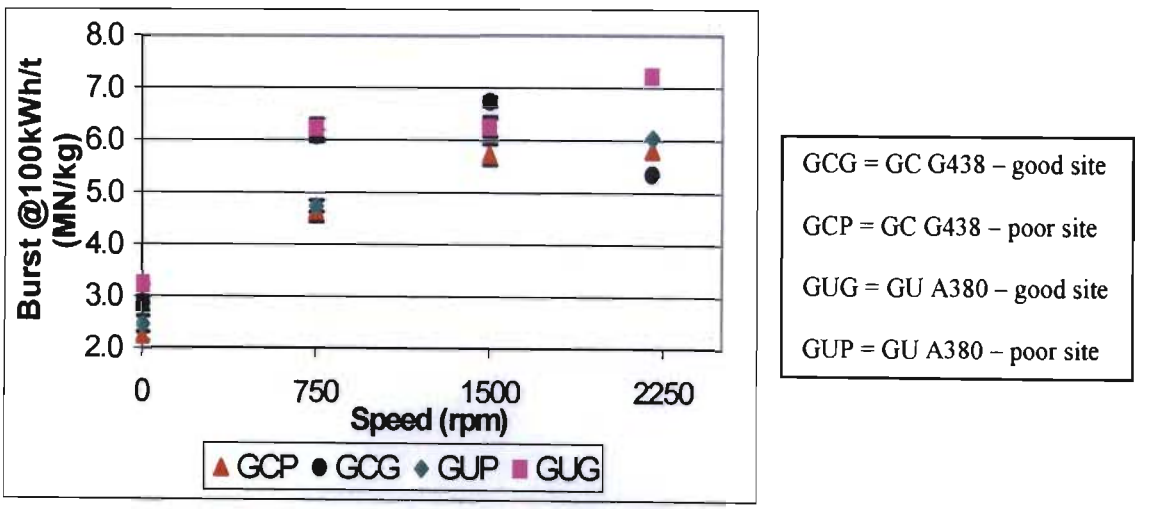


Figure 6.25: Graph of Burst strength for the four compartments at an SRE of 100kWh/t using 3 different speeds

Figure 6.25 shows the burst strength for the four compartments refined at 100 kWh/t using three different speeds. For the GUG the highest burst strength occurred at 2200 rpm, while the other

two speeds resulted in similar burst strength (Table 6.8). For the GCP and GUP refining at 750 rpm resulted in the lowest burst strength while the two higher speeds gave similar burst strength (Table 6.8). When refining at 1500 rpm the GCG had the highest mean burst strength. When refining at 750 rpm and 2200 rpm, the GUG had the highest burst strength. When refined at 750 rpm, the burst strength correlated with the pulp fibre length, pulp fibre diameter and initial pulp coarseness (r = 0.66, 0.51 and –0.95 respectively). When refining at 2200 rpm, burst strength correlated strongly with the pulp fibre diameter and lumen diameter (r = 0.95 and 0.96 respectively).

The results from the multiple regression analysis using initial wood and pulp properties (Tables 6.9 and 6.10), showed that at the two lower speeds the initial pulp and wood coarseness could account for differences in burst strength. According to Britt (1966), less coarse fibres were seen to have a higher degree of interfibre bonding. At 2200rpm tables 6.9 and 6.10 show that the initial pulp and wood lumen diameter was able to account for the differences in burst strength among the different pulps.

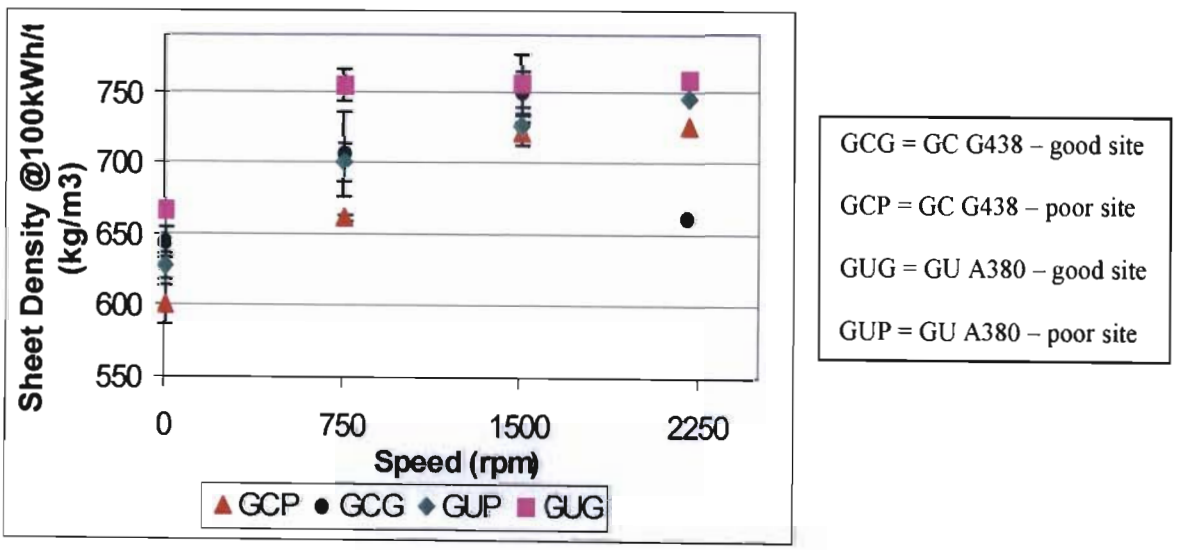


Figure 6.26: Graph of sheet density for the four compartments at an SRE of 100kWh/t using 3 different speeds

When refined at 750 rpm, the good sites had a significantly higher (Table 6.7) sheet density than the poor sites (figure 6.26). The sheet density for the GUG was the highest and the lowest sheet density was for the GCP. There were no significant differences in sheet density between the GCG and the GUP. The results obtained showed that the sheet density correlated with the pulp fines

content, fibre diameter and lumen diameter (r = 0.52, 0.72 and 0.71 respectively), when refined at 750 rpm. When refined at 1500 rpm, the differences in sheet density were less marked than at the other two speeds. When refined at 2200 rpm, the sheet density of the GCG was the lowest while the other three pulps had similar sheet density. The GU clones had a higher sheet density than GC clones. There were strong correlations between sheet density and fines content, fibre diameter, fibre length and lumen diameter (r = 0.87, 0.79, 0.57 and 0.83 respectively) when refined at 2200 rpm.

The results from the multiple regression analysis showed that at 1500 rpm the sheet density could not be predicted in terms of the initial pulp properties or wood properties (Tables 6.9 and 6.10). At 750 rpm, the initial lumen diameter together with initial fines content could explain 70% of the variation in sheet density. At 2200 rpm the ratio of initial fibre length over initial fibre diameter could account for 43% of the variation in sheet density. For the wood properties, it was seen that at 750 rpm the wood cell wall thickness accounted for 82% of the variation in sheet density at 100 kWh/t. At 2200 rpm the wood fibre diameter was seen to account for 67% of the differences in sheet density.

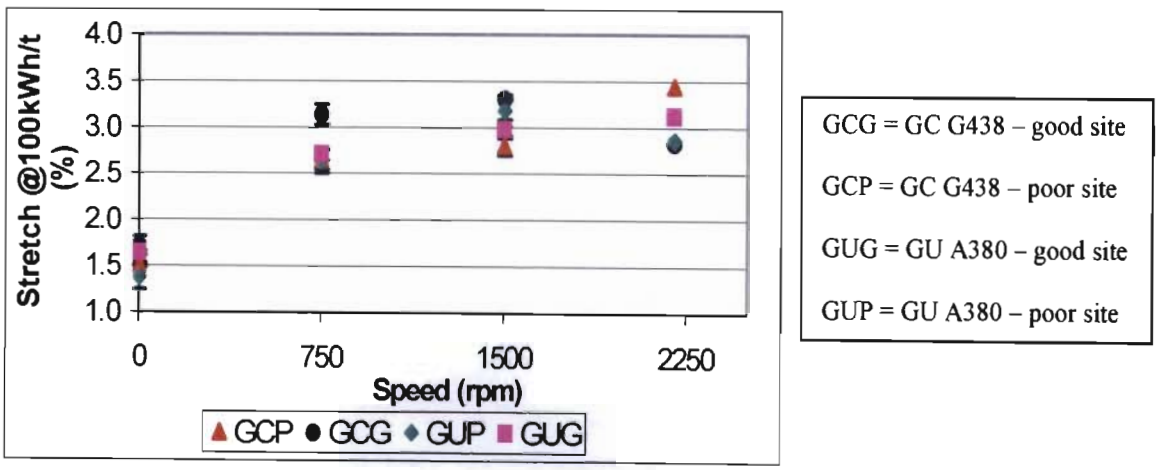


Figure 6.27: Graph of stretch for the four compartments at an SRE of 100kWh/t using 3 different speeds

There was a general increase in stretch from when refining at 750 rpm to when refining at 1500 rpm (figure 6.27). There was a further increase in stretch for the GCP and GUG when refined at 2200 rpm however the stretch of the GCG and GUP decreased. This decrease was significant at the 95% confidence level for the GCG (Table 6.8). The stretch of the GUP at 2200 rpm was

mutually similar to the stretch at 750 rpm and 1500 rpm. The results from the multiple regression analysis (Table 6.9 and 6.10) showed that when refined at 750 rpm the initial pulp lumen diameter together with the initial pulp coarseness could account for 65% of the variation in stretch among the sites. At 1500 rpm and 2200 rpm the pulp physical properties could not account for the variation in stretch among the sites.

Figure 6.28 shows the TEA for the four sites after refining to 100kWh/t using three different speeds. The TEA behaves in a similar manner as the stretch. There was a 0.72 correlation between TEA and pulp fibre length. There were no significant differences in TEA at 1500 rpm at the 95% confidence level (Table 6.7). The results of the multiple regression analysis showed that when refined at 750 rpm and 2200 rpm, the initial pulp or wood coarseness could be used to account for some of the differences in TEA. At 1500 rpm, neither pulp nor wood properties could predict the TEA.

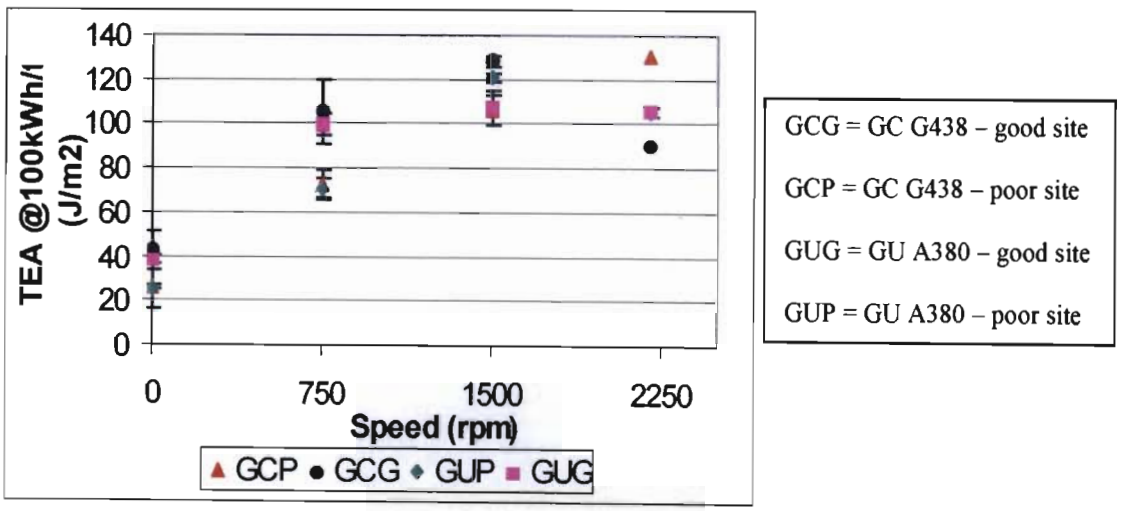
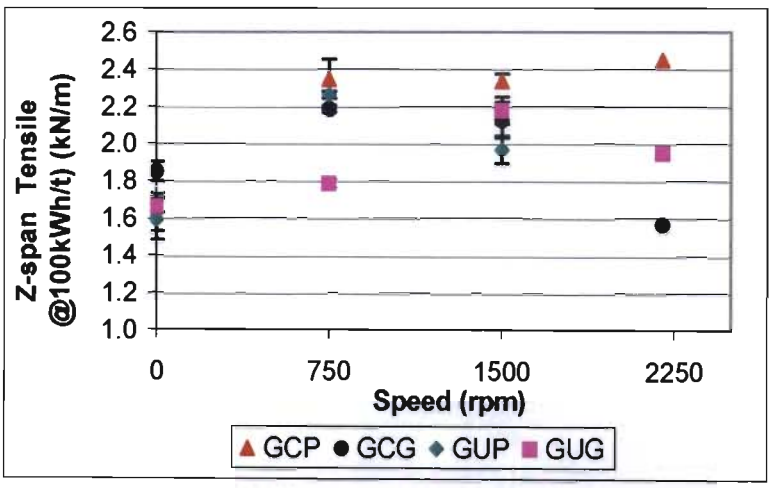


Figure 6.28: Graph of TEA for the four compartments at an SRE of 100kWh/t using 3 different speeds

The GCP had a higher zero-span tensile than the other three pulps at all speeds (Figure 6.29). This was more marked at the two higher speeds. At 750 rpm the GCP, GCG and GUP had similar zero-span tensile strength and the GUG had the lowest zero-span tensile strength. At 1500 rpm the GUP had the lowest mean zero-span tensile strength and the GCG and GUG had similar strength. When refining at 2200 rpm, the GCG had the lowest zero-span tensile strength and the GUG and GUP had similar strength. From the results of multiple regression analysis (Tables 6.9 and 6.10) it was seen that at the different refining speeds there were different variables that were

accounting for most of the differences in zero-span tensile. At 2200 rpm either the initial pulp or wood coarseness could be used to account for more than 60% of the differences in zero-span tensile. For refining carried out at 1500 rpm it was seen that either the initial pulp or wood fibre diameter could be used to account for more than 75% of the differences in zero-span tensile. At 750 rpm the initial pulp fibre length was able to give a good prediction of the zero-span tensile but the measured wood properties could not give a good prediction.



GCG = GC G438 – good site

GCP = GC G438 – poor site

GUG = GU A380 – good site

GUP = GU A380 – poor site

Figure 6.29: Graph of zero-span tensile for the four compartments at an SRE of 100kWh/t using 3 different speeds

Table 6.9: Multiple regression analysis results using initial pulp anatomy to predict pulp freeness and sheet properties after refining to a fixed SRE of 100 kWh/t

750 rpm (SEL range = 0.15 -0.22 Ws/m))								
	Freeness	**Tensile**	**Tear**	**Burst**	**Sheet density**	**Stretch**	**TEA**	**Z-span**
Model R^2	**37.35**	**79.87**	**83.04**	**88.66**	**70.23**	**64.52**	**88.34**	**91.99**
p-value	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
Contributors to the model and their percentage contribution								
i-Coarse	37.35	56.31		88.66		38.31	80.71	
i-LD		23.56			42.31	26.21		
i-FL			83.04				7.63	86.4
i-fines					27.92			
i-Collaps								5.59

1500 rpm (SEL range = 0.31 Ws/m - 0.43 Ws/m)								
	Freeness	**Tensile**	**Tear**	**Burst**	**Sheet density**	**Stretch**	**TEA**	**Z-span**
Model R^2	**86.59**	**-**	**83.13**	**45.71**	**-**	**-**	**-**	**75.49**
p-value	<0.0001	<0.0001	<0.0001	<0.0001				<0.0001
Contributors to the model and their percentage contribution								
i-Coarse				45.71				
i-LD	8.29							
i-FL	78.3		77.98					
i-fines								
i-Collaps								
i-FD			5.15					75.49

2200 rpm (SEL range =0.45Ws/m - 0.52 Ws/m								
	Freeness	**Tensile**	**Tear**	**Burst**	**Sheet density**	**Stretch**	**TEA**	**Z-span**
Model R^2	**88.91**	**44.76**	**88.56**	**72.22**	**42.89**	**-**	**60.23**	**81.55**
p-value	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001		<0.0001	<0.0001
Contributors to the model and their percentage contribution								
i-Coarse	8.36						47.15	68.34
i-LD		44.76	14.44	72.22				
i-FL	69.54		74.12				13.08	
i-fines								
i-Collaps	11.01							13.21
i-FD								
i-FL/FD					42.89			

Table 6.10: Multiple regression analysis results using initial wood anatomy and density to predict pulp freeness and sheet properties after refining to a fixed SRE of 100 kWh/t

750 rpm (SEL range = 0.15 - 0.22 Ws/m)								
	Freeness	**Tensile**	**Tear**	**Burst**	**Sheet density**	**Stretch**	**TEA**	**Z-span**
Model R^2	**38.24**	**89.59**	**51.84**	**91.28**	**81.63**	**69.37**	**82.12**	**37.05**
p-value	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
Contributors to the model and their percentage contribution								
Density	38.24							
WCWT		83.81	21.5		81.63			
WLD		6.28				28		
w-Coarse			30.34	91.28			82.12	37.05
WFD						41.37		

1500 rpm (SEL range 0.31 Ws/m - 0.43 Ws/m)								
	Freeness	**Tensile**	**Tear**	**Burst**	**Sheet density**	**Stretch**	**TEA**	**Z-span**
Model R^2	**33.64**	**-**	**69.24**	**41.3**	**-**	**-**	**-**	**86.03**
p-value	<0.0001	<0.0001	<0.0001	<0.0001				<0.0001
Contributors to the model and their percentage contribution								
WCWT			40					
w-Coarse	33.64		29.24	41.3				
WFD								86.03

2200 rpm (SEL range =0.45 Ws/m - 0.52 Ws/m)								
	Freeness	**Tensile**	**Tear**	**Burst**	**Sheet density**	**Stretch**	**TEA**	**Z-span**
Model R^2	**83.4**	**52.95**	**74.3**	**80.92**	**66.76**	**-**	**42.55**	**78.31**
p-value	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001		<0.0001	<0.0001
Contributors to the model and their percentage contribution								
WCWT	24.93							
WLD				80.92				
w-Coarse	58.47		34.19				42.55	62.35
WFD		52.95			66.76			
w-Collaps			40.11					15.96

6.5 Results at constant freeness (400ml)

6.5.1 Introduction

In this section the results are compared at a constant freeness of 400 ml. Industry is generally interested in pulp having freeness levels in this range due to drainage constraints on the papermachine. When the results are compared in this way the impact of the different quality pulps on the refining process itself was seen in terms of how much of refining was needed to achieve this freeness level.

6.5.2 Discussion

Figure 6.30 shows the pulp anatomy of the four sites after being refined to freeness of 400ml using three different refining treatments. The three speeds used provided three different refining intensities with the lowest speed being the lowest intensity and the highest speed being the highest intensity. When refining each of the clones with the different intensities, it was seen that the pulp from the GUG and GUP had a significantly higher resultant fibre length when refined at the lowest speed compared to when they were refined at the two higher speeds (Table 6.12). The GCG and GCP had no significant differences in fibre length when refined using the different refining treatments. In considering differences across sites, when refining was carried out at the lowest speed, the GCG and GUG had similar fibre lengths (Table 6.11). With the exception of the similarity just mentioned, the fibre length of the GCG was the highest while the GUP had the shortest fibre lengths. The fibre lengths were similar for the pulp from the GCP and GUG when refined at the two higher speeds.

Figure 6.30 also shows that the pulp fibre diameter and lumen diameter behaved similarly. The GUG had the highest fibre and lumen diameters at all refining intensities (Table 6.11). The pulp fibre and lumen diameters for the pulp from the GCG and GCP were similar at all refining intensities. These pulps had the lowest pulp fibre and lumen diameter.

The pulp cell wall thickness (figure 6.30) appeared to be higher when refined at the highest intensity for three of the sites. However after carrying out an analysis of variance it was seen that these differences were not significant at the 95% confidence level (Table 6.12)

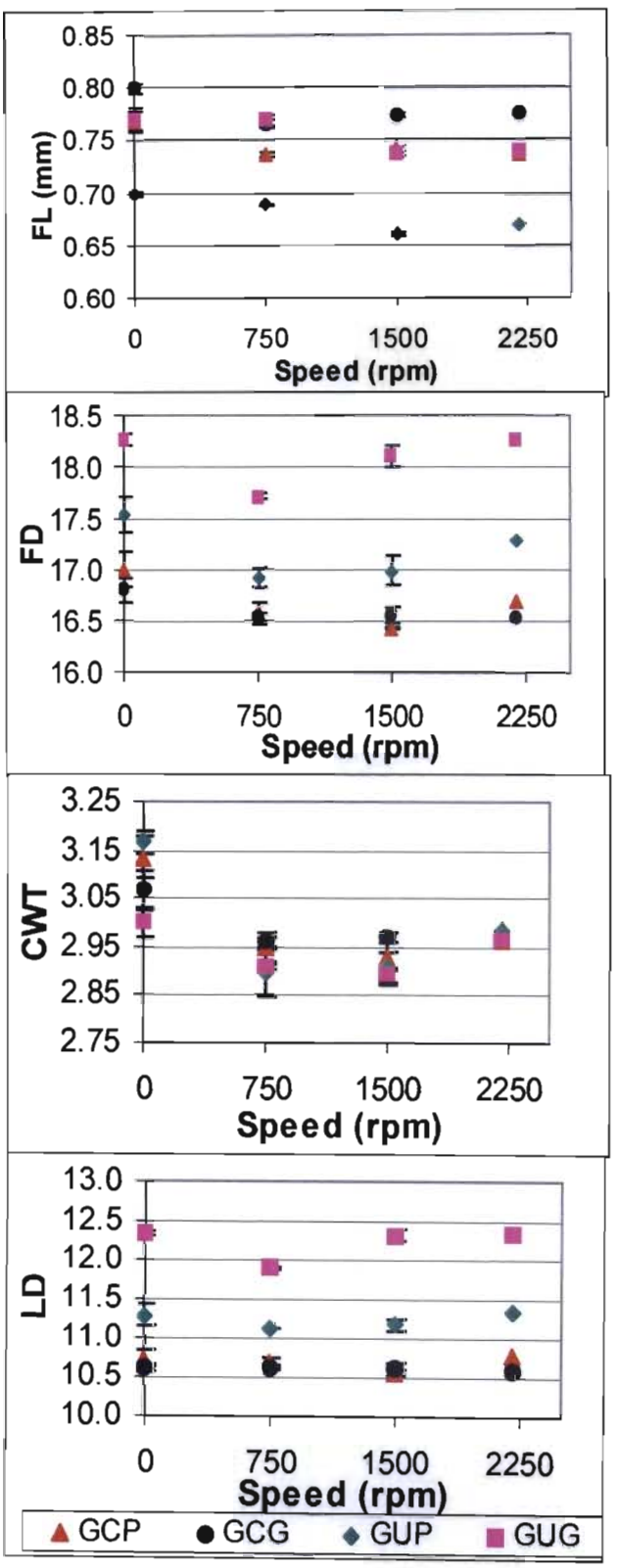


Figure 6.30: Pulp anatomy at 400CSF

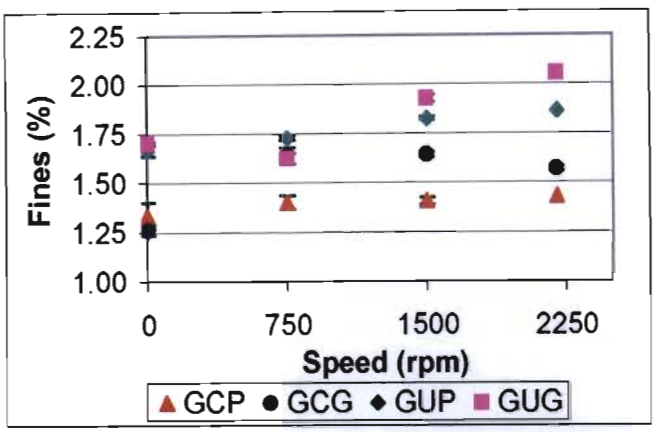


Figure 6.31: Graph of pulp fines content at the different refining speeds

For pulp from the GUG and GUP refining at the two higher speeds resulted in a higher pulp fines content than refining at the lowest speed (figure 6.31). This difference was significant at the 95% confidence level (Table 6.12). The fines content of the GCG was significantly higher than the fines content of the GCP (Table 6.11). For the GU clones, the fines content of the GUG was significantly higher than the fines content of the GUP at the two higher speeds. At the two higher speeds it was also seen that both GU clones had a significantly higher fines content than the two GC clones. At 750 rpm only the GCP had a significantly lower fines content than the other three pulps. The fines content would increase as a result of fibre cutting during the refining process. While refining treatment is mild and does not result in much fibre cutting fibre shortening almost always occurs to some degree even if only very slightly. It would be noted in figure 6.30, that the GUG and GUP underwent a significant reduction in fibre length when refined at the two higher intensities. These corresponded to the highest fines content. There was not much fibre length reduction noted in the GCG and GCP when compared at the different refining intensities. This fibre length reduction or lack of fibre length reduction displayed by the different pulps corresponds to the increase in pulp fines content.

Tables 6.11 and 6.12 show the results of an analysis of variance (ANOVA) and the Duncan test. The letters in the table show which groups are similar and which are different. Table 6.11 reads across the table for the four pulps at each speed and table 6.12 reads down the table for each pulp across the three speeds. Similar letters indicate no significant differences in the property at the 95 % confidence level, while different letters indicate that there are significant differences at the 95% confidence level. The higher-ranking letters indicate a higher property value. The results indicated in the table are referred to while discussing the properties.

Table 6.11: Results of Duncan multiple range test for homegeneneity across the different pulps at the same refining speed at constant freeness (400 ml)

SRE

Speed (rpm)	GCG	GCP	GUG	GUP	p-value
750	A	C	A	B	0.0011
1500	B	B	B	A	0.0002
2200	C	AB	B	A	<0.0001

TEA

Speed (rpm)	GCG	GCP	GUG	GUP	p-value
750	C	AB	BC	A	0.0412
1500	B	A	AB	A	0.0225
2200	B	AB	B	A	0.0788

Tensile

Speed (rpm)	GCG	GCP	GUG	GUP	p-value
750	AB	A	B	AB	0.1815
1500	B	AB	AB	A	0.1360
2200	AB	A	B	A	0.0221

% Fines

Speed (rpm)	GCG	GCP	GUG	GUP	p-value
750	B	A	B	B	0.0020
1500	B	A	D	C	<0.0001
2200	B	A	D	C	<0.0001

Tear

Speed (rpm)	GCG	GCP	GUG	GUP	p-value
750	C	AB	BC	A	0.0138
1500	C	B	B	A	0.0002
2200	D	B	C	A	<0.0001

FL

Speed (rpm)	GCG	GCP	GUG	GUP	p-value
750	C	B	C	A	0.0002
1500	C	B	B	A	<0.0001
2200	C	B	B	A	<0.0001

Burst

Speed (rpm)	GCG	GCP	GUG	GUP	p-value
750	B	AB	C	A	0.0028
1500	C	B	BC	A	0.0002
2200	B	A	C	A	<0.0001

FD

Speed (rpm)	GCG	GCP	GUG	GUP	p-value
750	A	A	B	A	0.0009
1500	A	A	C	B	<0.0001
2200	A	A	C	B	<0.0001

Sheet density

Speed (rpm)	GCG	GCP	GUG	GUP	p-value
750	AB	A	C	B	0.0067
1500	BC	AB	C	A	0.0289
2200	AB	A	C	BC	0.0051

CWT

Speed (rpm)	GCG	GCP	GUG	GUP	p-value
750	A	A	A	A	0.5750
1500	A	A	A	A	0.3718
2200	A	A	A	A	0.9330

Stretch

Speed (rpm)	GCG	GCP	GUG	GUP	p-value
750	B	A	A	AB	0.1249
1500	C	AB	BC	A	0.0167
2200	C	AB	B	A	0.0050

Table 6.12: Results of Duncan multiple range test for homegeneneity for each of the four pulps across the three different refining speeds at constant freeness (400ml)

SRE

Speed (rpm)	GCG	GCP	GUG	GUP
750	A	B	C	C
1500	A	A	A	A
2200	A	A	B	B
p-value	0.3750	0.0002	0.0022	<0.0001

TEA

Speed (rpm)	GCG	GCP	GUG	GUP
750	AB	A	B	B
1500	B	A	AB	B
2200	A	A	A	A
p-value	0.0690	0.7399	0.0497	0.0196

Tensile

Speed (rpm)	GCG	GCP	GUG	GUP
750	A	A	A	A
1500	B	A	A	A
2200	A	A	A	A
p-value	0.0056	0.2570	0.6970	0.1680

% Fines

Speed (rpm)	GCG	GCP	GUG	GUP
750	A	A	A	A
1500	A	A	B	B
2200	A	A	C	B
p-value	0.2240	0.8800	<0.0001	0.0061

Tear

Speed (rpm)	GCG	GCP	GUG	GUP
750	A	B	B	B
1500	A	AB	A	A
2200	A	A	A	A
p-value	0.1750	0.0143	0.0087	0.0011

FL

Speed (rpm)	GCG	GCP	GUG	GUP
750	A	A	B	C
1500	A	A	A	A
2200	A	A	A	B
p-value	0.2360	0.7030	0.0540	0.0001

Burst

Speed (rpm)	GCG	GCP	GUG	GUP
750	AB	A	B	B
1500	B	A	A	A
2200	A	B	B	A
p-value	0.0230	0.0238	0.0040	0.0032

FD

Speed (rpm)	GCG	GCP	GUG	GUP
750	A	A	A	A
1500	A	A	B	A
2200	A	A	B	A
p-value	0.9760	0.3290	0.0041	0.2104

Sheet Density

Speed (rpm)	GCG	GCP	GUG	GUP
750	AB	AB	A	B
1500	B	B	A	A
2200	A	A	A	AB
p-value	0.0730	0.1053	0.6770	0.0717

CWT

Speed (rpm)	GCG	GCP	GUG	GUP
750	A	A	AB	A
1500	A	A	A	A
2200	A	A	B	A
p-value	0.9020	0.8100	0.0832	0.2780

Stretch

Speed (rpm)	GCG	GCP	GUG	GUP
750	A	A	AB	B
1500	A	A	B	AB
2200	A	A	A	A
p-value	0.2070	0.1340	0.0227	0.0157

Figure 6.32 shows the refining energy required to refine the pulp to a freeness of 400ml at the different speeds. It was seen that generally refining at lower intensities required significantly more energy to refine the pulp to a specific freeness (Table 6.12). This difference was more marked for the pulps from the poor sites than the pulps from the good site. When refining at the lowest intensity it is seen that the GCP was the most difficult to refine and required significantly more energy than the other three sites (Table 6.11). The pulps from the good sites were refined with similar ease and required the less energy than the poor sites to be refined to a freeness of 400ml when refined at the lowest speed. When refining at the highest speed an ANOVA showed that statistically for both species the pulp from the poor sites required less energy than the good sites to be refined to a freeness of 400ml. While the SRE for the GUG and GUP were statistically different to each other, both were similar to the SRE for the GCP. Multiple regression analysis showed that the wood coarseness could account for a large percentage of the differences in refining energy required to reach a freeness level of 400 ml for the different pulps when refining at 750 rpm and 2200 rpm (Table 6.14). At 1500 rpm, the wood properties could not give a good prediction of the SRE required to refine the pulp to a freeness of 400 ml, however the wood coarseness could account for 29% of the differences in SRE required to reach a freeness of 400 ml. For the pulp properties, at the lowest refining speed the initial pulp coarseness could account for 80% of the differences in SRE required to reach a freeness of 400 ml. At the two higher speeds, the initial pulp fibre length was best able to account for the differences in SRE required to reach a freeness of 400 ml (Table 6.13).

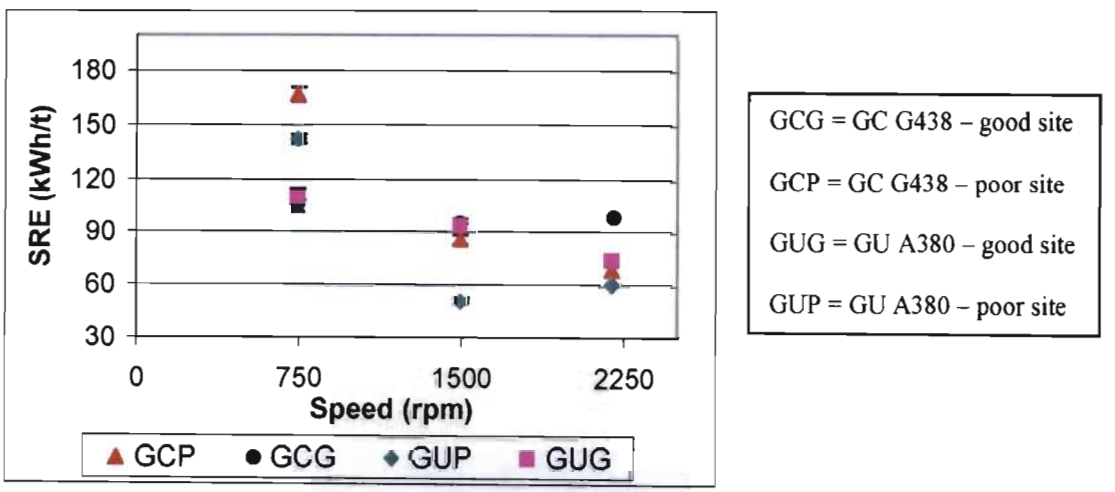


Figure 6.32: SRE required to reach 400CSF at the different speeds

The results indicate that refining of these four pulps at the lowest speed (lowest intensity range) should be avoided since the SRE requirements to reach a freeness of 400 ml are very much larger than when refined at the two higher speeds. Alami *et al.* (1997), also found that using lower intensities reduced the SRE to obtain a given pulp quality however the studies in that case was refining in the manufacture of thermomechanical pulp (TMP). The energy is one of the major costs of the paper industry and refining at the two higher speeds would reduce this cost and strength properties will still be achieved.

Figure 6.33 shows the tensile index at a freeness of 400ml (400CSF). When refining was carried out at the lowest intensity only the tensile strength of the GCP and GUG were statistically different at the 95% confidence level (Table 6.11). When refining at 1500 rpm, the only significant difference in tensile strength was between the GCG and GUP. At the highest refining intensity it was seen that the GUG had the highest tensile strength while the tensile strength for the other three sites were not significantly different at the 95% confidence level. For all pulps except the GCG, there were no significant differences in tensile strength at the three different refining speeds (Table 6.12). For the GCG refining at 1500 rpm gave higher tensile strength. Multiple regression analysis was carried out to determine what wood and initial pulp properties were impacting on the tensile strength. The regression was carried out at each speed separately. It was seen that the measured wood and pulp properties could not give a good prediction of the tensile strength at 400CSF. Tables 6.13 and 6.14 shows the outcome of the multiple regression analysis

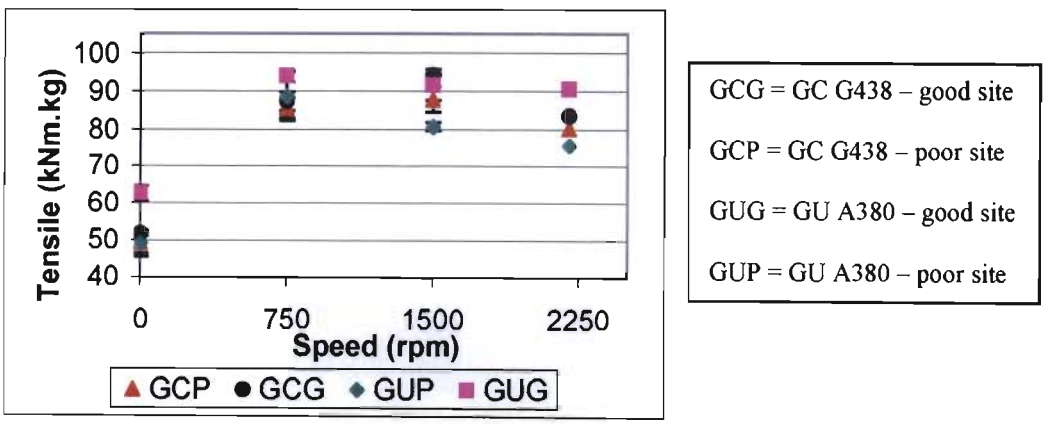
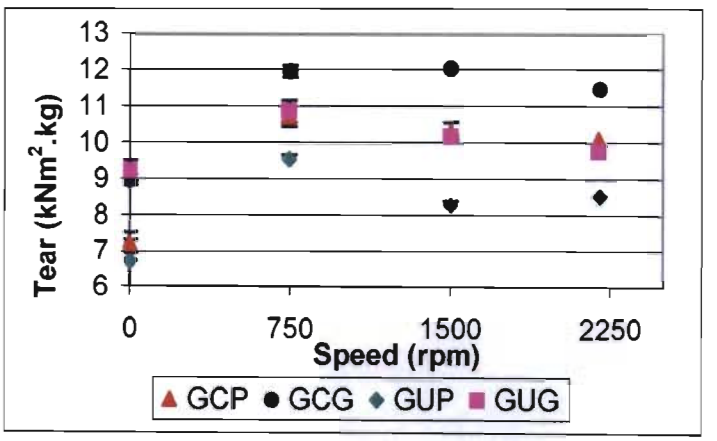


Figure 6.33: Graph of tensile index at 400CSF

Figure 6.34 shows the results of the tear strength at 400CSF using three different refining speeds. There were significant differences in tear strength among the four pulps at 400CSF (Table 6.11). The GCG had the highest tear strength at all refining speeds. The GUP had the lowest tear strength at all speeds. The other two sites had similar tear strength at all refining speeds. There were no significant differences in tear strength for the GCG when refined at the three different intensities (Table 6.12). The other sites had a significantly higher tear strength when refined at the lowest speed than when refined at the two higher speeds.

For paper grades requiring higher tear strength the GCG is recommended since it gives the highest tear strength at all speeds, however refining at 1500 rpm will be better due to the lower SRE requirement and it also gives high values for all the other strength properties at this speed. If the other three pulps were used then refining at 750 rpm maximises the strength however it must be noted that this speed also uses the most energy and the other strength properties are not necessarily high.

From the results of the multiple regression analysis it was seen that at all speeds the initial pulp fibre length could account for most of the differences in tear strength at 400CSF. The wood coarseness and Runkel ratio could also explain some of the differences in tear strength at 400CSF at all three speeds.



GCG = GC G438 – good site

GCP = GC G438 – poor site

GUG = GU A380 – good site

GUP = GU A380 – poor site

Figure 6.34: Graph of tear index at 400CSF

Figure 6.35 shows the burst strength of the four pulps at 100 kWh/t. The burst strength of the clones from the good sites was generally significantly higher than the burst strength of the clones from the poor sites (Table 6.11). When refined at the lowest and highest speeds, the GUG had the

highest burst strength. At 1500 rpm it was seen that GCG had a higher mean burst strength than the GUG however it was seen from an analysis of variance that this difference was not significant at the 95% confidence level. There were significant differences in burst strength for each of the four pulps when refined at the three different speeds (Table 6.12). The GCG had the highest burst strength when it was refined at 1500 rpm while the GCP achieved a higher burst strength when it was refined at 2200 rpm. The GUP had a higher burst strength when it was refined at 750 rpm, while the GUG had similar burst strength at 750 rpm and 2200 rpm and a lower burst strength at 1500 rpm.

It can be seen in table 6.13 that when refined at 750 rpm and 2200 rpm the initial pulp coarseness was able to account for some of the differences in burst strength. When refined at 1500 rpm, the initial pulp fibre length seemed to be more important. The wood density and properties related to the density was also seen to influence the burst strength of the different pulps at all speeds.

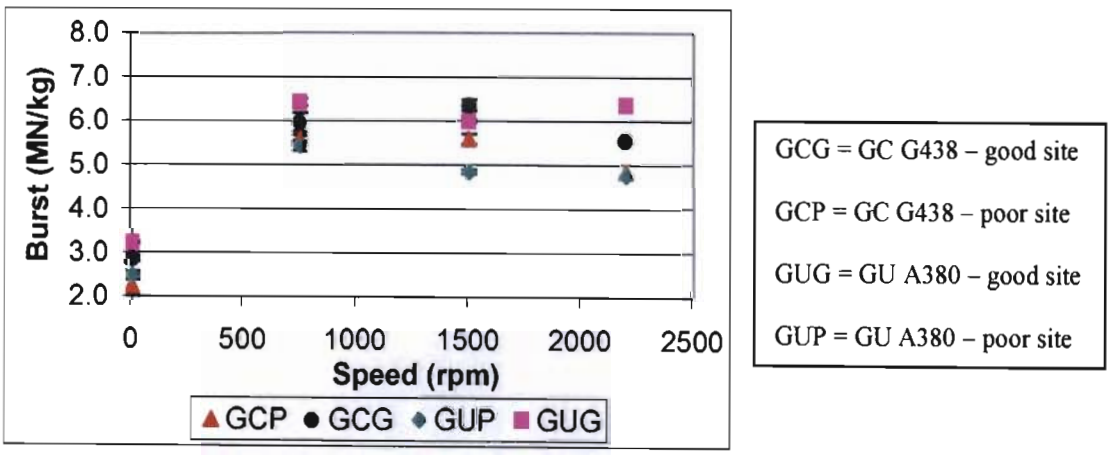


Figure 6.35: Graph of Burst index at 400CSF

Figure 6.36 shows the sheet density at 400CSF. There were significant differences in sheet density both across sites and across the different refining treatments (Tables 6.11 and 6.12). The pulp from the GUG produced sheets with the highest sheet density, however at 1500 rpm it was not significantly higher than the sheet density of the pulp from the GCG. The GUG was not affected differently by the three different refining speeds. The two GC clones had a significantly higher sheet density when refined at 1500 rpm than when refined at 2200 rpm. For the GUP the highest sheet density occurred when refined at 750 rpm.

The results of the multiple regression analysis (Tables 6.13 and 6.14), showed that either the initial pulp or wood lumen diameter could account for most of the differences in sheet density at 400CSF. When refined at 1500 rpm, the wood or initial pulp coarseness was able to account for some of the differences in sheet density. For refining carried out at 750 rpm, it was seen that the wood Runkel ratio or the initial pulp fibre diameter could be used to account for most of the differences in sheet density.

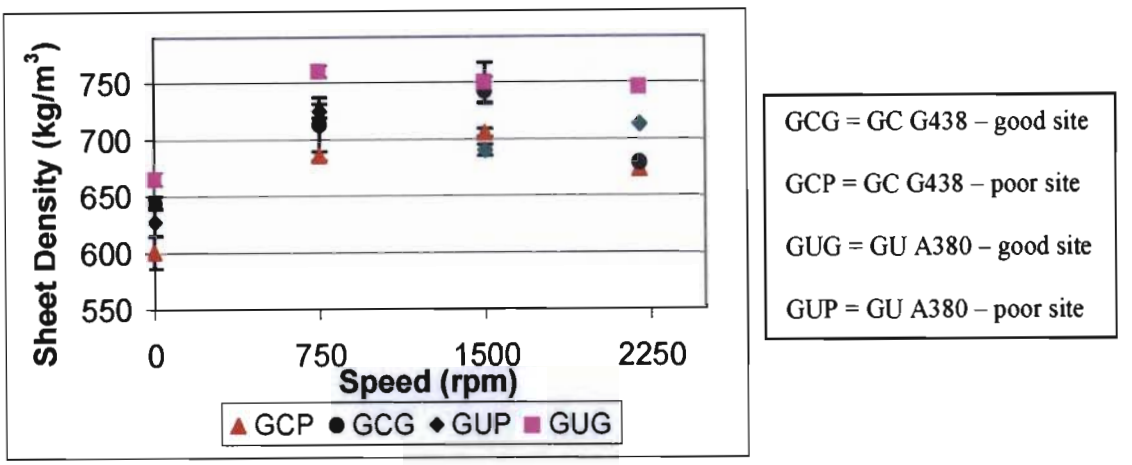


Figure 6.36: Graph of sheet density at 400CSF

The pulp from the GCG resulted in sheets with higher mean stretch at all three speeds (Figure 6.37). The pulp from the GUP resulted in sheets with the lowest stretch when refined at the two higher speeds (Table 6.13). For the two GC clones there were no significant differences in stretch with the three different speeds (Table 6.12). For the GUG the stretch of the pulp refined at 1500 rpm was significantly higher than when refined at 2200 rpm. For the GUP refining at 750 rpm resulted in significantly higher stretch than when refined at 2200 rpm.

Multiple regression analysis (Tables 6.13 and 6.14), showed that at 750 rpm neither initial pulp nor wood properties could give a good prediction of the stretch. At the two higher speeds the initial pulp fibre length and also the wood coarseness and wood Runkel ratio was able to account for some of the differences in stretch.

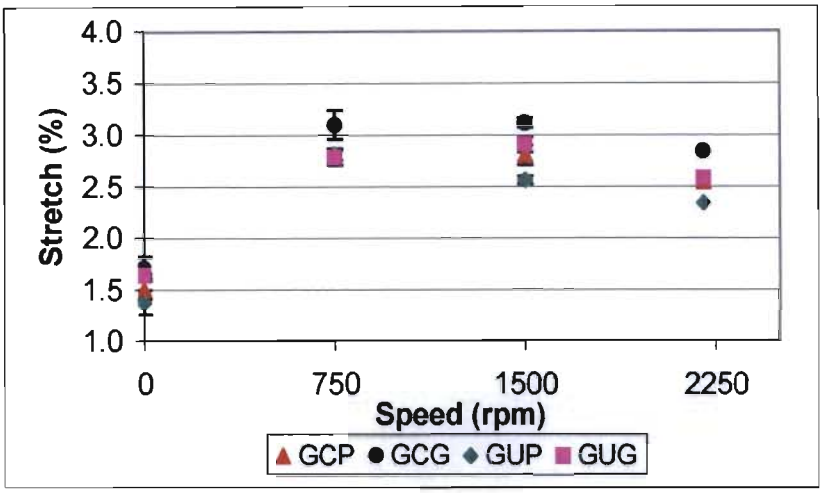


Figure 6.37: Graph of stretch at 400CSF

Figure 6.38 shows the tensile energy absorbed by the pulps at 400CSF. It was seen that when refined at the highest speed, the pulps had the lowest TEA. The results of the multiple regression analysis (Tables 6.13 and 6.14), show that at all speeds the initial pulp fibre length was able to predict the TEA to some extent though not very strongly. At the two lower speeds the wood coarseness was able to explain some of the differences in TEA.

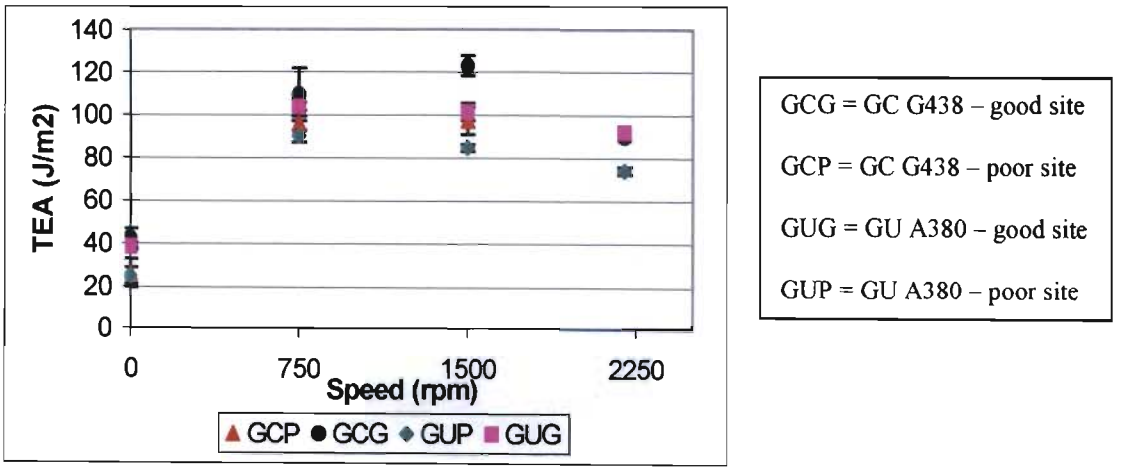


Figure 6.38: Graph of TEA at 400CSF

With the exception of the GCP the other sites all had the highest zero span tensile strength when refined at 750 rpm (figure 6.39). For the GCP, the zero span tensile strength did not change much with the different speeds of refining when compared at a freeness of 400 ml, the other sites decreased with increasing speed. The differences in zero span tensile strength due to the different pulps were most marked when refined at 2200 rpm. The results from the multiple regression analysis (Tables 6.13 and 6.14), show that at 2200 rpm the wood or initial pulp coarseness was able to account for most of the differences in zero-span tensile at 400CSF. When refining was carried out at 1500 rpm, the wood cell wall thickness was a good predictor of the zero-span tensile and from the initial pulp properties, a combination of pulp coarseness and fibre length also gave a good prediction of the zero-span tensile.

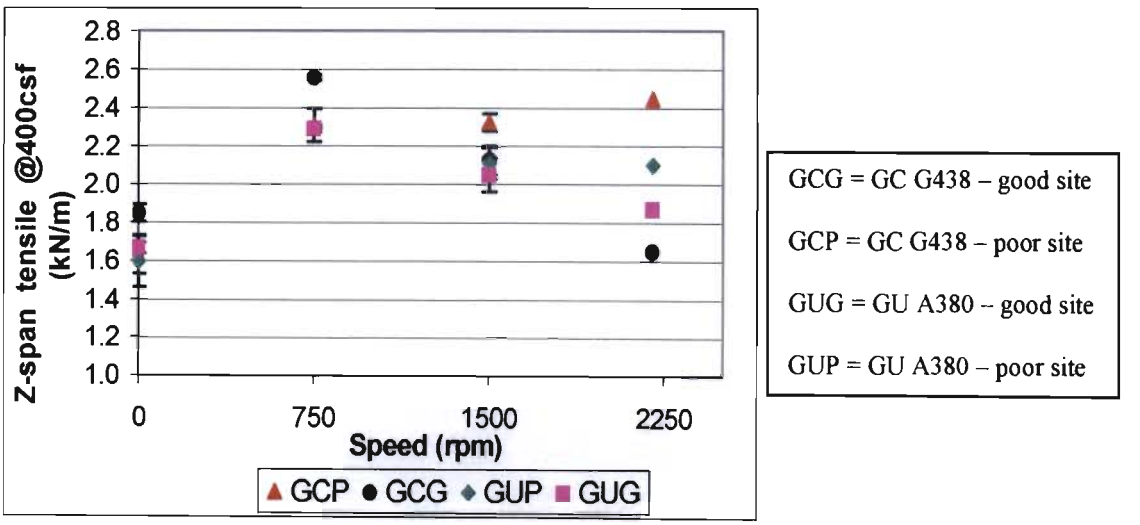


Figure 6.39: Graph of TEA at 400CSF

Table 6.13: Multiple regression analysis results using initial pulp anatomy to predict pulp freeness and sheet properties at constant freeness (400ml)

750 rpm (SEL range = 0.15 Ws/m - 0.22 Ws/m)									
	SRE	SEL	Tensile	Tear	Burst	Sheet density	Stretch	TEA	Z-span
Model R^2	80.41	61.01	36.2	61.67	58.21	78.44	32.97	59.02	90.5
p-value	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
Contributors to the model and their percentage contribution									
i-Coarse	80.41				45.34				34.47
I-LD		42.83	36.2						56.03
i-FL		18.18		61.67				59.02	
i-fines						17.59	32.97		
i-Collaps					12.87				
i-FD						60.85			

1500 rpm (SEL range = 0.31 Ws/m - 0.43 Ws/m)									
	SRE	SEL	Tensile	Tear	Burst	Sheet density	Stretch	TEA	Z-span
Model R^2	77.01	87.83	34.97	74.53	89.4	82.29	56.48	50.95	89.6
p-value	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
Contributors to the model and their percentage contribution									
i-Coarse		18.3			12.47	47.3			44.94
I-LD									
i-FL	77.01	69.53	34.97	74.53	76.93		56.48	50.95	44.66
i-CWT						34.99			

2200 rpm (SEL range = 0.45 Ws/m - 0.52 Ws/m)									
	SRE	SEL	Tensile	Tear	Burst	Sheet density	Stretch	TEA	Z-span
Model R^2	61.72	40.32	58.08	92.67	87.41	57.39	58.4	43.31	96.85
p-value	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
Contributors to the model and their percentage contribution									
i-Coarse					57.88				91.23
I-LD			23.89	17.93	22.64	57.39			
i-FL	61.72	40.32	34.19	74.74	6.89		58.4	43.31	5.62

Table 6.14: Multiple regression analysis results using initial wood anatomy to predict pulp freeness and sheet properties at constant freeness (400ml)

750 rpm (SEL range = 0.15 Ws/m - 0.22 Ws/,)									
	SRE	SEL	Tensile	Tear	Burst	Sheet density	Stretch	TEA	Z-span
Model R^2	79.21	74.98	37.64	54.78	62.44	72.76	30.66	45.17	99.18
p-value	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
Contributors to the model and their percentage contribution									
Density					62.44				
WCWT		74.98							23.06
w-Coarse	79.21			30.88				45.17	
WFD							30.66		76.12
w-Collaps			37.64						
w-Runkel				23.9		72.76			

1500 rpm (SEL range = 0.31 Ws/m - 0.43 Ws/m)									
	SRE	SEL	Tensile	Tear	Burst	Sheet density	Stretch	TEA	Z-span
Model R^2	28.52	93.06	23.13	77.59	65.1	50.58	53.08	58.51	71.79
p-value	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
Contributors to the model and their percentage contribution									
WCWT		14.14							71.79
w-Coarse	28.52	60.06	23.13	34.19	53.57	50.58	38.27	34.18	
w-Collaps		18.86							
w-Runkel				43.4	11.53		14.81	24.33	

2200 rpm (SEL range = 0.45 Ws/m - 0.52 Ws/m)									
	SRE	SEL	Tensile	Tear	Burst	Sheet density	Stretch	TEA	Z-span
Model R^2	91.76	33.89	39.5	83.18	81.12	73.39	67.04	-	87.43
p-value	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
Contributors to the model and their percentage contribution									
Density			39.5						
WCWT					71.15				
WLD						73.39			
w-Coarse	54.22	33.89		28.52	9.97		36.48		87.43
Runkel	37.54			54.66			30.56		

6.6 Summary of findings

Wood Anatomy and Density

- There were larger differences in density due to differences in site than differences in species. These significant differences due to site must be considered when selecting where to grow these species.
- There were significant differences in the wood anatomical properties measured except for:
    - GCG and GCP which had similar lumen diameter
    - GCG, GCP and GUP which had similar collapsibility
    - GCG and GUP which had similar cell wall thickness
    - GCP and GUP which had similar fibre diameter

Pulp properties

- Good sites had a higher yield than poor sites.
- The good sites had longer and less coarse fibres than the poor sites. The GU clones have shorter fibres than the GC clones
- The GUG had the largest fibre diameter and lumen diameter and the thinnest cell walls. Thus they were the most collapsible fibres compared to the other three pulps.

Overall strength properties

- The SRE was the best predictor for freeness and all strength properties except the tear strength. For the tear strength the best predictor was the initial pulp fibre length
- Tensile strength developed the slowest when refined at the lowest speed of 750 rpm.
- GCG gave the highest tear strength and the GUP gives the lowest tear strength at all speeds. The GCP and GUG have similar tear strength
- At 1500 rpm, the GCG quickly achieved the highest tear strength but the tear strength declined rapidly. At other speeds the maximum tear strength achieved was maintained for longer. The GCG gave the best tear tensile relationship.
- At 750 rpm the maximum tear strength for the pulps occurred at about 70 kNm/kg and the higher speeds the maximum tear strength occurred at a higher tensile strength (about 90 kNm/kg)

- At 1500 rpm, differences in burst strength, tensile strength, TEA, sheet density and zero-span tensile among the different pulps was small.
- For stretch the least difference amongst pulps occurred at the highest speed (2200 rpm).
- For the zero-span tensile, the largest most differences due to different pulps occurred when refined at 2200 rpm.

At constant SRE

- GUP, which had the lowest fibre length initially, underwent the largest decrease in fibre length
- With refining the amount of fines increased with higher speeds for the GU clones.
- Least differences in freeness among the four pulps occurred at 750 rpm.
- There was an increase in tensile strength from 750 rpm to 1500 rpm but for all the pulps except the GUG the tensile strength dropped at 2200 rpm. The GUG developed its tensile strength the fastest.
- GCG gives the highest tear strength and the GUP gives the lowest tear strength at all speeds. The GCP and GUG have similar tear strength
- At the lowest speed, the good sites have higher burst strength than the poor sites. At the highest speed both GU clones higher burst strength than the GC clones.
- The biggest differences in zero-span tensile among the different pulps occurred at 2200 rpm.

Constant Freeness

- Only the GU clones underwent very slight decrease in pulp fibre length.
- There was a general decrease in pulp cell wall thickness which was independent of the refining speed used.
- The GU sites had a larger increase in fines content with the GUG having the highest increase in fines content.
- GCG gives the highest tear strength and the GUP gives the lowest tear strength at all speeds. The GCP and GUG have similar tear strength
- There was a decrease in stretch and TEA at the highest speed.
- Zero-span tensile for the good sites decreased at 2200 rpm.

Chapter 7

Conclusions and Recommendations

Phase 1

It was seen that although different variables were used to vary the specific refining energy the SRE was still a very good predictor of the pulp properties, even though the variables themselves were not good predictors of the properties. It was noted that the control of flow rate led to good development of the tear strength compared to the other methods used to vary the SRE. This finding could have important implications if this finding is backed up with confirmatory studies on different pulps. Further investigations should be done on this since it is desirable to develop the optimum tear strength for specific grades. However the results indicated that the high tear strength occurred at low flow rates. This would affect the production rates in the mill and it should be noted that the opportunity to manipulate flow rate is fairly limited in an industrial environment and the practical limitations should be taken into account in an experimental design.

In personal communications with a number of refiner experts (Joris 2005, Pauck 2004-2005), it was concluded that the existing refiner plate pattern was not ideal for low consistency refining of *eucalyptus* pulps. The 10 mm groove between sectors was higher than normally acceptable in a refiner of this size. Due to machining limitations , this is the smallest groove size achievable in normal plate production. In order to resolve this technical limitation, future plates would have to be manufactured with casting technology. It was decided that while the plate pattern is not ideal, it was the best at the time and its limitations do not invalidate the work done using this plate It is recommended that a more appropriate plate pattern be specially cast to obviate machining limitations.

Phase 2

The results from phase 2 of the project showed that there were differences in the refining characteristics between bleached and unbleached pulp. However the results indicated that the differences in the refining characteristic occurred in a predictable manner. This indicated that

refining work carried out on unbleached pulp could be used to predict how fully bleached pulp would behave on refining. This finding indicated that it was acceptable to carry out phase 3 of the project on different genetic material in an unbleached form.

Phase 3

With the range of different pulp characteristics it was found that, the SRE was still the best predictor of the pulp freeness and other strength properties measured except for tear strength. If SRE and SEL were left out of the multiple regression analysis and only the pulp properties were considered in the multiple regression, then it was seen that pulp cell wall thickness gave good predictions for most of the pulp properties and the fines content gave a fairly good prediction of the sheet density. For tear strength, initial pulp fibre length was the best predictor.

When refining *eucalyptus* pulps using a low refiner speed of 750 rpm (SEL range for the different pulps = 0.15 to 0.22 Ws/m), the specific refining energy required to reach a freeness of 400 ml was significantly higher than when refining at the two higher refining speeds. This implies that the SRE demand could be lowered if refining was carried out at higher intensities. It was seen in the case of the GCG clone that by refining at an intensity of about 0.4 Ws/m instead of 0.2 Ws/m, the high tear strength was still maintained while the other strength properties increased and the SRE required to reach 400 ml was lower than when refined at an intensity of 0.2 Ws/m.

All clones responded in a similar manner to refining conditions. This would indicate that clones with different characteristics can be processed together under the same conditions. However there were significant differences between the clones, most notably for tear strength. These differences were driven by anatomical characteristics and remained fairly constant throughout at different refining conditions. It is therefore recommended that if products with specific characteristics are required then material with appropriate characteristics should be selected.

The GCG should be used in grades where high tear strength is required. This pulp should be refined using a SEL of about 0.4 Ws/m as this was seen to be the most favourable. For this pulp refining at this intensity resulted in this pulp achieving its highest strength properties. The GUG resulted in good tensile strength and moderate tear strength. This pulp would be ideal for grades requiring high tensile strength and where high tear strength is not required.

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Appendix A

Equations

1. Calculations for pulping properties

The equations below show how the pulp yield and rejects were calculated.

$$Screened\ pulp\ yield\ (\%) = \frac{Mass\ of\ oven\ dry\ pulp}{mass\ of\ oven\ dry\ chips} \times 100\% \qquad \ldots A1$$

$$\text{Re}\ jects\ (\%) = \frac{Mass\ of\ oven\ dry\ rejects}{mass\ of\ oven\ dry\ chips} \times 100\% \qquad \ldots A2$$

$$Total\ pulp\ yield\ (\%) = Screened\ pulp\ yield\ (\%) + \text{Re}\ jects\ (\%) \qquad \ldots A3$$

2. Calculations for refining energy and refining intensity

The control panel on the refiner gives the percentage of the nominal power that is being used. The no-load power (P_o) was calculated by running the refiner with only water at the appropriate speed. The net refining power was calculated as the difference between the gross refiner power (P) and the no-load power.

$$P_{net} = P - P_o \qquad \ldots A4$$

The stock flow rate in litres per second was converted to a volumetric flow rate (m^3/hour). Assuming a stock density of 1 ton/m^3 the volumetric flow rate was converted to a mass flow rate (m).

$$m\ (ton/h) = stock\ \ flow\ rate(l/s) \times \frac{1m^3}{1000l} \times \frac{3600s}{1h} \times \frac{1ton}{1m^3} \qquad \ldots A5$$

Using the stock consistency the fibre flow (M) rate can be calculated.

$$M\ (ton/h) = m\ (ton/h) \times \frac{consistency\ (\%)}{100\%} \qquad \ldots A6$$

The specific refining energy (SRE) was then calculated as the net power divided by the fibre flow rate.

$$SRE\,(kWh/ton) = \frac{P_{net}\,(kW)}{M\,(ton/h)} \qquad \ldots A7$$

The refining intensity (SEL) was calculated as,

$$SEL\,(Ws/m) = \frac{P_{net}\,(kW)}{CEL\,(m/rev) \times speed\,(rev/s)} \qquad \ldots A8$$

The CEL is the cutting edge length in meters per revolution. This is fixed for a given set of refiner plate. For the refiner plates that was used the CEL was 279.01 m/rev in the anticlockwise direction which was used. The speed is the speed of rotation of the refiner plates in revolutions per second when used in this equation.

3. Calculations for pulp properties

a) Freeness

The pulp freeness was recorded as the volume of water (ml) that drained out of the side orifice of the freeness tester. The freeness was corrected for temperature and mass according to the equations listed in the Tappi standards.

b) Basis Mass

The average mass of the conditioned sheets in grams were determined. The bone dry mass was calculated by assuming that the conditioned sheets had a moisture content of 7%. The diameter of one handsheet is 20cm or 0.2m. The area of the handsheet was determined and the basis mass was calculated using equation A1.

$$Basis\ mass\,(g/m^2) = \frac{Average\ bone\ dry\ mass\,(g)}{Area\ of\ sheet\,(m^2)} \qquad \ldots A9$$

c) Sheet Density

Bulk thickness values were recorded on micrometer. Sheet density in kg/m^3 was calculated by dividing the basis mass in kg/m^2 by the bulk thickness m (equation A2).

$$Sheet\ density(kg/m^3) = \frac{Basis\ mass\ (kg/m^2)}{bulk\ thickness\ (m)} \qquad \ldots A10$$

d) Burst Index

The units for burst strength from the instrument were in kilopascals (kNm^{-2}). The burst index was obtained by dividing the burst strength by the basis mass (equation A3).

$$BUSRT\ INDEX\ (kN/g) = \frac{Average\ bursting\ strength(kN/m^2)}{Basis\ Mass(g/m^2)} \qquad \ldots A11$$

The burst results will be presented in the units of MN/kg. The results in MN/kg are numerically equal to the results in kN/g since 1kN/g = 1MN/kg

e) Tear Index

The machine gave the tear strength in milli-Newtons (mN). The tear index was calculated by dividing the tear strength in Newtons(N) by the basis mass in kg/m^2 (equation A4).

$$TEAR\ INDEX\ (Nm^2/Kg) = \frac{Average\ Tear\ Strength\ (N)}{Basis\ Mass\ (kg/m^2)} \qquad \ldots A12$$

f) Tensile Index

The machine gave the tensile force in Newtons (N). The tensile strip had a width of 15 mm or 0.015 m. The tensile strength was calculated as the tensile force (N) divided by the strip width (m). Then the tensile index was calculated from equation A5.

$$TENSILE\ INDEX\ (Nm/g) = \frac{Average\ Tensile\ Strength\ (N/m)}{Basis\ Mass\ (g/m^2)} \qquad \ldots A13$$

The results were presented in kNm/kg. The results in kNm/kg are numerically equal to the results in Nm/g since 1 Nm/g = 1 kNm/kg.

g) Stretch

The stretch was recorded from the tensile machine together with the tensile force. The stretch was recorded as a percentage and presented in the same way.

h) Tensile energy absorbed (TEA)

The TEA was recorded from the tensile machine together with the tensile force. The TEA was recorded in J/m^2 and presented in the same way.

i) Zero-span tensile (Z-span)

The machine gave the tensile force in Newtons (N). This was divided by the strip width (0.015m) to give the zero-span tensile force in N/m. The results had to be corrected to a basis mass of 60 g/m^2. This was done by my multiplying the zero-span tensile force by (60 g/m^2/basis mass (g/m^2).

$$ZERO\ SPAN\ TENSILE\ (N/m) = \frac{Average\ Zero\ span Tensile\ Strength\ (N/m) \times 60 g/m^2}{Basis\ Mass\ (g/m^2)} \quad \ldots A14$$

4. Calculations of certain morphological properties

a) Coarseness

The wood coarseness was calculated using equation A15 (Miles *et al.* 1991). The pulp fibre collapsibility was obtained by multiplying the wood coarseness by the yield (Britt 1966).

$$Coarseness = wood\ fibre\ diameter \times wood\ density \quad \ldots A15$$

b) Collapsibility

The collapsibility gives an indication of how collapsible the fibre are. The higher the collapsibility the more collapsible the fibres. The collapsibility was calculated according to equation A16

$$Collapsibility = \frac{3 \times fibre\ diameter + 5 \times cell\ wallt\ hickness}{(cell\ wall\ thickness)^2} \quad \ldots A16$$

c) Muhlsteph Ratio

The muhlsteph ratio is also an indication of fibre collapsibility. The lower the muhlsteph ratio the more collapsible the fibres. Equation A17 gives the equation for the muhlsteph ratio (Seth *et al.* 1997)

$$Muhlsteph = \frac{(fibre\ diameter)^2 - (lumen\ diameter)^2}{fibre\ diameter} \quad \ldots A17$$

d) Runkel Ratio

The Runkel ratio is also an indication of collapsibility. Equation A18 gives the equation for the Runkel ratio.

$$Runkel\ ratio = \frac{2 \times cell\ wall\ thickness}{fibre\ diameter}$$

Table B1: Energy calculation results for when varying flow rate

run 1

Gap setting	micron	25	25	25	25
% power	%	53.90	62.66	61.43	62.87
% no load power	%	29.38	29.38	29.38	29.38
full power	kW	18.50	18.50	18.50	18.50
flow	l/s	0.60	1.00	1.50	2.00
consistency	%	3.04	3.04	3.04	3.04
Power	kW	9.97	11.59	11.36	11.63
Po	kW	5.44	5.44	5.44	5.44
Speed	rpm	2200.00	2200.00	2200.00	2200.00
P-Po	kW	4.54	6.16	5.93	6.20
Peripheral-speed	m/s	23.37	23.37	23.37	23.37
Vol Flow	M^3/h	2.16	3.60	5.40	7.20
Mass Flow	ton/hr	2.16	3.60	5.40	7.20
M	ton/hr	0.07	0.11	0.16	0.22
CEL	m/rev	279.01	279.01	279.01	279.01
Ls	m/s	10230.33	10230.33	10230.33	10230.33
SRE	**kWh/ton**	**69.08**	**56.25**	**36.12**	**28.31**
SEL	**Ws/m**	**0.44**	**0.60**	**0.58**	**0.61**

run 2

Gap setting	micron	25	25	25	25
% power	%	53.31	61.83	60.99	62.19
% no load power	%	29.38	29.38	29.38	29.38
full power	kW	18.50	18.50	18.50	18.50
flow	l/s	0.60	1.00	1.50	2.00
consistency	%	2.98	2.98	2.98	2.98
Power	kW	9.86	11.44	11.28	11.51
Po	kW	5.44	5.44	5.44	5.44
Speed	rpm	2200	2200	2200	2200
Peripheral-speed	m/s	23.37	23.37	23.37	23.37
P-Po	kW	4.43	6.00	5.85	6.07
Vol Flow	M^3/h	2.16	3.60	5.40	7.20
Mass Flow	ton/hr	2.16	3.60	5.40	7.20
M	ton/hr	0.06	0.11	0.16	0.21
CEL	m/rev	279.01	279.01	279.01	279.01
Ls	m/s	10230.33	10230.33	10230.33	10230.33
SRE	**kWh/ton**	**68.78**	**55.95**	**36.34**	**28.29**
SEL	**Ws/m**	**0.43**	**0.59**	**0.57**	**0.59**

run3

Gap setting	micron	25	25	25	25
% power	%	53.72	60.62	60.99	62.86
% no load power	%	29.38	29.38	29.38	29.38
full power	kW	18.50	18.50	18.50	18.50
flow	l/s	0.60	1.00	1.50	2.00
consistency	%	2.96	2.96	2.96	2.96
Power	kW	9.94	11.22	11.28	11.63
Po	kW	5.44	5.44	5.44	5.44
Speed	rpm	2200	2200	2200	2200
Peripheral-speed	m/s	23.37	23.37	23.37	23.37
P-Po	kW	4.50	5.78	5.85	6.19
Vol Flow	M^3/h	2.16	3.60	5.40	7.20
Mass Flow	ton/hr	2.16	3.60	5.40	7.20
M	ton/hr	0.06	0.11	0.16	0.21
CEL	m/rev	279.01	279.01	279.01	279.01
Ls	m/s	10230.33	10230.33	10230.33	10230.33
SRE	**kWh/ton**	**70.43**	**54.24**	**36.59**	**29.06**
SEL	**Ws/m**	**0.44**	**0.56**	**0.57**	**0.61**

Table B2: Energy calculation results for when varying consistency

run 1

Gap setting	micron	25	25	25	25
% power	%	62.98	63.10	64.70	65.05
% no load power	%	30.30	30.30	30.30	30.30
full power	kW	18.50	18.50	18.50	18.50
flow	l/s	1.00	1.00	1.00	1.00
consistency	%	**2.60**	**2.97**	**4.00**	**4.78**
Power	kW	11.65	11.67	11.97	12.03
Po	kW	5.61	5.61	5.61	5.61
Speed	rpm	2200.00	2200.00	2200.00	2200.00
Peripheral-speed	m/s	23.37	23.37	23.37	23.37
P-Po	kW	6.05	6.07	6.36	6.43
Vol Flow	M^3/h	3.60	3.60	3.60	3.60
Mass Flow	ton/hr	3.60	3.60	3.60	3.60
M	ton/hr	0.09	0.11	0.14	0.17
CEL	m/rev	279.01	279.01	279.01	279.01
Ls	m/s	10230.33	10230.33	10230.33	10230.33
SRE	kWh/ton	64.59	56.75	44.19	37.36
SEL	Ws/m	0.59	0.59	0.62	0.63

run 2

Gap setting	micron	25	25	25	25
% power	%	61.47	62.16	64.59	65.01
% no load power	%	30.30	30.30	30.30	30.30
full power	kW	18.50	18.50	18.50	18.50
flow	l/s	1.00	1.00	1.00	1.00
consistency	%	**2.60**	**3.00**	**4.00**	**4.78**
Power	kW	11.37	11.50	11.95	12.03
Po	kW	5.61	5.61	5.61	5.61
Speed	rpm	2200.00	2200.00	2200.00	2200.00
Peripheral-speed	m/s	23.37	23.37	23.37	23.37
P-Po	kW	5.77	5.89	6.34	6.42
Vol Flow	M^3/h	3.60	3.60	3.59	3.61
Mass Flow	ton/hr	3.60	3.60	3.59	3.61
M	ton/hr	0.09	0.11	0.14	0.17
CEL	m/rev	279.01	279.01	279.01	279.01
Ls	m/s	10230.33	10230.33	10230.33	10230.33
SRE	kWh/ton	61.61	54.58	44.19	37.17
SEL	Ws/m	0.56	0.58	0.62	0.63

run 3

Gap setting	micron	25	25	25	25
% power	%	61.78	63.81	66.31	66.80
% no load power	%	30.30	30.30	30.30	30.30
full power	kW	18.50	18.50	18.50	18.50
flow	l/s	1.00	1.00	1.00	1.00
consistency	%	**2.60**	**3.00**	**4.00**	**4.78**
Power	kW	11.43	11.80	12.27	12.36
Po	kW	5.61	5.61	5.61	5.61
Speed	rpm	2200.00	2200.00	2200.00	2200.00
Peripheral-speed	m/s	23.37	23.37	23.37	23.37
P-Po	kW	5.82	6.20	6.66	6.75
Vol Flow	M^3/h	3.60	3.60	3.59	3.60
Mass Flow	ton/hr	3.60	3.60	3.59	3.60
M	ton/hr	0.09	0.11	0.14	0.17
CEL	m/rev	279.01	279.01	279.01	279.01
Ls	m/s	10230.33	10230.33	10230.33	10230.33
SRE	kWh/ton	62.22	57.40	46.45	39.24
SEL	Ws/m	0.57	0.61	0.65	0.66

Table B3: Energy calculation results for when varying speed

run 1

Gap setting	micron	25	25	25	25
% power	%	28.64	42.84	52.67	68.82
% no load power	%	14.06	21.86	29.60	33.22
full power	kW	18.50	18.50	18.50	18.50
flow	l/s	1.05	1.05	1.05	1.05
consistency	%	3.05	3.05	3.05	3.05
Power	kW	5.30	7.93	9.74	12.73
Po	kW	2.60	4.04	5.48	6.15
Speed	rpm	**1500**	**1750**	**2000**	**2200**
Peripheral-speed	m/s	15.9	18.59	21.25	23.37
P-Po	kW	2.70	3.88	4.27	6.59
Vol Flow	M^3/h	3.78	3.78	3.78	3.78
Mass Flow	ton/hr	3.78	3.78	3.78	3.78
M	ton/hr	0.12	0.12	0.12	0.12
CEL	m/rev	279.01	279.01	279.01	279.01
Ls	m/s	6975.23	8137.76	9300.30	10230.33
SRE	kWh/ton	23.40	33.67	37.02	57.13
SEL	Ws/m	0.39	0.48	0.46	0.64

run 2

Gap setting	micron	25	25	25	25
% power	%	29.58	42.02	57.75	70.16
% no load power	%	14.23	21.17	28.80	34.35
full power	kW	18.50	18.50	18.50	18.50
flow	l/s	1.03	1.03	1.03	1.03
consistency	%	3.07	3.07	3.07	3.07
Power	kW	5.47	7.77	10.68	12.98
Po	kW	2.63	3.92	5.33	6.35
Speed	rpm	**1500**	**1750**	**2000**	**2200**
Peripheral-speed	m/s	15.9	18.59	21.25	23.37
P-Po	kW	2.84	3.86	5.36	6.63
Vol Flow	M^3/h	3.71	3.71	3.71	3.71
Mass Flow	ton/hr	3.71	3.71	3.71	3.71
M	ton/hr	0.11	0.11	0.11	0.11
CEL	m/rev	279.01	279.01	279.01	279.01
Ls	m/s	6975.23	8137.76	9300.30	10230.33
SRE	kWh/ton	24.93	33.89	47.04	58.20
SEL	Ws/m	0.41	0.47	0.58	0.65

run3

Gap setting	micron	25	25	25	25
% power	%	28.64	41.75	57.54	69.17
% no load power	%	14.23	21.17	28.80	34.35
full power	kW	18.50	18.50	18.50	18.50
flow	l/s	1.00	1.00	1.00	1.00
consistency	%	3.01	3.01	3.01	3.01
Power	kW	5.30	7.72	10.64	12.80
Po	kW	2.63	3.92	5.33	6.35
Speed	rpm	**1500**	**1750**	**2000**	**2200**
Peripheral-speed	m/s	15.9	18.59	21.25	23.37
P-Po	kW	2.67	3.81	5.32	6.44
Vol Flow	M^3/h	3.60	3.60	3.60	3.60
Mass Flow	ton/hr	3.60	3.60	3.60	3.60
M	ton/hr	0.11	0.11	0.11	0.11
CEL	m/rev	279.01	279.01	279.01	279.01
Ls	m/s	6975.23	8137.76	9300.30	10230.33
SRE	kWh/ton	24.60	35.14	49.06	59.45
SEL	Ws/m	0.38	0.47	0.57	0.63

Table B4: Raw Data for work from phase 1

Speed (rpm)	Gap (micron)	Consistency (%)	Flow (l/s)	SRE (kWh/t)	SEL (Ws/m)	Freeness (ml)	Basis Mass (g/m^2)	Burst (MN/kg)	Tear kNm^2/kg	Tensile (kNm/kg)	Stretch (%)	Sheet Density (kg/m^3)	TEA (J/m^2)
2200	25	4.78	1	39.24	0.66	406.03	60.44	4.37	10.10	62.54	2.75	639.94	76.99
2200	25	4.78	1	37.36	0.63	452.31	61.87	3.36	9.65	56.07	2.52	611.06	64.83
2200	25	4.78	1	37.17	0.63	424.41	61.43	4.12	10.31	67.17	2.62	668.08	71.14
2200	25	4	1	44.19	0.62	418.97	57.28	4.30	9.39	72.23	2.72	641.41	83.77
2200	25	4	1	46.45	0.65	429.61	57.97	4.44	9.76	72.90	2.86	673.23	77.77
2200	25	4	1	44.19	0.62	445.30	56.64	4.08	8.93	69.04	2.65	663.10	71.20
2200	25	3	1	56.75	0.59	386.14	59.55	3.75	9.10	64.12	2.54	653.61	83.58
2200	25	3	1	54.58	0.58	393.65	60.93	4.12	10.08	70.10	2.71	677.03	80.42
2200	25	3	1	57.40	0.61	375.86	60.09	4.41	8.85	73.46	2.76	677.11	90.02
2200	25	2.6	1	61.61	0.56	393.15	59.06	4.29	9.39	66.39	2.84	635.60	70.98
2200	25	2.6	1	62.22	0.57	374.45	62.71	4.77	9.07	66.99	2.48	683.06	81.02
2200	25	2.6	1	64.59	0.59	400.84	58.71	4.13	9.50	62.91	2.76	651.35	65.02
0	0	0	0	0.00	0.00	533.40	60.59	2.01	7.20	42.42	1.84	571.73	33.01
0	0	0	0	0.00	0.00	522.99	60.59	2.01	6.95	42.42	1.89	571.73	37.00
0	0	0	0	0.00	0.00	543.70	57.73	2.34	7.14	44.52	1.79	592.90	40.00
2200	25	3	2	28.31	0.61	431.84	60.34	3.60	9.86	55.53	2.31	645.54	55.68
2200	25	3	2	28.29	0.59	444.90	57.68	4.30	8.89	66.18	2.63	622.59	70.51
2200	25	3	2	29.06	0.61	433.36	57.03	3.79	8.98	64.26	2.54	648.74	60.90
2200	25	3	1.5	36.12	0.58	417.02	56.00	3.86	10.08	65.94	2.31	647.18	62.99
2200	25	3	1.5	36.34	0.57	421.31	58.51	3.93	8.75	64.74	2.65	657.27	56.67
2200	25	3	1.5	36.59	0.57	428.21	59.30	4.03	9.89	58.80	2.71	634.46	68.94
2200	25	3	1	55.95	0.59	393.15	59.06	4.29	9.39	69.21	2.84	635.60	71.98
2200	25	3	1	54.24	0.56	374.45	62.71	4.77	9.72	66.99	2.48	683.06	81.02
2200	25	3	1	56.25	0.60	400.84	58.71	4.13	10.36	71.43	2.70	651.35	69.02
2200	25	3	0.6	70.43	0.44	299.49	53.63	5.78	10.83	79.72	3.43	699.53	94.52
2200	25	3	0.6	68.78	0.43	333.56	56.39	5.21	10.45	83.45	3.47	694.07	104.45
2200	25	3	0.6	69.08	0.44	318.77	56.10	5.04	10.51	73.23	3.42	695.18	96.37

...Table B4 continued

Speed (rpm)	Gap (micron)	Consistency (%)	Flow (l/s)	SRE (kWh/t)	SEL (Ws/m)	Freeness (ml)	Basis Mass (g/m^2)	Burst (MN/kg)	Tear kNm^2/kg	Tensile (kNm/kg)	Stretch (%)	Sheet Density (kg/m^3)	TEA (J/m^2)
0	0	0	0	0.00	0.00	531.33	63.25	2.05	6.98	41.18	1.47	576.47	40.98
0	0	0	0	0.00	0.00	548.57	56.39	2.48	7.27	45.87	1.77	592.75	35.34
0	0	0	0	0.00	0.00	548.57	56.39	2.48	7.27	45.87	1.77	592.75	40.98
2200	25	3	1	58.20	0.65	400.72	56.64	4.42	9.14	63.83	2.75	671.84	81.62
2200	25	3	1	59.45	0.63	412.42	56.05	4.19	8.97	70.98	2.71	671.46	74.40
2200	25	3	1	57.13	0.64	428.31	63.50	4.21	9.37	65.83	2.53	670.36	74.40
1500	25	3	1	23.40	0.39	480.92	63.35	3.06	8.28	53.81	2.65	617.21	62.93
1500	25	3	1	24.60	0.38	462.74	60.59	3.46	8.58	56.91	2.66	617.89	62.93
1500	25	3	1	24.93	0.41	472.41	57.28	3.64	9.40	58.58	2.63	633.53	63.46
1750	25	3	1	33.67	0.48	456.01	63.84	3.38	9.46	55.46	2.60	625.41	65.37
1750	25	3	1	35.14	0.47	443.09	53.19	3.59	10.24	62.80	2.59	638.24	65.37
1750	25	3	1	33.89	0.47	437.50	53.38	4.00	10.31	62.72	2.72	638.48	62.66
2000	25	3	1	37.02	0.46	439.40	65.42	3.67	9.24	59.40	2.53	652.41	70.48
2000	25	3	1	49.06	0.57	422.00	60.09	4.45	9.80	66.28	2.89	682.45	70.48
2000	25	3	1	47.04	0.58	407.76	54.27	4.16	9.14	61.71	2.65	637.45	72.43

Table C1: Raw data for refining trials carried out on unbleached pulp in phase 2

Sample	Stage& Replicate	SRE	SEL	Freeness	Basis mass	Burst	Tear	Tensile	Stretch	Sheet Density	TEA
		(kWh/t)	(Ws/m)	(ml)	(g/m^2)	(MN/kg)	(kNm^2/kg)	(kNm/kg)	(%)	(kg/m^3)	(J/m^2)
Unbleached	0A	0.00	0.00	527.00	62.90	2.28	7.40	35.37	1.21	580.84	26.33
Unbleached	0B	0.00	0.00	544.00	65.99	1.84	6.80	30.33	1.29	590.37	30.25
Unbleached	0C	0.00	0.00	515.64	58.47	2.34	7.21	42.58	1.83	605.71	28.68
Unbleached	1A	34.58	0.72	406.57	60.07	3.49	9.19	58.53	1.98	626.78	69.16
Unbleached	1B	32.00	0.68	410.92	65.19	3.67	9.31	55.58	2.48	674.36	62.96
Unbleached	1C	32.48	0.60	438.36	61.96	3.84	9.78	62.33	2.68	658.01	70.74
Unbleached	2A	69.17	0.72	376.32	60.88	4.20	9.91	62.66	2.76	647.89	76.84
Unbleached	2B	64.01	0.68	359.00	65.19	4.37	9.14	67.90	3.22	718.61	85.56
Unbleached	2C	64.96	0.60	390.00	62.10	3.85	9.82	68.05	2.60	670.31	73.30
Unbleached	3A	103.75	0.72	347.56	60.29	4.60	9.68	70.34	2.81	637.44	85.12
Unbleached	3B	96.01	0.68	315.00	63.44	5.06	8.51	74.89	3.11	752.51	99.21
Unbleached	3C	97.43	0.60	337.33	56.85	4.78	8.83	79.48	3.22	700.95	99.42
Unbleached	4A	138.34	0.72	233.42	60.80	5.41	8.87	89.37	3.08	716.70	118.40
Unbleached	4B	128.02	0.68	242.00	65.73	6.01	8.53	83.78	3.39	810.32	121.11
Unbleached	4C	129.91	0.60	264.42	60.70	6.01	8.18	84.53	3.68	748.40	107.30
Unbleached	5A	172.92	0.72	201.00	57.10	5.78	7.88	91.52	3.10	709.68	114.10
Unbleached	5B	160.02	0.68	175.00	62.70	6.62	7.43	95.72	4.06	822.94	136.19
Unbleached	5C	162.39	0.60	212.34	58.06	6.79	7.53	93.92	3.55	781.43	127.61
Unbleached	6A	207.51	0.72	131.98	60.23	5.87	7.97	95.84	3.83	703.24	161.20
Unbleached	6B	192.02	0.68	109.00	63.00	6.22	7.03	105.24	4.05	850.63	170.42
Unbleached	6C	194.87	0.60	162.98	62.10	6.81	7.66	101.35	4.23	826.43	191.39

Table C2: Raw data for refining trials carried out on bleached pulp in phase 2

Sample	Stage& Replicate	SRE	SEL	Freeness	Basis mass	Burst	Tear	Tensile	Stretch	Sheet Density	TEA
		(kWh/t)	(Ws/m)	(ml)	(g/m^2)	(MN/kg)	(kNm^2/kg)	(kNm/kg)	(%)	(kg/m^3)	(J/m^2)
Bleached	0A	0.00	0.00	460.71	61.08	2.16	6.94	36.37	2.18	580.95	31.27
Bleached	0B	0.00	0.00	472.74	61.72	2.07	7.46	35.54	2.11	578.64	31.66
Bleached	0C	0.00	0.00	452.83	58.81	2.48	7.90	40.71	2.38	584.05	37.49
Bleached	1A	22.11	0.40	366.48	60.07	3.56	9.24	57.16	3.01	636.04	76.73
Bleached	1B	24.22	0.44	384.23	54.86	3.39	8.66	56.41	2.71	615.30	66.57
Bleached	1C	23.76	0.45	349.60	60.19	3.87	8.47	57.59	3.24	644.92	84.39
Bleached	2A	44.23	0.40	315.92	60.88	3.81	9.73	57.69	3.12	552.76	89.42
Bleached	2B	48.43	0.44	337.29	61.33	4.02	8.77	58.32	2.91	631.70	81.51
Bleached	2C	47.52	0.45	304.75	63.20	5.06	8.88	73.77	3.48	721.16	100.29
Bleached	3A	66.34	0.40	311.80	61.88	4.31	8.87	66.96	3.64	658.10	105.44
Bleached	3B	72.65	0.44	283.19	64.34	5.12	9.30	70.03	3.90	713.75	121.11
Bleached	3C	71.28	0.45	272.30	63.05	5.58	8.19	76.86	4.15	743.03	128.80
Bleached	4A	88.45	0.40	225.22	62.88	5.26	9.00	80.80	3.77	674.72	120.16
Bleached	4B	96.87	0.44	243.60	63.00	5.34	9.61	76.54	4.30	713.26	146.24
Bleached	4C	95.05	0.45	260.20	61.67	5.67	8.73	77.70	4.20	747.55	127.70
Bleached	5A	110.56	0.40	163.78	60.29	5.86	8.63	84.43	4.29	676.15	158.35
Bleached	5B	121.09	0.44	188.33	64.34	5.47	8.42	76.76	4.31	805.61	150.22
Bleached	5C	118.81	0.45	154.67	63.05	5.80	7.56	76.95	3.86	776.05	146.40
Bleached	6A	132.68	0.40	169.49	61.29	6.63	8.77	96.13	4.04	668.62	171.94
Bleached	6B	145.30	0.44	152.39	63.00	6.19	7.69	88.62	4.41	768.87	168.68
Bleached	6C	142.57	0.45	141.43	61.67	5.96	7.87	79.66	3.86	807.35	142.68

Table D1: Wood anatomy results for the four sites

Sample	WMFD	WMLD	WMCWT	Collaps	Muhlsteph	Runkel	FD/LD	FD/CWT	CWT/LD
	(micron)	(micron)	(micron)						
GCG	13.052	6.409	3.321	5.057	0.759	0.509	2.036	3.931	0.518
GCG	13.297	7.062	3.117	5.709	0.718	0.469	1.883	4.265	0.441
GCG	13.314	5.722	3.796	4.088	0.815	0.570	2.327	3.507	0.664
GCG	13.204	6.444	3.380	4.946	0.762	0.512	2.049	3.906	0.525
GCG	13.134	6.657	3.238	5.303	0.743	0.493	1.973	4.056	0.486
GCG	13.255	7.098	3.079	5.818	0.713	0.465	1.868	4.305	0.434
GCG	13.179	6.498	3.341	5.039	0.757	0.507	2.028	3.945	0.514
GCG	13.054	6.219	3.417	4.816	0.773	0.524	2.099	3.820	0.549
GCG	13.164	5.976	3.595	4.447	0.794	0.546	2.203	3.662	0.602
GUG	14.618	10.238	2.190	11.427	0.510	0.300	1.428	6.675	0.214
GUG	14.712	8.893	2.910	6.931	0.635	0.396	1.654	5.056	0.327
GUG	15.500	9.609	2.945	7.057	0.616	0.380	1.613	5.262	0.307
GUG	14.698	9.822	2.438	9.467	0.553	0.332	1.496	6.028	0.248
GUG	14.987	10.276	2.355	10.227	0.530	0.314	1.458	6.363	0.229
GUG	14.416	9.999	2.208	11.132	0.519	0.306	1.442	6.528	0.221
GUG	15.266	9.753	2.756	7.846	0.592	0.361	1.565	5.540	0.283
GUG	14.191	8.766	2.712	7.632	0.618	0.382	1.619	5.232	0.309
GUG	14.506	9.184	2.660	8.029	0.599	0.367	1.579	5.453	0.290
GUG	15.053	10.083	2.485	9.328	0.551	0.330	1.493	6.059	0.246
GCP	14.217	6.512	3.852	4.172	0.790	0.542	2.183	3.690	0.592
GCP	15.022	6.073	4.474	3.369	0.837	0.596	2.473	3.358	0.737
GCP	13.988	5.955	4.016	3.847	0.819	0.574	2.349	3.483	0.674
GCP	13.634	6.686	3.474	4.827	0.760	0.510	2.039	3.924	0.520
GCP	14.089	6.256	3.916	4.033	0.803	0.556	2.252	3.598	0.626
GCP	13.170	6.448	3.361	4.984	0.760	0.510	2.043	3.918	0.521
GCP	13.808	6.799	3.506	4.797	0.758	0.508	2.031	3.939	0.516
GCP	13.710	5.931	3.889	4.006	0.813	0.567	2.311	3.526	0.656
GCP	13.857	6.096	3.881	4.048	0.806	0.560	2.273	3.570	0.637
GUP	14.088	7.300	3.395	5.140	0.732	0.482	1.930	4.150	0.465
GUP	14.211	6.708	3.751	4.362	0.777	0.528	2.118	3.788	0.559
GUP	14.536	7.885	3.324	5.450	0.706	0.457	1.843	4.373	0.422
GUP	15.398	8.712	3.343	5.630	0.680	0.434	1.767	4.606	0.384
GUP	13.635	6.635	3.500	4.768	0.763	0.513	2.055	3.896	0.528
GUP	14.220	6.380	3.919	4.053	0.799	0.551	2.229	3.629	0.614
GUP	14.033	8.548	2.742	7.422	0.629	0.391	1.642	5.118	0.321
GUP	14.136	8.115	3.011	6.340	0.670	0.426	1.742	4.695	0.371
GUP	14.260	7.924	3.167	5.843	0.691	0.444	1.800	4.502	0.400

Table D2: Wood anatomy results for the four sites

Sample	Densiy (kg/m^3)
GCP	633.315
GCP	673.307
GCP	624.675
GCP	623.287
GCP	649.911
GUP	580.349
GUP	564.394
GUP	549.927
GUP	564.355
GUP	579.901
GCG	421.961
GCG	423.260
GCG	417.381
GCG	416.883
GCG	398.968
GCG	406.850
GCG	399.459
GCG	423.641
GCG	439.125
GUG	354.834
GUG	363.957
GUG	356.382
GUG	344.061
GUG	392.499
GUG	345.748
GUG	350.137

It was initially planned to do anatomy on ten samples, one from each tree felled, however some of the samples broke as they were being prepared and therefore the number of samples for each compartment is different. This will not affect the results since it was the whole compartment density that was needed and this can still be calculated from the data available.

Table D3: Initial pulp anatomical properties

Sample	i-FL	i-fines	i-FD	i-CWT	i-LD	i-Collaps	i-Muhlsteph	i-Runkel	i-FD/LD	i- FD/CWT	i-CWT/LD	i-FL/FD	i-Coarse
	(mm)	(%)	(µm)	(µm)	(µm)								(mg/m)
GCG	0.79	1.27	16.60	3.10	10.40	6.80	0.61	0.37	1.60	5.35	0.30	47.59	0.03
GCG	0.80	1.27	17.30	3.15	11.00	6.82	0.60	0.36	1.57	5.49	0.29	46.24	0.03
GCG	0.79	1.25	17.00	3.05	10.90	7.12	0.59	0.36	1.56	5.57	0.28	46.47	0.03
GCG	0.81	1.33	16.60	3.15	10.30	6.61	0.62	0.38	1.61	5.27	0.31	48.80	0.03
GCG	0.79	1.34	17.00	3.15	10.70	6.73	0.60	0.37	1.59	5.40	0.29	46.47	0.03
GCG	0.78	1.36	16.20	2.95	10.30	7.28	0.60	0.36	1.57	5.49	0.29	48.15	0.03
GCG	0.83	1.11	16.50	3.10	10.30	6.76	0.61	0.38	1.60	5.32	0.30	50.30	0.03
GCG	0.79	1.40	17.10	3.15	10.80	6.76	0.60	0.37	1.58	5.43	0.29	46.20	0.03
GCG	0.78	1.28	16.80	2.95	10.90	7.49	0.58	0.35	1.54	5.69	0.27	46.43	0.03
GCP	0.76	1.16	17.20	3.25	10.70	6.42	0.61	0.38	1.61	5.29	0.30	44.19	0.05
GCP	0.76	1.29	17.10	3.05	11.00	7.15	0.59	0.36	1.55	5.61	0.28	44.44	0.05
GCP	0.77	1.20	17.20	3.15	10.90	6.79	0.60	0.37	1.58	5.46	0.29	44.77	0.05
GCP	0.77	1.21	17.40	3.25	10.90	6.48	0.61	0.37	1.60	5.35	0.30	44.25	0.05
GCP	0.78	1.20	16.90	3.20	10.50	6.51	0.61	0.38	1.61	5.28	0.30	46.15	0.05
GCP	0.77	1.17	17.00	3.20	10.60	6.54	0.61	0.38	1.60	5.31	0.30	45.29	0.05
GCP	0.78	1.63	16.60	3.05	10.50	6.99	0.60	0.37	1.58	5.44	0.29	46.99	0.05
GCP	0.77	1.23	16.70	3.15	10.40	6.64	0.61	0.38	1.61	5.30	0.30	46.11	0.05
GCP	0.76	1.93	16.90	2.90	11.10	7.75	0.57	0.34	1.52	5.83	0.26	44.97	0.05
GUG	0.78	1.53	19.00	3.20	12.60	7.13	0.56	0.34	1.51	5.94	0.25	41.05	0.04
GUG	0.78	1.72	18.60	3.10	12.40	7.42	0.56	0.33	1.50	6.00	0.25	41.94	0.04
GUG	0.77	1.53	18.00	3.00	12.00	7.67	0.56	0.33	1.50	6.00	0.25	42.78	0.04
GUG	0.78	1.63	18.50	3.10	12.30	7.39	0.56	0.34	1.50	5.97	0.25	42.16	0.04
GUG	0.75	1.71	18.50	3.05	12.40	7.61	0.55	0.33	1.49	6.07	0.25	40.54	0.04
GUG	0.77	1.61	18.90	3.10	12.70	7.51	0.55	0.33	1.49	6.10	0.24	40.74	0.04
GUG	0.76	1.92	17.90	2.95	12.00	7.87	0.55	0.33	1.49	6.07	0.25	42.46	0.04
GUG	0.78	1.62	18.40	3.00	12.40	7.80	0.55	0.33	1.48	6.13	0.24	42.39	0.04
GUG	0.77	1.57	18.50	3.05	12.40	7.61	0.55	0.33	1.49	6.07	0.25	41.62	0.04
GUP	0.70	1.75	17.40	3.15	11.10	6.85	0.59	0.36	1.57	5.52	0.28	40.23	0.05
GUP	0.71	1.62	18.50	3.40	11.70	6.27	0.60	0.37	1.58	5.44	0.29	38.38	0.05
GUP	0.70	1.54	17.60	3.20	11.20	6.72	0.60	0.36	1.57	5.50	0.29	39.77	0.05
GUP	0.70	1.66	17.70	3.10	11.50	7.14	0.58	0.35	1.54	5.71	0.27	39.55	0.05
GUP	0.69	1.61	17.40	3.15	11.10	6.85	0.59	0.36	1.57	5.52	0.28	39.66	0.05
GUP	0.70	1.58	17.50	3.05	11.40	7.28	0.58	0.35	1.54	5.74	0.27	40.00	0.05
GUP	0.70	1.79	17.30	3.15	11.00	6.82	0.60	0.36	1.57	5.49	0.29	40.46	0.05
GUP	0.70	1.65	17.40	3.10	11.20	7.04	0.59	0.36	1.55	5.61	0.28	40.23	0.05
GUP	0.70	1.56	17.90	3.25	11.40	6.62	0.59	0.36	1.57	5.51	0.29	39.11	0.05

Table D4: Energy calculation for refining the pulps at 750 rpm

		GUG - 750 RPM			GUC - 750 RPM		
Gap setting	micron	25	25	25	25	25	25
Run		1	2	3	1	2	3
% power	%	4.78	4.69	4.77	4.94	5.93	5.99
% no load power	%	1.88	1.88	1.88	1.89	1.89	1.89
full power	kW	18.50	18.50	18.50	18.50	18.50	18.50
flow	l/s	1.00	1.00	1.00	1.00	1.00	1.00
consistency	%	3.00	3.00	3.00	3.00	3.00	3.00
Power	kW	0.88	0.87	0.88	0.91	1.10	1.11
Po	kW	0.35	0.35	0.35	0.35	0.35	0.35
Speed	rpm	750.00	750.00	750.00	750.00	750.00	750.00
P-Po	kW	0.54	0.52	0.53	0.57	0.75	0.76
Vol Flow	M^3/h	3.60	3.60	3.60	3.60	3.60	3.60
Mass Flow	ton/hr	3.60	3.60	3.60	3.60	3.60	3.60
M	ton/hr	0.11	0.11	0.11	0.11	0.11	0.11
CEL	m/rev	279.01	279.01	279.01	279.01	279.01	279.01
Ls	m/s	3487.61	3487.61	3487.61	3487.61	3487.61	3487.61
SRE	**kWh/ton**	**4.96**	**4.80**	**4.94**	**5.24**	**6.92**	**7.02**
SEL	**Ws/m**	**0.15**	**0.15**	**0.15**	**0.16**	**0.21**	**0.22**

		GUP - 750 RPM			GCP - 750 RPM		
Gap setting	micron	25	25	25	25	25	25
Run		1	2	3	1	2	3
% power	%	4.70	4.71	4.53	4.90	4.92	4.91
% no load power	%	0.75	0.75	0.75	0.75	0.75	0.75
full power	kw	18.50	18.50	18.50	18.50	18.50	18.50
flow	l/s	1.00	1.00	1.00	1.00	1.00	1.00
consistency	%	3.00	3.00	3.00	3.00	3.00	3.00
Power	kW	0.87	0.87	0.84	0.91	0.91	0.91
Po	kW	0.14	0.14	0.14	0.14	0.14	0.14
Speed	rpm	750.00	750.00	750.00	750.00	750.00	750.00
P-Po	kW	0.73	0.73	0.70	0.77	0.77	0.77
Vol Flow	M^3/h	3.60	3.60	3.60	3.60	3.60	3.60
Mass Flow	ton/hr	3.60	3.60	3.60	3.60	3.60	3.60
M	ton/hr	0.11	0.11	0.11	0.11	0.11	0.11
CEL	m/rev	279.01	279.01	279.01	279.01	279.01	279.01
Ls	m/s	3487.61	3487.61	3487.61	3487.61	3487.61	3487.61
SRE	**kWh/ton**	**6.76**	**6.79**	**6.47**	**7.11**	**7.14**	**7.13**
SEL	**Ws/m**	**0.21**	**0.21**	**0.20**	**0.22**	**0.22**	**0.22**

The tables show the SRE per stage of refining. For multiple passes through the refiner the SRE is accumulated per stage while the SEL is not cumulative but is the same SEL for all stages

Table D5: Energy calculation for refining the pulps at 1500 rpm

		GUG - 1500 RPM			GCG - 1500 RPM		
Gap setting	micron	25	25	25	25	25	25
Run		1	2	3	1	2	3
% power	%	27.38	29.01	28.11	29.94	29.53	29.42
% no load power	%	13.40	13.40	13.40	13.39	13.39	13.39
full power	kW	18.50	18.50	18.50	18.50	18.50	18.50
flow	l/s	1.00	1.00	1.00	1.00	1.00	1.00
consistency	%	3.00	3.00	3.00	3.00	3.00	3.00
Power	kW	5.07	5.37	5.20	5.54	5.46	5.44
Po	kW	2.48	2.48	2.48	2.48	2.48	2.48
Speed	rpm	1500.00	1500.00	1500.00	1500.00	1500.00	1500.00
P-Po	kW	2.59	2.89	2.72	3.06	2.99	2.96
Vol Flow	M^3/h	3.60	3.60	3.60	3.60	3.60	3.60
Mass Flow	ton/hr	3.60	3.60	3.60	3.60	3.60	3.60
M	ton/hr	0.11	0.11	0.11	0.11	0.11	0.11
CEL	m/rev	279.01	279.01	279.01	279.01	279.01	279.01
Ls	m/s	6975.23	6975.23	6975.23	6975.23	6975.23	6975.23
SRE	**kWh/ton**	**23.95**	**26.75**	**25.20**	**28.35**	**27.65**	**27.45**
SEL	**Ws/m**	**0.37**	**0.41**	**0.39**	**0.44**	**0.43**	**0.43**

		GUP - 1500 RPM			GCP - 1500 RPM		
Gap setting	micron	25	25	25	25	25	25
Run		1	2	3	1	2	3
% power	%	25.29	24.65	24.96	27.60	27.76	27.25
% no load power	%	13.36	13.36	13.36	13.94	13.94	13.94
full power	kW	18.50	18.50	18.50	18.50	18.50	18.50
flow	l/s	1.00	1.00	1.00	1.00	1.00	1.00
consistency	%	3.00	3.00	3.00	3.00	3.00	3.00
Power	kW	4.68	4.56	4.62	5.11	5.14	5.04
Po	kW	2.47	2.47	2.47	2.58	2.58	2.58
Speed	rpm	1500.00	1500.00	1500.00	1500.00	1500.00	1500.00
P-Po	kW	2.21	2.09	2.15	2.53	2.56	2.46
Vol Flow	M^3/h	3.60	3.60	3.60	3.60	3.60	3.60
Mass Flow	ton/hr	3.60	3.60	3.60	3.60	3.60	3.60
M	ton/hr	0.11	0.11	0.11	0.11	0.11	0.11
CEL	m/rev	279.01	279.01	279.01	279.01	279.01	279.01
Ls	m/s	6975.23	6975.23	6975.23	6975.23	6975.23	6975.23
SRE	**kWh/ton**	**20.44**	**19.35**	**19.88**	**23.40**	**23.67**	**22.80**
SEL	**Ws/m**	**0.32**	**0.30**	**0.31**	**0.36**	**0.37**	**0.35**

The tables show the SRE per stage of refining. For multiple passes through the refiner the SRE is accumulated per stage while the SEL is not cumulative but is the same SEL for all stages

Table D6: Energy calculation for refining the pulps at 2200 rpm

		GUG - 2200 RPM			GCG - 2200 RPM		
Gap setting	micron	25	25	25	25	25	25
Run		1	2	3	1	2	3
% power	%	64.02	61.42	60.28	61.26	64.77	65.20
% no load power	%	35.06	35.06	35.06	34.87	34.87	34.87
full power	kW	18.50	18.50	18.50	18.50	18.50	18.50
flow	l/s	1.00	1.00	1.00	1.00	1.00	1.00
consistency	%	3.00	3.00	3.00	3.00	3.00	3.00
Power	kW	11.84	11.36	11.15	11.33	11.98	12.06
Po	kW	6.49	6.49	6.49	6.45	6.45	6.45
Speed	rpm	2200.00	2200.00	2200.00	2200.00	2200.00	2200.00
P-Po	kW	5.36	4.88	4.67	4.88	5.53	5.61
Vol Flow	M^3/h	3.60	3.60	3.60	3.60	3.60	3.60
Mass Flow	ton/hr	3.60	3.60	3.60	3.60	3.60	3.60
M	ton/hr	0.11	0.11	0.11	0.11	0.11	0.11
CEL	m/rev	279.01	279.01	279.01	279.01	279.01	279.01
Ls	m/s	10230.33	10230.33	10230.33	10230.33	10230.33	10230.33
SRE	**kWh/ton**	**49.61**	**45.17**	**43.21**	**45.19**	**51.21**	**51.95**
SEL	**Ws/m**	**0.52**	**0.48**	**0.46**	**0.48**	**0.54**	**0.55**

		GUP - 2200 RPM			GCP- 2200 RPM		
Gap setting	micron	25	25	25	25	25	25
Run		1	2	3	1	2	3
% power	%	59.78	59.33	58.65	61.00	61.39	59.22
% no load power	%	34.41	34.41	34.41	34.61	34.61	34.61
full power	kW	18.50	18.50	18.50	18.50	18.50	18.50
flow	l/s	1.00	1.00	1.00	1.00	1.00	1.00
consistency	%	3.00	3.00	3.00	3.00	3.00	3.00
Power	kW	11.06	10.98	10.85	11.29	11.36	10.96
Po	kW	6.37	6.37	6.37	6.40	6.40	6.40
Speed	rpm	2200.00	2200.00	2200.00	2200.00	2200.00	2200.00
P-Po	kW	4.69	4.61	4.48	4.88	4.95	4.55
Vol Flow	M^3/h	3.60	3.60	3.60	3.60	3.60	3.60
Mass Flow	ton/hr	3.60	3.60	3.60	3.60	3.60	3.60
M	ton/hr	0.11	0.11	0.11	0.11	0.11	0.11
CEL	m/rev	279.01	279.01	279.01	279.01	279.01	279.01
Ls	m/s	10230.33	10230.33	10230.33	10230.33	10230.33	10230.33
SRE	**kWh/ton**	**43.45**	**42.68**	**41.52**	**45.21**	**45.87**	**42.16**
SEL	**Ws/m**	**0.46**	**0.45**	**0.44**	**0.48**	**0.48**	**0.45**

The tables show the SRE per stage of refining. For multiple passes through the refiner the SRE is accumulated per stage while the SEL is not cumulative but is the same SEL for all stages

Table D7: Raw data for results from the refining trials of the GCP

Sample	Speed	Stage & Replicate	SEL	SRE	Freeness	Tensile Index	Tear	Burst Index	Sheet Density	Stretch	TEA	Z-span	Fibre Length (Ln)	Fibre Length (Ll)	Fibre Length (Lw)	Fines	LD	Pulp fibre diameter	Pulp CWT
	(rpm)		(Ws/m)	(kWh/t)	(ml)	(kNm/kg)	(kNm^2/kg)	(MN/kg)	(kg/m^3)	(%)	(J/m^2)	(N/m)	(mm)	(mm)	(mm)	(%)	(µm)	(µm)	(µm)
GCP	1500	0A	0.00	0.00	587.37	51.30	8.32	2.36	636.45	1.50	26.95	1688.84	0.63	0.77	0.86	1.21	10.90	17.40	3.25
GCP	1500	0B	0.00	0.00	594.25	52.85	7.00	2.52	612.88	1.55	31.11	1688.84	0.64	0.78	0.87	1.20	10.50	16.90	3.20
GCP	1500	0C	0.00	0.00	592.22	50.67	7.69	2.31	616.52	1.28	24.04	1688.84	0.63	0.77	0.86	1.17	10.60	17.00	3.20
GCP	1500	1A	0.36	23.40	482.86	65.74	9.07	3.75	676.28	1.97	51.69	1797.16	0.61	0.74	0.84	1.35	10.40	16.40	3.00
GCP	1500	1B	0.37	23.67	505.47	68.27	8.05	3.77	635.10	2.08	53.71	1797.16	0.59	0.73	0.87	1.60	10.90	16.50	2.80
GCP	1500	1C	0.35	22.80	485.97	68.54	8.90	3.82	646.81	1.93	51.38	1797.16	0.62	0.76	0.84	1.31	10.70	17.00	3.15
GCP	1500	2A	0.36	46.80	486.62	71.89	9.02	3.96	641.83	2.04	56.40	2137.06	0.61	0.74	0.83	1.31	10.70	16.80	3.05
GCP	1500	2B	0.37	47.35	513.47	83.30	10.12	4.83	702.17	2.53	83.22	2137.06	0.57	0.71	0.80	1.73	11.30	17.60	3.15
GCP	1500	2C	0.35	45.60	476.69	84.95	9.81	5.24	694.24	2.44	79.42	2137.06	0.58	0.71	0.81	1.44	10.40	16.10	2.85
GCP	1500	3A	0.36	70.20	436.02	74.67	11.04	5.02	747.06	2.60	79.50	2173.01	0.61	0.76	0.86	1.34	10.70	16.90	3.10
GCP	1500	3B	0.37	71.02	426.99	81.54	10.99	5.23	684.40	2.81	93.93	2173.01	0.63	0.77	0.86	1.29	10.70	16.80	3.05
GCP	1500	3C	0.35	68.40	414.45	96.28	9.38	5.90	700.82	2.91	110.81	2173.01	0.62	0.76	0.87	1.24	10.30	16.30	3.00
GCP	1500	4A	0.36	93.60	407.64	87.43	10.28	5.22	697.64	2.83	99.16	2120.68	0.61	0.75	0.84	1.40	10.35	16.15	2.90
GCP	1500	4B	0.37	94.69	381.08	83.00	11.65	5.62	701.70	2.76	88.45	2120.68	0.61	0.74	0.84	1.37	10.30	16.10	2.90
GCP	1500	4C	0.35	91.20	391.49	93.69	10.44	6.01	719.94	2.81	101.12	2120.68	0.60	0.75	0.84	1.44	10.40	16.20	2.90
GCP	1500	5A	0.36	117.00	368.46	86.01	10.20	6.16	713.38	2.86	97.39	2171.30	0.61	0.75	0.85	1.33	10.80	16.50	2.85
GCP	1500	5B	0.37	118.37	355.55	100.26	10.28	6.43	734.07	3.82	130.04	2171.30	0.61	0.75	0.85	1.45	10.50	16.50	3.00
GCP	1500	5C	0.35	114.00	337.02	94.66	9.90	6.84	730.88	3.32	127.76	2171.30	0.61	0.75	0.84	1.41	10.10	15.90	2.90
GCP	1500	6A	0.36	140.39	329.64	92.98	10.09	6.54	750.74	3.11	115.90	2053.31	0.58	0.72	0.82	1.58	10.50	15.70	2.60
GCP	1500	6B	0.37	142.04	291.31	96.46	10.88	7.08	736.09	3.33	133.96	2053.31	0.59	0.72	0.82	1.56	10.90	16.70	2.90
GCP	1500	6C	0.35	136.80	278.92	104.94	10.26	7.03	734.39	3.45	142.68	2053.31	0.60	0.74	0.83	1.34	10.50	16.20	2.85
GCP	2200	0A	0.00	0.00	592.80	43.79	6.26	1.87	579.14	1.29	21.68	1365.36	0.63	0.76	0.85	1.16	10.70	17.20	3.25
GCP	2200	0B	0.00	0.00	583.15	46.43	7.10	2.28	606.42	1.35	24.23	1365.36	0.62	0.76	0.86	1.29	11.00	17.10	3.05
GCP	2200	0C	0.00	0.00	608.11	40.41	5.90	1.96	565.58	1.27	18.91	1365.36	0.63	0.77	0.86	1.20	10.90	17.20	3.15
GCP	2200	1A	0.48	45.21	468.61	77.49	10.92	4.47	683.76	2.62	98.20	1791.00	0.62	0.75	0.85	1.35	10.70	16.90	3.10
GCP	2200	1B	0.48	45.87	439.86	67.48	9.04	4.16	664.82	2.25	68.02	1791.00	0.61	0.75	0.84	1.38	10.60	16.20	2.80
GCP	2200	1C	0.45	42.16	467.91	74.38	10.32	4.04	692.13	2.37	73.45	1791.00	0.61	0.74	0.83	1.39	10.60	16.40	2.90
GCP	2200	2A	0.48	90.41	393.16	76.33	10.10	4.93	669.64	2.78	89.66	1561.57	0.61	0.75	0.85	1.35	10.80	16.80	3.00
GCP	2200	2B	0.48	91.75	339.24	81.46	10.00	5.10	648.29	2.52	86.55	1561.57	0.60	0.73	0.82	1.43	11.00	16.90	2.95
GCP	2200	2C	0.45	84.31	363.76	91.33	10.48	6.32	713.54	3.01	102.27	1561.57	0.57	0.71	0.81	1.59	10.90	16.70	2.90
GCP	2200	3A	0.48	135.62	281.89	93.62	9.38	6.71	730.90	3.28	119.70	1697.00	0.58	0.72	0.82	1.65	10.70	16.50	2.90
GCP	2200	3B	0.48	137.62	256.96	93.21	10.16	6.83	727.44	3.47	125.47	1697.00	0.57	0.71	0.80	1.70	10.80	16.80	3.00
GCP	2200	3C	0.45	126.47	275.51	96.17	9.15	6.87	730.40	3.39	130.00	1697.00	0.57	0.71	0.80	1.54	10.70	16.40	2.85

...Table D7 Continued

Sample	Speed	Stage & Replicate	SEL	SRE	Freeness	Tensile Index	Tear	Burst Index	Sheet Density	Stretch	TEA	Z-span	Fibre Length (Ln)	Fibre Length (Ll)	Fibre Length (Lw)	Fines	LD	Pulp fibre diameter	Pulp CWT
	(rpm)		(Ws/m)	(kWh/t)	(ml)	(kNm/kg)	(kNm^2/kg)	(MN/kg)	(kg/m^3)	(%)	(J/m^2)	(N/m)	(mm)	(mm)	(mm)	(%)	(μm)	(μm)	(μm)
GCP	2200	4A	0.48	180.82	224.44	100.96	10.42	6.92	729.13	4.03	167.57	2102.54	0.59	0.73	0.83	1.56	10.80	16.60	2.90
GCP	2200	4B	0.48	183.49	206.79	92.07	9.08	7.08	723.43	3.23	117.70	2102.54	0.58	0.71	0.80	1.57	10.70	16.30	2.80
GCP	2200	4C	0.45	168.62	214.11	101.00	9.84	7.28	699.24	3.52	144.89	2102.54	0.56	0.70	0.80	1.68	10.70	16.60	2.95
GCP	2200	5A	0.48	226.03	205.61	92.67	9.65	7.10	733.16	3.55	131.82	1973.98	0.58	0.72	0.83	1.53	10.50	15.90	2.70
GCP	2200	5B	0.48	229.37	180.42	100.43	9.57	7.46	751.84	3.34	120.69	1973.98	0.57	0.71	0.80	1.62	10.50	16.00	2.75
GCP	2200	5C	0.45	210.78	205.01	99.31	9.32	7.48	760.16	3.60	145.81	1973.98	0.57	0.71	0.81	1.59	11.00	16.70	2.85
GCP	2200	6A	0.48	271.23	219.45	102.15	10.46	7.24	751.79	3.56	144.01	1930.60	0.57	0.71	0.81	1.64	10.40	15.90	2.75
GCP	2200	6B	0.48	275.24	165.86	101.10	9.15	7.92	788.51	3.54	115.49	1930.60	0.56	0.70	0.80	1.80	11.10	16.80	2.85
GCP	2200	6C	0.45	252.94	184.53	101.95	10.47	7.93	778.57	3.79	159.06	1930.60	0.57	0.71	0.80	1.67	10.70	16.20	2.75
GCP	750	0A	0.00	0.00	588.93	51.72	7.05	2.11	601.64	1.33	25.35	2484.12	0.62	0.78	0.88	1.63	10.50	16.60	3.05
GCP	750	0B	0.00	0.00	575.78	54.38	8.36	2.21	627.48	1.49	28.03	2484.12	0.63	0.77	0.86	1.23	10.40	16.70	3.15
GCP	750	0C	0.00	0.00	598.62	51.56	7.50	2.61	561.00	2.46	36.00	2484.12	0.64	0.76	0.76	1.93	11.10	16.90	2.90
GCP	750	1A	0.22	7.11	543.59	55.39	8.09	2.81	594.39	1.64	34.91	2126.52	0.63	0.77	0.86	1.17	10.80	16.80	3.00
GCP	750	1B	0.22	7.14	549.88	62.63	8.52	3.21	602.81	1.93	48.37	2126.52	0.62	0.78	0.90	1.30	10.40	16.30	2.95
GCP	750	1C	0.22	7.13	553.76	51.08	7.32	1.93	647.54	1.26	43.00	2126.52	0.63	0.76	0.86	1.27	10.90	17.30	3.20
GCP	750	5A	0.22	35.54	507.60	55.85	9.96	3.50	642.13	2.08	46.38	1940.14	0.63	0.76	0.86	1.29	10.50	16.90	3.20
GCP	750	5B	0.22	35.70	530.13	55.34	9.70	2.74	599.00	1.57	47.54	1940.14	0.63	0.77	0.87	1.25	10.60	16.50	2.95
GCP	750	5C	0.22	35.63	510.72	67.21	9.44	3.29	628.10	1.96	54.58	1940.14	0.61	0.75	0.85	1.52	10.70	16.60	2.95
GCP	750	10A	0.22	71.09	494.87	62.99	11.41	4.12	671.00	2.43	62.81	2136.71	0.63	0.76	0.86	1.32	10.40	16.40	3.00
GCP	750	10B	0.22	71.40	441.19	74.55	10.71	5.07	675.66	2.48	69.47	2136.71	0.60	0.74	0.84	1.43	10.40	15.90	2.75
GCP	750	10C	0.22	71.26	463.66	69.99	10.74	4.14	600.36	2.28	63.59	2136.71	0.61	0.75	0.84	1.28	10.80	17.30	3.25
GCP	750	15A	0.22	106.63	463.40	77.15	10.38	4.69	656.89	2.70	81.80	2179.76	0.61	0.75	0.84	1.42	10.40	16.20	2.90
GCP	750	15B	0.22	107.09	423.16	72.52	11.02	4.53	700.08	2.52	73.96	2179.76	0.61	0.74	0.83	1.34	10.50	16.40	2.95
GCP	750	15C	0.22	106.89	408.37	71.83	11.86	4.75	641.79	2.49	71.67	2179.76	0.61	0.74	0.84	1.43	10.70	16.90	3.10
GCP	750	20A	0.22	142.18	458.18	78.40	9.93	4.99	673.51	2.67	82.96	2264.06	0.64	0.77	0.87	1.23	10.50	16.30	2.90
GCP	750	20B	0.22	142.79	438.72	78.52	9.31	5.35	680.31	2.76	85.51	2264.06	0.61	0.75	0.85	1.47	10.30	16.20	2.95
GCP	750	20C	0.22	142.52	442.34	80.09	10.67	4.90	658.44	2.67	85.52	2264.06	0.62	0.76	0.87	1.31	10.50	16.50	3.00
GCP	750	25A	0.22	177.72	428.05	78.97	11.74	5.35	669.92	2.28	98.00	2557.76	0.62	0.76	0.86	1.41	11.20	17.20	3.00
GCP	750	25B	0.22	178.49	390.78	80.60	10.46	4.94	711.94	2.65	99.58	2557.76	0.60	0.74	0.84	1.57	10.60	16.50	2.95
GCP	750	25C	0.22	178.15	391.99	96.59	8.82	6.21	669.38	3.02	103.00	2557.76	0.55	0.68	0.78	1.78	11.10	16.80	2.85

Table D8: Raw data for results from the refining trials of the GCG

Sample	Speed	Stage & Replicate	SEL	SRE	Freeness	Tensile Index	Tear	Burst Index	Sheet Density	Stretch	TEA	Z-span	Fibre Length (Ln)	Fibre Length (Ll)	Fibre Length (Lw)	Fines	LD	Pulp fibre diameter	Pulp CWT
	(rpm)		(Ws/m)	(kWh/t)	(ml)	(kNm/kg)	(kNm^2/kg)	(MN/kg)	(kg/m^3)	(%)	(J/m^2)	(N/m)	(mm)	(mm)	(mm)	(%)	(µm)	(µm)	(µm)
GCG	1500	0A	0.00	0.00	624.48	64.93	10.04	3.50	698.11	2.10	60.40	2048.64	0.66	0.81	0.90	1.33	10.30	16.60	3.15
GCG	1500	0B	0.00	0.00	599.45	53.22	8.19	2.83	634.25	1.50	29.57	2048.64	0.64	0.79	0.89	1.34	10.70	17.00	3.15
GCG	1500	0C	0.00	0.00	587.49	53.01	7.74	2.51	675.44	1.55	27.82	2048.64	0.63	0.78	0.88	1.36	10.30	16.20	2.95
GCG	1500	1A	0.44	28.35	513.36	81.91	10.92	4.73	726.13	2.47	83.37	2161.49	0.63	0.79	0.90	1.53	11.00	16.90	2.95
GCG	1500	1B	0.43	27.65	516.03	71.21	10.52	4.14	670.33	2.20	57.60	2161.49	0.61	0.78	0.88	1.64	10.80	17.10	3.15
GCG	1500	1C	0.43	27.45	522.26	71.14	11.85	3.93	650.54	2.27	61.50	2161.49	0.63	0.78	0.88	1.45	10.40	16.60	3.10
GCG	1500	2A	0.44	56.71	458.80	91.16	12.42	6.18	756.51	3.02	112.04	2212.85	0.62	0.78	0.88	1.61	10.80	17.20	3.20
GCG	1500	2B	0.43	55.31	462.55	79.53	11.28	5.76	754.02	2.67	90.30	2212.85	0.61	0.77	0.87	1.63	10.40	16.50	3.05
GCG	1500	2C	0.43	54.90	447.93	77.76	11.68	5.66	671.00	2.56	74.77	2212.85	0.61	0.77	0.87	1.59	10.70	16.60	2.95
GCG	1500	3A	0.44	85.06	436.64	92.59	12.97	5.76	751.92	3.04	118.13	2212.38	0.63	0.80	0.91	1.48	10.50	16.60	3.05
GCG	1500	3B	0.43	82.96	426.32	92.90	11.65	6.98	771.27	3.42	132.80	2212.38	0.61	0.76	0.85	1.57	10.70	16.90	3.10
GCG	1500	3C	0.43	82.35	403.75	88.43	12.23	5.76	699.49	2.96	97.92	2212.38	0.60	0.76	0.85	1.71	10.30	16.20	2.95
GCG	1500	4A	0.44	113.41	391.53	105.13	12.05	7.18	780.21	3.67	164.93	2404.56	0.62	0.77	0.87	1.63	10.60	16.50	2.95
GCG	1500	4B	0.43	110.62	361.38	96.91	12.18	7.03	792.57	3.45	153.76	2404.56	0.62	0.78	0.88	1.63	10.00	15.80	2.90
GCG	1500	4C	0.43	109.80	386.65	98.25	11.16	6.83	697.85	3.04	111.75	2404.56	0.60	0.76	0.86	1.64	10.70	16.70	3.00
GCG	1500	5A	0.44	141.76	366.35	100.30	11.87	7.06	769.67	3.57	155.76	2230.91	0.64	0.80	0.91	1.49	10.40	16.30	2.95
GCG	1500	5B	0.43	138.27	329.34	109.11	10.35	7.01	808.04	3.82	186.18	2230.91	0.61	0.78	0.89	2.07	10.90	16.70	2.90
GCG	1500	5C	0.43	137.25	318.66	105.64	11.77	7.38	714.06	3.36	135.95	2230.91	0.62	0.78	0.90	1.63	11.00	16.80	2.90
GCG	1500	6A	0.44	170.12	286.78	105.00	10.55	8.01	797.91	3.67	163.85	2004.86	0.60	0.75	0.85	1.81	10.60	16.20	2.80
GCG	1500	6B	0.43	165.92	312.79	107.83	10.75	8.15	804.18	3.76	171.67	2004.86	0.60	0.77	0.86	1.83	11.00	16.80	2.90
GCG	1500	6C	0.43	164.70	285.18	101.10	10.85	7.07	725.62	3.25	127.21	2004.86	0.60	0.75	0.85	1.71	10.60	16.30	2.85
GCG	2200	0A	0.00	0.00	626.42	50.61	8.99	2.26	602.71	1.51	29.60	2127.28	0.65	0.79	0.88	1.27	10.40	16.60	3.10
GCG	2200	0B	0.00	0.00	605.92	50.35	8.09	2.70	607.37	1.46	24.94	2127.28	0.65	0.80	0.90	1.27	11.00	17.30	3.15
GCG	2200	0C	0.00	0.00	610.65	65.49	10.04	3.29	646.72	1.86	47.05	2127.28	0.64	0.79	0.88	1.25	10.90	17.00	3.05
GCG	2200	1A	0.48	45.19	426.62	80.48	10.98	5.14	619.45	2.77	86.05	2192.24	0.62	0.78	0.88	1.70	10.20	16.10	2.95
GCG	2200	1B	0.54	51.21	437.97	73.03	11.19	4.62	600.13	2.31	60.92	2192.24	0.63	0.78	0.88	1.63	10.90	16.90	3.00
GCG	2200	1C	0.55	51.95	469.47	83.18	12.03	5.23	637.38	2.61	83.10	2192.24	0.60	0.80	0.89	1.43	10.90	16.70	2.90
GCG	2200	2A	0.48	90.38	418.04	78.83	11.24	4.81	615.88	2.64	79.06	2449.68	0.63	0.78	0.88	1.48	10.20	16.00	2.90
GCG	2200	2B	0.54	102.42	408.11	91.36	11.45	5.92	752.03	3.15	122.50	2449.68	0.61	0.77	0.87	1.65	10.30	16.20	2.95
GCG	2200	2C	0.55	103.89	403.47	77.44	10.38	5.26	692.59	2.66	59.74	2449.68	0.62	0.78	0.88	1.57	10.25	16.10	2.93
GCG	2200	3A	0.48	135.57	366.41	86.22	11.96	6.03	661.68	3.07	104.53	2309.04	0.60	0.76	0.87	1.74	10.50	16.20	2.85
GCG	2200	3B	0.54	153.63	347.56	87.42	11.20	5.88	740.07	3.10	108.06	2309.04	0.62	0.78	0.88	1.57	10.50	16.60	3.05
GCG	2200	3C	0.55	155.84	322.03	90.82	11.88	6.70	717.43	3.10	112.45	2309.04	0.59	0.75	0.85	1.81	11.00	17.00	3.00

...Table D8 Continued

Sample	Speed	Stage & Replicate	SEL	SRE	Freeness	Tensile Index	Tear	Burst Index	Sheet Density	Stretch	TEA	Z-span	Fibre Length (Ln)	Fibre Length (Ll)	Fibre Length (Lw)	Fines	LD	Pulp fibre diameter	Pulp CWT
	(rpm)		(Ws/m)	(kWh/t)	(ml)	(kNm/kg)	(kNm^2/kg)	(MN/kg)	(kg/m^3)	(%)	(J/m^2)	(N/m)	(mm)	(mm)	(mm)	(%)	(µm)	(µm)	(µm)
GCG	2200	4A	0.48	180.77	334.41	93.07	11.76	6.10	658.74	3.36	126.79	2546.13	0.60	0.76	0.87	1.68	10.60	16.60	3.00
GCG	2200	4B	0.54	204.84	275.70	97.93	12.62	6.73	711.03	3.48	140.93	2546.13	0.61	0.76	0.86	1.68	10.00	15.80	2.90
GCG	2200	4C	0.55	207.78	279.47	100.09	10.79	7.16	701.37	3.75	150.80	2546.13	0.62	0.79	0.90	1.52	10.60	16.20	2.80
GCG	2200	5A	0.48	225.96	298.36	94.72	11.17	6.29	696.21	3.33	119.97	2461.40	0.60	0.76	0.85	1.68	10.80	16.60	2.90
GCG	2200	5B	0.54	256.05	253.79	96.81	10.56	7.66	718.63	3.35	121.02	2461.40	0.60	0.76	0.87	1.66	10.10	15.70	2.80
GCG	2200	5C	0.55	259.73	293.87	97.25	11.71	6.44	668.85	3.42	125.74	2461.40	0.61	0.77	0.87	1.66	10.40	16.70	3.15
GCG	2200	6A	0.48	271.15	286.01	103.32	12.25	7.39	753.57	3.63	141.54	2335.52	0.62	0.78	0.89	1.63	10.50	16.50	3.00
GCG	2200	6B	0.54	307.26	247.71	107.93	10.32	8.30	806.33	3.78	171.21	2335.52	0.58	0.74	0.84	1.84	11.00	16.80	2.90
GCG	2200	6C	0.55	311.67	289.31	109.26	10.88	8.03	802.33	3.63	161.99	2335.52	0.60	0.76	0.86	1.74	10.80	16.70	2.95
GCG	750	0A	0.00	0.00	607.24	53.83	9.24	3.18	723.83	2.02	73.56	1370.13	0.68	0.83	0.92	1.11	10.30	16.50	3.10
GCG	750	0B	0.00	0.00	589.66	51.21	8.52	2.60	591.72	1.56	26.80	1370.13	0.64	0.79	0.90	1.40	10.80	17.10	3.15
GCG	750	0C	0.00	0.00	586.76	50.24	9.15	2.82	617.73	1.55	27.11	1370.13	0.64	0.78	0.87	1.28	10.90	16.80	2.95
GCG	750	1A	0.16	5.24	590.21	59.14	9.76	3.42	681.42	1.85	48.82	1607.88	0.64	0.79	0.88	1.52	10.50	16.80	3.15
GCG	750	1B	0.21	6.92	559.26	59.04	9.70	3.22	612.31	1.84	40.32	1607.88	0.63	0.78	0.87	1.46	10.50	16.70	3.10
GCG	750	1C	0.22	7.02	570.66	52.74	8.70	3.18	622.91	1.83	41.50	1607.88	0.65	0.80	0.90	1.31	10.60	17.00	3.20
GCG	750	5A	0.16	26.18	491.71	69.23	12.31	4.64	689.48	2.33	69.89	2065.82	0.62	0.78	0.87	1.54	10.40	16.40	3.00
GCG	750	5B	0.21	34.59	528.54	73.10	12.13	4.61	699.01	2.59	85.32	2065.82	0.64	0.79	0.89	1.44	10.30	16.20	2.95
GCG	750	5C	0.22	35.11	519.66	66.03	11.82	4.33	640.16	2.26	57.42	2065.82	0.63	0.78	0.88	1.47	10.30	16.30	3.00
GCG	750	10A	0.16	52.37	476.89	76.33	12.42	5.43	711.00	2.76	90.08	2216.75	0.64	0.79	0.89	1.42	10.50	16.30	2.90
GCG	750	10B	0.21	69.19	457.27	78.33	11.93	5.12	697.48	2.78	94.36	2216.75	0.61	0.78	0.90	1.68	11.00	17.10	3.05
GCG	750	10C	0.22	70.21	414.43	77.06	11.66	4.99	682.35	2.60	82.06	2216.75	0.63	0.79	0.90	1.53	10.90	16.80	2.95
GCG	750	15A	0.16	78.55	442.80	74.38	11.47	5.65	720.16	2.90	89.60	2366.99	0.63	0.78	0.88	1.43	10.90	17.20	3.15
GCG	750	15B	0.21	103.78	413.62	81.79	11.56	5.80	680.91	3.29	104.76	2366.99	0.60	0.75	0.84	1.68	10.40	16.20	2.90
GCG	750	15C	0.22	105.32	434.33	89.90	11.17	6.00	743.81	3.03	107.18	2366.99	0.62	0.77	0.87	1.58	10.50	16.30	2.90
GCG	750	20A	0.16	104.73	389.61	91.85	11.68	5.86	702.65	3.41	127.33	2263.36	0.60	0.76	0.85	1.66	10.90	17.40	3.25
GCG	750	20B	0.21	138.37	345.80	83.07	11.17	6.21	675.01	3.08	92.51	2263.36	0.62	0.78	0.90	1.58	10.60	16.80	3.10
GCG	750	20C	0.22	140.43	365.51	86.86	11.37	7.30	751.84	3.15	122.19	2263.36	0.59	0.75	0.84	1.82	10.30	15.90	2.80
GCG	750	25A	0.16	130.91	326.95	99.45	11.42	7.12	762.20	3.75	152.70	2281.50	0.62	0.78	0.88	1.68	10.60	16.40	2.90
GCG	750	25B	0.21	172.97	355.24	98.77	11.49	6.68	781.05	3.82	156.01	2281.50	0.57	0.72	0.82	1.89	10.40	15.70	2.65
GCG	750	25C	0.22	175.54	321.76	87.21	11.19	6.62	707.35	3.19	123.86	2281.50	0.59	0.74	0.85	1.75	11.00	16.80	2.90

Table D9: Raw data for results from the refining trials of the GUP

Sample	Speed	Stage & Replicate	SEL	SRE	Freeness	Tensile Index	Tear	Burst Index	Sheet Density	Stretch	TEA	Z-span	Fibre Length (Ln)	Fibre Length (Ll)	Fibre Length (Lw)	Fines	LD	Pulp fibre diameter	Pulp CWT
	(rpm)		(Ws/m)	(kWh/t)	(ml)	(kNm/kg)	(kNm^2/kg)	(MN/kg)	(kg/m^3)	(%)	(J/m^2)	(N/m)	(mm)	(mm)	(mm)	(%)	(µm)	(µm)	(µm)
GUP	1500	0A	0.00	0.00	572.10	72.98	8.48	2.50	656.89	2.04	56.25	1638.33	0.56	0.70	0.82	1.66	11.50	17.70	3.10
GUP	1500	0B	0.00	0.00	583.23	53.37	7.52	2.67	645.93	1.59	31.37	1638.33	0.56	0.69	0.78	1.61	11.10	17.40	3.15
GUP	1500	0C	0.00	0.00	577.17	55.49	5.61	2.72	655.78	1.53	31.54	1638.33	0.57	0.70	0.79	1.58	11.40	17.50	3.05
GUP	1500	1A	0.32	20.44	454.68	50.23	6.64	2.49	620.23	1.38	24.90	1690.43	0.53	0.66	0.75	1.90	11.10	16.90	2.90
GUP	1500	1B	0.30	19.35	431.46	81.51	7.96	3.35	699.11	2.52	75.21	1690.43	0.55	0.68	0.78	1.78	11.90	18.00	3.05
GUP	1500	1C	0.31	19.88	478.92	69.13	7.78	3.74	674.30	2.12	53.96	1690.43	0.54	0.66	0.75	1.79	11.70	17.40	2.85
GUP	1500	2A	0.32	40.89	465.22	64.19	7.87	4.15	677.32	2.21	54.75	1900.60	0.54	0.67	0.75	1.82	10.90	16.60	2.85
GUP	1500	2B	0.30	38.69	445.39	94.02	9.43	4.89	631.20	2.12	64.12	1900.60	0.54	0.67	0.75	1.73	10.90	16.70	2.90
GUP	1500	2C	0.31	39.75	429.25	75.79	8.11	4.94	686.82	2.51	71.56	1900.60	0.54	0.66	0.75	1.73	10.80	16.20	2.70
GUP	1500	3A	0.32	61.33	380.59	71.24	8.27	3.82	719.23	2.02	55.57	2120.75	0.53	0.65	0.73	1.85	11.40	17.50	3.05
GUP	1500	3B	0.30	58.04	361.25	95.59	8.06	5.72	624.55	2.74	101.24	2120.75	0.53	0.65	0.74	1.86	10.70	16.50	2.90
GUP	1500	3C	0.31	59.63	372.25	84.37	8.49	4.95	691.74	2.54	78.59	2120.75	0.54	0.67	0.75	1.88	10.90	16.50	2.80
GUP	1500	4A	0.32	81.77	357.64	86.79	7.93	5.56	727.58	2.93	99.54	2108.97	0.54	0.65	0.73	1.72	11.10	16.90	2.90
GUP	1500	4B	0.30	77.38	342.59	95.89	8.26	5.77	732.74	3.04	115.08	2108.97	0.53	0.65	0.74	1.84	11.30	17.20	2.95
GUP	1500	4C	0.31	79.51	319.16	98.47	8.18	6.27	703.48	3.03	112.05	2108.97	0.53	0.65	0.74	1.80	11.10	16.50	2.70
GUP	1500	5A	0.32	102.21	315.10	97.48	8.50	6.49	753.87	3.17	120.72	2183.35	0.53	0.66	0.74	1.76	11.30	17.60	3.15
GUP	1500	5B	0.30	96.73	261.46	94.28	8.09	6.00	740.16	3.69	157.10	2183.35	0.52	0.64	0.73	2.16	11.10	16.70	2.80
GUP	1500	5C	0.31	99.39	310.13	100.97	7.30	6.24	702.77	3.20	125.59	2183.35	0.52	0.64	0.72	1.96	11.00	16.60	2.80
GUP	1500	6A	0.32	122.66	295.90	98.44	8.43	6.81	746.23	3.27	129.78	1871.59	0.52	0.65	0.74	2.02	11.00	16.50	2.75
GUP	1500	6B	0.30	116.08	294.85	93.86	8.26	6.64	731.33	3.38	132.02	1871.59	0.52	0.64	0.73	2.11	11.10	16.90	2.90
GUP	1500	6C	0.31	119.26	281.14	107.41	8.69	6.72	687.74	3.31	119.02	1871.59	0.52	0.64	0.73	1.93	11.30	16.70	2.70
GUP	2200	0A	0.00	0.00	584.70	46.87	6.53	2.36	648.57	1.38	23.61	1552.11	0.56	0.70	0.80	1.75	11.10	17.40	3.15
GUP	2200	0B	0.00	0.00	591.54	45.60	5.90	2.30	653.48	1.37	22.84	1552.11	0.57	0.71	0.81	1.62	11.70	18.50	3.40
GUP	2200	0C	0.00	0.00	577.10	50.02	6.68	2.35	651.47	1.29	22.82	1552.11	0.57	0.70	0.78	1.54	11.20	17.60	3.20
GUP	2200	1A	0.46	43.45	455.52	67.43	8.46	3.78	669.95	2.02	50.18	1812.81	0.56	0.69	0.81	1.72	11.40	17.20	2.90
GUP	2200	1B	0.45	42.68	445.44	69.01	8.73	4.08	667.36	2.17	56.99	1812.81	0.53	0.66	0.74	1.84	11.50	17.60	3.05
GUP	2200	1C	0.44	41.52	447.69	70.45	8.47	4.04	685.33	2.15	58.22	1812.81	0.55	0.68	0.77	1.73	11.60	17.60	3.00
GUP	2200	2A	0.46	86.90	345.38	81.45	8.59	5.23	706.42	2.59	80.91	1927.54	0.54	0.67	0.75	1.87	11.00	16.70	2.85
GUP	2200	2B	0.45	85.36	325.70	78.94	8.34	5.45	724.75	2.72	86.34	1927.54	0.54	0.67	0.75	1.80	10.80	16.30	2.75
GUP	2200	2C	0.44	83.03	334.92	91.69	8.46	5.78	723.03	2.66	96.48	1927.54	0.52	0.64	0.73	2.02	11.50	17.30	2.90
GUP	2200	3A	0.46	130.35	248.39	88.16	9.18	6.09	750.73	3.10	111.01	1966.68	0.52	0.65	0.74	1.91	11.20	17.10	2.95
GUP	2200	3B	0.45	128.04	253.32	98.99	7.99	6.73	778.02	3.20	129.88	1966.68	0.52	0.65	0.74	1.90	11.60	17.50	2.95
GUP	2200	3C	0.44	124.55	234.39	98.86	8.91	7.45	870.46	3.24	125.39	1966.68	0.53	0.66	0.75	1.99	11.00	16.30	2.65

...Table D9 Continued

Sample	Speed	Stage & Replicate	SEL	SRE	Freeness	Tensile Index	Tear	Burst Index	Sheet Density	Stretch	TEA	Z-span	Fibre Length (Ln)	Fibre Length (Ll)	Fibre Length (Lw)	Fines	LD	Pulp fibre diameter	Pulp CWT
	(rpm)		(Ws/m)	(kWh/t)	(ml)	(kNm/kg)	(kNm^2/kg)	(MN/kg)	(kg/m^3)	(%)	(J/m^2)	(N/m)	(mm)	(mm)	(mm)	(%)	(µm)	(µm)	(µm)
GUP	2200	4A	0.46	173.80	197.91	110.42	7.51	8.17	790.27	3.22	137.76	1778.70	0.51	0.63	0.71	2.17	11.00	16.40	2.70
GUP	2200	4B	0.45	170.72	200.05	106.19	7.99	7.56	796.78	3.34	145.17	1778.70	0.51	0.64	0.72	2.14	11.60	17.30	2.85
GUP	2200	4C	0.44	166.06	196.54	108.42	8.00	7.85	793.48	4.29	163.71	1778.70	0.50	0.63	0.72	2.28	11.10	16.20	2.55
GUP	2200	5A	0.46	217.26	142.33	103.00	8.66	8.49	840.61	3.58	150.99	1969.72	0.51	0.65	0.75	2.18	11.50	17.30	2.90
GUP	2200	5B	0.45	213.40	129.72	113.63	7.38	8.73	834.34	3.54	162.93	1969.72	0.49	0.61	0.70	2.37	11.30	16.90	2.80
GUP	2200	5C	0.44	207.58	117.94	120.99	6.53	8.67	834.77	3.92	186.17	1969.72	0.48	0.61	0.70	2.56	11.30	16.60	2.65
GUP	2200	6A	0.46	260.71	126.23	109.75	8.18	8.57	829.33	3.07	133.26	1789.70	0.48	0.61	0.70	2.60	11.10	16.70	2.80
GUP	2200	6B	0.45	256.08	84.94	112.44	7.15	8.75	885.96	3.08	136.58	1789.70	0.47	0.60	0.69	2.78	11.50	16.30	2.40
GUP	2200	6C	0.44	249.09	91.86	119.53	6.38	9.16	863.30	4.14	201.36	1789.70	0.47	0.61	0.69	2.79	12.30	17.90	2.80
GUP	750	0A	0.00	0.00	552.70	47.31	5.97	2.30	611.00	1.47	24.83	1599.29	0.57	0.70	0.79	1.79	11.00	17.30	3.15
GUP	750	0B	0.00	0.00	567.48	48.50	7.03	2.59	666.13	1.35	23.49	1599.29	0.57	0.70	0.79	1.65	11.20	17.40	3.10
GUP	750	0C	0.00	0.00	548.80	51.47	7.17	2.53	604.90	1.31	26.96	1599.29	0.57	0.70	0.79	1.56	11.40	17.90	3.25
GUP	750	1A	0.21	6.76	527.61	58.39	6.93	2.83	635.57	1.50	32.88	1674.79	0.56	0.69	0.78	1.67	11.10	17.00	2.95
GUP	750	1B	0.21	6.79	528.15	58.42	7.07	2.82	639.73	1.54	32.75	1674.79	0.57	0.70	0.80	1.66	11.00	17.50	3.25
GUP	750	1C	0.20	6.47	507.84	56.50	6.75	2.76	621.29	1.51	31.63	1674.79	0.57	0.70	0.79	1.57	11.40	17.60	3.10
GUP	750	5A	0.21	33.82	518.64	66.90	6.89	3.34	645.98	1.83	42.40	1963.12	0.56	0.69	0.78	1.65	11.00	17.00	3.00
GUP	750	5B	0.21	33.95	467.08	66.75	7.30	3.55	663.91	1.90	49.31	1963.12	0.57	0.70	0.79	1.69	11.00	17.10	3.05
GUP	750	5C	0.20	32.35	485.24	70.47	8.14	3.71	648.91	2.04	57.03	1963.12	0.56	0.69	0.77	1.68	11.20	17.20	3.00
GUP	750	10A	0.21	67.64	438.16	79.55	8.55	4.03	673.76	2.44	76.59	1935.18	0.55	0.67	0.76	1.61	10.90	16.90	3.00
GUP	750	10B	0.21	67.89	444.88	76.78	8.92	4.09	694.21	2.43	74.33	1935.18	0.54	0.68	0.76	1.90	10.90	16.60	2.85
GUP	750	10C	0.20	64.69	436.26	73.29	8.67	4.15	735.29	2.95	76.40	1935.18	0.56	0.69	0.79	1.70	10.80	16.50	2.85
GUP	750	15A	0.21	101.45	407.43	78.90	8.49	4.73	687.42	2.33	66.46	1791.85	0.55	0.68	0.77	1.67	10.90	16.50	2.80
GUP	750	15B	0.21	101.84	438.65	80.61	9.51	4.66	692.49	2.65	85.40	1791.85	0.55	0.68	0.77	1.77	10.80	16.80	3.00
GUP	750	15C	0.20	97.04	416.78	77.57	9.07	5.31	714.78	2.90	70.60	1791.85	0.55	0.69	0.77	1.84	10.60	16.20	2.80
GUP	750	20A	0.21	135.27	442.74	84.28	7.99	4.76	699.45	2.43	84.22	2062.10	0.56	0.68	0.77	1.67	11.80	17.70	2.95
GUP	750	20B	0.21	135.79	434.66	83.61	7.94	4.81	700.96	2.53	77.80	2062.10	0.55	0.69	0.78	1.88	11.00	16.70	2.85
GUP	750	20C	0.20	129.38	429.25	83.61	9.95	5.16	678.43	2.36	74.32	2062.10	0.56	0.69	0.78	1.67	11.40	17.50	3.05
GUP	750	25A	0.21	169.09	433.29	81.68	8.67	5.33	729.47	2.35	90.24	2173.34	0.57	0.72	0.82	1.80	11.70	17.80	3.05
GUP	750	25B	0.21	169.73	413.21	91.63	10.73	6.00	718.61	2.76	84.00	2173.34	0.58	0.71	0.82	1.50	11.00	16.80	2.90
GUP	750	25C	0.20	161.73	411.83	92.14	9.67	5.53	776.18	2.77	91.30	2173.34	0.57	0.70	0.78	1.69	11.90	18.30	3.20

Table D10: Raw data for results from the refining trials of the GUG

Sample	Speed	Stage & Replicate	SEL	SRE	Freeness	Tensile Index	Tear	Burst Index	Sheet Density	Stretch	TEA	Z-span	Fibre Length (Ln)	Fibre Length (Ll)	Fibre Length (Lw)	Fines	LD	Pulp fibre diameter	Pulp CWT
	(rpm)		(Ws/m)	(kWh/t)	(ml)	(kNm/kg)	(kNm^2/kg)	(MN/kg)	(kg/m^3)	(%)	(J/m^2)	(N/m)	(mm)	(mm)	(mm)	(%)	(μm)	(μm)	(μm)
GUG	1500	0A	0.00	0.00	600.91	73.14	10.63	3.52	723.85	1.88	54.05	1996.70	0.61	0.78	0.89	1.63	12.30	18.50	3.10
GUG	1500	0B	0.00	0.00	594.08	57.26	8.88	2.90	658.62	1.61	33.38	1996.70	0.59	0.75	0.86	1.71	12.40	18.50	3.05
GUG	1500	0C	0.00	0.00	578.98	53.17	8.20	2.89	639.53	1.35	24.02	1996.70	0.60	0.77	0.88	1.61	12.70	18.90	3.10
GUG	1500	1A	0.37	23.95	487.83	85.89	9.49	4.68	727.35	2.23	68.36	2250.50	0.58	0.74	0.85	1.78	12.60	18.40	2.90
GUG	1500	1B	0.41	26.75	482.50	70.85	10.27	4.14	690.63	2.07	53.05	2250.50	0.60	0.76	0.88	1.61	12.30	18.30	3.00
GUG	1500	1C	0.39	25.20	475.22	78.43	10.26	4.32	677.28	2.28	62.03	2250.50	0.58	0.74	0.84	1.92	11.90	17.50	2.80
GUG	1500	2A	0.37	47.90	420.57	93.84	9.54	5.38	728.07	2.50	82.31	2237.55	0.58	0.75	0.87	1.81	11.90	17.20	2.65
GUG	1500	2B	0.41	53.49	447.79	84.86	10.01	5.38	713.05	2.55	75.69	2237.55	0.59	0.76	0.89	1.88	12.50	18.20	2.85
GUG	1500	2C	0.39	50.40	427.91	88.36	9.76	5.68	730.17	2.43	75.04	2237.55	0.57	0.73	0.84	1.85	12.60	18.70	3.05
GUG	1500	3A	0.37	71.85	420.56	83.31	9.87	5.32	770.69	2.67	81.07	1970.70	0.59	0.75	0.86	1.79	12.10	18.20	3.05
GUG	1500	3B	0.41	80.24	425.91	81.15	10.86	5.47	699.53	2.37	66.13	1970.70	0.59	0.75	0.87	1.82	12.30	17.80	2.75
GUG	1500	3C	0.39	75.61	410.23	95.33	9.92	5.82	777.49	2.98	115.14	1970.70	0.57	0.73	0.84	1.98	12.20	17.70	2.75
GUG	1500	4A	0.37	95.80	400.68	86.52	10.53	5.60	756.54	2.90	100.17	2081.57	0.56	0.72	0.83	2.11	12.90	18.90	3.00
GUG	1500	4B	0.41	106.98	417.77	106.95	10.55	6.74	728.25	3.40	150.05	2081.57	0.58	0.75	0.87	2.01	12.80	18.80	3.00
GUG	1500	4C	0.39	100.81	395.96	91.17	10.02	6.41	770.54	2.91	115.23	2081.57	0.59	0.76	0.87	1.85	12.10	18.00	2.95
GUG	1500	5A	0.37	119.75	399.32	89.23	10.09	6.19	773.19	2.91	105.85	2134.09	0.56	0.72	0.83	1.99	12.40	18.00	2.80
GUG	1500	5B	0.41	133.73	390.73	85.86	11.06	5.80	780.05	3.04	93.54	2134.09	0.58	0.74	0.85	1.88	12.10	17.60	2.75
GUG	1500	5C	0.39	126.01	370.83	102.92	9.56	6.90	733.18	3.36	129.00	2134.09	0.56	0.73	0.85	2.22	12.80	18.50	2.85
GUG	1500	6A	0.37	143.70	345.26	100.51	9.61	6.82	778.69	3.14	126.67	2097.97	0.58	0.74	0.85	1.82	12.30	18.30	3.00
GUG	1500	6B	0.41	160.48	325.98	99.21	11.24	6.91	787.30	3.86	125.00	2097.97	0.57	0.74	0.87	2.05	12.00	17.90	2.95
GUG	1500	6C	0.39	151.21	330.00	110.40	9.06	7.40	784.04	3.21	126.24	2097.97	0.56	0.72	0.83	2.07	12.10	17.90	2.90
GUG	2200	0A	0.00	0.00	546.51	60.84	8.73	3.65	647.45	1.53	32.14	1841.70	0.62	0.76	0.88	1.53	12.60	19.00	3.20
GUG	2200	0B	0.00	0.00	586.77	73.43	8.90	3.97	700.95	1.95	37.00	1841.70	0.61	0.78	0.88	1.72	12.40	18.60	3.10
GUG	2200	0C	0.00	0.00	571.50	59.63	10.10	3.74	696.99	1.90	41.65	1841.70	0.61	0.77	0.89	1.53	12.00	18.00	3.00
GUG	2200	1A	0.52	49.61	423.91	89.69	10.12	6.42	726.70	2.50	80.89	2308.86	0.56	0.73	0.84	2.23	12.50	18.40	2.95
GUG	2200	1B	0.48	45.17	473.59	71.80	10.65	6.03	763.14	2.32	82.97	2308.86	0.56	0.72	0.83	1.97	12.30	18.40	3.05
GUG	2200	1C	0.46	43.21	444.57	85.25	10.56	5.82	757.76	2.44	84.56	2308.86	0.58	0.75	0.86	1.83	12.60	19.10	3.25
GUG	2200	2A	0.52	99.22	366.67	110.85	10.18	7.11	731.51	2.80	97.40	1985.23	0.58	0.77	0.91	2.13	12.50	18.50	3.00
GUG	2200	2B	0.48	90.33	355.25	91.08	9.98	6.76	714.02	2.62	91.14	1985.23	0.58	0.74	0.85	1.91	12.00	17.80	2.90
GUG	2200	2C	0.46	86.42	399.59	89.86	9.50	6.75	792.35	2.77	103.83	1985.23	0.55	0.72	0.83	2.24	11.70	17.60	2.95
GUG	2200	3A	0.52	148.83	313.33	110.31	9.41	7.94	765.36	2.99	127.50	1969.02	0.56	0.73	0.84	2.26	12.60	18.30	2.85
GUG	2200	3B	0.48	135.50	305.23	95.88	9.33	7.39	761.13	2.97	109.00	1969.02	0.55	0.71	0.83	2.22	12.60	17.80	2.60
GUG	2200	3C	0.46	129.63	269.18	108.10	9.15	8.13	814.45	3.19	146.51	1969.02	0.57	0.74	0.87	2.23	12.80	18.40	2.80

...Table D10 Continued

Sample	Speed	Stage & Replicate	SEL	SRE	Freeness	Tensile Index	Tear	Burst Index	Sheet Density	Stretch	TEA	Z-span	Fibre Length (Ln)	Fibre Length (Ll)	Fibre Length (Lw)	Fines	LD	Pulp fibre diameter	Pulp CWT
	(rpm)		(Ws/m)	(kWh/t)	(ml)	(kNm/kg)	(kNm^2/kg)	(MN/kg)	(kg/m^3)	(%)	(J/m^2)	(N/m)	(mm)	(mm)	(mm)	(%)	(µm)	(µm)	(µm)
GUG	2200	4A	0.52	198.44	236.13	110.31	9.28	8.70	754.48	3.04	127.13	2169.35	0.55	0.72	0.83	2.35	12.10	17.70	2.80
GUG	2200	4B	0.48	180.66	221.25	107.16	9.21	8.63	796.59	3.19	127.75	2169.35	0.54	0.71	0.82	2.49	11.80	17.50	2.85
GUG	2200	4C	0.46	172.84	194.21	117.32	7.49	9.59	852.17	3.73	178.67	2169.35	0.55	0.73	0.84	2.55	12.10	17.60	2.75
GUG	2200	5A	0.52	248.05	183.88	111.63	9.92	8.74	770.00	3.38	140.93	2010.49	0.53	0.71	0.83	2.67	12.40	17.90	2.75
GUG	2200	5B	0.48	225.83	205.22	104.24	8.73	8.14	775.00	3.44	162.00	2010.49	0.52	0.68	0.80	2.78	13.00	18.90	2.95
GUG	2200	5C	0.46	216.06	192.62	118.07	7.77	9.65	882.43	3.36	183.00	2010.49	0.54	0.72	0.84	2.53	12.00	17.40	2.70
GUG	2200	6A	0.52	297.67	141.40	110.12	8.81	9.39	810.47	3.41	140.67	1702.42	0.52	0.70	0.81	3.05	11.60	17.40	2.90
GUG	2200	6B	0.48	270.99	114.28	120.78	8.85	9.03	844.04	4.03	186.73	1702.42	0.52	0.70	0.82	2.92	12.90	18.40	2.75
GUG	2200	6C	0.46	259.27	166.89	121.21	7.71	9.50	878.94	4.00	212.23	1702.42	0.53	0.71	0.83	2.74	12.20	17.60	2.70
GUG	750	0A	0.00	0.00	588.22	64.66	9.46	3.40	687.76	1.74	40.44	1158.89	0.59	0.76	0.88	1.92	12.00	17.90	2.95
GUG	750	0B	0.00	0.00	595.62	58.97	9.43	3.14	650.46	1.54	35.47	1158.89	0.61	0.78	0.89	1.62	12.40	18.40	3.00
GUG	750	0C	0.00	0.00	607.29	63.98	8.73	3.13	658.47	1.65	40.44	1158.89	0.61	0.77	0.88	1.57	12.40	18.50	3.05
GUG	750	1A	0.15	4.96	573.29	64.16	9.20	3.49	625.59	1.76	40.88	1292.48	0.60	0.77	0.87	1.51	12.00	17.90	2.95
GUG	750	1B	0.15	4.80	564.95	73.08	10.26	4.16	685.68	2.08	55.55	1292.48	0.60	0.77	0.88	1.86	12.30	18.50	3.10
GUG	750	1C	0.15	4.94	597.76	73.35	10.26	3.98	726.22	1.99	40.88	1292.48	0.61	0.77	0.88	1.63	12.10	18.10	3.00
GUG	750	5A	0.15	24.79	571.93	81.24	10.49	4.86	757.75	2.15	65.81	1269.47	0.60	0.76	0.86	1.64	12.45	18.35	2.95
GUG	750	5B	0.15	23.99	562.73	66.41	11.04	3.15	648.21	1.84	56.25	1269.47	0.60	0.76	0.86	1.74	12.30	18.30	3.00
GUG	750	5C	0.15	24.68	521.12	79.08	11.19	3.93	688.73	2.10	65.81	1269.47	0.62	0.83	0.88	1.63	12.60	18.40	2.90
GUG	750	10A	0.15	49.57	494.87	77.67	10.68	4.67	709.48	2.34	69.69	1681.77	0.61	0.77	0.80	1.58	11.20	17.10	2.95
GUG	750	10B	0.15	47.98	496.02	82.67	11.89	4.91	780.90	2.43	71.40	1681.77	0.62	0.78	0.89	1.56	12.10	18.40	3.15
GUG	750	10C	0.15	49.35	507.68	77.84	10.38	4.34	707.37	2.40	69.69	1681.77	0.61	0.77	0.88	1.65	11.70	17.50	2.90
GUG	750	15A	0.15	74.36	452.09	88.66	9.98	5.59	738.16	2.31	76.71	2307.20	0.60	0.75	0.86	1.71	12.10	18.20	3.05
GUG	750	15B	0.15	71.97	445.88	91.29	10.48	5.79	735.17	2.44	91.63	2307.20	0.60	0.69	0.79	1.61	11.60	17.60	3.00
GUG	750	15C	0.15	74.03	446.67	91.37	10.29	5.55	753.69	2.55	76.71	2307.20	0.61	0.77	0.88	1.49	11.80	17.40	2.80
GUG	750	20A	0.15	99.15	419.40	91.52	11.38	6.05	741.26	2.55	90.89	2266.60	0.61	0.76	0.87	1.56	12.20	18.10	2.95
GUG	750	20B	0.15	95.96	405.38	91.30	9.95	6.23	745.30	2.80	111.39	2266.60	0.61	0.77	0.88	1.66	11.60	17.40	2.90
GUG	750	20C	0.15	98.70	414.69	92.50	11.09	6.13	765.93	2.93	90.89	2266.60	0.61	0.78	0.89	1.67	12.10	18.00	2.95
GUG	750	25A	0.15	123.93	381.98	104.43	10.77	6.89	756.55	3.01	127.26	2334.05	0.60	0.77	0.88	1.72	12.00	17.50	2.75
GUG	750	25B	0.15	119.95	394.59	94.51	11.04	6.61	744.95	2.75	85.71	2334.05	0.62	0.78	0.89	1.59	12.40	18.30	2.95
GUG	750	25C	0.15	123.38	388.32	91.75	11.90	6.99	785.54	2.72	127.26	2334.05	0.63	0.80	0.92	1.67	11.80	17.60	2.90

Table D11: Multiple regression analysis results using actual pulp properties after each stage of refining for all three speeds together

	Freeness	Tensile	Tear	Burst	Sheet density	Stretch	TEA	Z-span
R 2	**78.76**	**70.57**	**56.08**	**73.24**	**65.27**	**63.2**	**55.46**	**7.56**
Contributors to the model								
FL		2.48	36.13	4.42				7.56
FD	8.54			4.73		3.2		
CWT	66.58	63.92	19.95	58.54	9.28	55.39	55.46	
fines	3.64	4.17		5.55	55.99	4.61		
LD								

Table D12: Pulp properties at constant SRE - 100 kWh/t

Sample	speed	SEL	Freeness	Tensile	Tear	Burst	Sheet density	Stretch	TEA	Z-span	FL	Fines	FD	CWT	LD
		(Ws/m)	(ml)	(kNm/kg)	(kNm^2/kg)	(MN/kg)	(kg/m^3)	(%)	(J/m^2)	(kN/m)	(micron)	(%)	(micron)	(micron)	(micron)
GCP	0	0	591.25	49.23	7.24	2.25	600.79	1.50	26.26	1.63	0.77	1.34	17.00	3.13	10.73
GCP	750	0.22	445.33	72.02	10.98	4.66	661.33	2.65	72.11	2.35	0.75	1.42	16.61	2.98	10.64
GCP	1500	0.36	377.64	96.50	10.55	5.74	721.00	2.81	106.33	2.34	0.74	1.42	16.37	2.91	10.55
GCP	2200	0.47	333.00	86.00	9.79	5.81	725.67	3.44	130.67	2.45	0.73	1.46	16.67	2.95	10.77
GCG	0	0	594.55	51.76	8.97	2.86	644.42	1.71	42.49	1.85	0.80	1.26	16.80	3.07	10.62
GCG	750	0.20	414.12	84.92	12.01	6.08	706.99	3.14	105.30	2.19	0.77	1.61	16.59	2.97	10.64
GCG	1500	0.43	401.43	97.17	12.24	6.73	749.67	3.31	128.00	2.13	0.77	1.64	16.57	2.97	10.62
GCG	2200	0.52	396.00	82.35	11.32	5.37	662.00	2.83	91.23	1.57	0.78	1.54	16.54	2.98	10.58
GUP	0	0	556.33	49.09	6.72	2.48	627.34	1.38	25.09	1.60	0.70	1.67	17.53	3.17	11.29
GUP	750	0.21	425.00	81.80	8.88	4.75	700.33	2.63	70.58	2.27	0.69	1.71	17.16	2.98	11.19
GUP	1500	0.31	303.20	96.16	8.28	6.26	725.71	3.18	120.61	1.97	0.65	1.95	16.75	2.83	11.09
GUP	2200	0.45	307.67	90.50	8.47	6.05	746.02	2.86	105.50	1.96	0.66	1.96	17.17	2.92	11.33
GUG	0	0	597.04	62.54	9.21	3.22	665.56	1.64	38.78	1.67	0.77	1.70	18.27	3.00	12.36
GUG	750	0.15	414.71	93.18	10.99	6.22	754.94	2.71	99.49	1.79	0.77	1.63	17.77	2.91	11.94
GUG	1500	0.39	401.85	94.64	10.26	6.25	755.05	2.98	107.13	2.18	0.74	1.93	18.14	2.90	12.34
GUG	2200	0.49	351.67	97.33	9.59	7.22	758.00	3.12	106.33	1.96	0.74	2.12	18.22	2.94	12.34

Table D13: Pulp properties at constant freeness - 400 ml

Sample	speed	SEL	SRE	Tensile	Tear	Burst	Sheet density	Stretch	TEA	Z-span	FL	Fines	FD	CWT	LD
		(Ws/m)	(kWh/t)	(kNm/kg)	(kNm^2/kg)	(MN/kg)	(kg/m^3)	(%)	(J/m^2)	(kN/m)	(micron)	(%)	(micron)	(micron)	(micron)
GCP	0	0	0.00	49.23	7.24	2.25	600.79	1.50	26.26	1.63	0.77	1.34	17.00	3.13	10.73
GCP	750	0.22	166.92	85.67	10.72	5.58	685.73	2.79	96.00	2.31	0.74	1.40	16.57	2.95	10.67
GCP	1500	0.36	85.67	87.90	10.30	5.58	705.81	2.80	97.35	2.33	0.74	1.41	16.43	2.93	10.56
GCP	2200	0.47	69.00	80.33	10.10	4.84	673.51	2.55	91.33	2.45	0.74	1.43	16.70	2.96	10.77
GCG	0	0	0.00	51.76	8.97	2.86	644.42	1.71	42.49	1.85	0.80	1.26	16.80	3.07	10.62
GCG	750	0.20	105.00	87.33	11.95	5.96	713.07	3.10	109.58	2.56	0.77	1.64	16.55	2.96	10.63
GCG	1500	0.43	94.67	94.33	12.03	6.35	742.70	3.12	123.14	2.13	0.77	1.64	16.56	2.97	10.62
GCG	2200	0.52	98.00	83.66	11.47	5.55	679.01	2.84	90.00	1.65	0.78	1.57	16.53	2.97	10.58
GUP	0	0	0.00	49.09	6.72	2.48	627.34	1.38	25.09	1.60	0.70	1.67	17.53	3.17	11.29
GUP	750	0.21	142.26	88.67	9.57	5.42	725.01	2.82	90.16	2.30	0.69	1.73	16.92	2.90	11.13
GUP	1500	0.31	51.17	80.83	8.28	4.84	690.35	2.56	84.83	2.11	0.66	1.83	16.99	2.91	11.17
GUP	2200	0.45	61.00	75.53	8.53	4.76	713.15	2.34	74.19	2.10	0.67	1.86	17.30	2.98	11.33
GUG	0	0	0.00	62.54	9.21	3.22	665.56	1.64	38.78	1.67	0.77	1.70	18.27	3.00	12.36
GUG	750	0.15	110.00	94.00	10.87	6.41	759.84	2.78	103.82	2.29	0.77	1.63	17.72	2.91	11.90
GUG	1500	0.39	93.33	91.75	10.18	5.99	749.97	2.91	101.43	2.05	0.74	1.93	18.11	2.89	12.32
GUG	2200	0.49	74.33	90.67	9.78	6.35	745.97	2.58	92.00	1.87	0.74	2.06	18.27	2.97	12.34

Table D14: Correlation table for results at 100 kWh/t at a speed of 750rpm

	Freeness	Tensile	Tear	Burst	Sheet density	Stretch	TEA	FL	Fines	Pulp Fibre	Pulp CWT	LD
Density	**0.66**	**-0.90**	-0.44	**-0.95**	**-0.84**	-0.45	**-0.85**	-0.56	-0.47	-0.51	0.47	-0.56
WVD	**-0.71**	**0.94**	0.18	**0.85**	**0.86**	0.37	**0.73**	0.29	**0.70**	0.58	-0.41	0.62
WVP	-0.59	0.63	**0.69**	**0.90**	0.52	**0.77**	**0.90**	0.64	0.29	0.02	-0.25	0.06
WVF	0.52	**-0.79**	0.44	-0.38	**-0.77**	0.15	-0.21	0.26	**-0.84**	**-0.80**	0.33	**-0.82**
WFD	-0.01	0.37	-0.50	-0.03	0.46	**-0.68**	-0.22	-0.19	0.20	**0.84**	-0.36	**0.86**
WLD	-0.38	**0.78**	-0.19	0.48	**0.81**	-0.30	0.27	0.10	0.45	**0.93**	-0.52	**0.97**
WCWT	0.55	**-0.92**	-0.04	**-0.73**	**-0.91**	0.00	-0.54	-0.28	-0.54	**-0.84**	0.54	**-0.90**
w-Collaps	-0.44	**0.85**	0.01	0.64	**0.87**	-0.14	0.45	0.29	0.41	**0.88**	-0.56	**0.94**
w-muhlsteph	0.44	**-0.84**	0.09	-0.58	**-0.86**	0.19	-0.38	-0.19	-0.47	**-0.91**	0.54	**-0.96**
w-Runkel	0.46	**-0.85**	0.11	-0.58	**-0.87**	0.18	-0.38	-0.17	-0.50	**-0.91**	0.53	**-0.96**
w-Coarse	0.64	**-0.78**	-0.61	**-0.96**	**-0.69**	**-0.65**	**-0.92**	**-0.63**	-0.38	**-0.25**	0.36	-0.30
yield	-0.48	**0.74**	**0.68**	**0.93**	**0.70**	0.40	**0.85**	**0.82**	0.08	0.41	-0.50	0.47
i-FL	-0.22	0.13	**0.92**	0.61	0.15	**0.66**	**0.74**	**0.90**	-0.48	-0.24	0.01	-0.23
i-fines	0.27	0.08	-0.41	-0.34	-0.11	**-0.66**	-0.41	-0.37	0.16	0.54	-0.12	0.53
i-FD	-0.33	**0.65**	-0.26	0.36	**0.74**	-0.27	0.12	-0.05	0.53	**0.88**	-0.43	**0.91**
i-CWT	-0.01	-0.26	-0.46	-0.25	0.05	0.12	-0.22	-0.46	0.24	-0.16	0.25	-0.20
i-LD	-0.31	**0.70**	-0.12	0.42	**0.69**	-0.29	0.18	0.09	0.44	**0.88**	-0.48	**0.92**
i-Collaps	-0.15	0.52	0.28	0.39	0.29	-0.23	0.25	0.38	0.03	0.55	-0.41	0.60
i-muhlsteph	0.24	**-0.66**	-0.09	-0.43	-0.51	0.29	-0.22	-0.24	-0.26	**-0.77**	0.49	**-0.82**
i-Runkel	0.24	**-0.65**	-0.09	-0.42	-0.51	0.29	-0.22	-0.24	-0.26	**-0.77**	0.48	**-0.82**
FL/FD	0.01	-0.24	**0.78**	0.25	-0.27	0.61	0.46	**0.66**	-0.61	-0.62	0.24	-0.63
inintial Ci	**0.66**	**-0.78**	-0.58	**-0.95**	**-0.68**	**-0.66**	**-0.91**	-0.60	-0.41	-0.23	0.34	-0.28
Freeness	1.00	**-0.77**	-0.18	**-0.67**	-0.63	-0.48	**-0.71**	-0.14	-0.60	-0.42	-0.09	-0.38
Tensile Index		1.00	0.12	**0.81**	**0.86**	0.20	**0.70**	0.27	0.64	**0.74**	-0.37	**0.76**
Tear Strength			1.00	0.61	0.09	**0.69**	**0.70**	**0.89**	-0.38	-0.27	-0.08	-0.24
Burst Index				1.00	**0.79**	0.60	**0.92**	**0.70**	0.27	0.37	-0.35	0.41
Sheet density					1.00	0.22	0.64	0.34	0.48	**0.72**	-0.41	**0.75**
Stretch						1.00	**0.74**	0.47	0.09	-0.29	0.28	-0.32
TEA							1.00	**0.72**	0.20	0.20	-0.15	0.22

Table D15: Correlation table for results at 100 kWh/t at a speed of 1500rpm

	Freeness	Tensile	Tear	Burst	Sheet density	Stretch	TEA	FL	Fines	FD	CWT	LD
Density	-0.55	0.10	-0.39	-0.59	-0.51	-0.33	-0.11	-0.42	-0.49	**-0.72**	-0.30	**-0.65**
WVD	0.28	-0.11	0.16	**0.65**	0.46	0.46	0.19	0.14	**0.70**	**0.70**	0.13	**0.67**
WVP	0.64	0.02	**0.72**	**0.72**	0.46	0.48	0.29	**0.66**	0.11	0.27	0.53	0.16
WVF	0.26	0.16	0.48	-0.34	-0.24	-0.30	-0.06	0.48	**-0.96**	**-0.73**	0.33	**-0.78**
WFD	-0.20	-0.23	**-0.65**	-0.37	0.02	-0.38	-0.39	-0.46	0.58	**0.74**	-0.47	**0.82**
WLD	0.10	-0.23	-0.33	0.05	0.29	-0.09	-0.23	-0.18	**0.75**	**0.96**	-0.23	**0.99**
WCWT	-0.27	0.20	0.07	-0.31	-0.41	-0.12	0.08	-0.03	**-0.74**	**-0.94**	0.04	**-0.94**
w-Collaps	0.28	-0.22	-0.13	0.14	0.37	-0.05	-0.20	0.03	**0.68**	**0.98**	-0.08	**0.98**
w-muhlsteph	-0.18	0.22	0.22	-0.14	-0.34	0.03	0.19	0.08	**-0.74**	**-0.97**	0.15	**-0.99**
w-Runkel	-0.16	0.22	0.24	-0.16	-0.34	0.00	0.17	0.10	**-0.77**	**-0.96**	0.16	**-0.98**
w-Coarse	-0.63	0.04	-0.60	**-0.68**	-0.50	-0.43	-0.21	-0.58	-0.29	-0.50	-0.45	-0.40
yield	**0.81**	-0.11	0.58	0.36	0.48	0.06	-0.06	**0.69**	0.17	**0.69**	0.43	0.60
i-FL	**0.90**	0.09	**0.89**	0.09	0.35	-0.07	0.02	**0.96**	-0.58	0.02	**0.68**	-0.12
i-fines	-0.28	-0.28	-0.53	0.22	0.17	0.18	-0.04	-0.53	**0.94**	**0.73**	-0.35	**0.79**
i-FD	0.05	-0.23	-0.46	-0.20	0.34	-0.25	-0.25	-0.24	0.64	**0.87**	-0.30	**0.91**
i-CWT	0.03	0.05	-0.05	**-0.65**	0.28	-0.24	0.19	0.08	-0.49	-0.33	0.14	-0.36
i-LD	0.04	-0.23	-0.44	-0.07	0.28	-0.20	-0.28	-0.25	**0.71**	**0.90**	-0.32	**0.95**
i-Collaps	0.02	-0.18	-0.23	0.37	-0.02	0.02	-0.31	-0.20	**0.74**	**0.77**	-0.29	**0.82**
i-muhlsteph	-0.01	0.23	0.38	-0.13	-0.15	0.10	0.31	0.26	**-0.78**	**-0.89**	0.34	**-0.94**
i-Runkel	-0.01	0.23	0.39	-0.13	-0.14	0.10	0.31	0.26	**-0.78**	**-0.88**	0.34	**-0.94**
FL/FD	0.58	0.20	**0.88**	0.20	0.03	0.11	0.16	**0.79**	**-0.76**	-0.50	0.64	-0.62
inintial Ci	-0.59	0.03	-0.59	**-0.71**	-0.49	-0.47	-0.24	-0.55	-0.31	-0.47	-0.44	-0.38
Freeness	1.00	-0.17	**0.83**	0.03	0.37	-0.21	-0.17	**0.93**	-0.38	0.31	0.63	0.19
Tensile Index		1.00	0.08	0.42	-0.03	0.47	0.51	0.04	-0.11	-0.34	-0.26	-0.28
Tear Strength			1.00	0.28	0.18	0.12	0.10	**0.93**	-0.53	-0.12	**0.70**	-0.25
Burst Index				1.00	0.17	**0.72**	0.47	0.17	0.32	0.02	0.09	0.00
Sheet density					1.00	0.41	0.59	0.30	0.27	0.41	0.51	0.31
Stretch						1.00	**0.89**	-0.06	0.41	-0.10	0.13	-0.12
TEA							1.00	0.00	0.19	-0.23	0.22	-0.26

Table D16: Correlation table for results at 100 kWh/t at a speed of 2200rpm

	Freeness	Tensile	Tear	Burst	Sheet density	Stretch	TEA	FL	Fines	FD	CWT	LD
Density	-0.61	-0.29	-0.41	-0.43	0.11	0.38	0.63	-0.49	-0.48	-0.55	-0.19	-0.51
WVD	0.44	0.34	0.20	0.43	-0.03	-0.55	**-0.72**	0.23	0.63	0.58	0.06	0.56
WVP	**0.88**	-0.13	**0.78**	-0.06	-0.54	-0.44	**-0.70**	**0.75**	-0.01	0.04	0.40	-0.01
WVF	0.19	-0.59	0.45	-0.63	-0.43	0.48	0.47	0.42	**-0.95**	**-0.76**	0.30	**-0.78**
WFD	-0.59	**0.76**	**-0.74**	**0.88**	**0.84**	0.23	0.27	-0.52	**0.82**	**0.88**	-0.42	**0.90**
WLD	-0.15	**0.75**	-0.39	**0.91**	0.60	-0.06	-0.15	-0.18	**0.92**	**0.98**	-0.24	**0.98**
WCWT	-0.16	-0.62	0.10	**-0.78**	-0.35	0.24	0.40	-0.07	**-0.84**	**-0.89**	0.09	**-0.87**
w-Collaps	0.05	**0.69**	-0.18	**0.87**	0.47	-0.08	-0.23	0.03	**0.84**	**0.94**	-0.13	**0.93**
w-muhlsteph	0.03	**-0.71**	0.27	**-0.88**	-0.52	0.11	0.23	0.07	**-0.89**	**-0.96**	0.18	**-0.95**
w-Runkel	0.03	**-0.71**	0.28	**-0.87**	-0.51	0.14	0.26	0.09	**-0.90**	**-0.95**	0.19	**-0.95**
w-Coarse	**-0.79**	-0.06	-0.63	-0.17	0.35	0.42	**0.69**	**-0.66**	-0.22	-0.28	-0.32	-0.24
yield	**0.68**	0.25	0.54	0.45	-0.11	-0.06	-0.37	**0.71**	0.26	0.50	0.28	0.46
i-FL	**0.85**	-0.18	**0.87**	-0.04	-0.47	0.14	-0.17	**0.96**	-0.37	-0.04	0.53	-0.10
i-fines	-0.44	0.42	**-0.67**	0.54	0.50	-0.47	-0.34	**-0.64**	**0.90**	**0.69**	-0.47	**0.73**
i-FD	-0.24	**0.68**	-0.48	**0.78**	0.56	-0.03	-0.07	-0.33	**0.82**	**0.93**	-0.07	**0.91**
i-CWT	-0.33	0.05	-0.42	-0.12	0.10	-0.02	0.16	-0.55	0.11	0.03	0.26	0.00
i-LD	-0.15	**0.71**	-0.38	**0.86**	0.57	-0.03	-0.12	-0.18	**0.84**	**0.98**	-0.15	**0.97**
i-Collaps	0.19	0.34	0.14	0.59	0.24	0.01	-0.19	0.37	0.37	0.51	-0.31	0.54
i-muhlsteph	-0.01	-0.61	0.15	**-0.84**	-0.48	0.01	0.18	-0.10	**-0.71**	**-0.87**	0.28	**-0.88**
i-Runkel	-0.01	-0.61	0.15	**-0.84**	-0.48	0.02	0.18	-0.09	**-0.71**	**-0.87**	0.28	**-0.88**
FL/FD	**0.75**	-0.55	**0.91**	-0.51	**-0.69**	0.11	-0.09	**0.88**	**-0.76**	-0.60	0.42	-0.63
inintial Ci	**-0.79**	-0.04	-0.63	-0.14	0.38	0.47	**0.72**	-0.64	-0.21	-0.26	-0.31	-0.21
Freeness	1.00	-0.37	**0.94**	-0.31	**-0.75**	-0.28	-0.54	**0.90**	-0.36	-0.18	**0.66**	-0.25
Tensile Index		1.00	-0.47	**0.89**	**0.73**	0.30	0.24	-0.29	**0.73**	**0.77**	-0.34	**0.78**
Tear Strength			1.00	-0.45	**-0.77**	-0.10	-0.36	**0.93**	-0.59	-0.41	0.57	-0.47
Burst Index				1.00	**0.77**	0.29	0.19	-0.20	**0.80**	**0.92**	-0.35	**0.93**
Sheet density					1.00	0.44	0.53	-0.59	0.63	0.63	-0.48	**0.67**
Stretch						1.00	**0.90**	0.08	-0.24	0.02	-0.02	0.03
TEA							1.00	-0.21	-0.23	-0.07	-0.07	-0.06

Table D17: Correlation table for results at constant freeness (400 ml) at a speed of 750rpm

	SEL	SRE	Tensile	Tear	Burst	Sheet Density	Stretch	TEA	FL	Fines	FD	CWT	LD
Density	0.78	0.89	-0.50	-0.45	-0.81	-0.69	-0.26	-0.61	-0.65	-0.43	-0.56	0.04	-0.56
WVD	-0.75	-0.88	0.52	0.25	0.67	0.76	0.23	0.45	0.41	0.66	0.59	-0.14	0.60
WVP	-0.45	-0.85	0.19	0.70	0.62	0.33	0.55	0.74	0.71	0.30	0.10	0.17	0.06
WVF	0.64	0.50	-0.55	0.31	-0.34	-0.80	0.14	0.05	0.14	-0.77	-0.72	0.38	-0.79
WFD	-0.52	0.09	0.49	-0.52	0.26	0.57	-0.61	-0.33	-0.16	0.12	0.80	-0.38	0.86
WLD	-0.81	-0.41	0.65	-0.20	0.61	0.83	-0.33	0.04	0.19	0.37	0.92	-0.33	0.97
WCWT	0.88	0.67	-0.65	-0.05	-0.74	-0.86	0.10	-0.28	-0.38	-0.47	-0.86	0.25	-0.89
w-Collaps	-0.87	-0.54	0.66	-0.01	0.74	0.83	-0.23	0.21	0.38	0.33	0.90	-0.26	0.94
w-muhlsteph	0.85	0.51	-0.66	0.10	-0.68	-0.85	0.26	-0.14	-0.28	-0.39	-0.91	0.30	-0.95
w-Runkel	0.85	0.52	-0.66	0.11	-0.67	-0.85	0.24	-0.14	-0.26	-0.42	-0.91	0.30	-0.95
Ci	0.63	0.90	-0.35	-0.61	-0.74	-0.51	-0.43	-0.71	-0.72	-0.37	-0.32	-0.08	-0.30
yield	-0.75	-0.74	0.44	0.58	0.89	0.53	0.18	0.67	0.87	0.05	0.52	0.07	0.49
i-FL	-0.29	-0.39	-0.05	0.81	0.56	-0.04	0.49	0.79	0.87	-0.46	-0.10	0.49	-0.20
i-fines	-0.06	0.34	0.45	-0.57	-0.01	-0.05	-0.62	-0.40	-0.37	-0.05	0.53	-0.09	0.54
i-FD	-0.67	-0.35	0.58	-0.21	0.46	0.80	-0.27	-0.14	0.04	0.48	0.83	-0.34	0.88
i-CWT	0.20	0.11	-0.34	-0.13	-0.43	0.22	0.36	-0.17	-0.43	0.37	-0.28	-0.24	-0.22
i-LD	-0.69	-0.37	0.65	-0.16	0.57	0.71	-0.37	-0.08	0.16	0.35	0.88	-0.26	0.91
i-Collaps	-0.48	-0.26	0.56	0.02	0.59	0.18	-0.45	0.07	0.39	-0.10	0.63	0.06	0.60
i-muhlsteph	0.62	0.33	-0.66	0.08	-0.62	-0.46	0.45	0.01	-0.29	-0.13	-0.81	0.11	-0.81
i-Runkel	0.61	0.33	-0.66	0.09	-0.61	-0.46	0.45	0.01	-0.28	-0.14	-0.81	0.11	-0.81
FL/FD	0.13	-0.10	-0.33	0.68	0.15	-0.44	0.50	0.63	0.59	-0.57	-0.50	0.53	-0.60
inintial Ci	0.60	0.91	-0.33	-0.60	-0.71	-0.50	-0.45	-0.70	-0.68	-0.40	-0.30	-0.08	-0.27
SEL	1.00	0.69	-0.59	-0.19	-0.78	-0.81	-0.06	-0.45	-0.51	-0.24	-0.83	-0.10	-0.79
SRE		1.00	-0.29	-0.41	-0.54	-0.56	-0.33	-0.46	-0.50	-0.58	-0.38	-0.16	-0.33
Tensile			1.00	0.15	0.64	0.46	0.11	0.28	0.21	0.25	0.59	-0.10	0.60
Tear				1.00	0.55	0.08	0.76	0.77	0.80	-0.19	-0.20	0.28	-0.26
Burst					1.00	0.62	0.26	0.72	0.78	-0.06	0.62	0.08	0.59
Sheet density						1.00	0.08	0.24	0.28	0.49	0.72	-0.32	0.77
Stretch							1.00	0.66	0.35	0.10	-0.34	0.32	-0.40
TEA								1.00	0.81	-0.20	0.09	0.23	0.03
FL									1.00	-0.30	0.19	0.15	0.15
Fines										1.00	0.20	-0.34	0.26
FD											1.00	-0.02	0.98
CWT												1.00	-0.23
LD													1.00

Table D18: Correlation table for results at constant freeness (400 ml) at a speed of 1500rpm

	SEL	SRE	Tensile	Tear	Burst	Sheet Density	Stretch	TEA	FL	Fines	FD	CWT	LD
Density	**-0.65**	-0.50	-0.47	-0.43	**-0.64**	**-0.73**	-0.52	-0.46	-0.42	**-0.66**	**-0.66**	0.02	-0.63
WVD	0.44	0.23	0.30	0.20	0.41	0.58	0.33	0.31	0.14	**0.82**	**0.69**	-0.08	0.66
WVP	**0.86**	0.61	0.58	**0.75**	**0.81**	**0.70**	**0.73**	**0.73**	**0.67**	0.27	0.18	0.27	0.13
WVF	0.20	0.32	0.14	0.44	0.20	-0.15	0.22	0.24	0.49	**-0.97**	**-0.80**	0.35	**-0.81**
WFD	-0.46	-0.23	-0.25	-0.64	-0.38	-0.04	-0.45	-0.57	-0.49	0.59	**0.81**	-0.55	**0.84**
WLD	-0.04	0.04	0.03	-0.30	0.01	0.34	-0.10	-0.21	-0.20	**0.84**	**0.98**	-0.44	**1.00**
WCWT	-0.24	-0.22	-0.20	0.04	-0.26	-0.53	-0.15	-0.05	-0.01	**-0.87**	**-0.94**	0.31	**-0.93**
w-Collaps	0.17	0.23	0.17	-0.10	0.21	0.49	0.08	-0.04	0.00	**0.80**	**0.98**	-0.37	**0.98**
w-muhlsteph	-0.08	-0.13	-0.10	0.19	-0.12	-0.42	0.00	0.11	0.11	**-0.85**	**-0.98**	0.40	**-0.99**
w-Runkel	-0.06	-0.11	-0.09	0.21	-0.10	-0.42	0.01	0.11	0.13	**-0.87**	**-0.98**	0.40	**-0.99**
Ci	**-0.80**	-0.59	-0.55	-0.63	**-0.76**	**-0.74**	**-0.66**	**-0.63**	-0.58	-0.46	-0.42	-0.15	-0.37
yield	**0.79**	**0.77**	0.59	0.61	**0.80**	**0.80**	0.64	0.53	**0.68**	0.38	0.59	0.01	0.56
i-FL	**0.85**	**0.89**	0.64	**0.88**	**0.89**	**0.66**	**0.78**	**0.74**	**0.96**	-0.40	-0.13	0.34	-0.17
i-fines	-0.26	-0.33	-0.25	-0.50	-0.30	0.09	-0.29	-0.34	-0.54	**0.94**	**0.81**	-0.37	**0.82**
i-FD	-0.19	-0.01	-0.12	-0.45	-0.10	0.31	-0.20	-0.28	-0.27	**0.71**	**0.90**	-0.50	**0.92**
i-CWT	-0.20	0.05	0.05	-0.09	-0.03	0.07	0.07	0.16	0.07	-0.54	-0.34	0.23	-0.36
i-LD	-0.14	-0.02	-0.12	-0.42	-0.09	0.29	-0.21	-0.30	-0.28	**0.79**	**0.93**	-0.53	**0.96**
i-Collaps	0.04	-0.04	-0.11	-0.20	-0.03	0.13	-0.17	-0.30	-0.21	**0.83**	**0.80**	-0.49	**0.83**
i-muhlsteph	0.08	0.05	0.14	0.36	0.08	-0.22	0.22	0.33	0.28	**-0.86**	**-0.92**	0.54	**-0.95**
i-Runkel	0.09	0.06	0.15	0.36	0.09	-0.21	0.23	0.34	0.29	**-0.86**	**-0.92**	0.54	**-0.95**
FL/FD	**0.69**	0.61	0.50	**0.86**	**0.66**	0.26	**0.65**	**0.67**	**0.81**	**-0.68**	-0.61	0.52	**-0.65**
inintial Ci	**-0.78**	-0.56	-0.53	-0.62	**-0.74**	**-0.72**	**-0.65**	-0.63	-0.56	-0.47	-0.39	-0.16	-0.35
SEL	1.00	**0.90**	0.63	**0.94**	**0.93**	**0.72**	**0.87**	**0.78**	**0.93**	-0.09	0.03	0.30	-0.02
SRE		1.00	0.56	**0.86**	**0.85**	**0.72**	**0.79**	0.64	**0.93**	-0.21	0.11	0.18	0.08
Tensile			1.00	**0.66**	**0.79**	0.49	**0.77**	**0.75**	**0.68**	-0.05	0.08	0.32	0.03
Tear				1.00	**0.87**	0.53	**0.85**	**0.77**	**0.94**	-0.34	-0.23	0.41	-0.28
Burst					1.00	**0.80**	**0.92**	**0.89**	**0.92**	-0.08	0.07	0.27	0.02
Sheet density						1.00	**0.75**	**0.75**	0.64	0.27	0.40	0.17	0.36
Stretch							1.00	**0.94**	**0.83**	-0.09	-0.01	0.40	-0.07
TEA								1.00	**0.76**	-0.12	-0.13	0.52	-0.20
FL									1.00	-0.38	-0.14	0.35	-0.18
Fines										1.00	**0.84**	-0.27	0.83
FD											1.00	-0.30	**0.99**
CWT												1.00	-0.43
LD													1.00

Table D19: Correlation table for results at constant freeness (400 ml) at a speed of 2200rpm

	SEL	SRE	Tensile	Tear	Burst	Sheet Density	Stretch	TEA	FL	Fines	FD	CWT	LD
Density	-0.49	-0.56	**-0.67**	-0.37	**-0.91**	-0.51	-0.47	-0.27	-0.49	-0.59	-0.51	0.02	-0.51
WVD	0.36	0.41	0.51	0.14	**0.79**	0.59	0.28	0.04	0.23	**0.73**	0.56	0.05	0.56
WVP	**0.70**	**0.88**	0.51	**0.73**	**0.68**	0.06	**0.75**	0.33	**0.74**	0.12	-0.01	-0.01	0.00
WVF	0.13	0.21	-0.21	0.50	-0.47	**-0.80**	0.31	0.32	0.41	**-0.96**	**-0.78**	-0.11	**-0.78**
WFD	-0.46	**-0.69**	0.24	**-0.71**	0.32	**0.76**	-0.59	-0.10	-0.50	**0.77**	**0.89**	-0.02	**0.90**
WLD	-0.11	-0.25	0.52	-0.39	**0.72**	**0.87**	-0.24	0.03	-0.17	**0.94**	**0.97**	-0.01	**0.98**
WCWT	-0.13	-0.07	-0.61	0.12	**-0.86**	**-0.81**	-0.03	-0.11	-0.07	**-0.90**	**-0.87**	0.01	**-0.87**
w-Collaps	0.05	-0.06	0.63	-0.19	**0.84**	**0.83**	-0.05	0.16	0.04	**0.89**	**0.93**	-0.04	**0.94**
w-muhlsteph	0.01	**0.13**	-0.57	0.28	**-0.79**	**-0.86**	0.13	-0.08	0.06	**-0.93**	**-0.95**	0.02	**-0.95**
w-Runkel	0.02	0.13	-0.56	0.29	**-0.78**	**-0.86**	0.13	-0.05	0.08	**-0.94**	**-0.94**	0.01	**-0.95**
Ci	-0.63	**-0.76**	-0.61	-0.59	**-0.82**	-0.27	**-0.65**	-0.32	**-0.66**	-0.35	-0.24	0.02	-0.24
yield	0.54	0.59	**0.80**	0.54	**0.95**	0.38	0.58	0.53	**0.72**	0.38	0.44	-0.11	0.46
i-FL	**0.68**	**0.81**	**0.63**	0.88	0.62	-0.18	**0.79**	0.70	**0.97**	-0.25	-0.10	-0.10	-0.09
i-fines	-0.34	-0.47	-0.11	**-0.74**	0.20	**0.70**	-0.60	-0.53	-0.64	**0.89**	**0.72**	-0.04	**0.73**
i-FD	-0.06	-0.33	0.40	-0.52	0.49	**0.70**	-0.44	-0.02	-0.32	**0.82**	**0.94**	0.33	**0.91**
i-CWT	-0.25	-0.36	-0.23	-0.45	-0.45	-0.12	-0.44	-0.12	-0.55	0.04	0.08	**0.77**	0.00
i-LD	0.02	-0.24	0.50	-0.42	**0.66**	**0.78**	-0.33	0.01	-0.17	**0.86**	**0.98**	0.11	**0.97**
i-Collaps	0.21	0.17	0.47	0.16	**0.75**	0.55	0.21	0.12	0.38	0.43	0.47	-0.60	0.53
i-muhlsteph	-0.13	0.05	-0.56	0.16	**-0.81**	**-0.78**	0.09	-0.06	-0.11	**-0.75**	**-0.84**	0.28	**-0.87**
i-Runkel	-0.13	0.05	-0.55	0.16	**-0.81**	**-0.77**	0.09	-0.05	-0.11	**-0.75**	**-0.84**	0.29	**-0.87**
FL/FD	0.51	**0.78**	0.20	**0.94**	0.13	-0.56	**0.82**	0.50	**0.87**	**-0.67**	**-0.65**	-0.26	-0.63
inintial Ci	-0.63	**-0.77**	-0.57	-0.58	**-0.79**	-0.26	-0.64	-0.29	-0.63	-0.34	-0.21	0.01	-0.21
SEL	1.00	**0.74**	0.41	**0.67**	0.41	-0.23	0.49	0.25	**0.73**	-0.17	-0.12	0.13	-0.13
SRE		1.00	0.37	**0.88**	0.41	-0.34	**0.81**	0.33	**0.82**	-0.27	-0.34	-0.07	-0.34
Tensile			1.00	0.40	**0.83**	0.31	0.42	0.63	0.57	0.32	0.49	0.11	0.48
Tear				1.00	0.34	-0.41	**0.93**	0.61	**0.93**	-0.52	-0.48	-0.05	-0.48
Burst					1.00	0.60	0.45	0.42	0.52	0.57	0.64	-0.07	**0.65**
Sheet density						1.00	-0.18	-0.03	-0.29	**0.85**	**0.83**	-0.01	**0.84**
Stretch							1.00	0.59	**0.83**	-0.34	-0.34	-0.01	-0.34
TEA								1.00	**0.67**	-0.22	0.01	0.31	-0.02
FL									1.00	-0.36	-0.25	-0.10	-0.24
Fines										1.00	**0.90**	0.01	**0.91**
FD											1.00	0.11	1.00
CWT												1.00	0.02
LD													1.00

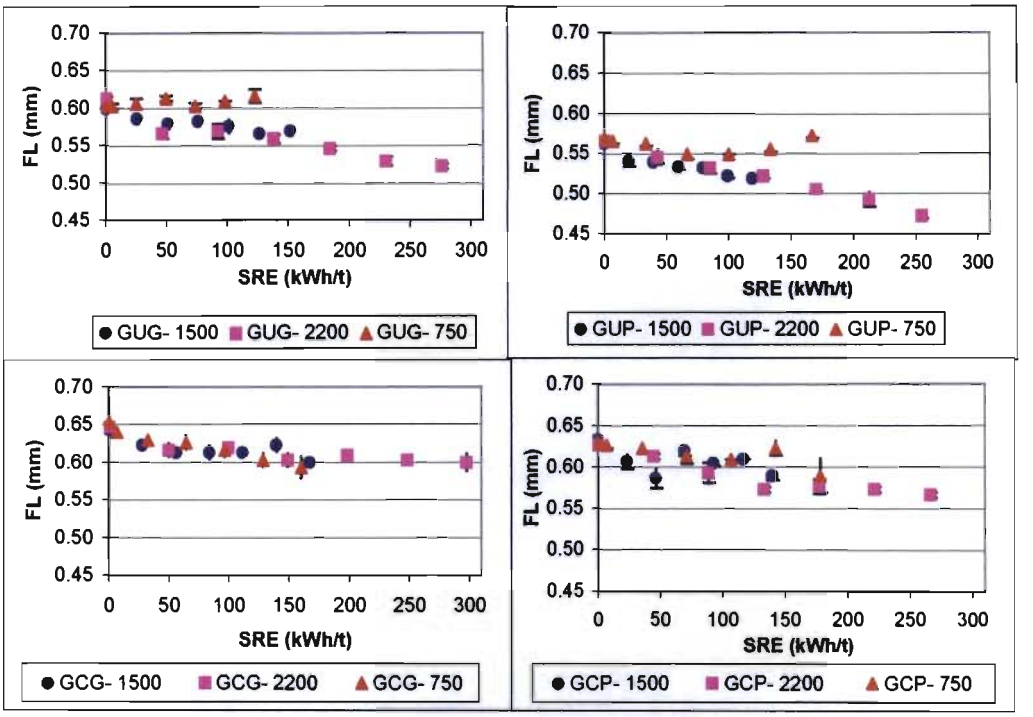

Figure D1: Graph of pulp fibre length (FL) against SRE at the three different refining speeds for each of the four pulps

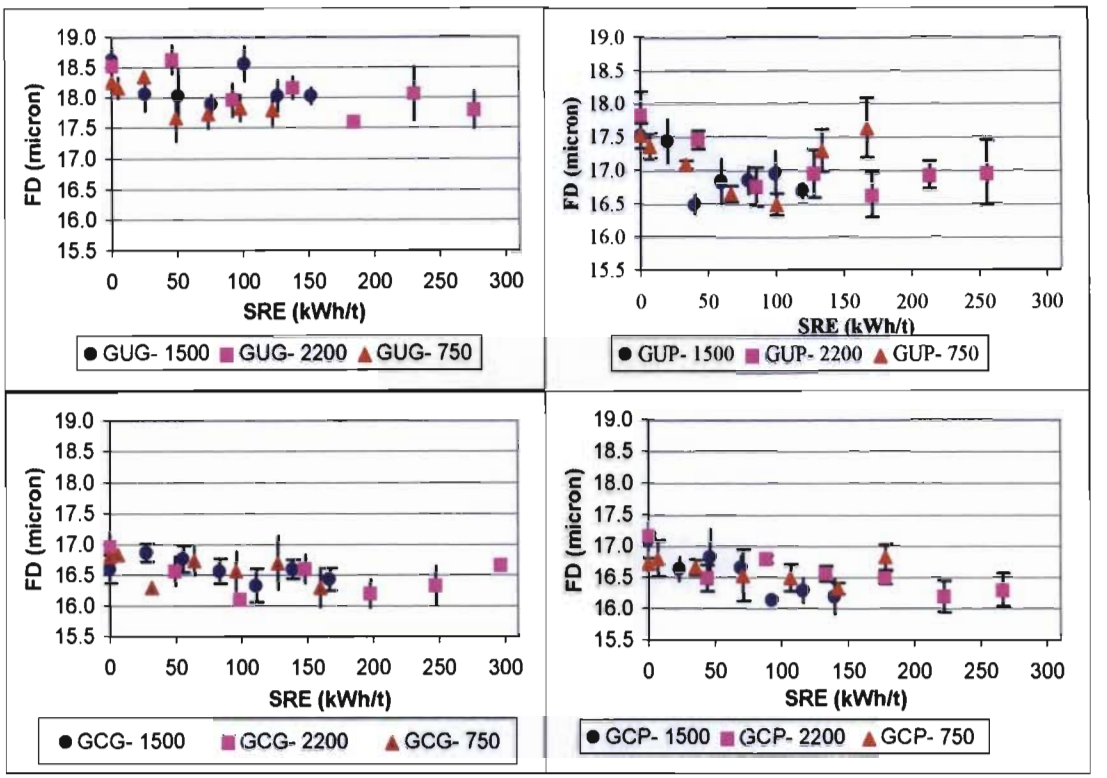

Figure D2: Graph of pulp fibre diameter (FD) against SRE at the three different refining speeds for each of the four pulps

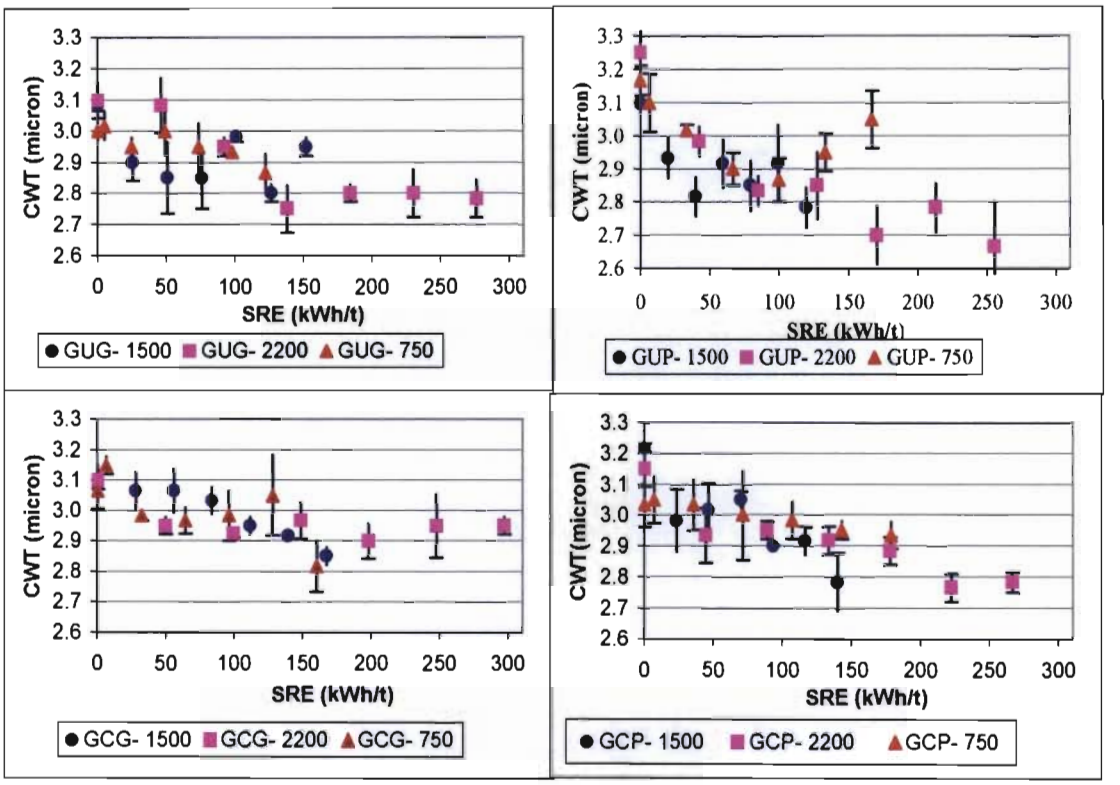

Figure D3:Graph of pulp cell wall thickness (CWT) against SRE at the three different refining speeds for each of the four pulps

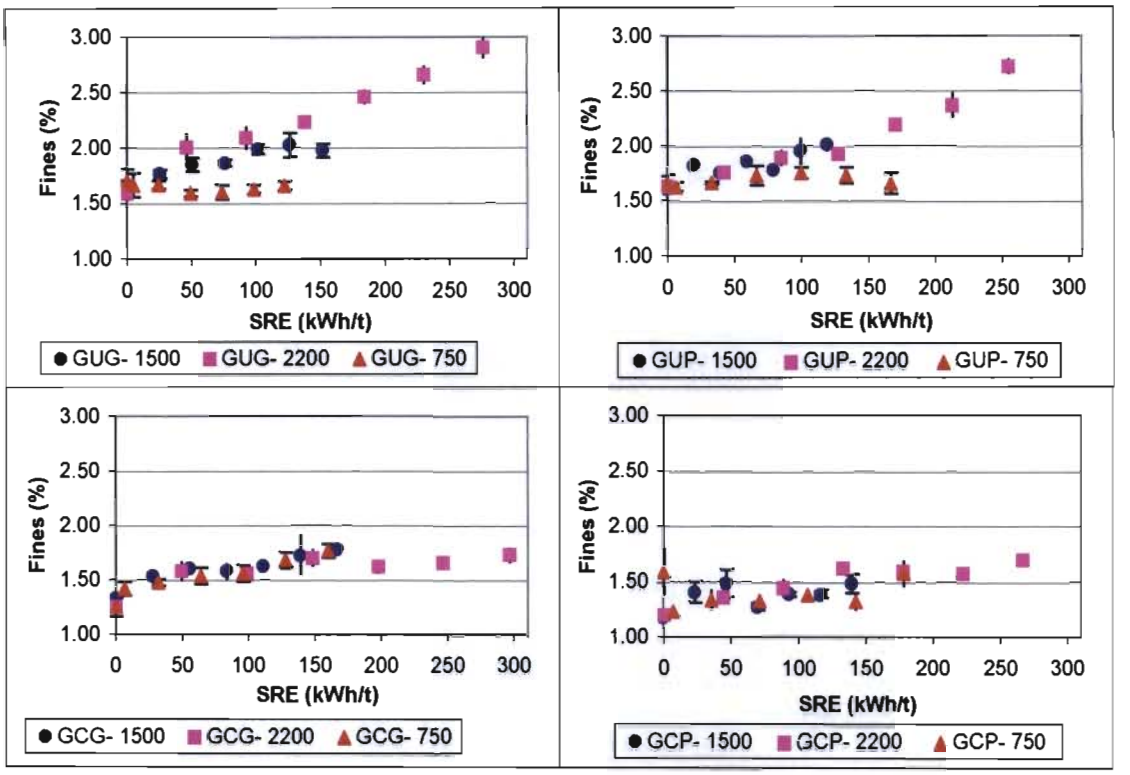

Figure D4: Graph of pulp fines content against SRE at the three different refining speeds for each of the four pulps

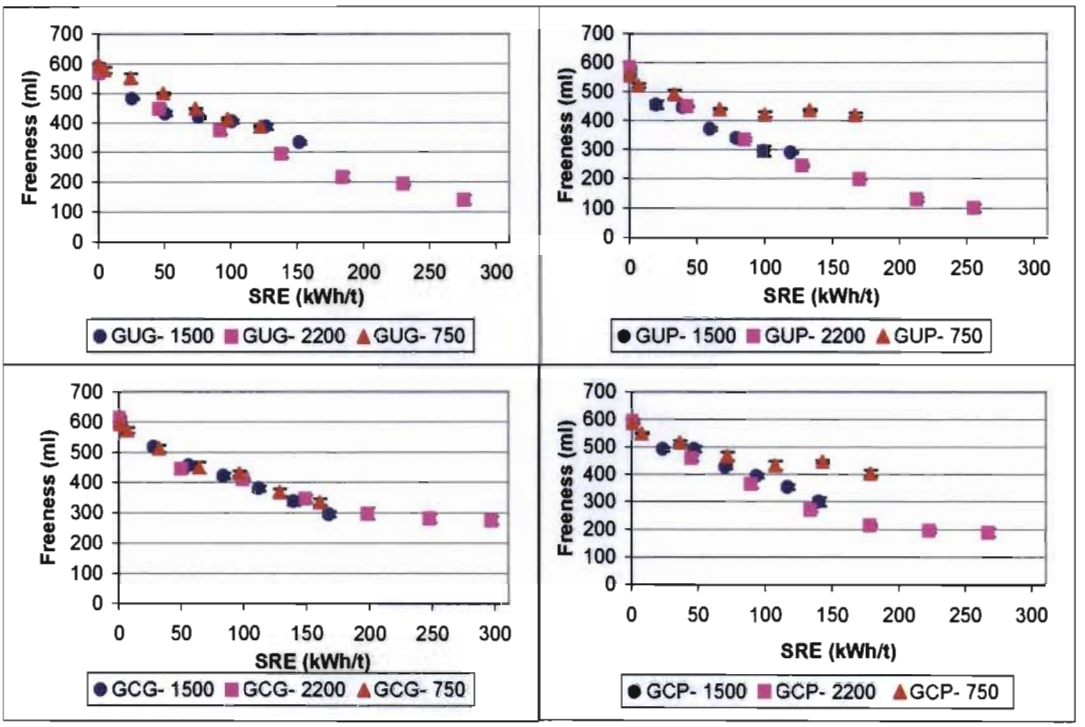

Figure D5: Graph of freeness against SRE at the three different refining speeds for each of the four pulps

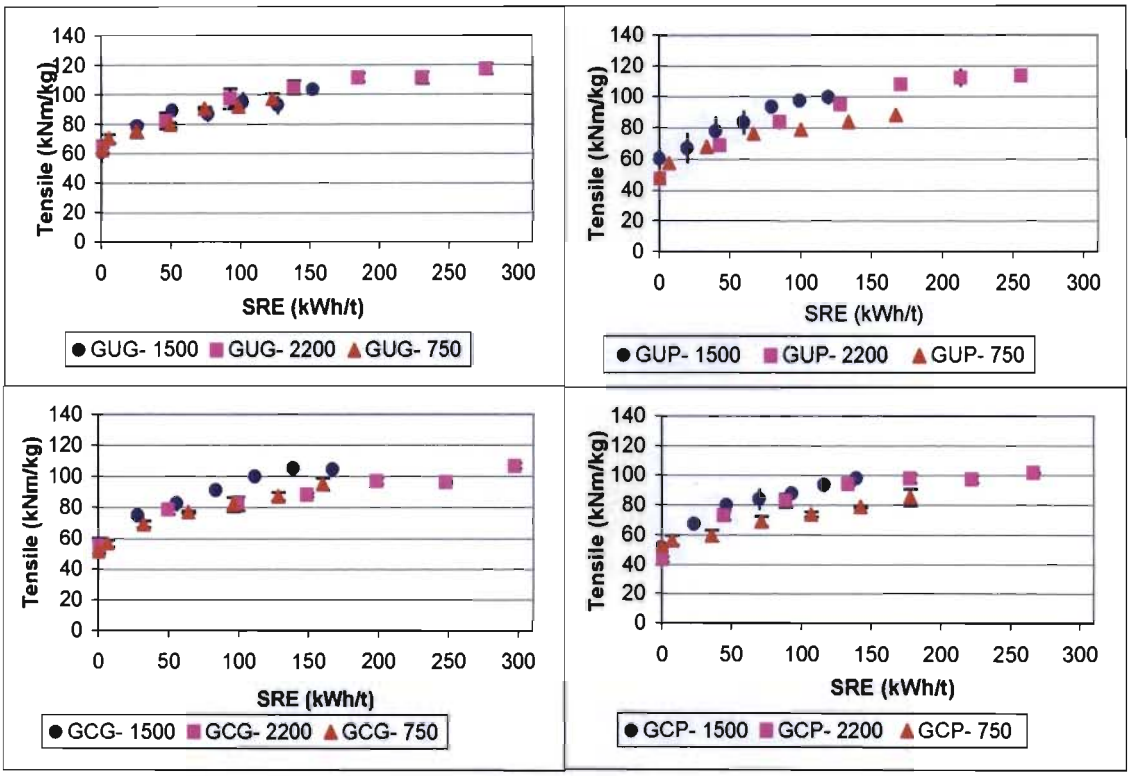

Figure D6: Graph of tensile against SRE at the three different refining speeds for each of the four pulps

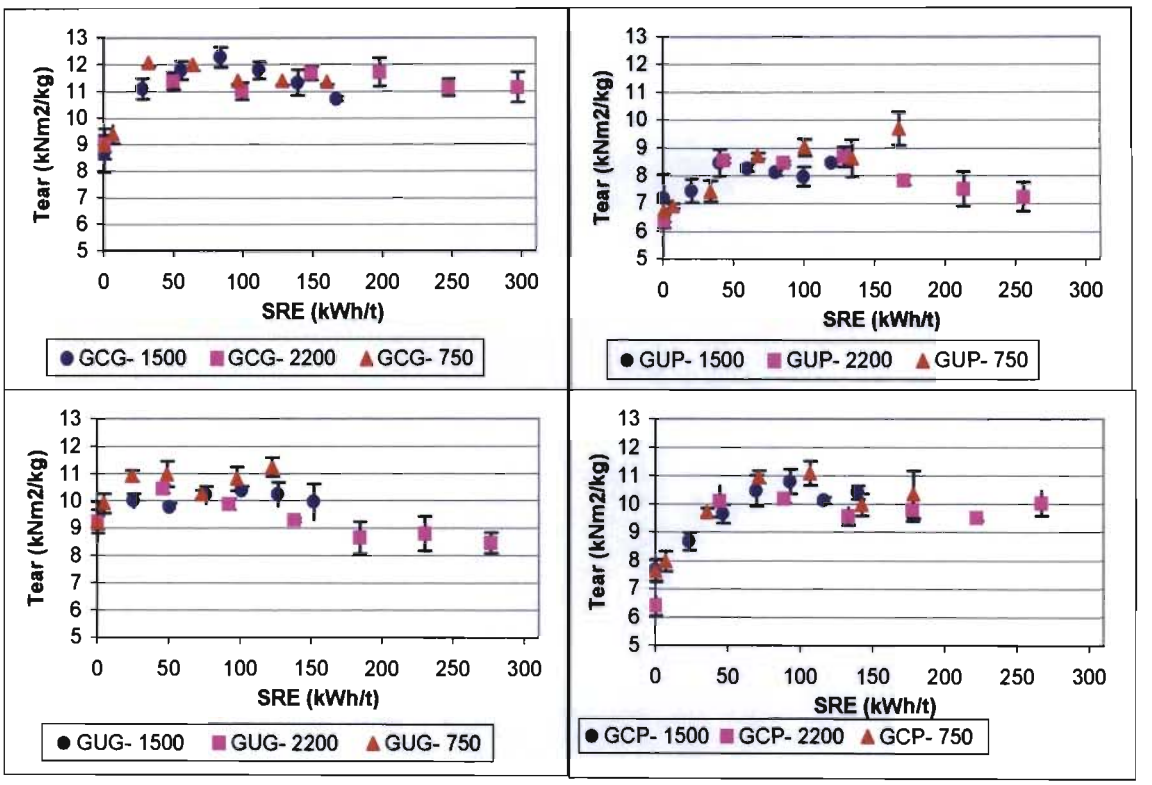

Figure D7: Graph of tear against SRE at the three different refining speeds for each of the four pulps

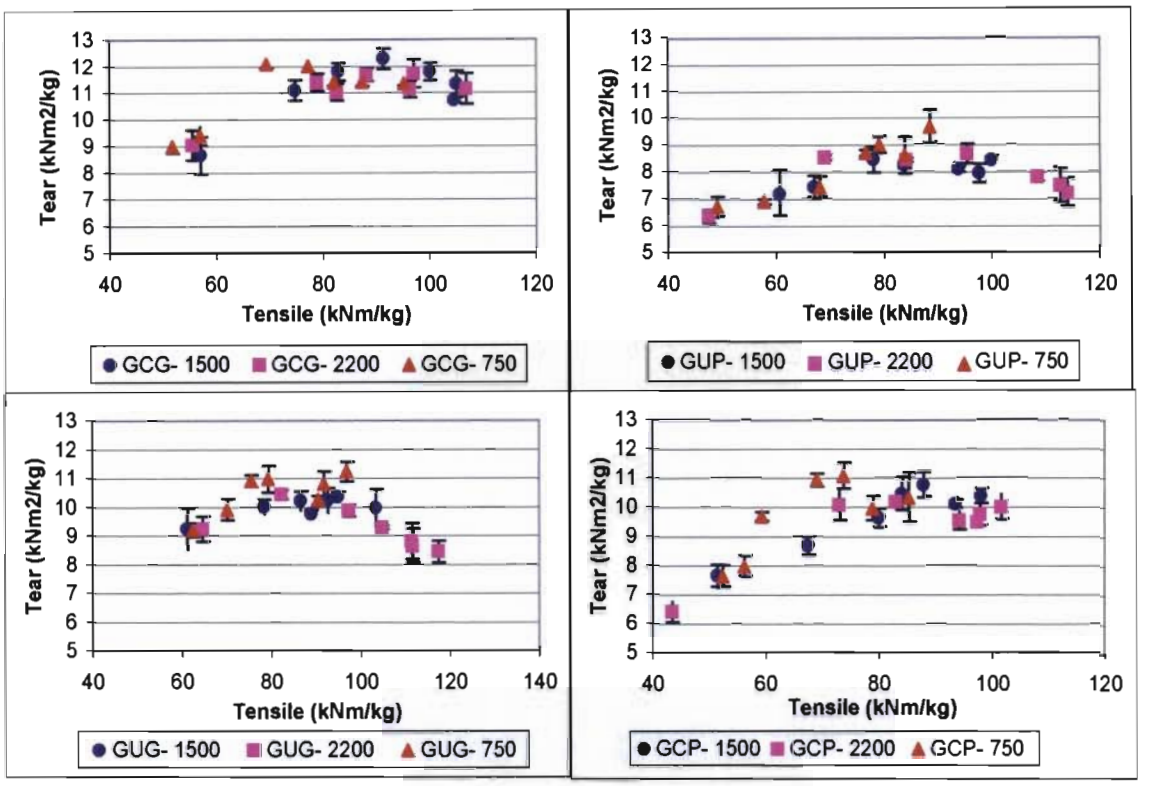

Figure D8: Graph of tear against tensile at the three different refining speeds for each of the four pulps

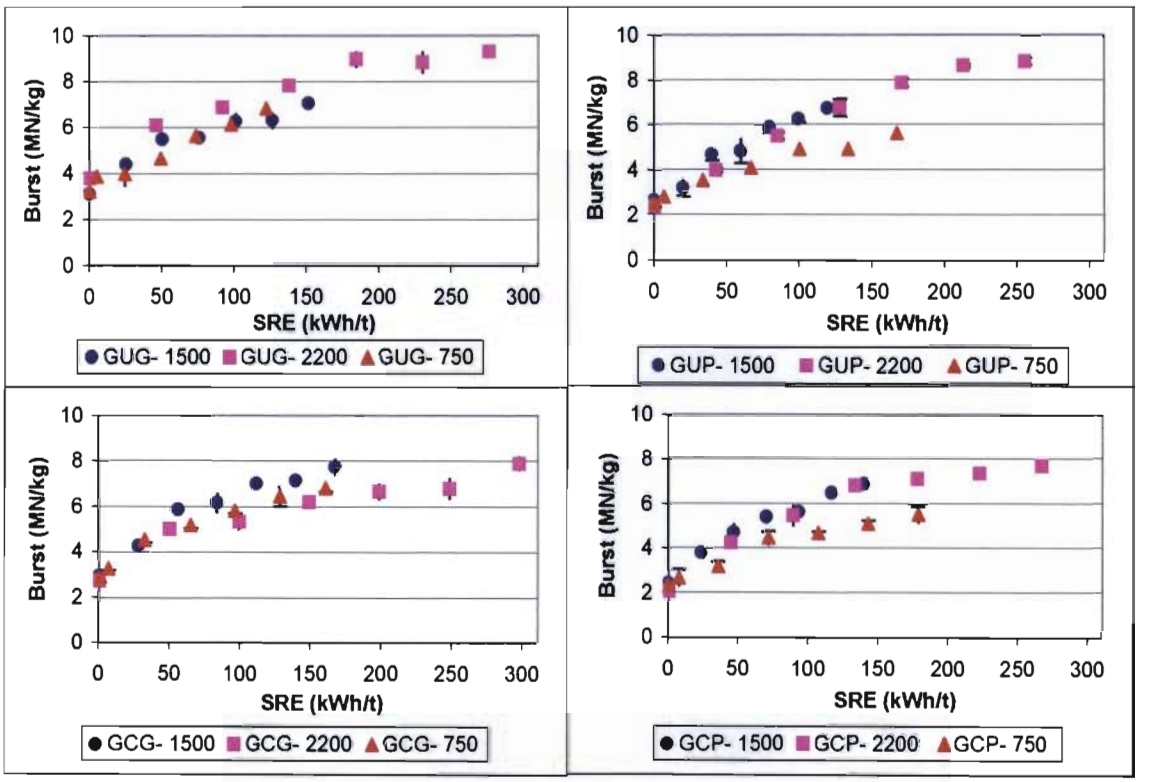

Figure D9: Graph of Burst against SRE at the three different refining speeds for each of the four pulps

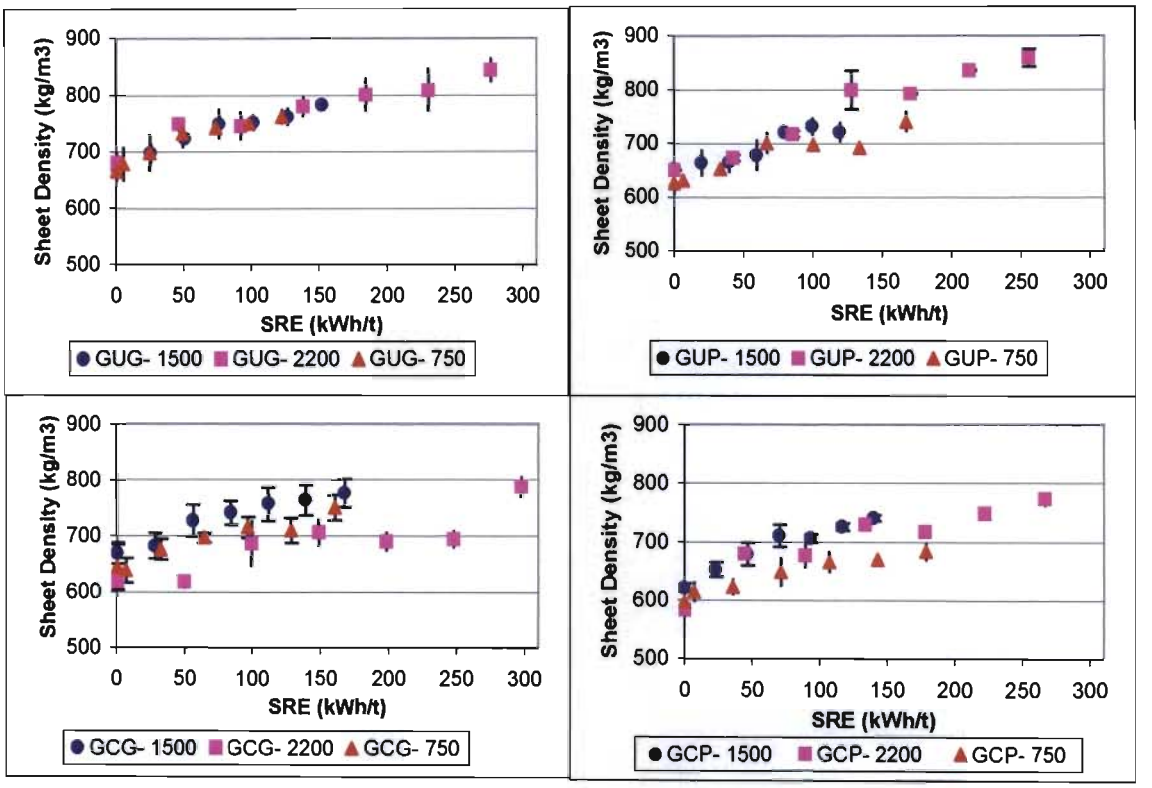

Figure D10: Graph of Sheet density against SRE at the three different refining speeds for each of the four pulps

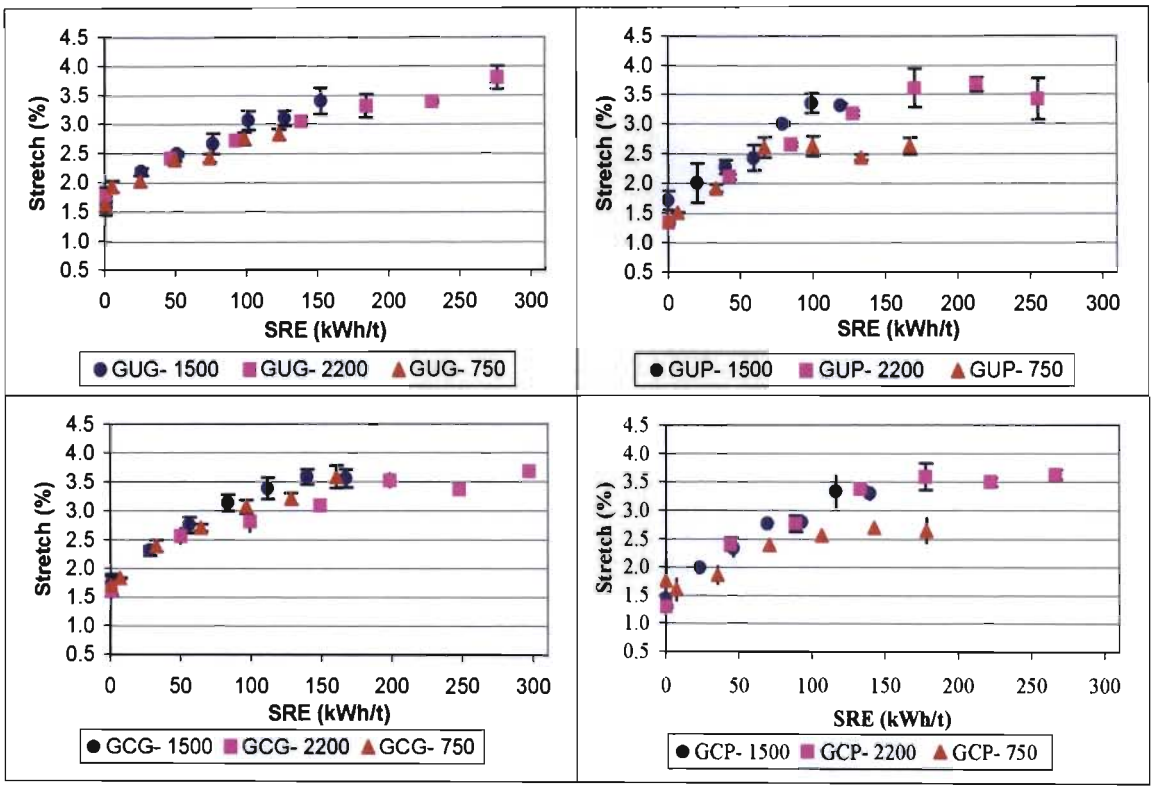

Figure D11: Graph of stretch against SRE at the three different refining speeds for each of the four pulps

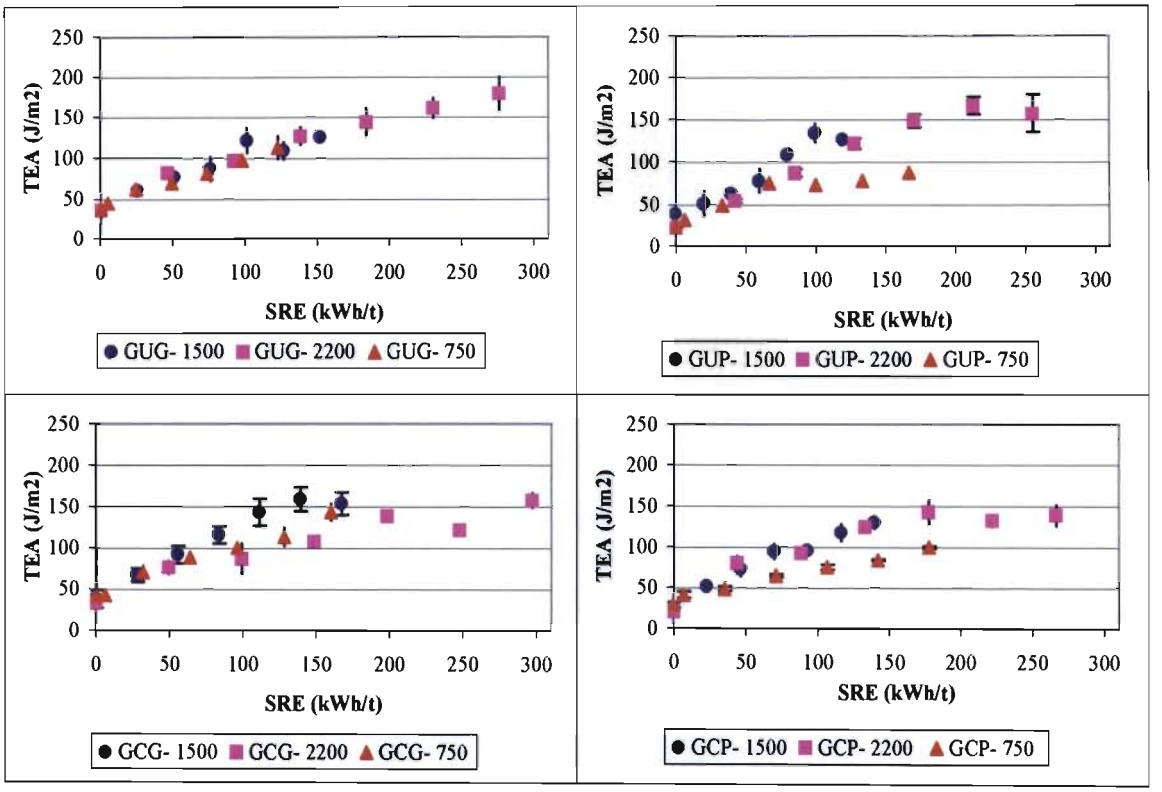

Figure D12: Graph of TEA against SRE at the three different refining speeds for each of the four pulps

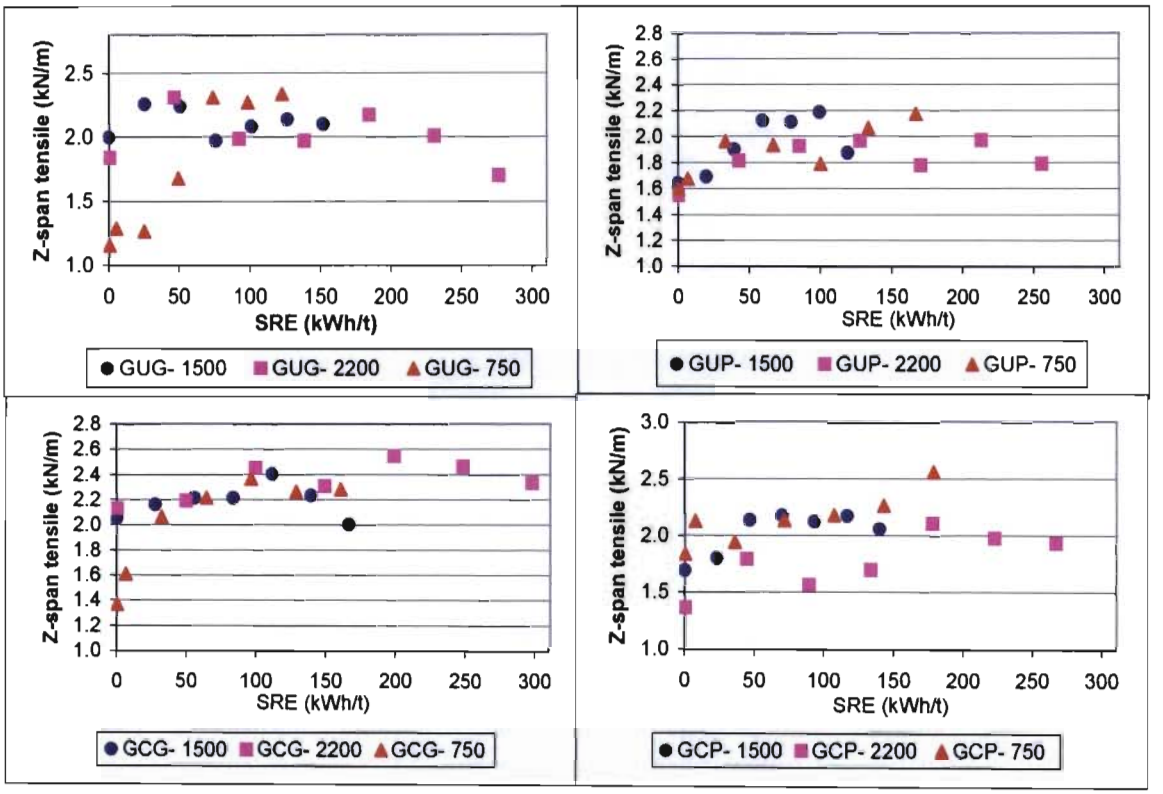

Figure D13: Graph of zero-span tensile against SRE at the three different refining speeds for each of the four pulps

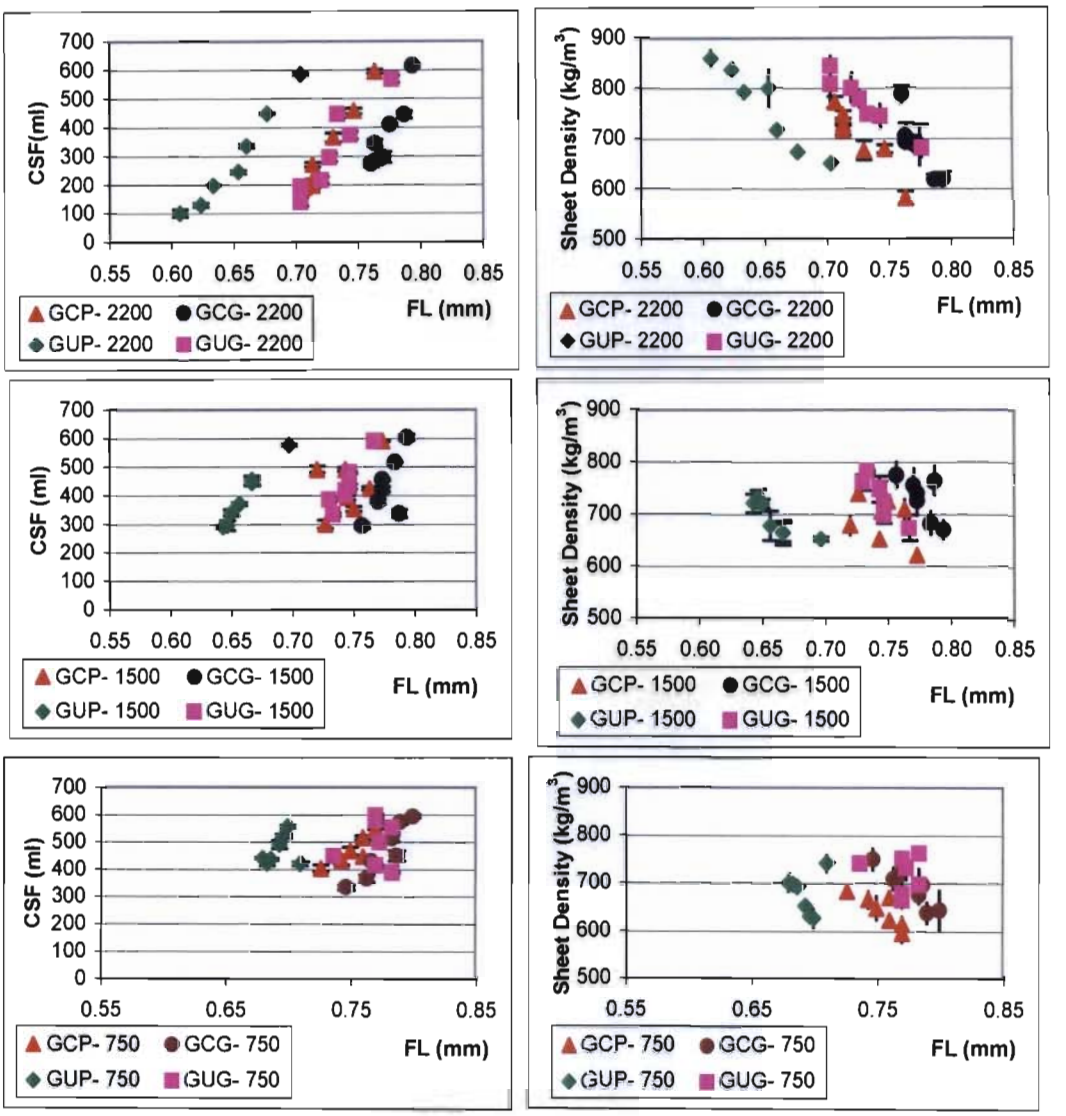

Figure D14: Graphs of pulp freeness and Sheet density versus pulp fibre length at the three refining speeds

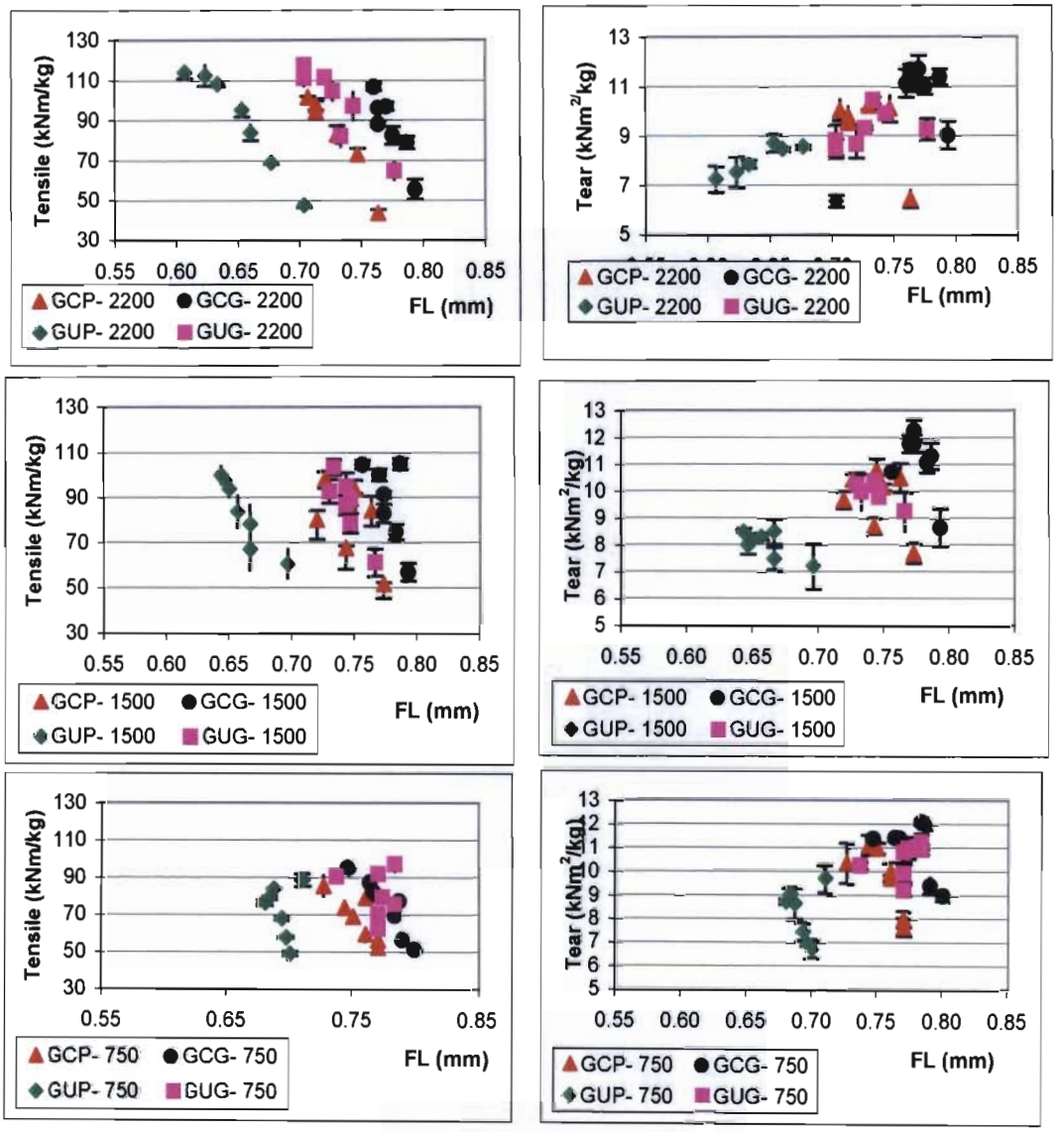

Figure D15: Graphs of tensile and tear versus pulp fibre length at the three refining speeds

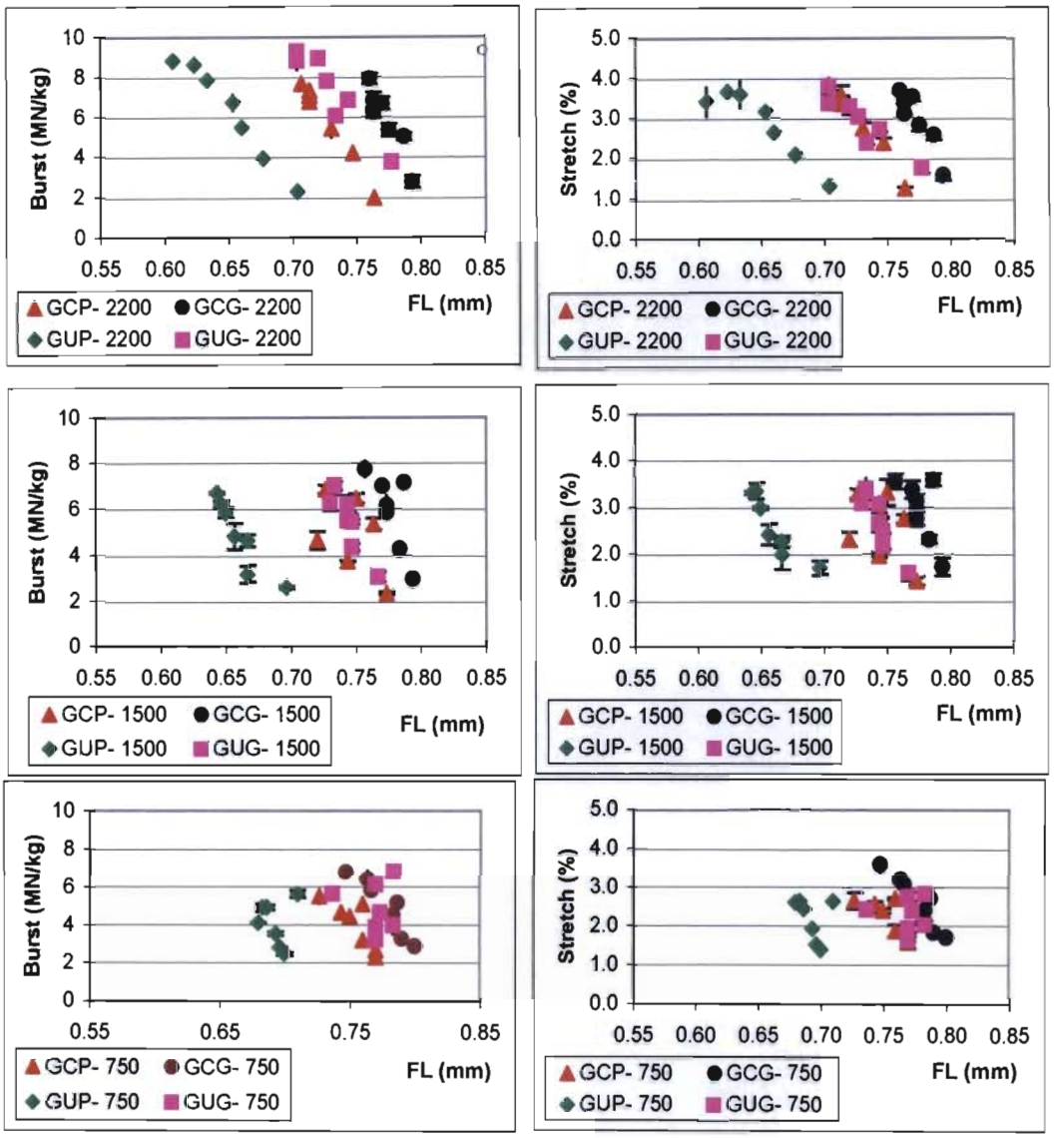

Figure D16: Graphs of burst and stretch versus pulp fibre length at the three refining speeds

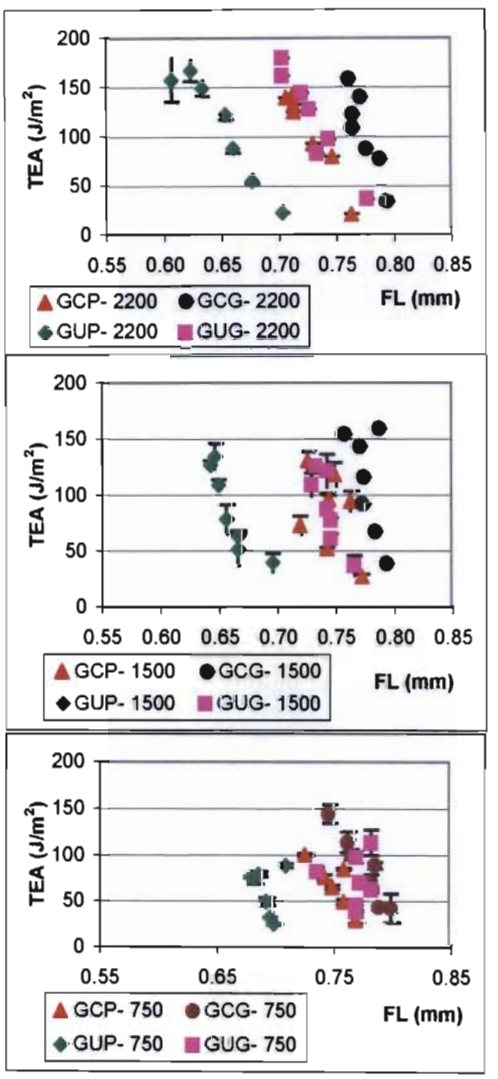

Figure D17: Graphs of TEA versus pulp fibre length at the three refining speeds