THE IMPACT OF THE CHEMICAL AND PHYSICAL PROPERTIES OF *PINUS PATULA* ON PULP AND PULP STRENGTH PROPERTIES.

by

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ABSTRACT

Due to the opportunity for afforestation in South Africa being severely limited, extensive research is being carried out on obtaining more wood per given area, improving the quality and value of the wood and on gaining a better understanding of how wood properties influence the characteristics of the pulp it produces. The last mentioned is the main focus of this study. If the variations in pulp, due to variations in wood properties, are better understood, then the existing fibre resource could be more efficiently managed and utilised to maximise its value.

The main objective of this study was to determine how variation in physical and chemical properties, from the existing *P.patula* resource drives variation in pulp strength properties. It is well known that differences in tree age and site index lead to major sources of variation of various wood properties. These two easily measured variables were used in this study to capture a significant amount of variation in the wood of the aforementioned genus that enters a mill. Samples were obtained from two extremes in site quality, as measured by site index, (viz. good and poor sites) and three age ranges (viz. 9-10 years, 13-14 years and 20-21 years) from the KwaZulu-Natal Midlands. Wood chips from each of the six sites were pulped for various lengths of time, using the Kraft pulping method and under the same pulping conditions. A wide range of anatomical and chemical properties of wood and pulp were measured to characterise these samples as extensively as possible. All pulp samples were beaten in a PFI mill, at four different levels. The freeness values of the beaten samples were measured. The physical properties measured on handsheets made from the pulp included sheet density, burst index, tear index, tensile index, tensile energy absorbed, stretch and zero-span tensile strength. Regression models were developed to quantify the impact of the measured variables on each of the strength properties.

Principal component analysis was performed on the wood characteristics measured and indicated that tree age is a more critical source of variation in wood properties than site index. The predictions of whole tree wood properties from the properties measured at breast height were excellent. Pulping studies showed that pulp yield, at kappa 20-30, increased with tree age. Wood cellulose proved to be a very good predictor of pulp yield. Xylose and mannose appeared to be most resistant to degradation during pulping.

The low yield pulps were easier to refine than those with high yield. This has important implications when considering high yield pulping processes. With regard to pulp strength, the younger material could not achieve the high tear strengths obtained by the older material. However, the tear strengths achieved by these younger sites were comparable with, if not higher than, that obtained by hardwood species. The implications of this is that younger *P. patula* trees could be used for grades of paper where very high tear strength is not essential, but tensile is (e.g. tissue paper) and that older material can be better used for the purpose of providing the high tear strength needed by certain paper grades (e.g. linerboard and sack-kraft). The maximum tensile strength achieved by the younger material was higher than that of the older material. When compared at constant freeness or sheet density, longer cooking times had a deleterious effect on strength properties. Strong predictions of pulp strength from basic wood properties were obtained when strength results were compared at constant freeness and sheet density.

Because of the great influence of fibre morphology and chemistry on refining rates and on the resultant strength properties, the results of the study suggest that fibres of greatly different chemical and anatomical characteristics should not be refined together, if beating energy and pulp strength are to be optimised. However, further work is required to evaluate if the separation of fibre resources, to improve pulp quality, would be economically viable.

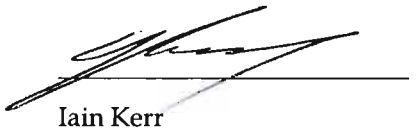
PREFACE

The experimental work described in this dissertation was carried out at the Forestry and Forest Products Research Centre (*ffp*), University of Kwazulu-Natal-CSIR, Durban. The author was registered with the School of Chemical Engineering, Durban from March 2003 to April 2005. Mr Iain Kerr, from the School of Chemical Engineering, University of Kwazulu-Natal, Professor Philip Turner, Director of *ffp* and Doctor John Zhang, a former project leader at *ffp*, 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.

Sachita Budhram



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LIST OF ABBREVIATIONS

Adj. R^2	Adjusted R^2.
AA	Active alkali (i.e. the sum of NaOH and Na_2S, expressed as Na_2O.
ANOVA	Analysis of variance.
BH	Breast height (a distance of 1.3m from the base of a tree).
Coll	Collapsibility.
CSIR	Council for scientific and industrial research.
CSF	Canadian standard freeness.
CWT	Cell wall thickness.
DBH	Diameter at breast height.
EW	Earlywood.
FD	Fibre diameter.
FL	Fibre length.
HT	Tree height.
Ht (7cm)	Tree height to a diameter of 7cm (i.e. merchantable tree height).
KAPPA	Kappa number of pulp.
LW	Latewood.
OD	Oven-dry or moisture free.
PCA	Principle component analysis.
Runk	Runkel ratio.
r(BH) r(35%) r(65%)	radius at breast height, 35% or 65% of tree height respectively.
SEM	Scanning electron microscope.
SI	Site index.
TEA	Tensile energy absorbed.
TPY	Total pulp yield.
Tree #	Tree number.
WMCWT	Whole tree weighted mean cell wall thickness of wood.
WMD	Whole tree weighted mean density of wood.
WMFD	Whole tree weighted mean fibre diameter of wood.
WMLD	Whole tree weighted mean lumen diameter of wood.
WT	Whole tree.

GLOSSARY

Active alkali. NaOH and Na_2S are the two active alkaline components of kraft pulping liquor.

Adj. R^2 value. 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 [Website – see References section].

Alkaline pulping. Chemical pulping achieved by the use of solutions of sodium hydroxide. When sodium sulphide is also used, the process is called the kraft pulping.

Anova. A statistical test of variability between more than two treatment groups.

Angiosperms. Plants having their seeds in an enclosed ovary. These plants include most of the seed plants and all hardwood trees.

Arabinose. A pentose sugar which has a lower molecular weight than glucose.

Basis weight. The weight per square area (g/m^2) of a sheet of paper..

Bark. The covering of stems and branches of trees.

Beater. An equipment that is used for mechanical treatment of pulp and for mixing pulps. Mechanical treatment refers to fibre beating or refining.

Beating. The mechanical treatment of pulp fibres to increase surface area, flexibility and promote bonding when dried.

Black liquor. Spent cooking liquor from a kraft cook. It contains dissolved organic wood material and residual alkali compounds.

Bursting strength. The resistance of paper to rupture as measured by the hydrostatic pressure required to burst it, when increasing pressure is applied uniformly to one side of the sheet.

Cambium. The ring or sheath of growing cells between the bark and the wood. This layer is capable of producing new cells.

Carbohydrates. Any group of neutral compounds composed of carbon, hydrogen and oxygen, with the hydrogen and the oxygen being in the same proportion as in water. These compounds include sugars, starches, cellulose and pentosans, etc.

Cell. One of the minute units or elements of which plants are formed.

Chemical pulp. Pulp obtained when wood is chemically digested (i.e. delignified using chemical means).

Chipper. Equipment that converts wood logs into chips.

Conifer. A tree of the gymnosperm group, so called from its bearing cones. A softwood.

Coniferous. Cone bearing.

Coniferyl alcohol. An alcohol of high molecular weight. It is related to lignin.

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

Cooking. Refers to the process of reacting fibrous raw material (e.g. wood) under pressure and at elevated temperatures to soften and/or remove lignin in order to separate the wood fibres. The terms cooking and pulping are used interchangeably.

Delignification. The removal of lignin (the substance that binds wood fibres together) during chemical pulping.

Digester. A reaction vessel in which wood chips are cooked with chemicals to separate the wood fibres by dissolving the lignin that binds them.

Earlywood. See Springwood.

External fibrillation. Partial detachment of fibrils from the outer layers of a fibre.

Fibres. See Tracheids.

Fibrils. Thread-like elements that "frays" away from the cell wall of cellulose fibres in pulp due to the action of refining or beating.

Freeness. Refers to how quickly water is able to drain from pulp, with pulp with a high freeness having a high water drainage ability. The freeness of pulp is used as a measure of the degree of beating or refining, with freeness decreasing with beating.

Galactan. A hexosan $(C_6H_{12}O_5)_n$, which on hydrolysis yields the sugar galactose.

Gymnosperms. Plants having their seeds naked i.e., not enclosed in an ovary. The conifers are the only common trees in this group.

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

Hardwood. A deciduous tree, distinguished by relatively broad, flat leaves from coniferous (softwood) trees. Hardwoods grow faster than softwoods but have shorter fibres compared to softwoods.

Heartwood. The dead central portion of the trunk of a tree or of a large branch.

Hemicellulose. Nonfibrous carbohydrates that are comparatively less resistant to hydrolysis.

Hexosan. A carbohydrate containing six carbon atoms as its radical.

Hydrate. A substance that has water added to its molecule.

Hydrolysis. The chemical decomposition of a compound that ensues when water is absorbed by it, causing the formation of one or more compounds.

Internal fibrillation. Refers to the loosening of internal bonds within fibres. During beating, fibres imbibe water and swell, which increases their flexibility.

Kappa number. A term used to quantify the amount of lignin in pulp. It is generally used to determine the degree of delignification.

Kraft pulp. See Alkaline pulping.

Latewood. See Summerwood.

Lignin. The principle noncellulosic constituent of wood that cements cellulose fibres together.

Lumen. The cell cavity.

Mannose. A hexose sugar.

Merchantable stem height. The height of the stem of trees to a top diameter of 7cm.

Middle lamella. Intercellular substance.

Moisture content. The amount of moisture in pulp and paper.

Oven-dry. Moisture free (bone-dry) condition of substance (e.g. wood, pulp or paper).

P-value. The p-value measures the statistical significance (or evidence) for testing a hypothesis. Usually, this hypothesis is either that two numbers are equal to each other, or that a number is different from zero. A p-value of less than .05, indicating that there is less than a five percent chance that any observed difference occurred by random chance alone, is often considered "statistically significant".

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

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

Pentosans. Carbohydrates of the general formula $(C_5H_{10}O_5)_n$, which yield pentoses (sugars of the formula $C_5H_{10}O_5$) on hydrolysis.

Pith. The softer, central part of a twig or stem.

PFI mill. A laboratory beater used for the mechanical treatment of pulp fibres. Beating improves the flexibility of fibres and their ability to form interfibre bonds. Excessive beating may damage the fibres.

Polymerise. To form a substance of higher molecular weight by the union of two or more molecules of the same substance.

Pulp. A suspension of fibrous material (cellulose fibres) produced by mechanically or chemically treating wood. Pulp is the material which is used to manufacture paper.

r-value. Correlation coefficient. 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. An r-value below 0 indicates an inverse relationship.

R^2 value. The percentage of variance in the data that is explained by a regression.

Refiner. An equipment used to mechanically treat pulp fibres.

Refining. Refers to the mechanical treatment of pulp fibres to enhance their papermaking potential by increasing the flexibility of the fibres and increasing the use of the available surface area for interfibre bonding.

Sheet density. Refers to the basis mass of a sheet divided by the thickness of the sheet. Bulk density is sometimes referred to as sheet density.

Softwood. See Conifer.

Springwood. The wood produced early in the growing season of each year. The cells of the wood formed here are characterised by larger lumens and thinner walls.

Sugars. Carbohydrates of comparatively low molecular weight.

Sulphate process. See Alkaline pulping.

Summerwood. The wood produced late in the growing season of each year. The cells of the wood produced here are charaterised by smaller lumens and thicker walls.

Tear test. A commonly used test to determine the tear resistance of paper.

Tear strength. A measure of how likely a paper is to break when pulled at opposite ends.

Tracheids. The long, narrow cells of coniferous wood which are cemented together by lignin. These cells are commonly called fibres and is the important part of wood used in papermaking.

White liquor. The aqueous solution of sodium hydroxide and sodium sulphide used in kraft pulping.

Wood. The hard part of the stem of a plant lying between the pith and the bark.

Wood fibres. Long, slender cells which make up the body of the wood of trees. These are the important part of the wood used in papermaking.

Xylan. The pentosan from which the sugar xylose is derived by hydrolysis.

Yield. A percentage expressing the ratio of the product output (pulp) and the raw material input (wood).

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Sincere appreciation is extended to my family and my fiancé for their great support during my studies.

CHAPTER 1

Introduction and Aims

Pinus patula represents approximately half of the softwood species that is grown in this country and is the principal pine species used for timber production (Malan *et al.* 1997, Naidu 2003). This was the species chosen for investigation in this study. All fibre used in the South African pulp and paper industry is derived from plantation forests. Due to the opportunity for afforestation in this country being severely limited, much effort is being aimed at maximising the potential of the available resources. This involves understanding how the natural environment impacts on the development of wood characteristics and how the various types of wood entering the mill, with the accompanying differences in chemical and physical properties, should be treated in order to obtain the desired quality of the end product as profitably as possible. For this to be achieved, firstly the cause and extent of variation in the measurable wood properties must be quantified. Thereafter, the impact of processing of these resources must be investigated in order to classify the raw materials according to the optimal type of processing treatment necessary to meet the desired end product requirements.

Wood fibre properties vary between species and from tree-to-tree (Naidu 2003). The age of the tree and the climatic and soil conditions also influence fibre properties. Added to these complexities are the different areas in the tree stem displaying different fibre properties. These variations within and among trees impart different properties to the resultant pulp, and may place limits on the paper making potential of the pulp produced.

In assessing wood for its pulping potential, there are two key aspects that are of prime importance to the pulp and paper maker:

- The yield of fibre per unit volume or the weight of wood.
- The quality of the resultant fibre

The first aspect depends mainly on the wood characteristics and the pulping conditions used in its conversion to paper. The pulp yield is of great economical importance since the cost of wood contributes substantially to the total production cost of Kraft pulps (Kleppe 1970). An understanding of how the yield is affected by changes in process variables and in the raw materials is valuable information for optimal resource utilisation.

The second aspect is a result of the morphological and chemical features of the individual fibres and the changes that occur during the various methods of conversion from wood to

paper. An understanding of the variations of wood properties is an important starting point. This, when combined with a knowledge of the impact of processing on fibre quality can assist in decision making, in the mill environment, about how best to process the raw materials.

Thus there are three aspects that need to be addressed:

a) An understanding of what drives wood property variation
b) Determining the optimum type of processing necessary for the wood raw material to meet the various end-product requirements.
c) Classification of the various wood raw material according to its ability to meet the various end-product requirements most cost effectively.

Quantification and manipulation of the interaction of the various factors that influence the end-product characteristics will result in the formulation of more effective protocols that ultimately result in more economic processing of resources, while maintaining the desired quality of end product. The aims of this study, which focuses on the three aforementioned aspects, were:

- To examine the pattern of change of wood chemical and physical properties of *P. patula* over extremes in silviculture site quality (as measured by site index – see Appendix A) and tree age.
- To determine how the rate of delignification, pulp yield, pulping chemical consumption and pulp anatomical and chemical properties are influenced by these differences in wood properties.
- To examine and quantify the impact of the various chemical and anatomical wood and pulp properties on the strength potential of pulp, under various processing conditions (i.e. varying lengths of pulping and refining).
- To gain an understanding on the type of end-product that the various raw materials under investigation in this study best suits and the optimal type of treatment that is necessary to achieve the end-product strength requirements.

The hypotheses, related to the aims mentioned, are:

- There is a substantial amount of variation in wood properties due to tree age and site quality.
- The pulping properties of wood and strength properties of paper can be predicted if the anatomical and chemical properties of wood or pulp are known.

CHAPTER 2

Review of Literature

2.1 The nature of wood

Botanically, trees are seed bearing plants (Spermatophytae) which are classified into two types viz. hardwoods (Angiospermae) and softwoods (Gymnospermae). Conifers, or cone bearing trees, are generally referred to as softwoods. Deciduous trees, those that lose their leaves in the autumn, are generally referred to as hardwoods.

Softwoods are mainly grown for sawn timber and pulpwood markets (Morris & Pallet 2000). *P. patula* was the chosen species for this study. In South Africa the main softwoods used are pines, the most important of which is *Pinus patula* (Kotze 1995). Almost half of the plantation area of South Africa under pines consists of this species (Malan 1997).

The structural features and chemical composition of hardwoods and softwoods differ, hence the processes used to convert them into pulp and paper. The papermaking potential of pulp is determined to a significant degree by the properties of the raw materials (Paavilainen 1989). Therefore, in order to explore possible avenues for improving the pulp and paper making process, both the physical and chemical nature of wood must be understood.

There are a number of factors that cause variability in timber. Some of these causes of variation are due to the genetics (Stairs *et al.* 1996), within tree variation (vertical-height variation and horizontal-pith to bark variation) and environmental factors. If age or any of the above mentioned factors change, then it is likely that the properties of wood change (Malan 2000). For pines, Morris & Pallet (2000) state that the anatomical and pulping properties can vary among sites and species. According to Dvorak *et al.* (2000), harvest or rotation age, climate and edaphic factors affect the wood of *P. patula*. This study looked at within tree variation of wood anatomical properties and variability in wood and pulp properties caused by the environment and tree age.

2.2 Background information

The paper-making process can be summarized as shown below:

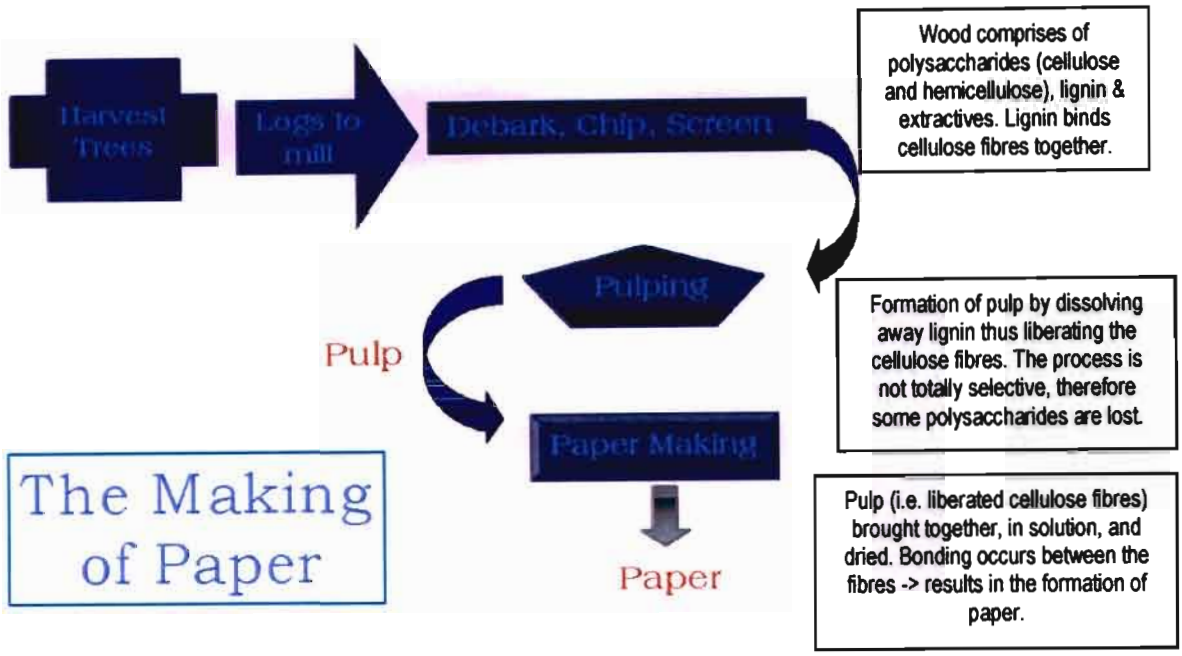


Fig. 2-1: Summary of the paper-making process.

Polysaccharides (cellulose and hemicelluloses), extractives and lignin are the main chemical components of cell walls of wood tracheid cells. These tracheid cells are also called fibres (Gullichsen *et al.* 1999). Wood is the principal source of cellulosic fibre for pulp and paper manufacture (Smook 1992). Pulping refers to any process by which the individual cellulose fibres are freed and are reduced to a fibrous mass. Pulping is an essential first step in the manufacture of paper, since it is impossible to produce paper without firstly reducing the raw materials to a fibrous state (Smook 1992). Pulping can be broadly classified into 2 types viz. chemical pulping and mechanical pulping. Whereas mechanical pulping uses mechanical means to liberate fibres from the wood matrix, chemical pulping uses chemical means to achieve this. One of the most commonly used chemical pulping processes is the Kraft process (Gullichsen *et al.* 1999) and it was the chosen pulping method for this study.

When wood is pulped chemically, the inorganic cooking chemicals react with the wood components. An ideal method of pulping would be one which selectively dissolves the nonfibrous portions of wood, mainly lignin, thus allowing for the unattacked polysaccharide chains that are left behind to be used for the making of paper. Both the amount and condition of cellulose in the fibre wall determines the strength of wood pulp fibres (Seth & Chan 1999). It is therefore imperative that the delignification of wood be achieved with least possible

damage to the fibre itself, so that the resulting pulp has the physical and chemical characteristics necessary for paper-making.

However, since the chemicals used to delignify wood are not exclusively reactive towards lignin, during the digestion process all constituents of wood are subject to some attack, although at considerably different rates (Stephenson 1950, Saucedo *et al.* 2002). Thus, the non fibrous components are not totally preserved during pulping. The cooking liquor reacts with the polysaccharides present in wood, some of which are more susceptible to the cooking chemicals than others. This degradation of polysaccharides affects the amount and condition of polysaccharides in the pulp and lowers the pulp yield and the degree of polymerisation of the polysaccharides. If this depolymerisation and degradation is left to continue excessively, the strength properties of the pulp may be adversely affected.

A major problem associated with the gross variation in the chemical and physical properties of the raw materials that enters a mill is that different woods require different treatments in order to produce pulp with optimum yield, uniform properties and the necessary strength and physical properties. Proper control over the woods pulped together and the pulping conditions used is thus essential during pulping, so that the resultant pulp has the required amount of lignin removed yet not compromising the amount and condition of the polysaccharides in the pulp, so as to produce paper of the desired physical and strength properties.

2.3 Chemical composition

Wood is a result of biological growth, thus its composition is variable. Differences exist among species, from tree to tree, and from cell to cell within a tree. The main chemical components of wood are cellulose, hemicelluloses, lignin and extractives (Gullichsen *et al.* 1999). The chemical and physical properties of these components are affected, among other factors, by their location in wood.

2.3.1 Cellulose

Cellulose is the main polysaccharide of wood fibres and is the skeletal framework substance of all wood cell walls (Britt 1970). It is a straight-chained, hydrophylic polysaccharide composed of a series of glucose anhydride units arranged in cellobiose pairs. Cellulose may be quantitatively hydrolysed, with diluted strong acids, to glucose (Stephenson 1950, Casey 1952).

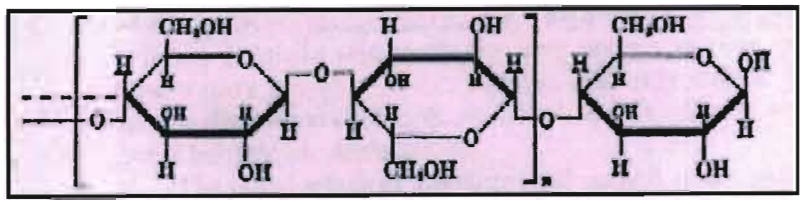


Fig. 2-2: Molecular structure of cellulose (Casey 1952)

The hydroxyl groups are responsible for its hydrophylic nature. These hydroxyl groups together with acid-sensitive acetal linkages are responsible for many of the reactions that cellulose undergoes (Casey 1952). The hydroxyl groups along the length of the cellulose chain allow for the formation of intermolecular hydrogen bonds during the making of paper. Hydrogen bonds between adjacent cellulose molecules give strength to wood and paper.

X-ray analysis of cellulose fibres has shown that the strong tendency that cellulose molecules have to form intra- and intermolecular hydrogen bonds results in cellulose molecules becoming bundled together in the form of microfibrils (Sjostrom 1981). In these microfibrils, definite crystalline (highly ordered) regions alternate with less ordered (amorphous) regions (Stephenson 1950). Crystallinity gives rigidity, strength and chemical stability to cellulose. In the amorphous regions, the molecular arrangement is random and less compact. Unlike the crystalline regions, these amorphous regions are more accessible to chemicals and water. Cellulose having many amorphous regions shows a great amount of swelling, since water preferentially enters these regions (Smook 1992). The ratio of crystalline to amorphous cellulose has an appreciable effect on the reactivity and the physical properties of cellulose fibres (Smook 1992, Casey 1952).

The degree of polymerization (chain length) of cellulose lies in the range of 10 000 in wood before pulping (Gullichsen *et al.* 1999). Due to their high chain length, cellulose is more resistant to attack by alkali than the other wood components. The greater the chain length of the constituent molecules, the stronger the fibre and the more resistant it is to heat and chemical degradation (Smook 1992, Casey 1952). Another consequence of long chain lengths is that cellulose molecules have high tensile strengths, since tensile strength increases approximately linearly with an increase in the degree of polymerisation (Casey 1952). Apart from the degree of polymerisation, the tensile strength of cellulosic fibres is also due to their ability to form both crystalline and amorphous regions (Britt 1970).

Quantification of cellulose can be achieved using various methods with varying degrees of accuracy (Kube & Raymond 2002). Some of the techniques that have been developed include a peroxy-acetic acid method, a nitric-acetic acid method and a dioxane-acetylacetone-hydrochloric acid method described by Siefert. Kube & Raymond (2002) states that on comparison of the various methods, the Siefert method gave the most accurate cellulose values and produced the purest cellulose residues. On analysis of the cellulose residues obtained by various methods Wright & Wallis (1998) concluded that the Siefert method not only contained the lowest amount of noncellulosic residues compared to other methods but also gave the best correlations with kraft pulp yield and more meaningful correlations with other wood properties due to the high accuracy of this method.

2.3.2 Hemicelluloses

Hemicelluloses refer to the amorphous, polymeric carbohydrates that occur throughout wood (Britt 1970). It is a more branched polymer than cellulose and has a lower degree of polymerization (lying between 150 to 200). Because these polymers exists in amorphous form, which means they are more accessible to cooking liquor, hemicelluloses are not as stable as cellulose to chemical degradation during pulping (Gullichsen *et al.* 1999).

Hemicellulose content and structure vary significantly among wood species. Its function in wood is very poorly understood. In pulp, however, the hemicelluloses play a vital role in contributing towards the development of strength.

During pulping the amounts, location and structure of the hemicelluloses present in the original wood can change dramatically (Britt 1970). These changes are largely dependant on the wood species and the cooking process. Due to the hemicelluloses being degraded during pulping, their amount in pulp is lower than in wood. The retention of hemicelluloses in pulp have a significant effect on pulp quality and is thus of considerable value for paper making purposes (Stephenson 1950). Imbibing water is the main action of the hemicelluloses in pulp and is due to the fact that hemicelluloses are rich in hydroxyl groups which promote fibre swelling (Britt 1970, Grant 1961). Swelling contributes positively to the development of interfibre bonding and thus the strength in paper. Therefore, when the hemicellulose content in pulp is high, hydration takes place rapidly and greater interfibre bonding develops (Stephenson 1950, Clarke 2000). Britt (1970) states that apart from imbibing water and thereby having a positive influence on the bonding strength of pulp fibres, one study indicated that hemicelluloses played an important role in contributing to the intrinsic fibre strength. Low hemicellulose content pulps have their advantages in certain applications by imparting higher absorbency, bulk and opacity to the paper made from such pulps (Stephenson 1950).

The acid hydrolysis of hemicelluloses yields the hexose sugars glucose, mannose and galactose and the pentose sugars arabinose and xylose (Britt 1970). Hydrolysis is achieved by firstly primary hydrolysis with a strong acid (such as 72% sulphuric acid) at about 30 to 20°C for about 4 hours, followed by dilution of the acid-wood mixture and then followed by a secondary hydrolysis by autoclaving for an hour at about 120°C (Britt 1970). Characterisation of hydrolysis products, found in the filtrate, is generally achieved by the various forms of chromatography (Sjostrom 1981), such as HPLC which yields the relative amounts of the component sugars of hemicellulose. Generally the same technique of isolation of hemicellulose in pulp as in wood is used (Britt 1970).

2.3.3 Lignin

Lignin is an amorphous and very complex aromatic polymer (Britt 1970) with a high molecular weight. It is made up a three-dimensional network of phenyl propane units held together by ether (-C-O-C-) and carbon (-C-C-) bonds.

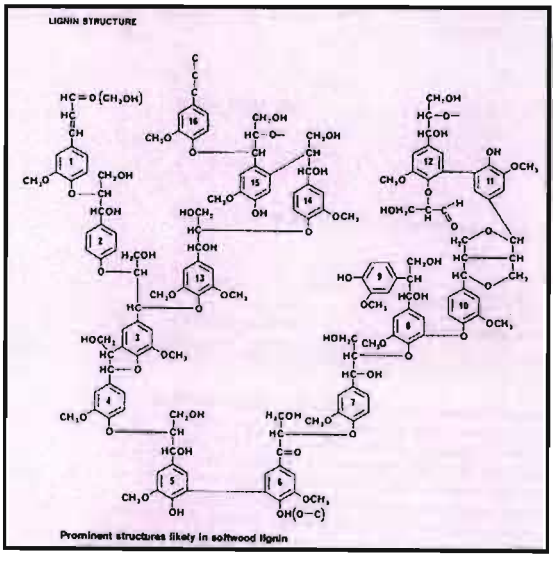


Fig. 2-3: Prominent structures likely in softwood lignin (Kocurek 1996)

Lignin can be classified according to its structural elements. Guaiacyl lignin alone occurs in all softwoods and is the result of the polymerization of coniferyl alcohol. Guaiacyl-syringyl lignin is found typically in hardwoods and is a co-polymer of coniferyl and sinapyl alcohols.

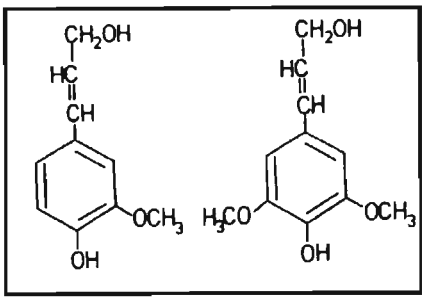


Fig. 2-4: Coniferyl and sinapyl alcohols (Stephenson 1950)

Its function is to bind cells together, providing rigidity and durability. Lignin is concentrated between fibres (middle lamella). This cementing layer between fibres is the key to any pulping process, as removing this layer during pulping separates the individual fibres. Lignin is undesirable in paper making since it reduces bond strength and also causes yellowing of pulp (Gullichsen *et al.* 1999).

One of the main aims of process control is to ensure that the required amount and quality of product is produced. In the pulp and paper industry, the quality of the pulp is determined and controlled by the residual lignin content in the pulp. The required degree of delignification is determined by the end use of the pulp. The degradation of lignin by the cooking liquor causes it to be broken down, by the hydroxyl and hydrosulphide ions in the cooking chemicals, into smaller, soluble fragments (Smook 1992). The amount of lignin remaining in fibres is inversely related to the degree of fibre bonding (Clark 1985, Thomson & Gustafson 2000). This is because lignin hinders the extent to which fibres can absorb water, thus preventing the development of surfaces available for interfibre bonding to occur (Ifju *et al.* 1975, Clark 1985). The interfibre bonding between the polysaccharide chains is responsible for the strength properties. Insufficient delignification yields pulp which produces a poor quality paper, not only because the large amounts of lignin still being present between the fibres adversely affects paper strength by hindering interfibre bonding from occurring but also because the lignin present discolours the paper (Gullichsen *et al.* 1999). Excessive delignification causes a greater extent of degradation to cellulose fibres, which in turn lowers pulp yield and strength characteristics of the pulp. Therefore the degree of delignification must be controlled in order to optimise the pulp yield while meeting certain quality specifications.

Due to its highly complex nature, very little is known about the basic physical and chemical properties of lignin. It varies in wood from different species and it also varies in wood of different ages of the same species (Casey 1952). Another difficulty is the isolation of lignin in

an unchanged state for study. All information regarding lignin thus far has been determined on isolated lignin or lignin derivatives (Casey 1952). Due to its complex and variable structure, it is very difficult to measure the lignin in wood and pulp. There are no known solvents that are capable of dissolving lignin quantitatively without degrading the carbohydrates present (Britt 1970). For softwoods and hardwoods, a highly accurate gravimetric method to determine the amount of acid insoluble lignin, called Klason lignin, has been developed. The method entails that after the complete hydrolysis of all carbohydrates to their soluble constituent sugars with 72% suphuric acid, as previously discussed, the acid insoluble lignin that remains be filtered, washed, dried and massed to determine the acid-insoluble lignin (Britt 1970).

Since the lignin content in pulp correlates well with the consumption of certain oxidants (such as potassium permanganate), there exist several international standards that express the residual lignin content in pulp samples to the consumption of oxidant in standard laboratory conditions. The Kappa number is one commonly used method. The Kappa test is a measure of the pulps ability to reduce $KMnO_4$ to MnO_2 (Gullichsen *et al.* 1999). It is the key control variable for the digesting process. Control over the degree of delignification is accomplished, in industry, by maintaining Kappa at a specific value and minimising the variability around this value.

Regression relationships for predicting Klason lignin from the Kappa number were developed and were used to predict the following relationship (TAPPI 1957).

Equation 2-1: $$Kappa\ Number\ x\ 0.13\ =\ Klason\ lignin\%$$

This relationship is applicable for Kraft pulps with a yield of 70% or less. Above 70% yield, there exists a portion of Klason lignin that is resistant to the permanganate oxidation under the specified test conditions. Since the consumption of permanganate is used as an indication of the amount of lignin in the sample, this means that a precise relationship between permanganate consumption to lignin in this high yield region cannot be established.

2.3.4 Extractives

The extractives refer to extraneous substances that are always present in wood (Britt 1970). The types and amounts of these substances vary with tree species, age, position within the tree and environmental factors. The major classes of extractives are aliphatic, terpenes/terpenoids and phenolic compounds. Extractives can be removed from wood by extraction with hot water or neutral organic solvents (Muneri 1994). Some appropriate solvents include ethanol,

acetone, toluene, ethanol-benzene (1:2 v/v) and benzene (Britt 1970). The average extractives content in pines is quite low (Dvorak *et al.* 2000). Extractives exhaust the usage of pulping chemicals, cause discolouration of unbleached pulp (Britt 1970, Muneri 1994) and also reduce pulp yield (Muneri 1994). Softwood extractives generally dissolve within the first few minutes of cooking (Gullichsen *et al.* 1999).

2.4 Wood anatomy

A wood fibre can be described as a hollow tube that is tapered at the ends (Gullichsen *et al.* 1999).

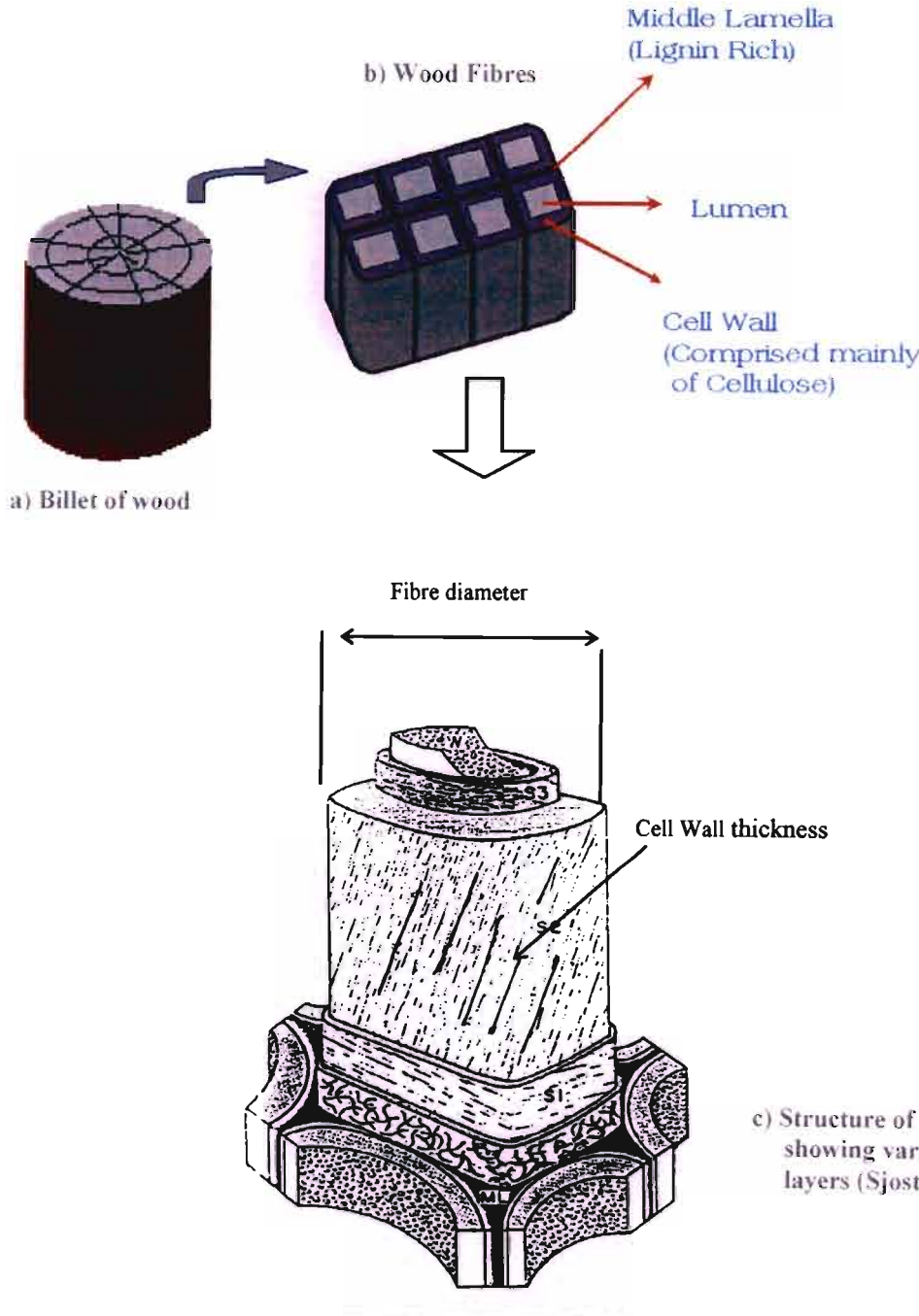


Fig. 2-5: Diagrams showing the main wood anatomical features

Fibres are made up of three layers, the middle lamella (ML), primary wall (P), the three layers of the secondary wall (S1, S2, S3) and the warty layer (W). The structure and chemical composition of these layers differ from each other. Each of the layers is of different thickness and has different cellulose microfibril orientation (Brandstrom 2001). The microfibril orientation is the angle between the microfibril and the tracheid axis.

The primary wall contains cellulose and hemicelluloses embedded in lignin (Sjostrom 1981). The thickest part of the secondary layer is the S2 layer, which makes up 80% of the wood fibre, and is the richest in cellulose (Fors 2000).

The individual cells are held together by the middle lamella (1-2 micron thick), which is composed mainly of lignin. As mentioned earlier, it is this cementing layer that pulping attempts to remove in order to release the individual fibres. Even though the lignin concentration of the middle lamella is high, only 20-25% of the total lignin is located in this layer, due to it being a thin layer (Fors 2000) and at least 70% of the total lignin in softwoods is located in the secondary wall of fibres due to it being thicker than the middle lamella (Sjostrom 1981, Gullichsen *et al.* 1999).

Heartwood (at the centre of the tree) is composed of dead wood cells. Because this part of the wood has a high concentration of resinous organic compounds (Britt 1970), the permeability of the wood is reduced here.

Wood anatomical properties can be used to a fair degree to predict most paper properties. Some measurable wood characteristics include wood density, cell-wall thickness, fibre diameter, lumen diameter and collapsibility. It has been shown that wood anatomical properties can be efficiently predicted from wood properties measured at breast height (Chikamai 1987, Evans *et al.* 1995, Evans *et al.* 1997). Chikamai (1987) reported that for *P. patula*, measurements of wood fibre length, fibre diameter and cell-wall thickness at breast height correlated well with the whole tree estimates of these properties. This finding was also observed for cell-wall thickness and wood density in *P. radiata* clones (Evans *et al*, 1997). The existence of strong correlations between wood properties at breast height and whole-tree properties offers the possibility of screening large numbers of wood specimens taken from breast height for their whole tree wood property estimates, without having to resort to laborious and expensive sampling at various heights along the tree to determine the whole tree properties.

2.4.1 Wood density

Wood density is defined as the amount of substance per unit volume. Density is affected by numerous wood properties, some of them being the chemical content of the wood, the proportion of earlywood, the cell-wall thickness, lumen diameter and the cell size (Malan 1991). Other factors such as tree age (Clarke *et al.* 2002, Kerr & Swann 1980), the quality of the site on which the tree is grown as well as the altitude of the site also affect the density (Clarke *et al.* 2002). In pines, there is either a slight negative (indicating a decrease) variation of density with tree height or it remains fairly constant, depending on the site (Corson 1991, Malan 2000, Evans *et al.* 1995). The decrease in density with increasing height could be due to decrease in the number of annual rings with height, which causes an increase in the proportion of juvenile wood (Malan and Retief 1996).

2.4.2 Fibre length

Tree age has been found to be the principal factor affecting fibre length, with young trees having shorter fibres than mature ones (Muneri 1994, Kerr & Swann 1981, Goyal *et al.* 1999). Fibre length increases radially from the centre of trees outwards (Gullichsen *et al.* 1999). With regard to the variability of fibre length with tree height, it increases for some distance up the tree before decreasing towards the top of the tree in *P. patula* (Muneri 1994, Muneri & Balodis 1998). Desch & Dinwoodie (1996) found that the longest fibres were about 30% up the tree. Ringo (1995) found fibre length decreased significantly with height in 27 year old *P. patula* trees from southern Tanzania. Longer fibres in pulp have larger contact area, tolerate greater stress and generally have higher tear strength and, to a lesser extent, higher burst and tensile strength (Ivkovich 2000, O'Neil *et al.* 1997). However, very long fibres can entangle with one another and disrupt sheet formation. This creates areas of weakness in the sheet, resulting in poor strength. Kibblewhite *et al.* (1997) concluded that wood density alone, without fibre length, can be a poor indicator of kraft pulp quality. Alexander *et al.* (1968) found that the ratio of fibre length to diameter correlated well with the tear strength of paper.

2.4.3 Cell-wall thickness

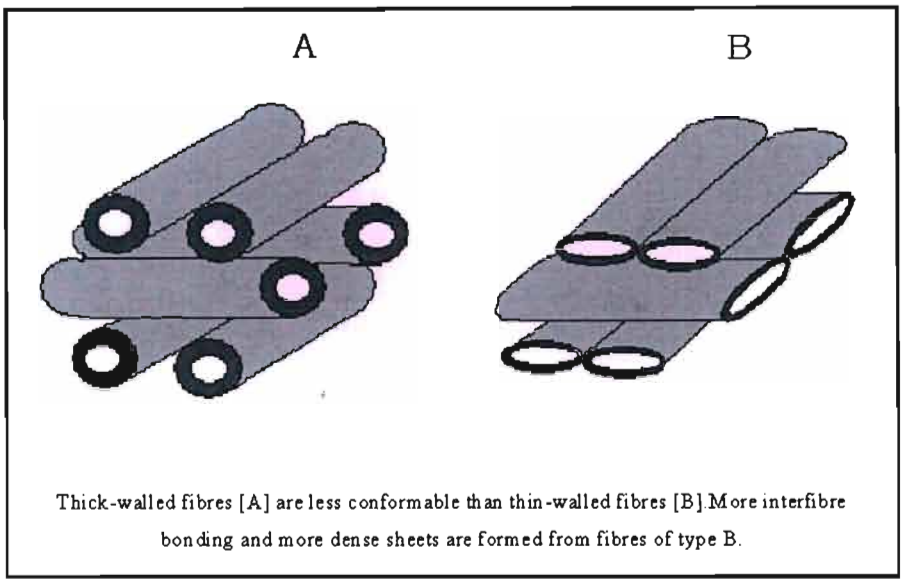
Cell-wall thickness can be used as a measure of fibre quality and correlates well with pulp fibre strength properties (Xu *et al.* 1997). The cell wall thickness of tracheids increases radially from the centre outward (Gullichsen *et al.* 1999). Evans *et al.* (1995) showed that average cell wall thickness decreased with increasing height in radiata pine. This was also observed by Chikamai (1987). During pulping, cell-wall thickness affects penetration of cooking chemicals into fibre walls (Kauppinen 1997). Due to the greater impermeability to cooking chemicals of pulps with thick cell walls, higher pulp yields are obtained in such pulps

due to lower reaction rates (Ivkovich 2000). Cell-wall thickness also controls the bonded area of the fibre network and its development during mechanical treatment of pulp fibres by beating or refining (Paavilainen 1994). This is due to it affecting the fibre collapse. Thick walled fibres do not collapse easily and produce rougher and bulkier sheets compared to thin walled fibres (Ivkovich 2000). Due to thick walled fibres resisting collapse, they are more difficult to beat to a low freeness and were found to have higher tear and low burst and tensile strength (Ivkovich 2000, Clarke 1985).

2.4.4 Fibre collapse

Fibre conformability plays an important role in the sheet structure and the strength properties of the pulp (Seth *et al.*1997). Fibres are conformable if they have lower resistance to bending. Due to fibres in wood being tubular in nature, they bend most easily when flattened or collapsed (Seth *et al.* 1997). Therefore, the degree of collapse of fibres is considered a good indicator of fibre conformability.

The external forces that fibres are subjected to during pulping and paper making treatments result in the collapse of fibres (Seth *et al.* 1997). The ability for fibres to collapse is determined by both the cell-wall thickness and the lumen diameter. Fibres that have thin cell walls and large lumen diameters tend to be more flexible and collapse easily. Collapsed fibres conform to the surface of other fibres in the sheet. This increases the apparent area of contact between the fibres and thus the area available for bonding during the making of paper. This in turn results in the formation of stronger and denser sheets (Seth *et al.* 1997, Britt 1970, Rudie 1998, Broderick *et al.* 1996, Muneri & Balodis 1998, Amidon 1981). Chemical pulps yield fibres that collapse more easily than mechanical pulps due to their lower lignin content. Fibres from lignin rich pulps are more rigid and less collapsible, due to lignin hindering pulp fibres from imbibing water and "swelling".



Thick-walled fibres [A] are less conformable than thin-walled fibres [B]. More interfibre bonding and more dense sheets are formed from fibres of type B.

Fig. 2-6: Schematic representation of thin-and-thick-walled fibre structures

The two most often used equations to determine the degree of collapse are the Runkel and Muhlsteph ratios (Seth *et al.* 1997)

Equation 2-2:

$$Runkel\ Ratio = \frac{2CWT}{LD}$$

Equation 2-3:

$$Muhlsteph\ Ratio = \frac{(FD^2 - LD^2)}{FD}$$

With CWT = cell wall thickness
FD = fibre diameter
LD = lumen diameter

Pulp fibres with a high Runkel or Muhlsteph ratio are considered less desirable for paper making, as they are less conformable since they have a low tendency to collapse. Thus, less interfibre bonding occurs in such pulps. Kibblewhite *et al.* (1997) found collapsibility to be a good predictor of tear, tensile and bursting strength properties of pulp.

2.4.5 Fibre coarseness

Fibre coarseness is defined as the mass of oven dried material per unit length of fibre. According to Ivkovich (2000), this ratio of fibre mass to length appears to be the best indicator of fibre flexibility. Fibre flexibility refers to the axial conformation of fibres, whereas fibre collapsibility refers to vertical conformation of fibres, towards the fibre axis (Paavilainen 1989 & 1991).

It is important to bear in mind that fibre coarseness as determined in wood is reduced during pulping by a fraction depending on the pulp yield (Britt 1966). In this study, pulp fibre coarseness was a derived trait (see Equation 2-4) from wood density and wood fibre diameter, with a correction factor of pulp yield applied.

Equation 2-4 (Miles *et al.* 1995):

$$Pulp\ Coarseness = Pulp\ yield\,(\%)\ x\ \frac{Wood\ density\ x(Fibre\,diameter)^2}{100}$$

Fibre coarseness is directly related to the cross sectional area of the fibre (Muneri 1994). Paavilainen (1993) showed that cell wall thickness explained over 78% of the raw material based coarseness variation in softwoods. Fibre coarseness alone is insufficient to predict pulp quality. This is because two fibres with the same coarseness can have different wall thickness if their perimeters are different (i.e. a thick walled, narrow fibre can have the same coarseness as a thin-walled narrow fibre, which would be more collapsible). Despite this limitation, coarseness has proved to be of great value in predicting paper properties. Coarser fibres produce bulky and porous sheets (Muneri 1994). Finer fibred pulp shows a great degree of interfibre bonding in the unbeaten state. Conversely, tear strength shows an advantage for coarser fibred pulps.

2.5 Earlywood and latewood

The growth rate and dimensions of fibres vary throughout the year (Gullichsen *et al.* 1999). Trees grow very little or not at all during the winter (Gullichsen *et al.* 1999). The annual ring structure of softwoods are characterized by alternative bands of earlywood and latewood tracheids. Earlywood (springwood) refers to wood cells formed during the early growing season and latewood cells grow later on (Svedman *et al.* 1998). Earlywood (EW) cells are large, thin-walled and have wide lumen (Esau *et al.*, Wilson & White 1986, Britt 1970). Latewood (summerwood) cells are thick-walled and are generally longer and thinner

(Kocurek 1996, Britt 1970). Latewood (LW) tracheids obtain their thick walls by the deposition of large amounts of the middle layer of the secondary wall (Ifju *et al.* 1975). Earlywood fibres are less dense than latewood fibres. Latewood may contain less polymers that, when hydrolysed, yield the monosaccharides xylose and arabinose and slightly more polymers that upon hydrolysis yield mannose, than earlywood (Britt 1970).

The thin cell walls and larger lumens of earlywood cells allow them to be able to collapse easily. Ifju & Labosky (1981) observed, in a study done on Loblolly pine, that more collapsible earlywood fibres impart high tensile strength and burst strength properties to the pulp fibres. It was also observed in this study that thick-walled latewood tracheids produced handsheets with high bulk and tear strength but low burst and tensile strength relative to the handsheets made from earlywood tracheids. These differences in sheet structure and strength, due to the amount of earlywood and latewood present, can be carefully manipulated to obtain the desired strength properties of the end-product.

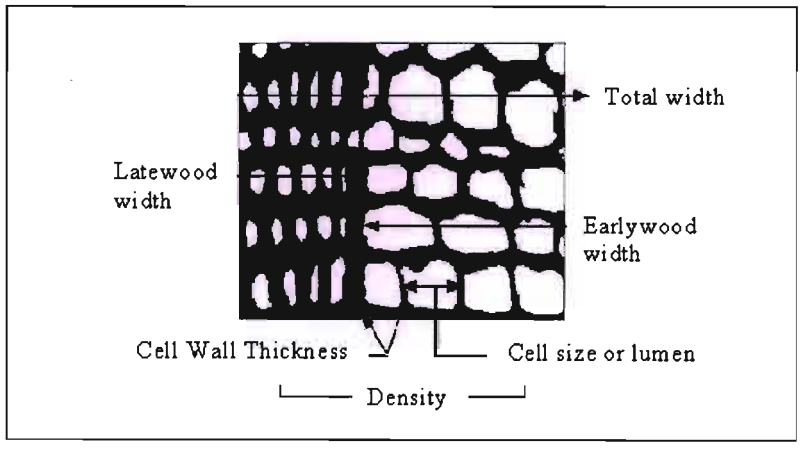


Fig. 2-7: EW - LW transition (Naidu 2003)

2.6 Juvenile and Mature Wood

Tree age is an important factor that impacts on wood cell structure and thus on the quality of wood. The portion of the stem that is closer to the pith possesses distinctly different cellular structure and wood properties to the wood in the outer part of the trunk (Ishengoma *et al.* 1995). The wood formed near the pith is called juvenile wood and that formed in the outer part of the trunk is called mature wood.

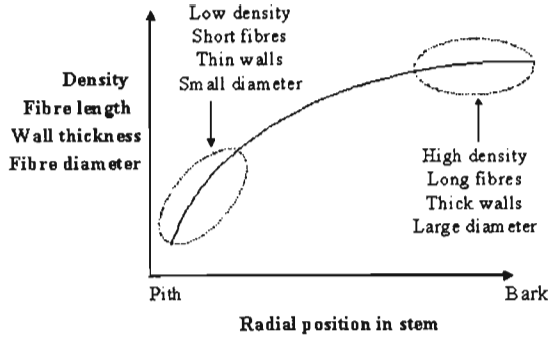


Fig. 2-8: Variation of wood properties from the pith to bark (Naidu 2003)

Most properties fluctuate with age, especially during the juvenile period of growth (Malan 2000). Ishengoma *et al.* (1995) found juvenile wood to be one of the most important sources of wood variability. Juvenile wood is found in young trees and in the tops and centre of older trees. Juvenile wood has lower density, shorter fibre length, inferior strength properties and often contain more earlywood than mature wood. It also has thinner walls, higher lignin, extractives and hemicellulose content (Zobel & Blair 1976, Hatton 1997). Hatton (1997) found the volume of juvenile wood to decrease with increasing tree age. Juvenile wood has been found to produce pulp with high tensile and burst strength, but low tear (Kirk *et al.* 1972, Zobel & Blair 1976, Brolin *et al.* 1995, Hatton 1997, Svedman *et al.* 1998, Zobel & Sprague 1998). Gullichsen *et al.* (1999) states that morphological differences within the stem of the same tree results in differences in pulp strength, with the outer surfaces of mature timber making stronger pulp than the chips from roundwood.

2.7 Variation of wood properties with site

Intersite differences are a major source of variation of wood properties (Corson 1999). Site index is one measure that is commonly used to classify a site as good or poor. On good sites, trees would be expected to grow bigger both radially and longitudinally. This is the basis on which site index is calculated. It is a measure of the average height of the 20% widest trees within a plot within the site.

There are many causes of site variation, such as differences in altitude, soil or the climate (Plumptre 1975). Muneri & Balodis (1998) found that fibre length was substantially different between sites, for *P. patula*. Malan (1994), however, found no clear site effect on fibre length for *P. patula*. In a study by Turner *et al.* (2000) on *P. patula*, cell diameter, lumen diameter and fibre length was found to increase with increasing site quality. No impact on cell wall thickness was found in that study. Schweingruber (1988) however states that greater cell wall

thickening occurs under good growth conditions. The contradictory results obtained could be attributed to various characteristics of the sites, which were used in these studies, which were different. The effect of the various characteristics of the sites that were under investigation in this study on the measured properties was not examined. However, various characteristics (such as soil type, altitude etc) of the sites are provided.

2.8 Pulping

In chemical pulping, digesters are used to cook wood chips with appropriate chemicals in an aqueous solution at elevated temperature and pressure, with the objective of degrading and dissolving away the lignin (delignification) in the middle lamella, with as little as possible damage to the fibres (Gullichsen *et al.* 1999). In this way the cellulose and hemicelluloses are left behind in the form of intact fibres.

The pulping chemicals travel via the cell lumens through the cell walls and into the middle lamella, the lignin is progressively dissolved, thereby loosening the individual fibres (Smook 1992). Most of the lignin is located in the cell walls, and is thus removed from here before enough of the lignin in the middle lamella has been removed to liberate the fibres (Stephenson 1950, Gullichsen *et al.* 1999, Kocurek 1996). However, as mentioned earlier, this delignification process is not totally selective since the polysaccharides react simultaneously. Even though these reactions can be regarded as side reactions (Gullichsen *et al.* 1999), they are highly undesirable because they not only decrease the pulp yield, but also adversely affect the pulp paper-making potential properties. In commercial cooking, the conditions for cooking are selected to give the optimum reaction with lignin, without excessive degradation of cellulose (Casey 1952).

- **Kraft pulping**

There are various chemical pulping processes, which are continuously being modified and changed with the aim of increasing the selectivity of the delignification process. In 1854, the soda process, which makes use of only caustic soda for the delignification process, was patented. In 1884, C. F. Dahl discovered that introducing sodium sulphide as well in the cooking liquor significantly accelerated delignification and produced stronger pulp (Smook 1992). This process, became known as the Kraft process. Today, more than 80% of chemical pulps are made using the Kraft process. It is such a dominant chemical pulping process because it can pulp any lignocellulosic material and is very energy efficient. It also has an efficient and economical chemical recovery process (Kleppe 1970). This process produces

very strong and flexible fibres from softwoods and is ideal for hardwoods due to its efficient handling of extractives.

Kraft pulping is performed with a solution of sodium hydroxide and sodium sulfide, named white liquor. The active components of white liquor are the hydroxyl ions and hydrosulphide ions. These ions are obtained from the NaOH and Na_2S. The concentration of these ions has major effect on the rate of delignification.

Various combinations of numerous variables can be used during pulping. Some of these variables include the active alkali charge, the ratio of cooking liquor to wood, the sulphidity of the cooking liquor and the cooking time. Maximum pulping temperatures of about 170-175°C are generally used. The maximum pulping temperature in the range of 150-175°C does not seem to have a significant impact on softwoods (Kleppe 1970). In this study, the various cooking conditions were kept constant, and only the cooking time was varied. It is apparent in the foregoing discussion that the effect of the period of cooking plays an important role in the quality of the pulp obtained. The degree of cooking is measured by the lignin content of the pulp (Casey 1952). Excessively long cooking times would result in much of the lignin being removed, but at the expense of the degradation of the carbohydrates. To achieve a given degree of delignification, various combinations of cooking time and pulping temperature can be used (Kocurek 1996). By arbitrarily assigning the relative reaction rate of 1 for 100°C, a concept called the H-factor was developed by Vroom (Kocurek 1996). When the relative reaction rate is plotted against the cooking time, the area under that curve is defined as the H-factor (Kocurek 1996). This method expresses cooking time and temperature as a single variable. This allows various combinations of cooking times and temperatures that can be used during pulping to be expressed as a single numerical value, regardless of the nature of the cycle (Kocurek 1996). This concept has been successfully employed in kraft pulping.

Due to the kinetics of kraft pulping being very complex, no general equation has been formulated which can describe the rate of delignification over all the various combinations of pulping conditions (Kleppe 1970).

A graphical plot showing the residual lignin at various stages during a cook indicates that there are three distinct phases of delignification.

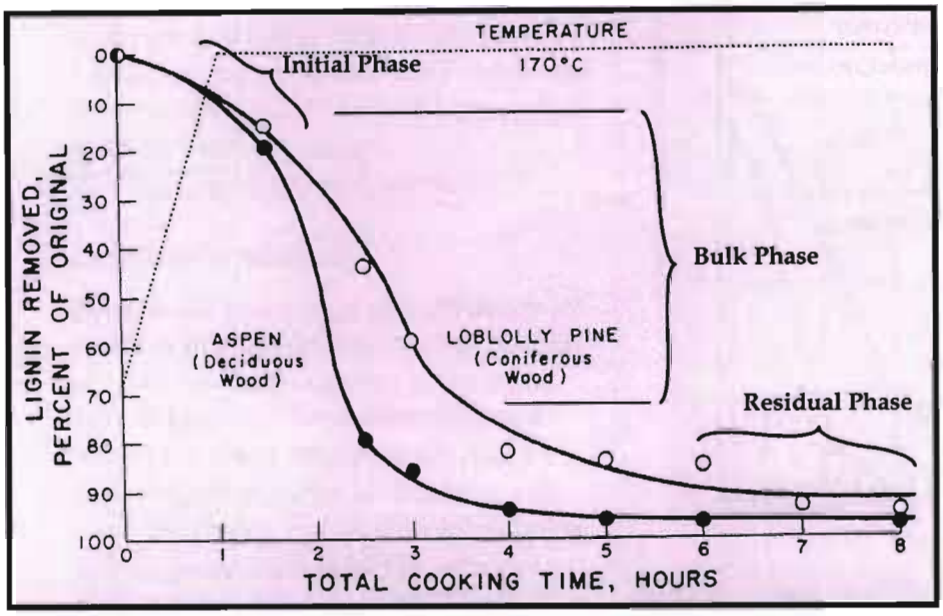


Fig. 2-9. Rate of delignification (Kocurek 1996)

Initial phase: Approximately 20% of the lignin is removed during this phase (Gullichsen *et al.* 1999, Miranda & Pereira 2002). It is believed that this phase takes place at temperatures below 140°C and is diffusion controlled.

Bulk Delignification: A further 70%-80% of the lignin is removed here (Gullichsen *et al.* 1999, Miranda & Pereira 2002). Delignification begins in the S2 layer of the secondary wall (see fig. 2-5) and progresses into the middle lamella (Gullichsen *et al.* 1999). This phase is believed to be chemically controlled (Miranda & Pereira 2002). It is strongly dependant on the OH^- ion and HS^- ion concentrations in the cooking liquor and on temperature (Gullichsen *et al.* 1999). Delignification during this stage proceeds at a useful rate only at temperatures above 150°C (Miranda & Pereira 2002). It is first order with respect to the remaining lignin concentration.

Residual delignification: The removal of the last vestiges of lignin occurs in this stage. This phase is considerably slower than the bulk phase (Smook 1992), due to difficulty in removing the residual lignin. Many problems can arise during this phase, if it is not carefully controlled, because soluble lignin undergoes condensation reactions if too much alkali is depleted and not enough is present during this phase (Gullichsen *et al.* 1999). Cellulose degradation is especially strong during this phase (Gullichsen *et al.* 1999). Therefore, continuing the delignification during the residual phase results in pulp yield loss and weaker fibres (Gullichsen *et al.* 1999).

2.9 Measuring the outcome of pulping

There are various properties of the pulp that can be measured. Properties such as residual lignin content in the pulp, estimates of carbohydrate degradation and fibre length distribution are some of these properties (Gullichsen *et al.* 1999). Pulp quality is largely determined by the properties of the pulp fibres (Karenlampi 1996, Ivkovich 2000). Ivkovich (2000) states that tracheid characteristics determine to a great extent the properties of the pulp fibres and therefore influences the physical properties of pulp and paper. Some relationships between wood and pulp properties have been established (Kube & Raymond 2002). This is useful information as it eliminates the need cook chips in lab digesters, which is slow, expensive and requires a large quantity of wood chips in order to determine the various pulping and pulp properties (Kube & Raymond 2002). Pulp and wood properties can be used in simulation models or statistical analysis to determine the relationship between these properties and the resultant paper properties. This helps in understanding how to improve paper properties by developing pulp fibre properties or choosing the appropriate resource with the necessary wood properties to yield the desired paper characteristics.

2.9.1 Pulp yield

The yield of the pulp is determined by the ratio of oven dried pulp produced to the amount of oven dried wood used. The amount of rejects is determined by screening on a standard laboratory screen with 0.15 or 0.25 mm slots and the screened yield is calculated as total minus rejects (Gullichsen *et al.* 1999). Insufficient penetration of the cooking liquor into the chips lowers the degree of cooking and increases the level of screen rejects (Smook 1992). Thus, the amount of rejects can be used as a measure of the uniformity of the delignification (Gullichsen *et al.* 1999).

As pulping time increases, the pulp yield decreases due to the removal of lignin and the shortening of cellulose and hemicellulose chain length. The loss of cellulose during Kraft pulping is fairly low (about 10-20%) (Kleppe 1970). A possible reason for this is due to the high degree of polymerization and the inaccessibility in the crystalline regions of cellulose to the hydroxyl ions (Kleppe 1970). Yield loss further occurs when the degraded carbohydrates reach a molecular size that is small enough to make them alkali-soluble .

The pulp yield is of great economical importance since the cost of wood contributes substantially to the total production cost of Kraft pulps (Kleppe 1970). One of the objectives during pulp manufacture is to increase the yield of usable pulp from a given quantity of wood, without compromising the strength properties (Smook 1992). Understanding of how the yield

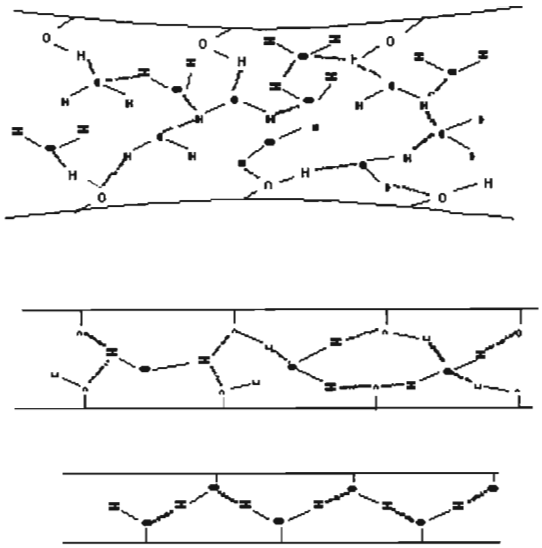
is affected by changes in process variables and in the raw materials is valuable information for optimal return on investments. Morris *et al.* (1993) found that felling age has an insignificant effect on pulp yield, with the weak trend of increase in yield with felling age. Clarke *et al.* (2002) concluded that pulp yield for five *Pinus* species grown in South Africa, was most influenced by species and age. In the same article, for *P. patula*, pulp yield increased with tree age. Kube & Raymond (2002) states that cellulose correlates well with pulp yield, and it appears to be the most reliable indicator of pulp yield for plantation *eucalypts*. This was also observed by Goyal *et al.* (1999). The yield and the quality of the pulp is largely dependant on original position of wood used in the tree (Stephenson 1950).

2.9.2 Active Alkali Consumption

The acidic reaction products from the carbohydrates consume most of the effective alkali in the pulping liquor. Thus, as pulping time increases, the amount of active alkali in the cooking chemicals decreases. Since the rate of reaction of cooking chemicals with the various wood components is almost directly dependant on the concentration of the cooking chemicals, one of the reasons that the rate of reaction decreases towards the end of the cook is due to the consumption of the chemicals (Smook 1992). The liquor that exits the digester with the cooked chips is called "black liquor". It is very dark in colour and, in addition to any residual inorganic material that was used to make up the cooking liquor, it has organic and inorganic material removed from wood during the cooking process.

2.10 Papermaking

The strength and other mechanical properties of the individual fibres depend on the physical state and the chemical composition of the cell wall (Seth & Chan 1999). When wet fibres are brought together during the making of paper, bonding is promoted by the polar attraction of water molecules for each other and for the hydroxyl groups covering the surface of fibres. When these wet sheets are dried, the water evaporates and the hydroxyl groups on opposing fibre surfaces ultimately link together by means of hydrogen bonding (see fig. 2-10). The strength of the paper is dependant to a significant extent on these bonds between the fibres.



Bonding loosely through water molecules occur when the sheet is wet

Bonding occurs more tightly as water evaporates from wet sheets during drying

Direct hydrogen bonding occurs when sheet has been dried.

Fig. 2-10: Different levels of hydrogen bonding.

Reliable pulp and paper test methods are essential for control over the paper manufacturing process and for the development of improved products and more efficient techniques (Britt 1970). There exists various bodies that have published methods for pulp and paper testing, the most authoritative of these bodies being The Technical Association of the Pulp and Paper Industry– TAPPI (Britt 1970). The methods described by this body were used for pulp hand sheet making and strength testing.

2.11 Beating

The properties of pulp fibres determine the achievable strength potential of the paper manufactured (Karenlampi 1996, Seth & Chan 1999). Mechanical treatment of the fibres can alter the degree of interfibre bonding, which in turn significantly affects the pulp strength properties (Karenlampi 1996).

Beating refers to the controlled modification of the cellulose pulp fibre properties by mechanical treatment (Smook 1992, Casey 1952), so that they felt together to form paper of the desired characteristics (Grant 1961). Beating of pulp can be achieved in a PFI mill (Law *et al.* 1999).

In the making of handsheets on which to perform strength tests, pulp is first beaten to a specific degree to develop the paper making potential of the fibres to their optimum value. The main effects beating has on pulp include the fracture and removal of the primary cell wall of the fibre, increase in fibre flexibility, formation of fibrils [external and internal fibrillation (Grant 1961)] and an increase in the specific surface of the fibre (Smook 1992, Jones 1998).

Refining also straightens fibres (Stoere *et al.* 2001). When the consistency of the pulp in the beater is high (more fibres and less water) and the knives of the beater sharp, the beating action can also, to some degree, cause some fibre cutting action (Smook 1992). The increase in available surface area and fibrillation is highly favourable during paper making, as both these factors are believed to contribute positively to the strength properties of the pulp.

No major chemical changes occur in the pulp fibres during beating (Casey 1952). Paper made from unbeaten pulp is generally low in strength and unfit for most uses, whereas beaten pulp fibres are readily formed into uniform sheets of paper which are strong and dense (Smook 1992, Casey 1952). However, the beating process needs to be carefully controlled so that the desirable attributes of the pulp be achieved with avoidance of gross damage to the fibre. Thus, in the development of the strength potential of the pulp, the fibre strength can be regarded as a limiting factor, since the strength of the fibres cannot be enhanced during beating, so preservation of the very high inherent strength of unbeaten fibres is essential while developing properties to enhance interfibre bonding.

Beating ruptures and fibrillates the fibre surfaces (see fig. 2-11) and also increases the fibre flexibility (Seth *et al.* 1997) and allows it to mat and contact neighbouring fibres better (Stephenson 1950). Paper made from such fibres has considerable strength compared to unfibrillated fibres by virtue of the readiness with which fibrillated fibres mechanically entangle with one another, which in turn enhances strength of the pulp (Stephenson 1950). Another consequence of fibrillation is that hemicelluloses are liberated from their bonded state in the fibres and the separated fibres are covered with a thin layer of hemicelluloses, thus making it available for bonding. There are many authors who see fibrillation as being far from a key factor promoting strength development. Their argument is that accompanying the splitting of fibres to produce fibrils, is significant damage in other areas of the fibre. This damage is brought about by the serious fracture lines at the base of these fibrils that result when they break out from the fibres (Bolam 1965).

Just as important as the external fibrillation that is described above, beating also results in a reduction in the rigidity of the cell walls (Grant 1961). This is called internal fibrillation. Structural changes in the fibre wall that result from beating result in an increased ability for fibres to swell by increasing their ability to imbibe water.

Fig. 2-11: Fibrillated fibres (Stephenson 1950)

Fig. 2-12: Hydrated wood fibres (Stephenson 1950)

This action of swelling lubricates the fibres and thus increases fibre flexibility and lowers the beating energy required to reach a low freeness (Britt 1970). Swelling also increases the available bonding area of the fibre (Britt 1970). A further advantage of swelling is that it loosens the structure in fibres and results in fibrillation of the cellulose fibres (Britt 1970). The cellulose in the pulp fibres has a high affinity for water (Casey 1952). This intake of water allows for interfibre bonding to occur. Interfibre bonding occurs due to hydrogen atoms which form "bridges" (see fig. 2-10) connecting oxygen atoms in adjacent fibres (Casey 1952). As beating proceeds, there is an increase in fibre surface area available for absorption of water. Internal fibrillation explains why the strength properties of paper can be developed without appreciable visible signs of external fibrillation (Grant 1961). It is believed that external fibrillation follows at a later stage in the beating process (Grant 1961).

Law *et al.* (1999) define fines as fibrous particles with a length of less than 0.2mm. Fines of softwood chemical pulp consist of primary fines present in unbeaten pulp and secondary fines that are formed as result of beating (Paavilainen 1990). Beating produces fines that are formed as a result of cell wall peeling and fibre shortening (Naidu 2003). Fines promote interfibre bonding, as they assist with sheet network consolidation by filling the voids between fibres, which in turn increases the surface area for interfibre bonding.

Different fibres react differently to beating. This is true even of pulp of the same species but which have cooked for different periods of time (Grant 1961). The amount of lignin in the pulp, the hemicellulose content and the anatomical properties of the fibres are some of the

factors influencing the effect of beating on pulp. The amount of lignin present in fibres and fibre flexibility are limiting factors on the amount of beating the fibres can be subjected to without causing physical degradation to the fibres (Alexander *et al.* 1968). Centola & Borruso (1967) investigated the effect of hemicellulose content on paper properties and concluded that hemicelluloses in pulp improve the fibre beatability. Thus, the properties of the pulp fibres determine the limits for the combinations of paper properties achievable from manipulation of interfibre bonding by beating (Karenlampi 1996).

2.12 Freeness

Freeness is a measure of the readiness with which water drains freely from pulp. Pulps with a high freeness allow water to drain easily, with the opposite holding true for low freeness pulps. The Canadian standard freeness test (CSF) is a general Tappi method that is commonly used to determine the freeness of pulp.

Freeness decreases as beating proceeds (Grant 1961) mainly due to the fibres becoming more flexible and collapsible (ribbon-like) when beaten (Law *et al.* 1999), thus forming a denser mat (see fig. 2-6) with very little voids in the fibrous mass through which water cannot easily flow through. Some other factors that affect the freeness of pulp include the fibre length (Ifju *et al.* 1975), the fines content of the pulp and the hemicelluloses and lignin content of the pulp. Longer fibres intertwine with one another and form a loose network through which water can readily flow. Dinwoodie (1965) states that the fibre length accounts for more variation in freeness than the collapsibility, as measured by the fibre cell wall thickness.

2.13 Basis mass and sheet density

Basis mass is defined as the mass of substance per unit area of paper. The thickness of the paper together with the basis weight is used to determine the sheet density. The density of paper increases with an increase in fibre collapsibility. Pulp with stiff fibres (i.e. fibres with low collapsibility), such as fibres in high yield pulps, are less conformable and produce bulky and less dense sheets (Stephenson 1950, Britt 1966). Collapsed fibres conform to the surface of other fibres in the sheet. This increases the paper density and decreases the porosity (Rudie 1998).

2.14 Pulp strength properties

The resistance to rupture when subjected to various stresses is of importance to practically all grades of paper (Stephenson 1950). The various end uses of paper require a certain minimum strength to withstand the treatment received by the product in use.

Many factors affect the strength potential of paper sheets. Individual fibre strength, the structure of the sheet and the strength of interfibre bonds all contribute significantly to the strength of the sheet (Jones 1972, Twimasi *et al.* 1996). These properties are highly dependant on the properties of the pulp, such as the length of the fibres in the pulp, the length of the cellulose chains (i.e. degree of polymerisation) and the hemicellulose content. The amount and type of mechanical treatment that the fibres have been subjected to also has a significant influence on the paper making potential of the pulp. Morris *et al.* (1993) found that in *P. patula*, the main determinant of pulp strength was the felling age. As already mentioned, age is one of the most important factors responsible for the variation of wood and pulp properties.

Strength properties of pulp are generally determined by preparing handsheets and testing them after a conditioning period. There exist several tests that determine the various strength properties of paper. Some of these tests have already been mentioned. The strength tests that were performed in this study are discussed further below. It must be noted that each of these tests are influenced, to various degrees, by combinations of various characteristics of the paper.

2.14.1 Tearing strength

This strength test is designed to determine the average force required to tear a single sheet of paper after the tear on the sheet has been started. The tearing strength is very sensitive to the physical and chemical properties of the fibre (Stephenson 1950, Dinwoodie 1965). Degradation of fibres during cooking shows up dramatically in a loss of tear. Clarke *et al.* (2002) concluded that the tear strength of five *Pinus* species increased with increasing tree age. Morris (1993) also observed this for two pine species. This effect is believed to be associated with the greater proportion of latewood found in older trees (Morris 1993). Fibre length and interfibre bonding influence the tear strength of paper, with longer fibres increasing the tear strength of paper (Grant 1961, Clarke 2000). The reason for this is that longer fibres will distribute the stress over a greater area, over more fibres and over more bonds, whereas in shorter fibres, the stress is concentrated in a smaller area. Insufficient interfibre bonding results in lower tear, since the fibres pull apart easily. As the amount of interfibre bonding increase due to increased beating of the pulp, tear also increases, but to a

maximum and then decreases. This occurs because, during beating, accompanying the increase in fibre flexibility and surface area for interfibre bonding is the reduction in fibre length and fibre strength, which reduces the tear strength of the paper. Karenlampi (1996), Alexander *et al.* (1968) and Dinwoodie (1965) describe in detail some theories that have been developed regarding the properties of paper that control tear.

2.14.2 Tensile strength

This test determines the tensile pull necessary to rupture a strip of paper, when the load is applied in a direction parallel to the paper. The stress is expressed as force per unit width of test specimen (Grant 1961).

There are a number of factors that affect the tensile strength of pulp hand sheets, some of which have already been described. Some of these factors include the strength of the individual fibres, the average length of the fibre and the bonding ability of the fibre surfaces, both in terms of the available bonding area and the strength per unit of bonded area (Stephenson 1950). It is believed that the interfibre bonding in paper is the predominant factor affecting tensile strength, with the strength of the individual fibres playing a secondary role (Stephenson 1950). However, fibres that have been chemically attacked and degraded during pulping will be weakened and will thus produce weak paper. The length of the fibres in the pulp is strongly related to the tensile strength of paper (O' Neil *et al.* 1997), with longer fibres producing stronger sheets. However, there is a limit to which long fibres will contribute to paper strength because too long fibres will result in uneven sheet formation. These sheets that have thick and thin areas have poor strength (Stephenson 1950). Page (1985) discusses, in detail, the various theories developed to explain the increase in tensile with beating. Tensile strength is an important property for bag and wrapping paper.

2.14.3 Burst strength

Bursting strength is the pressure required to produce rupture of the material, by a rubber diaphragm when pressure is applied at a controlled increasing rate through the diaphragm to a circular area of the material under test (Britt 1970, Grant 1961). Burst strength ultimately gives an indication of the resistance of the paper to rupture in use (Britt 1970). The amount of interfibre bonding, the individual fibre strength and the stretch of the paper are all of predominant importance in determining the burst strength of paper (Stephenson 1950). It is also positively affected by the hemicellulose content of the pulp (Stephenson 1950). Clarke (2000) states that the pentosans of the hemicelluloses are the major constituent of the outer layers of the fibre wall and due to their very branched structure, they contribute to paper strength, burst in particular, through increased inter-molecular hydrogen bonding. The burst

strength of paper has been shown to be inversely related to tear strength and usually concur with the trends observed for tensile strength (Morris *et al.* 1993). Burst strength is an important property for wrapping papers and boxboards, where the paper is subjected to a similar stress that is exerted in the burst strength test.

2.14.4 Stretch of paper and tensile energy absorbed (TEA)

It is common, when performing the tensile test, to determine the amount of elongation the test specimen undergoes. The stretch at break is the increase in length of the paper strip at the moment of rupture and is expressed as a percentage of the original length. Some of the factors that affect the stretch of paper include the fibre elasticity and strength and the density of the paper. Dinwoodie (1965) mentions that a close relation between tear resistance and stretch has been observed. Stretch is an important property in grades such as toweling, tissues, cable wrapping papers and corrugating paper. By integrating the area under the stress-strain curve, the total energy that can be absorbed by the sheet before failure (TEA) is obtained. TEA is an important property in papers that are likely to be exposed to local stresses, such as a grocery bag when it is packed.

2.14.5 Zero span tensile strength

The zero-span tensile strength methods was originally developed to measure fibre strength. (Jones 1972, Mohlin *et al.* 1996). The increases in zero-span strength with increased beating could however not be explained, as fibre strength cannot be improved by beating. Recent work has shown that it is sensitive to fibre deformation (Mohlin *et al.* 1996, Page 1985). Page developed a theory that states that kinks and curls (i.e. types of fibre deformations), which are present in the unbeaten state, straighten out during beating, due to the swelling action induced by beating (Cowan 1995). This leads to an improvement in the load bearing capability of fibres, which is shown in the zero-span test as an increase in fibre strength with increased beating. When the fibres are straight, no further change in zero-span strength is observed. Thus, the zero-span can only be used as a measure of fibre strength when the fibres are straight. Mohlin *et al.* (1996) defines two types of fibre defects viz, reversible and irreversible deformations. Irreversible defects were defined as the difference between the zero-span strength of a damaged fibre (i.e. chemical and mechanical damage) and the same fibre in the undamaged state, when both are straight. This difference is mainly due to chemical degradation during pulping, but it can also include mechanical damage to fibres. Reversible deformation is defined as the increase in zero-span strength achieved by laboratory beating. This increase is due to the straightening of fibres, by the removal of kinks and curls, as a result of beating. Reversible damage can be used to explain the increase in zero-span with beating.

Chapter 3

MATERIALS AND METHODS

3.1 Introduction

Species, tree age and natural environmental factors are major contributors to variations in the wood quality supplied to pulp mills. The properties of the raw materials determine, to a large extent, the strength development potential of the finished paper product. An understanding of how these major causes of variation in wood properties, under various kraft pulping process conditions, impacts on the product quality, is imperative for effective use of the available resource.

3.2 Project design

The softwood species *Pinus patula* was investigated in this study. A single species was used to eliminate variability due to genotype. The project was designed such that extremes in site quality and age were used to simulate the range of variation of wood properties in logs entering mills. Trees in age ranges of 9-10, 13-14 and 20-21 years were selected from the two site quality classes (see Fig. 3-1).

Age / [Site Index]$_{20}$	9-10 years	13-14 years	20-21 years
Good Sites	34.7 20 trees	32.3 20 trees	30 20 trees
Poor Sites	24.2 20 trees	22.8 20 trees	24.5 20 trees

Fig. 3-1. Matrix showing compartments under investigation (N.B. Site index was calculated at base age 20*)

* See Appendix A for explanation.

3.3 General experimental plan

The following flow diagram illustrates an outline of the experiments carried out.

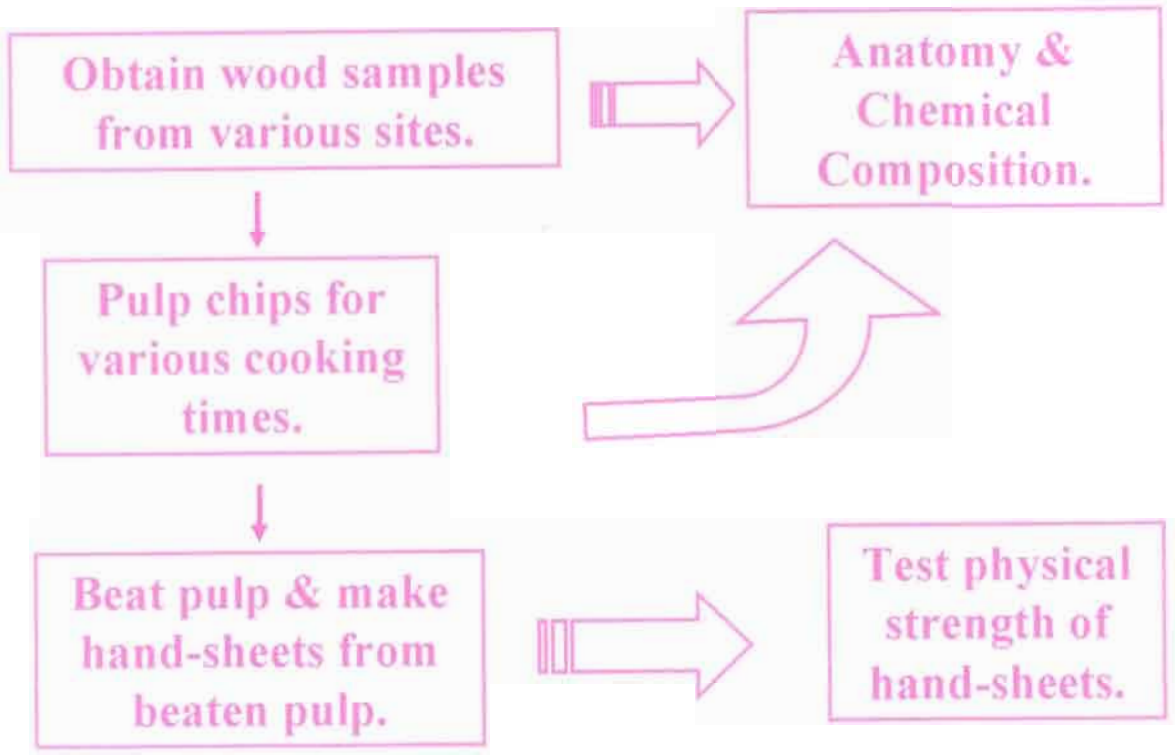


Fig. 3-2. General plan of analyses performed

3.4 Field sampling

All sampling was performed in the Kwazulu-Natal Midlands, South Africa. A shortlist of potential sites that satisfied the requirements of the project design (see section 3.2) was made from compartment listings provided by two local forestry companies, Sappi and Mondi. Sampling was performed between July 2003 and January 2004.

Site index is generally used to determine the quality of a site. An enumeration procedure used to determine site index of each site, described in Appendix A, was used as a measure of site quality. The site index of each compartment was determined on a microsite (15m radius plot) at each of the sites in the short list. From these measurements, those compartments which best suited the requirements of the project design were identified. The location of the sites under investigation is shown in Fig. 3-3. Various characteristics of these selected sites are shown in Table 3-1.

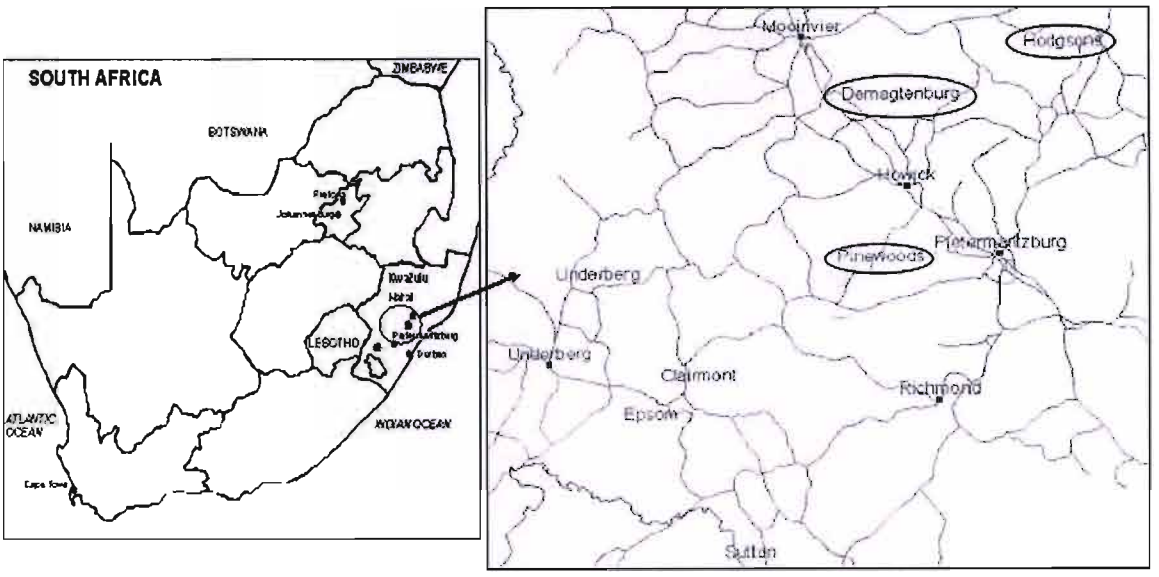


Fig. 3-3. Location of sites under investigation.

Table 3-1. Characteristics of the compartments sampled.

Region	Hodgsons	Demagtenburg	Pinewoods	Pinewoods	Pinewoods	Pinewoods
Age [years]	9	10	13	14	20	21
Altitude [m]	1148	1597	1480	1366	1469	1425
Alt. Class	1000-1200	1400-1600	1400-1600	1200-1400	1400-1600	1400-1600
MAT	16	15	15	16	15	15
0-12 ° C	46	32	7	58	21	54
13-20 ° C	50	17	64	42	37	40
20-35 ° C	4	34	25		38	6
36-50 ° C		17	4		4	
Avg Pres	877	1089	900	886	900	900
Geology	sandstone	basic igneous	sandstone	sandstone	sandstone	sandstone
Measured Site Index	34.72	24.23	22.8	32.3	24.5	30
Mean DBH [m]	17.82	19.04	20.54	23.14	30.6	33.62
SD DBH	0.48	0.56	0.52	0.48	0.7	0.83
Mean Total Height	16.76	11.93	14.59	21.67	21.39	27.06
SD Height	0.18	0.13	0.19	0.22	0.36	0.43

MAT = Mean Annual Temperature (obtained from Sappi)- number of days, in the temperature ranges shown, are indicated in the table.

DBH = Measured diameter at breast height at the time of sampling [m].

Mean total height [m]

SD = Standard Deviation

It can be seen from the above table that apart from the sites being different from each other with respect to site quality and tree age, there are various other factors, such as altitude and MAT, that differentiate the sites from each other. These variables are also known to influence wood properties, thus they were also taken into account in the statistical analysis of all results (Clarke *et al.* 2002, Naidu 2003).

At each of the six selected sites, twenty trees within the 15m radius micro plot on which the site index measurement was made, were randomly selected and felled. Upon felling, two sets of samples were obtained (one set for wood property anatomy and density determination and one set for wood chemistry and pulping studies) [see Fig. 3-4 and Fig. 3-5].

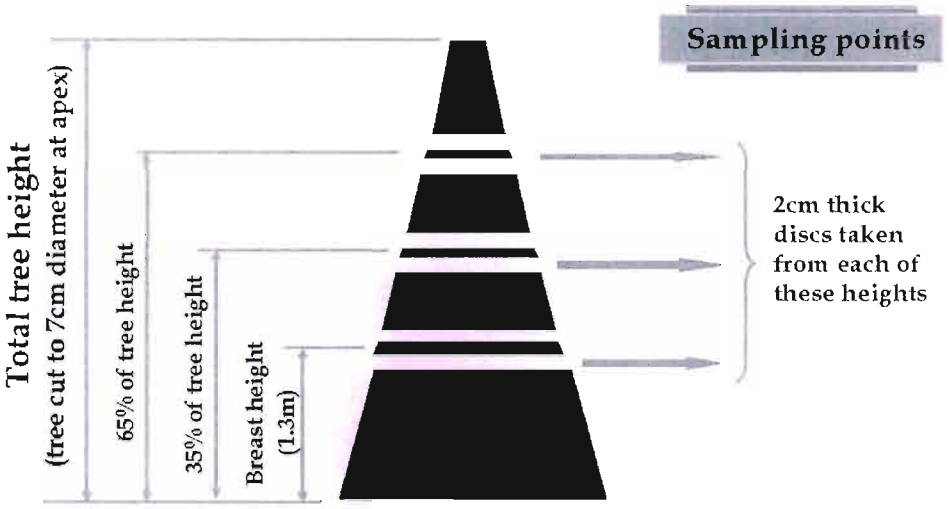


Fig. 3-4. Diagram showing sampling points for wood anatomy and density measurements.

Of the twenty trees felled, five were randomly chosen to obtain samples for wood density and anatomy. The total tree height and the height to a stem diameter of 7cm were recorded. The height to 7cm diameter is the merchantable part of the stem. For each of these five trees, breast height (a distance of 1.3m from the base of the tree), 35% and 65% of the total merchantable stem height were marked. Knot-free discs of about 2.5cm thickness were sampled at each of these heights (see Fig. 3-4). These samples were labeled using an indelible pencil. This same procedure was followed at each of the six sites.

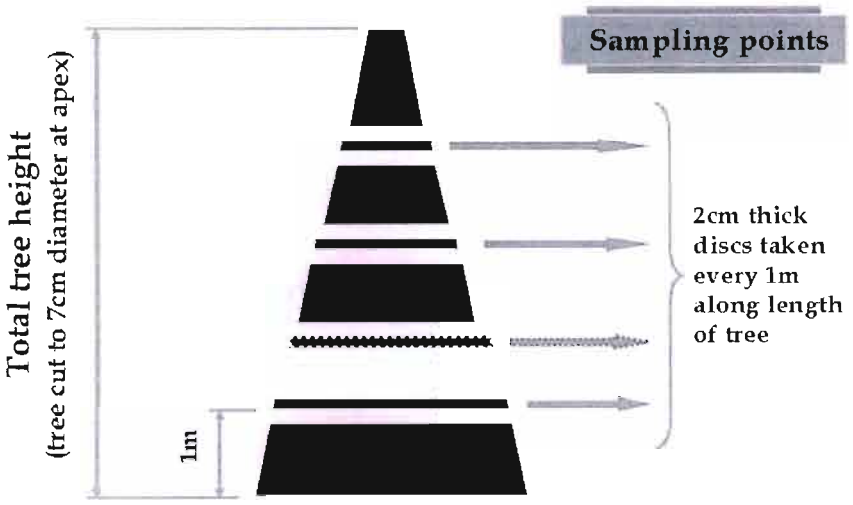


Fig. 3-5. Diagram showing sampling points for pulping.

The second set of samples (as shown in Fig. 3-5) was obtained for pulping studies. The discs were taken from each of the twenty trees felled (N.B. those trees used for wood physical property analysis were also used). Sampling for pulping involved taking 2cm thick discs at 1m intervals along the length of the tree, starting at the point at which it was cut up to 7cm tree diameter (see Fig. 3-5). For each compartment, the discs obtained from the 20 trees were combined together, resulting in six batches of discs, representing each of the six compartments.

3.5 Analyses performed and basic statistical analysis of results

All discs obtained were transported to the CSIR - Forestry and Forest Products (*ffp*) Research Center. The disc samples that were to be used for wood physical property analysis were immediately prepared for wood anatomy and density analysis (see section 3.5.1). Samples that were to be used for pulping were chipped and left to air dry.

3.5.1 Wood properties

The physical wood properties measured in this study were wood density, fibre cell-wall thickness, fibre lumen diameter and fibre diameter. The chemical components determined included Klason lignin, solvent soluble extractives, cellulose and the hemicelluloses. The hemicelluloses measured comprised arabinose, galactose, glucose, mannose and xylose.

- **Wood anatomy and density**

Measurements of density and anatomical characteristics were performed from pith to bark on each disc, for each of the five trees selected for anatomy analysis, from each compartment. It

must be noted that for the 21 year old site, one of the trees sampled for wood physical property analysis was partially decayed. The three disc samples obtained from this tree were discarded. Therefore, only four trees, sampled at three heights, were used for wood anatomy analysis for this compartment. Pith-to-bark strips from each of the discs were cut (see Fig. 3-6) and used to determine the mean wood anatomical properties as well as the density variation from pith to bark. The pith to bark variation of the percentage of earlywood, earlywood density and latewood density were measured on breast height samples only. The strips on which density was measured were conditioned in a controlled atmosphere room of 23°C and 50% relative humidity prior to determining the wood properties. The reason for carrying out the density measurements at the same moisture content for all the samples was that the water present in the sample would affect the densitometer's measurement of the amount of radiation that passes through the sample.

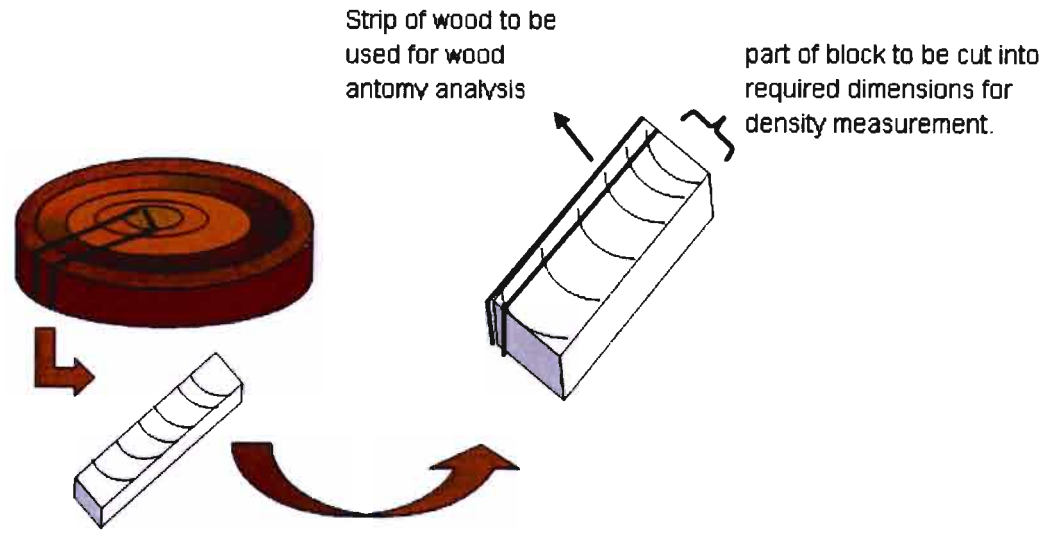


Fig. 3-6. Sample preparation for density and wood anatomical properties.

Wood density was measured using gamma ray densitometry. The theory behind gamma-ray densitometry is described by Malan (1991) and Naidu (2003). By scanning the samples from pith-to-bark, at 0.5mm intervals, the density profile for each disc was obtained. The weighted mean density of the entire disc was calculated from the density profile (discussed shortly). The density profile of all the breast height samples was also used to determine the earlywood and latewood densities as well as the percentage of earlywood for each of those discs.

Extractives were not removed from the wood samples prior to measuring the density. However, the average solvent soluble extractives for each of the sites were determined, thus the percentage extractives were used to calculate the extracted density for each compartment, according to Equation 3-1.

Equation 3-1:

Extracted Density = Measured Density - (% Extractives x Measured Density/100)

Image analysis techniques were used to measure the wood anatomical properties. Wood strips were softened by immersion in water prior to sectioning with a sliding microtome. Unbroken transverse sections were cut from the wood strips for image analysis (see fig. 3-6). These sections were placed on a glass slide and doused with 99% ethanol to prevent imprecise measurements due to evaporative shrinkage of cells (Naidu 2003). The use of ethanol also made it possible to obtain a clearer image of the cells under the fluorescent light of the microscope, thus ensuring accurate identification and measurement of the fibre properties. A research microscope with fluorescent light, combined with software developed by Leica was used capture to the images as the strip was scanned from pith to bark, at 0.5mm intervals. The weighted average wood anatomical characteristics measured were:

- fibre diameter (FD)
- lumen diameter (LD)
- cell wall thickness (CWT)

The lumen diameter was calculated by subtracting twice the cell-wall thickness from the fibre diameter. Fibre collapse was chosen as a measure of fibre conformability and was calculated from the measurements above. The equation used to calculate the collapsibility of wood fibres was:

Equation 3-2: $$Collapsibility = \frac{(3xFD) + (5xCWT)}{(CWT)^2}$$

The results for the wood density and anatomical properties were calculated on a whole-tree basis, from the three discs sampled along the length of the tree. The measurements obtained from pith to bark were used to calculate the weighted mean property for each disc. Calculation of the weighted mean disc value was achieved using the measurement of the property at each position from pith to the bark, which was weighted by the surface area covered between the growth rings at which the measurement was made.

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

WM_{disc} = weighted mean property of the disc
x_i = wood property value measured at the i^{th} ring
A_i = area of the i^{th} ring
n = number of observations made, from pith to bark

For comparisons at each tree height, the weighted mean properties of the wood discs at that tree height were compared. Variations of the properties along the length of the tree as well as inter-site comparisons at each tree height were made.

The whole-tree mean wood density and wood anatomical properties were determined by weighting by volume, the weighted mean values obtained for each disc along the length of the tree.

$$WM_{tree} = \frac{\sum_{i=1}^{n} WM_{disc} V_i}{\sum_{i=1}^{n} V_i}$$

WM_{tree} = weighted mean property of the tree
WM_{disc} = weighted mean disc property at position i
V_i = volume of the i^{th} section of the tree (see Fig. 3-7.)
n = number of observations made (in this study, n=3
i.e. values at breast height, 35% and 65% of tree height)

The volume of each section of the trees, between the sampling points along the height of the trees, is found below.

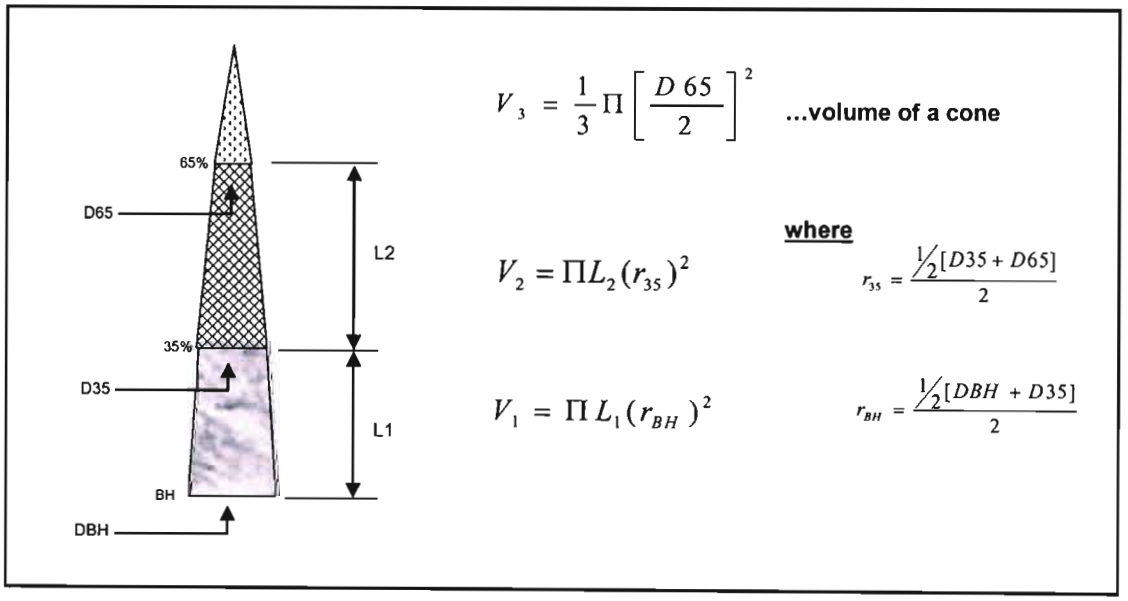


Fig. 3-7. Estimates of tree volumes used to calculate weighted mean (by volume) properties.

The results obtained were analysed for differences due to site quality and for differences due to age, using a one-way Analysis of Variance (ANOVA) at the 95% confidence level. The Duncan multiple range test was used to determine homogeneity. The mean of the measured values and standard error bars were used in the graphical representation of the data. The data were analysed using the statistical package StatGraphics for Windows 3.0 (Statistical Graphics Corporation 1994-1997) and also Windows Excel XP.

Only the breast height wood samples were analysed for radial variation in density and for determining the percentage of earlywood and the densities of earlywood and latewood.

- **Wood chemistry**

The wood discs that were sampled at 1m intervals along the length of the trees in each compartment were chipped using a laboratory guillotine chipper. They were then screened using a vibratory screen to remove oversize and undersize chips and thus minimise the effect of variation in chip thickness on pulping. For each compartment, the chips obtained were thoroughly mixed together. Approximately 100 gram samples were taken from each of the six compartments batch of chips and ground into sawdust. The sawdust from each compartment was used to determine the wood chemical composition.

Standard Tappi methods were used to determine the Klason lignin, extractives and the hemicelluloses content of the wood (See Table 3-3). The extractives content of the sawdust produced from the wood chips for each compartment was quantitatively determined by extraction for three hours using soxhlet extraction tubes. The extraction solvent used was a mixture of 1:2 (by volume) ethanol-toluene. The extracted sawdust was thereafter used to carry out all wood chemical composition analyses. High performance liquid chromatography (HPLC) was used to quantify the relative amounts of the various constituent monosaccharides of the hemicelluloses in the wood from each compartment. Details of the method followed in the HPLC analysis of the samples are found in Appendix B1. All tests were done in triplicate, in order to test for repeatability of results.

The Siefert method was used to determine the amount of cellulose. This method, when compared to other methods used to determine the amount of wood cellulose, was found to produce the purest cellulose residues and results that most meaningfully correlated with pulp yield and other wood properties (Kube & Raymond 2002, Wright & Wallis 1998).

Differences due to site quality and age were determined using a one-way Analysis of Variance (ANOVA) at the 95% confidence level. The Duncan multiple range test was used to test for homogeneity.

3.5.2 Pulp properties

For each compartment, the chips obtained from the discs from the 20 trees were pooled together and thoroughly mixed and then left to air-dry for 2 weeks to a constant moisture content.

The moisture content for each compartment was determined from representative samples of chips from each batch of chips. This was done by determining the ratio of the mass of water that evaporated from the chips, when placed in an oven at 105°C for 24 hours, to the original mass of chips used. After a 90 minute ramp up time, the chips from each compartment were pulped isothermally, at 170°C for seven different cooking times, using the Kraft process and under the same pulping conditions shown in Table 3-2. A rotating batch digester was used to carry out this series of cooks. These cooks were performed in triplicate, to test for repeatability of the results. Thus, for each of the six compartments a total of 21 cooks were performed (7 cooking times x 3). Altogether, a total 108 cooks were performed. Pulping experiments were conducted for various lengths of digestion time in order to examine the change in the measured pulp properties with increasing cooking time.

Table3-2. Kraft cooking conditions

Parameter	Condition
A.A charge (expressed as % Na_2O):	22%
Sulphidity:	32.8%
Liquor-to-wood ratio:	5.4 : 1
Pulping cycle	
AMBIENT TO 170 °C (min):	90
COOKING TIME AT 170 °C (min):	0 ; 35 ; 65 ; 85 ; 95 ; 120 ; 180
H-FACTORS:	124; 658; 1122; 1429; 1583 1967 2888

For the kraft process, the cooking chemicals used included sodium hydroxide (NaOH) and sodium sulphide (Na_2S). The preparation and standardisation of the cooking liquor and details of the calculations involved in obtaining the required liquor-to-wood ratio are discussed in Appendix B2. After pulping, a black liquor sample was collected from each cook and the active alkali consumption was determined according to the standard TAPPI method (see

Table 3-3). The hot pulp was thoroughly washed to remove the residual black liquor using tap water.

Pulp yield was determined based on the oven dried mass of wood chips initially charged into the digester (in this study, this was chosen to be a constant 800g for all cooks).

Equation 3-3:

$$Pulp\ Yield\ (\%) = \frac{mass\ of\ oven\ dried\ pulp\ obtained\ after\ pulping\ (g)}{OD\ mass\ of\ chips\ pulped}$$

The rejects were separated from the pulp through a 10-mesh screen (1.7mm screen size). The accepts were then passed through a 200-mesh screen (75um screen size) to remove fines. The screened pulp samples were then spin dried. Samples for chemical component and fibre anatomical analyses were taken from the spin dried pulp. The rest of the pulp samples were sealed in plastic bags. These samples were stored in a fridge at 4°C, for the making of hand sheets. The maximum period of storage, prior to the making of hand sheets was two months.

The same methods used for chemical analysis of chips were followed for the chemical analysis of the pulps (Table 3-3). The fibre length and cross section dimensions of unrefined pulp fibres were measured using a Fibre Lab Analyser.

Variability in pulp properties were analysed according to tree age, site quality and pulping time. These variations were tested using a one-way ANOVA at the 95% confidence level.

Thomson and Gustafson (2000) state that pulp with a kappa value from the low 20's to the middle 30's gives the strongest softwood kraft pulp compared with other pulps with a higher or lower kappa value. The results, for each compartment, obtained at kappa closest to 30 were compared with each other. Kappa has an important impact on the pulp properties, thus by comparing the compartments at a constant kappa, the effects of different pulp lignin content on the pulp properties was minimised.

3.5.3 Pulp strength properties

A PFI mill was used as the fibre refining method. The pulp samples obtained from all of the cooks were beaten at four levels; 1000, 2500, 4500 and 6500 revolutions (i.e. 100, 250, 450 and 650 beating). These beating treatments were performed in accordance with the Tappi method T 248 cm-85.The Canadian Standard Freeness (CSF) of each beaten pulp sample was

determined. General mass and temperature corrections, described in the standard TAPPI method T 227 om-94, were made to the measured freeness value.

The strength of the pulp was tested by preparing handsheets from the beaten pulp samples as per standard method T 205 sp-95. The handsheets were conditioned in a controlled environment of 23°C and 50% humidity. The characteristics on the conditioned handsheets that were measured are shown in Table 3-3.

Table 3-3: Methods used for chemical and strength analyses

Test	Test Method
Klason lignin	T222 om-88
Kappa	T236 cm-85
Active alkali consumption	T625 cm-85
Wood cellulose	Siefert method
Tear index	T414 om-88
Burst index	T403 om-91
Tensile index	T494 om-88
Stretch	
Tensile energy absorbed (TEA)	

3.5.4 SEM images of handsheets

For the 35 minute cooks, at the 100 and 650 beating levels, images of cross sections of the handsheets, from all six compartments, were captured using scanning electron microscopy (SEM). Samples of the handsheets were embedded in epoxy resin and sectioned transversely. Sectioned block faces were subsequently immersed in KOH methoxide for 1.5 hours, to remove resin and expose the handsheet's internal structure.

3.6 Other statistical analyses performed

- **Cluster analysis**

Cluster analysis was used as an exploratory technique. The primary goal of this analysis was to partition the results obtained into groups, based on the similarity between the measured properties. These groups or clusters represent the underlying structure in the data. The results for tear strength, at kappa 30, were analysed using cluster analysis. Those variables that clustered together would exhibit similar patterns of change.

- **Relating the whole tree properties to properties measured at a single sampling point**

As already mentioned, the measurement of various wood properties is essential when carrying out any research on the optimal use of the available resource. The process of obtaining samples from various heights along the length of a tree, determining the properties at each of the those heights and then using these results to predict the whole tree property is time consuming, tedious and involves destruction of the entire tree. Other more efficient screening tools are being sought to predict whole-tree properties. One of the common methods involves sampling only at a single point along the length of the tree in order to predict the whole tree property. Measuring properties at breast height (a length of 1.3 m along the tree from the base) has been found in various studies to achieve this very accurately (Naidu 2003, Evans *et al.,* 1997). Since the wood anatomical properties as well as density were measured at three positions along the length of the tree, one of them being breast height, it was decided to check the strength of the relationship between the properties measured at each of the sampling points and the whole tree estimates (which used the measurements at the three sampling heights in its calculation).

- **Principal component analysis**

This analysis was performed prior to performing multiple regression analysis (discussed below). The aims here were to identify autocorrelations among the measured variables and to identify the variables that contributed most to the variations, and thus to reduce the number of variables to be used in the multiple regression analysis

Principal component analysis was also used to determine whether tree age or site quality was the main contributor to the variation in the measured wood variables. This was obtained by considering the component weights for both these variables in the first factor obtained from this analysis.

- **Multiple regression**

Prior to performing multiple regression, principal component analysis (PCA) was performed to eliminate autocorrelations in the measured variables and to identify pertinent variables to use in multiple regression. Stepwise regression analysis was performed in order to quantify the effect of each variable used in the model developed. The contribution of any variable to the model was determined by calculating the change in the adjusted R^2 value that occurred when that variable was added to the model.

In the multiple regression analysis, those wood and pulp properties that were identified, from the PCA analysis, as being able to capture the variation in data, were used to predict the different strength properties of the resultant pulp. Multiple regression analysis thus identified and quantified the impact of the measured wood and pulp properties on each of the pulp strength properties. The development of these relationships was performed using anatomy and chemistry results separately. Some analyses were performed using both anatomy and chemistry together in the prediction of the strength properties. The development of these empirical relationships aided in identifying the main drivers of variation in each of the measured strength properties. This is useful information since wood and pulp with those properties that were identified to favour the development of the desired end-product strength properties could possibly be used separately in the manufacture of those paper products.

In a situation where information regarding the source of the timber entering the mill (such as tree age, altitude etc.) is available, empirical relationships describing the impact of these sources of variation on the resultant pulp strength properties would be very useful. These relationships would allow for rapid allocation of the various sources of wood to the process where it would yield the desired paper strength attributes. However, in industry, the characteristics of the sites on which wood was obtained is not always available, so the results from the analyses performed here is of very limited use if this trend continues.

In order to understand the impact of processing by refining on the development of the strength of fibres, a comparison of the strength properties achieved at two extremes in refining were compared (1000 and 6500 revolutions). This comparison allowed for the identification of the main driver's of variation in strength at each of these extremes in refining. Multiple regression analyses were also performed on the strength properties of the pulp that were interpolated at constant freeness and at constant sheet density.

CHAPTER 4

Variation of wood properties

4.1 Introduction

Wood quality is an important factor for the pulp and paper industry as it influences end-product properties and the overall economics of pulping. The properties of softwood fibres vary among species, forest stands and geographic location (Paavilainen 1993, Svedman *et al.* 1998). Within individual trees, these fibre properties vary with height, age and distance from the pith (Svedman *et al.* 1998).

Much research has been done and is still ongoing in identifying how the various wood properties influence pulp properties and in optimising the use of various tree species with their different wood characteristics to improve profitability. Identification and quantification of various factors that drive the variation in the properties of wood from trees is very valuable information as it can lead to the prediction of wood properties and thus allow for efficient management of the available fibre resource by pre-allocation of stands to a process that is designed to produce the required paper end-product quality. For this to be achieved, vast numbers of samples need to be screened in order to capture the full extent of variation in the wood properties. Non-destructive sampling techniques are therefore essential if this is to be carried out cost effectively. One of the most common non-destructive techniques for wood property evaluation is the prediction of whole-tree wood properties from properties measured from breast height core sampling. Strong relationships between core values and whole tree measurements of wood density, fibre diameter and percentage of cellulose have been shown in a number of studies (Kube & Raymond 2002, Clarke *et al.* 2002). This technique is cost effective and allows for a large number of samples to be screened in a short period of time.

This chapter discusses the results obtained for the variation in wood chemical and anatomical properties due to site quality, as measured by site index, and tree age. Principal component analysis was performed on the data to determine whether tree age or site index was more responsible for the patterns of change of the measured variables. The prediction of whole-tree wood properties from samples obtained at a single point along the length of the tree is also discussed.

4.2 Wood anatomy

Within trees, fibre properties change with age, height and distance from the pith. Variation is also introduced by the fact that softwood fibres form thin-walled earlywood fibres at the beginning of the growing season and later on, thick-walled latewood fibres. The measured results obtained for the wood density and anatomy were analysed for variation with site quality, tree age and tree height (longitudinally). Radial variation for wood density was also investigated. The average weighted mean percentage of earlywood for each site, that was calculated from the discs from breast height, is also discussed.

4.2.1 Variation of wood density

Fig. 4-1 shows the whole-tree weighted mean unextracted density (WMD) for the six compartments. The tree age and the site quality for each compartment are indicated on the horizontal axis (not scaled). The letters below the standard error bars are the results from the Duncan multiple range test. For the Duncan test, common letters indicate that there were no significant differences at the 95% confidence level.

The extracted wood density followed the same trends as that shown in Fig. 4-1. The results for extracted density are found in Fig. C-2 [Appendix C].

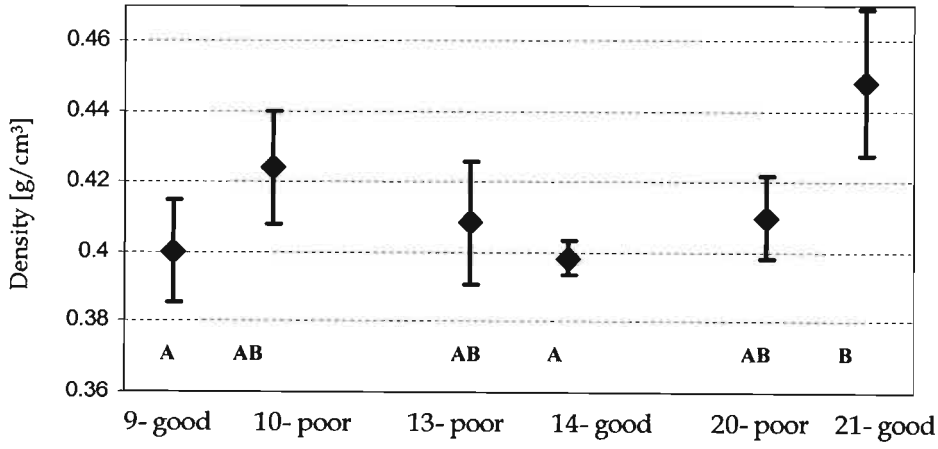


Fig. 4-1. Effects of tree age and site quality on unextracted density.

The WMD ranged from a minimum of 0.398g/cm^3 for the 14 year old site to a maximum of 0.448g/cm^3 for the 21 year old site. There was a 10.7% increase in mean density with tree age (from the 9 year old good site to the 21 year old good site). For the youngest trees (9-10 years), the poor site had the slightly higher density, whereas for the older trees (20-21 years), the good site had the higher mean density. No significant differences in density due to age existed (ANOVA p-value > 0.05). Harvest or rotation age for softwoods is generally around

14 years. Based on these results, differences in density, at rotation age, due to site quality may not be a critical criteria in the utilisation of *P. patula* as pulpwood. Similar findings were noted by Muneri & Balodis (1998) for 14 year old *P. patula* grown in Zimbabwe, Lowin *et al.* (1991) for New Zealand *P. radiata* and by Naidu (2003) for 14 year old *P. patula* grown in South Africa.

Density is dependant on a number of characteristics, such as cell-wall thickness, cell size and the ratio of earlywood to latewood (Malan 1991). The results obtained from the breast height discs for amount and density of earlywood and latewood for the various sites, and the effects of these variables on the observed whole tree density WTD, are discussed below.

Table 4-1. Percentage earlywood and density of earlywood and latewood (Good sites are highlighted)

Compartment	% Earlywood	Earlywood density	Latewood density
9 – good	81.683	0.366	0.723
10 – poor	78.059	0.362	0.669
13 – poor	78.124	0.348	0.609
14 – good	76.999	0.369	0.663
20 – poor	79.770	0.364	0.705
21 – good	75.595	0.396	0.764

Wood is made up of earlywood and latewood, forming the annual ring in a cross section of stem of the tree. Since the cell walls of latewood cells are thicker than that of earlywood cells, the density of latewood is greater than that of earlywood (Muneri & Balodis 1998). Table 4-1 indicates that the results in this study agree with this. Table 4-1 also shows that for all age groups, the good sites had higher earlywood and latewood densities than the poor sites, which may imply that these sites would have a higher whole tree density than the poor sites. However this is only the case in the 20-21 year old compartments.

The results in Table 4-1 also show the percentage earlywood for the good sites decreased with increasing tree age. The percentage of earlywood for the poor sites increased with tree age. It was also noted that for the younger trees, the good sites had a markedly larger percentage of earlywood than the poor sites, whereas the opposite held true for the oldest trees (i.e. the 20-21 year old range). Therefore, even though the earlywood and latewood densities for the good sites are higher than the poor sites, for the 9-10 year old sites the markedly higher percentage of earlywood in the good site than the poor site could account for it having lower density than the poor site. Also, the decrease in the proportion of earlywood with tree age for the good

sites, accompanied by the increase in earlywood with age for the poor sites could then account for the whole tree density for the good site being higher than the poor site for the oldest trees (i.e. the 20-21 year age range).

High density wood, like that of the 21 year old site, has been found to produce bulkier sheets that drain easily (Ivkovich 2000). The fibres with low whole tree density (WTD) and accompanied by a higher percentage of earlywood (i.e. the 9 year old site) are expected to collapse easily and produce strong interfibre bonds, which in turn is expected to result in paper with strong burst and tensile strength (Muneri 1994, Ivkovich 2000). However, the collapsibility of fibres is not only dependant on wood density, or the amount of earlywood and latewood, but is also dependant on distribution of the various combinations of fibre wall thickness and diameter that make up the tree. The results obtained for collapsibility of the fibres are discussed in section 4.2.5.

Fig. 4-2 shows the variation of weighted mean disc density with increasing height of the tree. The values on the x-axis indicate the percentage height up the tree, with BH representing breast height (1.3m).

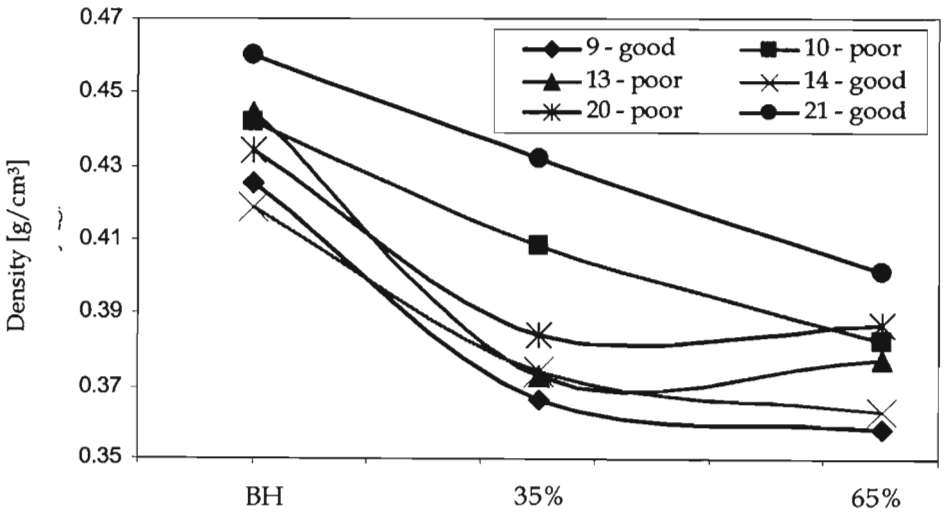


Fig. 4-2. Variation of unextracted density along the length of the tree.

Weighted mean density decreased with increasing tree height. This is in agreement with results from previous studies (Robertson 1991, Muneri & Balodis 1998, Malan 2000, Naidu 2003). Clarke (2002) states that for all pines the density at breast height has been found to be the highest compared to the density at other heights along the tree. Malan & Retief (1996) suggest that the decrease in weighted mean density with increasing height can be attributed to

the increase in the proportion of juvenile wood along the length of the tree. Since juvenile wood is present only in the center of the tree, a higher proportion of juvenile wood is in fact found near the top of the tree, since trees taper towards the top. Thus the higher density at breast height could in fact be attributed to the higher proportion of thicker walled mature fibres at the base of the tree and the lowering density with tree height could be due to the higher proportion of lower density of thin walled juvenile wood near the tree top.

The Duncan test results for homogeneity and the P-values determined at each tree height are shown in Table 4-2. This table shows differences in density among the six sites, at each of the tree heights at which wood physical property analysis was performed (i.e. the table should be read horizontally). The results shown should not be interpreted for differences within a particular site. The above premise will apply for all Duncan test results displayed in this chapter.

Table 4-2: Duncan test results for differences in density, among sites, at each height

		Tree Age					
	P-value	**9**	**10**	**13**	**14**	**20**	**21**
35%	0.0373	A	AB	A	A	A	B
65%	0.0881	A	ABC	ABC	AB	BC	C
BH	0.6827	A	A	A	A	A	A

From Table 4-2 it can be seen that no significant differences in density due to age occurred among the six sites at both breast height and 65% of the total tree height (P-value > 0.05). Significant differences occurred due to age at 35% of the total tree height (P-value < 0.05). Marked differences due to site quality that occurred among the compartments at 65% of the total tree height were also observed in a study by Naidu (2003) on 14 year old *P. patula* grown in South Africa.

Fig. 4-3 shows the radial variation of density at breast height (variation with increasing growth rings).

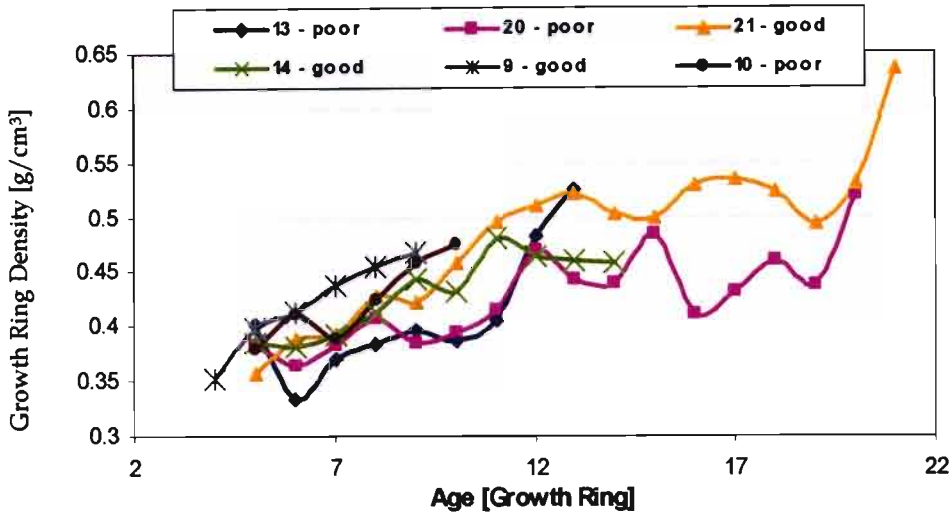


Fig. 4-3. Pith to bark variation of tree density.

The general increase in weighted mean density with distance from the pith has been observed by other authors (Muneri & Balodis 1998, Leggate *et al.* 1998). Two of the poor sites (13 and 20 year old sites) showed an initial decrease in growth ring density, which was then followed by an increase towards the bark. Adlard *et al.* (1979) reported similar patterns on *P. patula* grown in Malawi. Naidu (2003) also observed such tends on *P. patula* grown in South Africa, and states that this initial high density could be due the build up of extractives near the pith. It is also noted that the rate of change of density from pith to bark was greater near the bark than near the pith. This is seen clearly in the 13, 20 and 21 year old sites.

4.2.2 Variation of fibre diameter

Fig. 4-4 shows the variation of weighted mean whole-tree fibre diameter (WMFD) among the six compartments. The Duncan test results are shown above the standard error bars.

There existed a general increase in WMFD with tree age. The 13 year old poor site had the lowest WMFD of 35μm. The 20 year old poor site had the highest WMFD of 38μm. The greatest change in WMFD with tree age occurred during the transition from 10 to 14 years, with the change in WMFD with tree age, prior to and after this transition period being negligible.

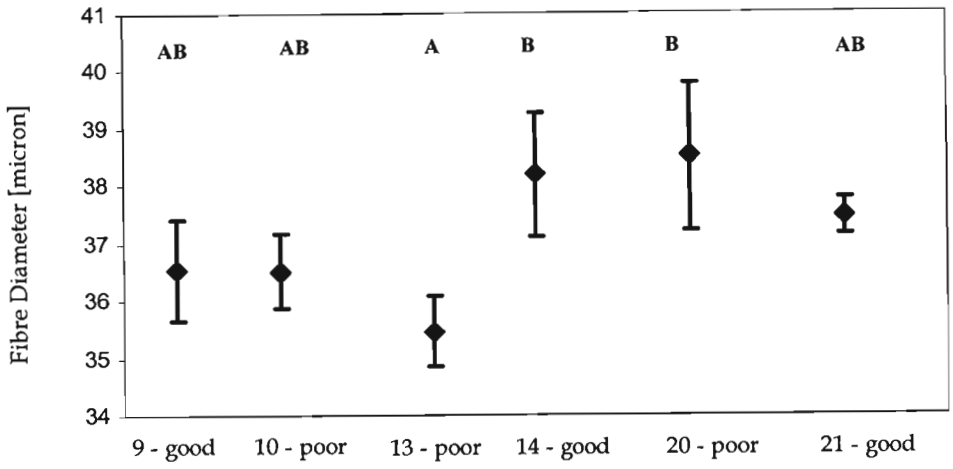


Fig. 4-4. Effects of tree age and site quality on fibre diameter.

Fig. 4-5 shows the change in fibre diameter with increasing tree height.

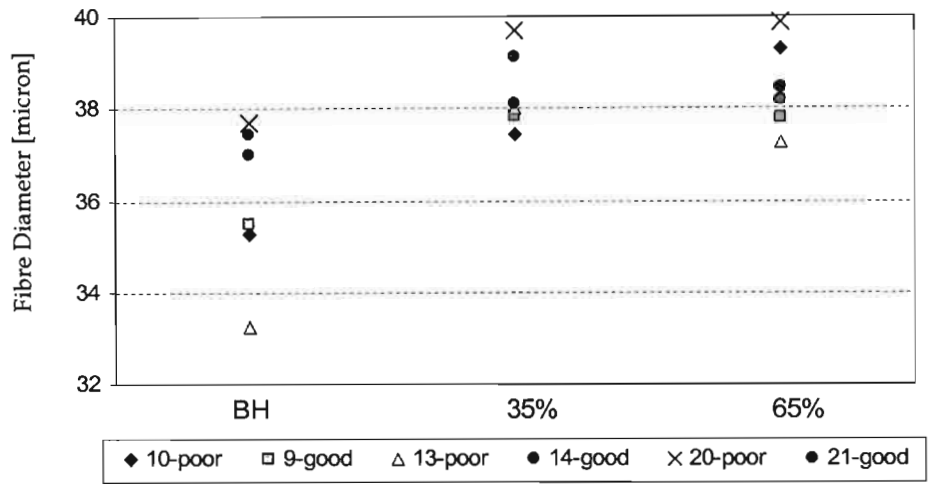


Fig. 4-5. Fibre diameter variation along the length of the tree.

Fibre diameter increased very slightly with increasing tree height. The low fibre diameter obtained at breast height for all compartments could be the result of the larger proportion of latewood cells that occur at the lower parts of the tree. Latewood cells generally have smaller diameters than earlywood cells. It must be noted that as the distance from pith to bark increases, that is, as the tree matures, the diameter of the earlywood and latewood cells increase. This implies that the cell wall thickness of the latewood fibres near the bark would be thicker than that of the latewood fibres near the pith. The same holds true for the

earlywood cells. [Cell wall thickness is discussed in section 4.2.3.] Therefore, when comparing the results at breast height, it is evident that since the 20 year old site had a very large weighted average percentage of earlywood (higher than all but the 9 year old site-section 4.2.1), it had the largest fibre diameter, due to the presence of a larger proportion of larger diameter earlywood fibres that would occur near the bark. The 9 year old site on the other hand had the largest percentage of earlywood, but had a smaller fibre diameter than the three oldest sites. This is due to the greater proportion of smaller diameter earlywood fibres being present in young material.

The Duncan test results for intersite differences at each tree height, and the overall P-values, at each height, are shown in Table 4-3.

Table 4-3: Duncan test results for differences in fibre diameter, among sites, at each height.

		Duncan Test					
	P-value	**9**	**10**	**13**	**14**	**20**	**21**
35%	> 0.05	A	A	A	A	A	A
65%	> 0.05	A	A	A	A	A	A
BH	0.0351	AB	AB	A	B	B	B

There existed statistically significant difference in fibre diameter among the six compartments due to tree age only at breast height. At this height it can be seen that the sites from the youngest and oldest age ranges exhibited no significant differences due to site quality. The significant difference in fibre diameter at breast height in the 13-14 year old age range was possibly due to the differences in site quality. This was also observed by Naidu (2003) for 14 year old *P. patula* grown in South Africa.

4.2.3 Variation of cell wall thickness

Fig. 4-6 shows the variation of weighted mean whole tree cell wall thickness (WMCWT) among the six compartments. The Duncan test results are shown below the horizontal axis.

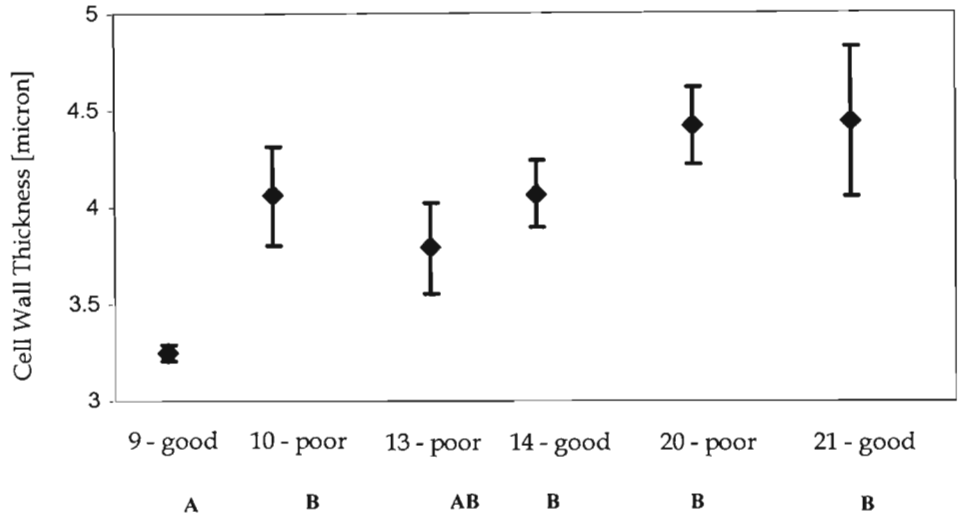


Fig. 4-6. Effects of tree age and site quality on cell wall thickness.

When considering cell wall thickness, the sites are significantly different from each other (ANOVA, P-value = 0.012). The general trend is that WMCWT increased with tree age. This would be expected, since the cell wall thickness of the fibres increase from pith to bark (i.e. with increasing age). This trend, of increasing cell wall thickness with age, was also observed by Turner *et al.* (2000). Differences in WMCWT due to site quality were more pronounced in the younger sites, with these differences becoming negligible in the older sites. For the 13-14 year old age range, the good site had a greater WMCWT than the poor site. This agrees with the results obtained in a study by Naidu (2003) on 14 year old *P. patula* where the good sites were also found to have higher WMCWT than poor sites. For the oldest trees (i.e. the 20 and 21 year old sites), the difference in site quality had no significant impact on WMCWT. This lack of significant differences of site quality on WMCWT, for these older trees, is in agreement with results obtained in a study Turner *et al.* (2000) on 25 to 30-year-old *P. patula*.

Schweingruber (1988) stated that greater thickening of fibre cell walls occur under good growth conditions. Nyakwengama *et al.* (1999) stated that the effect of the environment on cell-wall thickness could possibly be due to micro-site differences in soil nutrients and moisture.

Fibre cell wall thickness can be used as a measure of fibre quality and correlates well with pulp fibre strength properties (Xu *et al.* 1997). It also affects the penetration of cooking chemicals into the fibre walls (Kauppinen 1997). Therefore, the sites with thicker cell walls are expected to have higher pulp yields, due to thick cell walls containing a large volume of cellulose and also because thick cell walls would inhibit the diffusion of cooking chemicals into the fibre.

Fig. 4-7 shows the variation of weighted mean disc cell wall thickness with tree height.

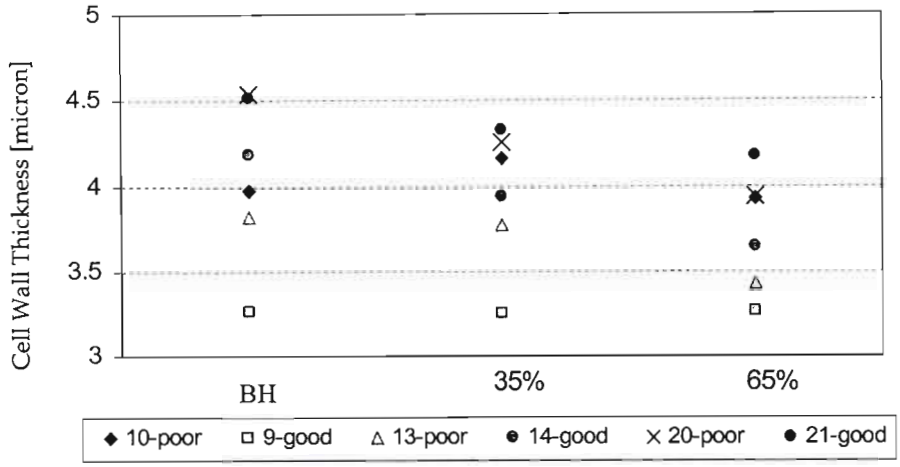


Fig. 4-7. Variation of cell wall thickness along the length of the tree.

There was a general decrease in the cell wall thickness with increasing tree height. This is accordance with results obtained by Naidu (2003) for 14 year old *P. patula*. Chikamai (1987) who also observed this in a study on 18 year old *P. patula* stated that this trend is evident since the proportion of latewood cells (i.e. thick cell-walled cells) decreases towards the top of the tree due to the tops of trees having a larger proportion of juvenile wood present. The 9 year old site did not show any marked change in cell wall thickness along the length of the tree. This site being very young would have the juvenile core of the tree making up most of its volume, even at the lower tree heights. Thus a significant proportion of thick walled mature fibres would probably not be present at breast height in order to yield a higher mean cell wall thickness at this height. Also, the 10 year old having a higher mean cell wall than the 13 and 9 year old sites is indicative of the interplay of the percentage of earlywood, cell size (as indicated by fibre diameter) and cell wall thickness of the cells from this site. It is obvious that in order to explain the results here, the radial profile of anatomical properties of the earlywood and latewood at each site needs to be investigated in more detail.

The Duncan test results for intersite differences at each tree height, and the overall P-values, at each height, are shown in Table 4-4.

Table 4-4: Duncan test results for differences in cell wall thickness, among sites, at each height

		Duncan Test					
	P-value	9	10	13	14	20	21
35%	> 0.05	A	B	AB	AB	B	B
65%	> 0.05	A	AB	AB	AB	AB	B
BH	0.039	A	AB	AB	B	B	B

Significant overall differences in CWT (P-value < 0.05) among the compartments occurred only at breast height. At breast height, differences in CWT due to site quality occur markedly in the younger sites, with no significant differences due to site quality occurring in the oldest sites.

4.2.4 Variation of lumen diameter

Fig. 4-8 shows the variation of weighted mean whole tree lumen diameter among the six compartments.

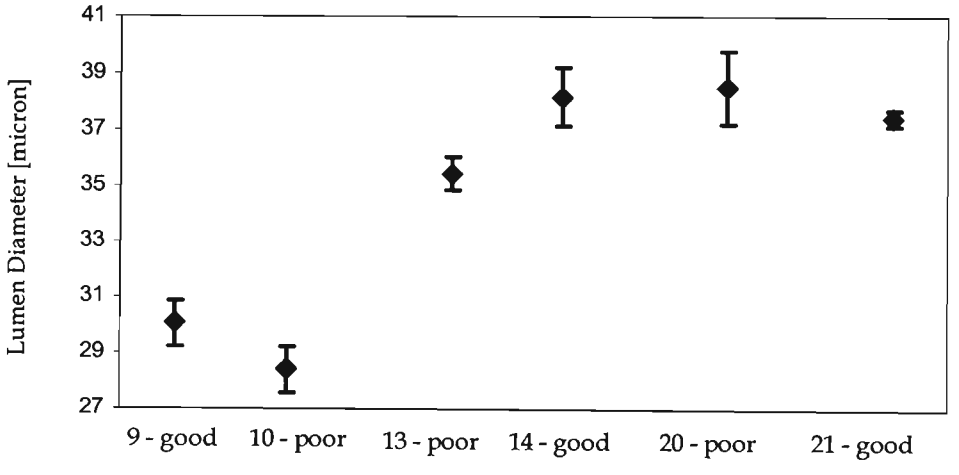


Fig. 4-8. Effects of tree age and site quality on lumen diameter.

There was a general increase in lumen diameter with age. The greatest change in lumen diameter occurred during the transition from 9-10 years to 13-14 years old. A smaller increase in lumen diameter occurred from 13 to 14 years. For the oldest trees, no significant difference in lumen diameter took place from 14 to 21 years. Naidu (2003) also observed no significant differences between sites for lumen diameter in a study on 14 year old *P. patula*.

4.2.5 Variation of collapsibility

Fig. 4-9 shows the variation of the weighted mean whole-tree fibre collapsibility among the six compartments.

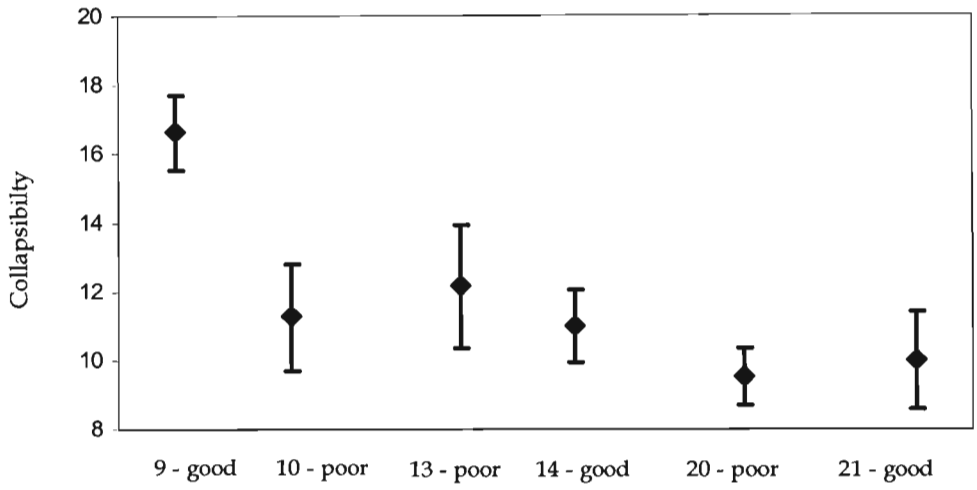


Fig. 4-9. Effects of tree age and site quality on collapsibility.

When considering collapsibility, the sites were significantly different from each other (ANOVA, P-value = 0.012). From Fig. 4-9, it can be seen that the general trend is that collapsibility decreased with tree age. This was expected since with increasing tree age, the significantly thicker cell walls accompanied by a smaller rate of increase in fibre diameter would be expected to result in less collapsible fibres. This decrease in collapsibility with age is in accordance with results obtained by Turner *et al.* (2000) for *P. patula* grown in South Africa. The decrease of fibre collapsibility with increase in site quality in the 13-14 year old age range was also observed by Naidu (2003) in a study on 14 year old *P. patula*. The impact of collapsibility on the properties of the pulp produced has been described in various studies. Therefore the observed differences in collapsibility could be useful since the wood resource from this species may be separated and processed appropriately to provide specified pulp quality for different paper grades.

4.2.6 Prediction of whole-tree properties from properties at each tree height

Table 4-5 shows the correlation coefficients obtained between whole-tree measured wood properties and those properties measured at the sampling points along the length of the tree. The properties obtained at 65% of the tree height did not correlate well with the whole tree estimates, and therefore have been omitted from the correlation table. Since the collapsibility of the fibres was not measured but calculated from the measured variables, this property was also not included in the correlation table, as the results obtained there would be subject to autocorrelations.

Table 4-5. r-values showing correlations between whole-tree (WT) properties and properties at a single sampling point (i.e. 35% and 65% of tree height).

	Density-WT	CWT-WT	FD-WT
BH property	0.94	0.93	0.93
35% property	0.90	0.85	0.83

It can be seen that breast height values correlated well with whole tree properties. The values obtained at 35% of the total tree height also correlated fairly well with the whole-tree properties. In a study on radiata pine, Evans *et al.* (1997) obtained good correspondence between breast height properties and whole tree estimates for cell wall thickness. As mentioned previously, these relationships are important in the development of rapid screening tools. The graphs showing the prediction of whole tree values from the breast height results, together with the R^2 values for these relations are found in Fig. C-1 [Appendix C].

4.3 Wood chemistry

The results obtained for the six compartments for the various wood chemical components were analysed for differences due to age and site quality.

4.3.1 Variation of cellulose in wood

Fig. 4-10 shows the variation of the percentage of cellulose in wood for the six compartments. It must be noted that the horizontal axis is not drawn to scale.

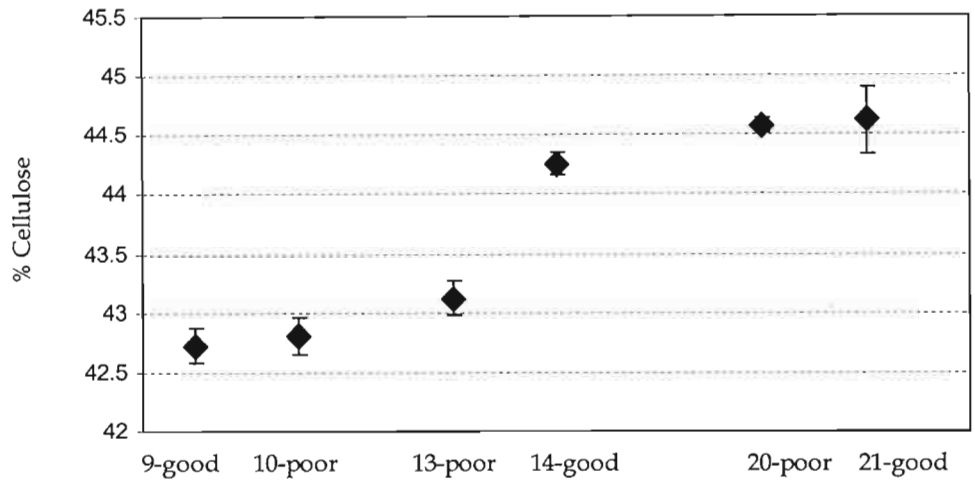


Fig. 4-10. Effects of tree age and site quality on the amount of cellulose in wood.

There existed a significant increase in the percentage of cellulose with tree age (P-value > 0.05). The most significant differences in the amount of cellulose occurred in the intermediate tree age range (13-14 years) with the good site having more cellulose than the poor site. Muneri (1994) stated that increased wood cellulose content is positively correlated with pulp yield. Kube & Raymond (2002) found cellulose content to be correlated to the extractives content and positively correlated to pulp yield. In the same study, it was stated that cellulose content appears to be the most reliable indicator of pulp yield for plantation eucalypts.

4.3.2 Variation in Klason lignin in wood

Fig. 4-11 shows the variation in Klason lignin in wood. All circle markers refer to the good sites and the diamond markers to the poor sites. The results from the Duncan test are shown below the standard error bars.

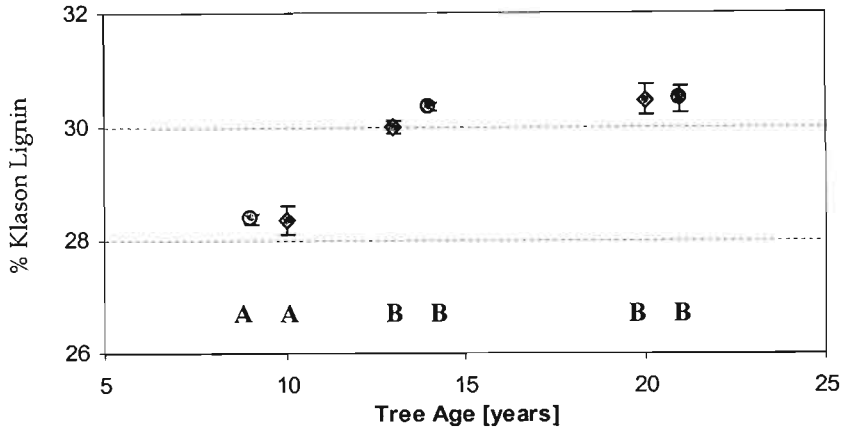


Fig. 4-11. Effects of tree age and site quality on Klason lignin in wood.

No significant differences due to site quality occurred in any of the age ranges, as indicated by the Duncan test. There existed a general trend of an increase in the proportion of klason lignin with tree age. The youngest material having significantly lower amounts of klason lignin than the older material could be due to a major proportion of these trees being made up of the juvenile core. The core contains a significant amount of extractives and resinous material. The results for the extractives content is discussed in section 4.3.5. Due to this, the relative proportion of lignin that makes up the wood would be expected to be lower. However, as tree age increases, the juvenile core contributes less to the total volume of the tree. Lignin is not only the binding material between the fibres, but is also found in the fibre walls. As mentioned in Chapter 4, the size of the fibres increases radially (i.e with increasing tree age). Since the major proportion of older material would be made up of larger earlywood and latewood fibres, compared to the younger material which are made up of smaller fibres with thinner walls, higher amounts of lignin would be expected in the older material.

4.3.3 Variation of glucose in wood

Fig. 4-12 shows the variation of glucose in wood. All circle markers refer to the good sites and the diamond markers to the poor sites. The results from the Duncan test is shown below the standard error bars.

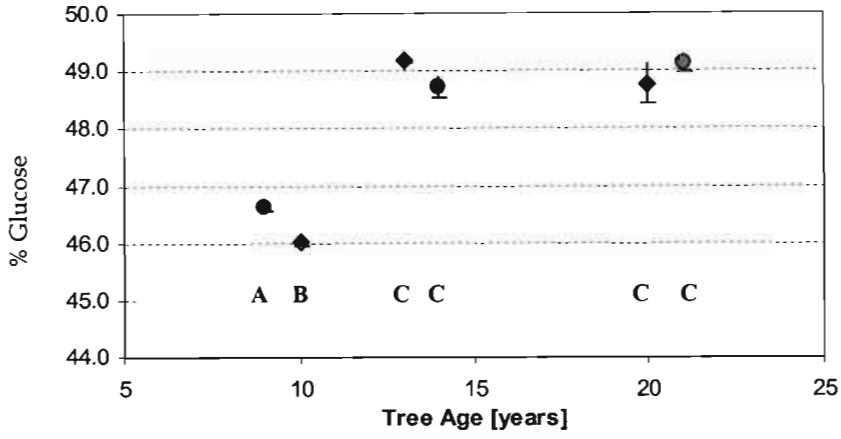


Fig. 4-12. Effects of tree age and site quality on the amount of glucose in wood.

There existed a general increase in the amount of glucose with tree age from the youngest sites to the 14 year old material. Thereafter, the percentage of glucose seemed to level off at around 49% from the intermediate to the oldest tree age range. The r-value between glucose and cellulose was found to be 0.73. Glucose is the monomer of cellulose polysaccharide chains, thus the correlation between these two variables is expected. Also, the increase in glucose with tree age would be expected since from fig. 4-10, it was observed that the amount of cellulose increased with tree age. The very high amount of glucose in the 13 year old site would not be expected since this site had a significantly lower proportion of cellulose compared to the 14 year old site. It must be noted here that these measured values show the relative percentage of glucose present at each site. Thus the high percentage of glucose in the 13 year old site could account for it having a relatively lower percentage of other wood chemical components.

4.3.4 Variation of hemicelluloses in wood

Figs. 4-13 to 4-16 shows the variation of hemicelluloses in wood. All circle markers refer to the good sites and the diamond markers to the poor sites. The results from the Duncan test are also shown on the graphs.

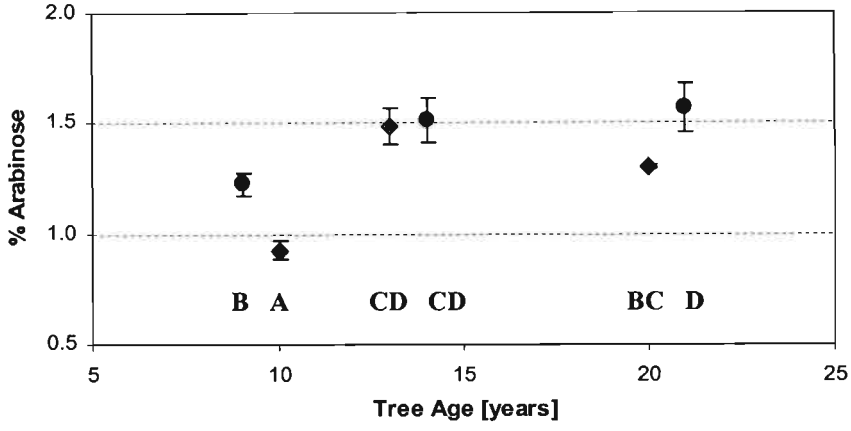


Fig. 4-13. The effects of tree age and site quality on the amount of arabinose in wood.

There existed statistically significant differences in the percentage of arabinose with tree age (ANOVA P-value < 0.05). The youngest trees had a markedly lower percentage of arabinose than the oldest sites. For all tree ages, the good sites had higher average arabinose content than the poor sites, with these differences due to site quality being significant for the youngest and oldest age ranges. No significant difference in the percentage of arabinose was evident in the intermediate age range.

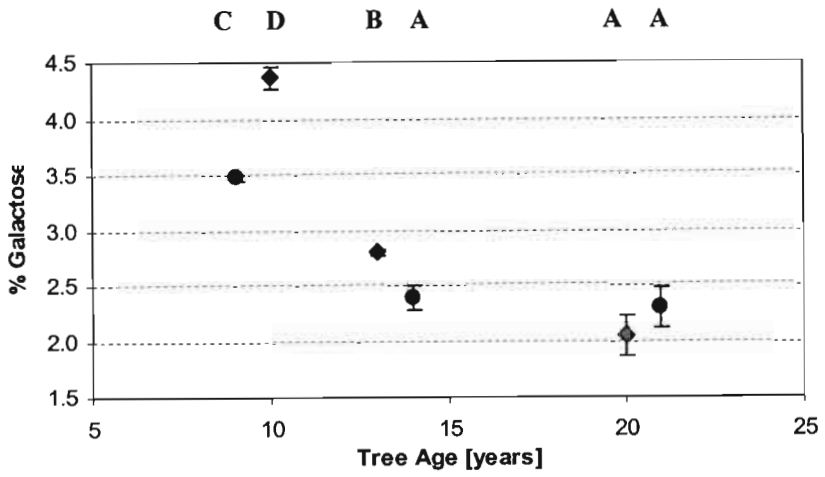


Fig. 4-14. The effects of tree age and site quality on the amount of galactose in wood.

There existed a general trend of decrease in the amount of galactose with increasing tree age. The difference in the percentage of galactose due to site quality was significantly greater for the younger trees than for the oldest material.

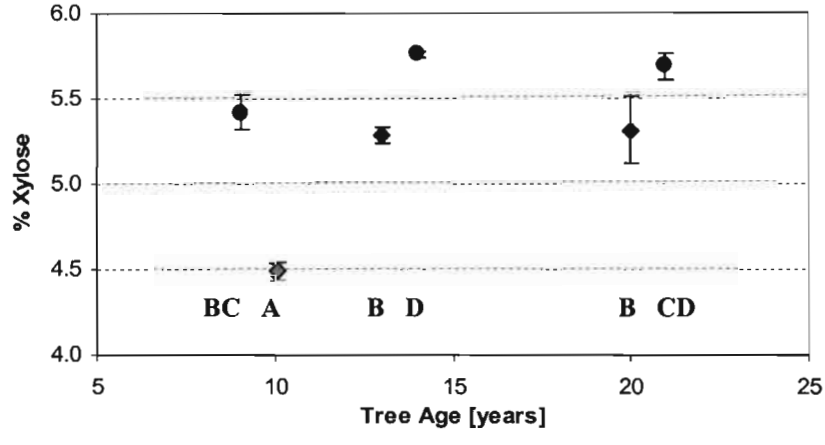


Fig. 4-15. The effects of tree age and site quality on the amount of xylose in wood.

Significant differences in the percentage of xylose occured with tree age (ANOVA P-value < 0.05). It was seen that in each tree age range, the good sites had significantly higher amounts of xylose than the poor sites. The results obtained were in agreement with the xylose content of softwoods usually being approximately less than 10% (Britt 1970).

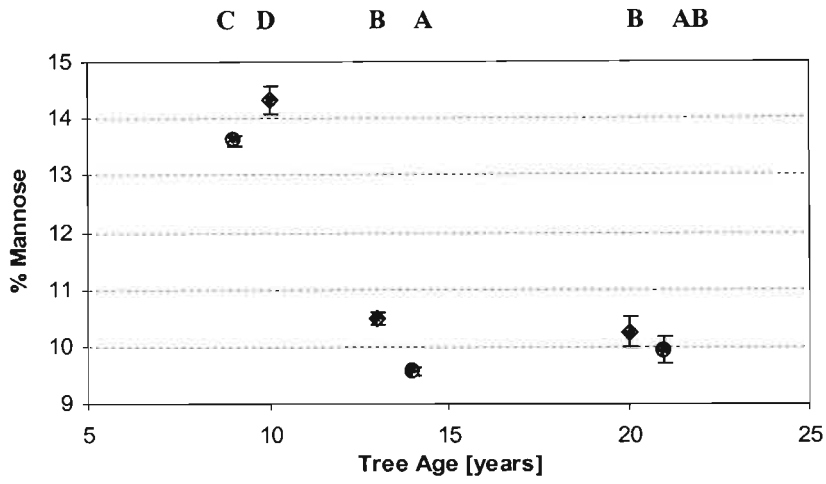


Fig. 4-16. The effects of tree age and site quality on the amount of mannose in wood.

Significant differences in the mannose content due to tree age existed (ANOVA P-value < 0.05). Softwoods generally contain more mannose than xylose (Britt 1970), with the mannose content usually lying in the range of 10-15% (Britt 1970). The results in this study agreed with these findings. A lower percentage of mannose was found in the older trees (13-21 years). The good sites had lower amounts of mannose than the poor sites. The most marked differences due to site quality occurred in the younger trees, with the impact of site being less apparent in the oldest trees.

4.3.5 Variation of extractives in wood

Fig. 4-17 shows the variation in toluene-ethanol extractives in wood.

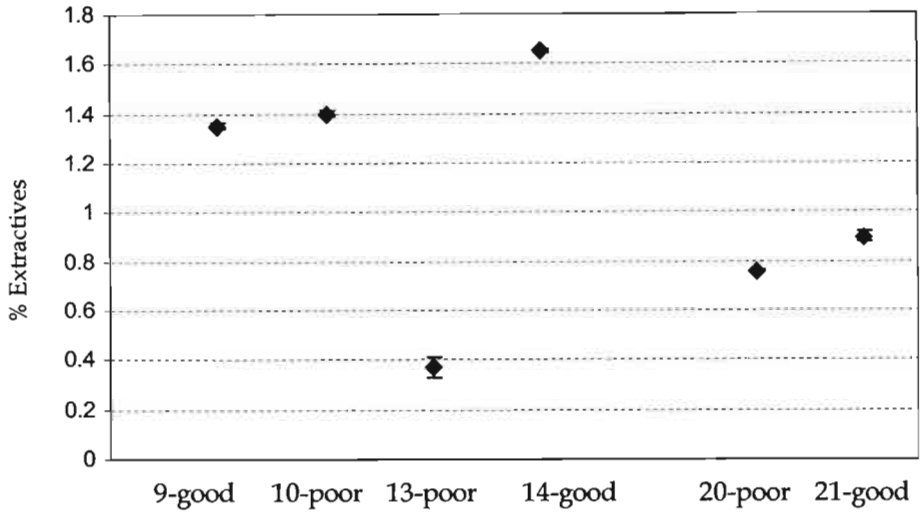


Fig. 4-17. The effects of tree age and site quality on the amount of toluene-ethanol extractives in wood.

When considering extractives, all sites were significantly different from each other. No trend existed between the amount of extractives and increases in tree age. For each age significant differences existed between the good and poor sites, with the good sites having more extractives than the poor sites. For the older trees, the differences in the amount of extractives due to site were more significant than the 9-10-year-old trees.

4.4 Principal component analysis (PCA)

The results obtained from the principal component analysis indicated that there were clear differences in the wood properties due to tree age, with site quality contributing less to the observed variation. This has important implications for mills, where variability in raw materials is a major cause of non-uniformity of the end-product. It is clearly evident that segregation of raw materials by their age would assist in solving this problem.

4.5 Conclusions

- The results from this study indicated that tree age was a major determinant of wood properties and had more critical effects than site index.
- The results obtained indicated that the wood properties measured varied significantly longitudinally and with tree age. The trends observed for wood lumen diameter, cell wall thickness and fibre diameter all indicated a general increase with tree age, and those of collapsibility showed a decrease with an increase in tree age.
- Wood density decreased markedly with increasing height position. The radial density profiles indicate that density increased from pith to bark. No trends with the percentage of earlywood and age were evident.
- Fibre diameter increased markedly from BH to the 35% height, and remained essentially unchanged between the 35% and 65% height.
- The relationships between properties measured at a fixed point (approximately breast height) and the whole tree property were good for wood density, fibre diameter and cell wall thickness, thus giving confidence to this well established non-destructive sampling technique.
- The percentage of cellulose, klason lignin and glucose increased with increasing tree age, with the greatest change in the amount of cellulose having occurred at the transition from 13 to 14 years. Differences in site quality had a small effect on these chemical components.
- There was a general decrease in the mannose content in wood with increasing age, with the good sites having lower amounts of this monosaccharide.
- The good sites had higher amounts of arabinose and xylose than the poor sites.
- No trend existed between tree age and extractives content. However, significant differences possibly due to site quality in each age range existed, with the good sites having a higher extractive content than the poor sites in the older material.

CHAPTER 5

Pulping & pulp properties

5.1 Introduction

Pulp is the fibrous mass left behind after wood fibres have been liberated during pulping. Chemical pulping involves the liberation of fibres by the use of chemicals which remove the cementing substance, lignin, from between the fibres.

The properties of pulp play a large role in determining the properties of the end product. Pulp properties also place limitations on the maximum strength potential of the paper manufactured. The properties of wood can, to a large degree, predict the properties of the pulp produced. Pulp yield is an important variable that mills attempt to maximise, however not at the expense of poor pulp quality. Relationships between wood and pulp can be useful since in determining the yield of pulp obtained from various wood sources, the traditional method of cooking wood chips in a digester is not only slow and expensive (Kube & Raymond 2002), but the large amount of chips that is required in such investigations requires that the trees that are felled and chipped, hence they are not available for future work. It is because of these reasons that many attempts have been made in finding more cost effective and faster methods of predicting pulp yield. Chemical components of wood have been shown, in a number of studies, to correlate strongly with pulp yield (Kube & Raymond 2002). Some of these chemical components include extractives, lignin and cellulose content (Kube & Raymond 2002).

This chapter presents the results for the pulping properties (i.e. pulp yield and active alkali consumption) and the chemical and physical properties of the pulp at each of the cooking times. Also, this chapter attempts to identify any relationships between wood and pulp properties. Correlation coefficients, between wood and pulp properties, were examined for any relationships between wood and pulp properties.

5.2 Pulping properties

The results obtained have been represented graphically and the mean value of the properties and standard error bars have also been displayed. Differences in the measured properties with cooking time, both within and among compartments, were analysed. Results at a kappa number closest to 30 have also been analysed for variation of pulp yield and active alkali consumption. Since the cooks that were stopped once the ramp up time was reached (0 minute cooks) did not produce any pulp but resulted in partially cooked chips, these samples could not be analysed for chemical, physical or strength properties.

5.2.1 Variation of pulp yield

Fig. 5-1 shows the variation of total pulp yield (TPY) with cooking time for each of the six compartments.

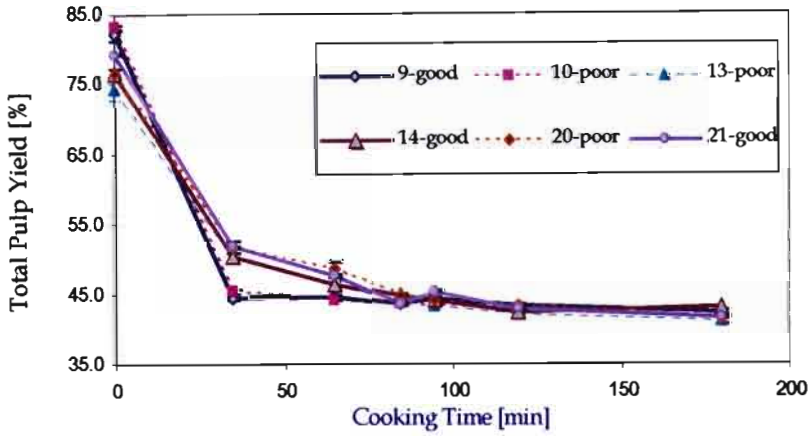


Fig. 5-1. Effect of cooking time on pulp yield.

TPY decreased as cooking time increased. This is expected since significant amounts of lignin are removed and to a lesser degree, the carbohydrates are degraded, as the cook proceeds. There were differences among sites. This was especially true during the early stages of the cooks. However, these differences become less significant after cooking for about 85 minutes.

Table 5-1 shows the Duncan test results and the P-values, at the 95% confidence level, for each cooking time. The results shown here are comparisons made among the six compartments, for differences in pulp yield obtained at each cooking time (i.e. the table

should be read horizontally). All other tabulated Duncan test results in this section follow the same format.

Table 5-1. Duncan test results and P-values for differences in pulp yield among the compartments, for each cooking time.

Cooking time (min)	9	10	13	14	20	21	P-value
35	A	A	B	BC	CD	D	<0.0001
65	A	A	B	BC	D	CD	0.0001
85	A	A	AB	B	B	A	0.0167
95	B	A	A	B	B	C	0.0001
120	D	B	A	AB	CD	BC	0.0007
180	BC	BC	A	C	AB	AB	0.0107

It is evident that significant differences (P-value < 0.05) in pulp yield, due to tree age, occurred among the compartments for all cooking times.

Fig. 5-2 shows the TPY obtained at kappa 20-30 for the various compartments.

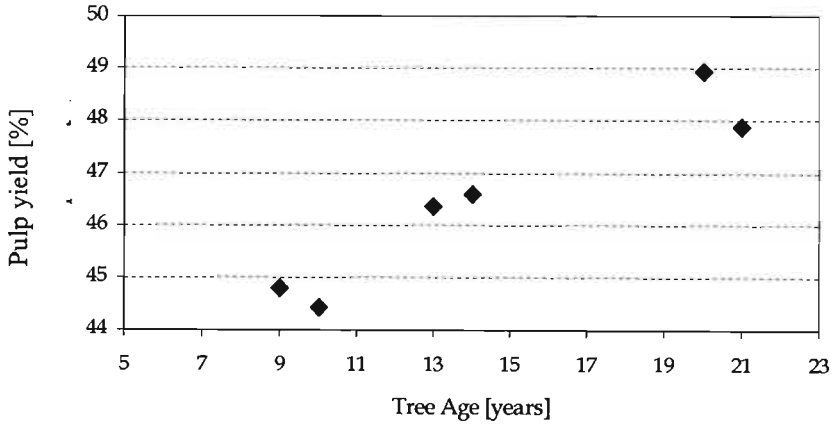


Fig. 5-2. Effect of tree age on pulp yield at kappa 20-30.

The general trend was an increase in pulp yield with tree age. This agreed with findings by Svedman *et al.* (1998). The density of the fibres increased from pith to bark (see section 4.2.1) and it is known that the cell wall thickness of fibres also increases with age. This would imply that older material would contain a relatively larger portion of fibres with thicker and denser cell walls, which would be expected to hinder the penetration of cooking chemicals into the fibre Kauppinen (1997). This would result in less degradation of the various chemical components, thus the higher pulp yield in the older material.

Another possible reason for the higher pulp yield in older material could be due to older material having thicker cell walls and higher amounts of cellulose than the younger material (as seen in Chapter 4). Cellulose is very resistant to degradation, thus large amounts of this component present in older material would result in higher pulp yield.

The polymer mannan is highly susceptible to degradation during pulping. Therefore, high wood mannan content would be expected to give a lower pulp yield and agrees with the findings in this study, as indicated by the negative r-values between wood mannose and yield ($r = -0.77$ at kappa 20-30 i.e. the 65 minute cooks). From section 4.3.4, it was seen that mannose, the monosaccharide that makes up the mannan polymer, content of wood decreased with increasing tree age. Thus, due to only small amounts of easily degradable mannan are present in older trees, this could partly contribute to the higher pulp yield in these older sites.

Clarke *et al.* (2002) also observed an increase in pulp yield with increases in tree age for *P. patula*. The pulp yield from juvenile wood being much lower than that from mature wood was observed by Hatton (1997), Malan (1997) and for *P. patula* by Morris *et al.* (1993). Since younger trees have significant amounts of juvenile wood (Goyal *et al.* 1999), the results from the aforementioned studies agree with results from this study. For the two younger age ranges, the good quality sites had higher pulp yields than the poorer sites. Similar trends due to site quality were obtained by Naidu (2003) for 14-year old *P. patula* grown in South Africa and by Turner *et al.* (2000) for *E. Grandis* TAG5.

Various authors have observed wood cellulose content to be positively correlated to pulp yield (Muneri 1994, Kube & Raymond 2002). The results in this study agreed with these findings, since multiple regression analysis resulted in wood cellulose solely accounting for 72% and 70% of the variation in the pulp yield at the 35 minute and 65 minute cooks, respectively. However, no strong relationships between cellulose and pulp yield were found at the longer cooking times. With multiple regression, Kube & Raymond (2002) could explain 78% of the variation in pulp yield, after correction to kappa 18, using wood cellulose.

From Table 5-1, it was noted that at kappa 30 (i.e. the 65 minute cooks), apart from the differences in pulp yield that occur due to tree age, no significant differences due to site quality occurred in the youngest material, with relatively small differences evident in the other two age ranges.

5.2.2 Variation of active alkali consumption

Fig. 5-3 shows the active alkali (AA) consumption for each of the six compartments at each cooking time.

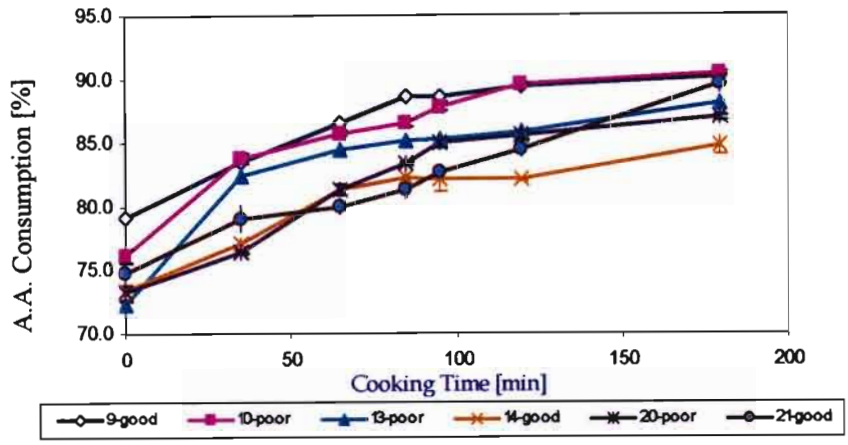


Fig. 5-3. Effect of cooking time on active alkali consumption.

The AA consumed increased as the cook proceeds. This is expected since cooking liquor is used in the various reactions with the wood components. In a study on two 11 to 25 year old pine species, one of them being *P. patula*, Morris *et al.* (1993) obtained an AA consumption of 69-76% when chips were pulped to kappa 35-40. The 13-21 year old material in this study lay in the age range of the above study, and achieved a kappa in that range between the 35 and 65 minute cooks (see section 5.3.1). The 13 year old material in this study consumed a considerably higher amount of AA (~83%) whereas the 14-21 year old material achieved that kappa with only a slightly higher AA consumption (76%-79%) compared to the aforementioned study. It must be noted that the AA of the cooking liquor used in that study was lower than that used in this study (17½ % AA compared to 22% used in this study). The higher initial %AA used in this study would create steeper concentration gradients between the chips and the cooking chemicals during pulping. This would be expected to increase the rate of reaction of the various wood components (hemicelluloses and extractives), accompanied by an increased use of alkali. Therefore, when comparing the amount of AA consumed at the similar residual pulp lignin content (as indicated by kappa), the initial concentration of alkali used must be considered. A higher initial alkali content would allow for a more rapid degradation of other chemical components accompanying the removal of lignin, thus a higher amount of chemical consumption at any residual lignin content.

It was observed that the youngest age compartments had the highest AA consumption. For the other four compartments, the poorer sites consumed higher amounts of AA than the good sites. This inverse relationship between site index and AA consumption was also observed by Turner *et al.* (2000).

Table 5-2 shows the Duncan test results and P-values (at the 95% confidence level) for differences in AA consumption among the compartments, at each cooking time.

Table 5-2: Duncan test results and P-values for differences in active alkali consumption among the compartments, for each cooking time.

cooking time (min)	9	10	13	14	20	21	P-value
35	A	A	A	C	C	B	<0.0001
65	D	D	C	B	B	A	<0.0001
85	E	D	C	AB	B	A	<0.0001
95	D	D	B	A	B	A	<0.0001
120	D	D	C	A	C	B	<0.0001
180	C	C	B	A	B	C	<0.0001

Significant differences (P-value < 0.05) in the amount of alkali consumed occurred among the compartments at each of the cooking times.

Fig. 5-4 shows the AA consumption at kappa 30 for the six compartments.

Fig. 5-4. Effect of tree age on active alkali consumption at kappa 20-30.

The AA consumed to reach kappa 20-30 decreased with increasing tree age. Apart from the youngest age range, for the other two age ranges, the poor sites consumed more AA than the good sites. From Table 5-2 it is seen that at kappa 30 (i.e. the 65 minute cooks), significant

differences due to site quality occur in the older compartments, but not the youngest age range.

5.3 Variation of pulp chemical composition

5.3.1 Kappa

Fig. 5-5 shows the rate of delignification for the six compartments.

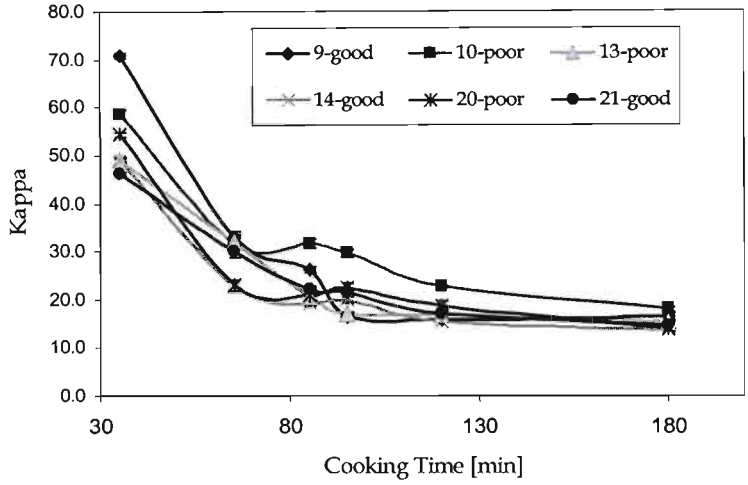


Fig. 5-5. Effects of tree age and site quality on the rate of delignification.

Significant differences in cooking time taken to achieve a target kappa were evident among the compartments. Kappa values as high as 60-70 were obtained for the younger material after cooking for 35 minutes. As the cook proceeded, the differences in the rates of delignification among the compartments became more marked. This was clearly seen in the residual delignification stage where, for example, the time taken to reach kappa 20 ranged from about 70 minutes for the 20 year old and the 14 year old compartments to about 150 minutes for the 10 year old compartment.

Table 5-3 shows the Duncan test results and P-values (at the 95% confidence level) for differences in kappa number among the compartments, each cooking time. Significant differences (P-value < 0.05) were evident among the compartments for each cooking time.

Table 5-3: Duncan test results and P-values for differences in kappa number among the compartments, for each cooking time.

Cooking time (min)	9	10	13	14	20	21	P-value
35	A	B	D	D	C	E	<0.0001
65	B	B	B	A	A	B	0.0001
85	C	B	A	A	A	A	<0.0001
95	A	C	A	B	B	B	<0.0001
120	AB	D	AB	A	C	B	<0.0001
180	C	D	BC	A	AB	AB	0.0001

5.3.2 Klason lignin

Fig. 5-6 shows the relationship between Kappa and Klason lignin. Since both these quantities give an indication of the amount of lignin remaining, it is expected that as Kappa decreases, Klason lignin will also decrease. The x-y plot shows a strong correlation between these two measures of residual lignin content and verifies the well established relationship between these two variables (TAPPI 1957).

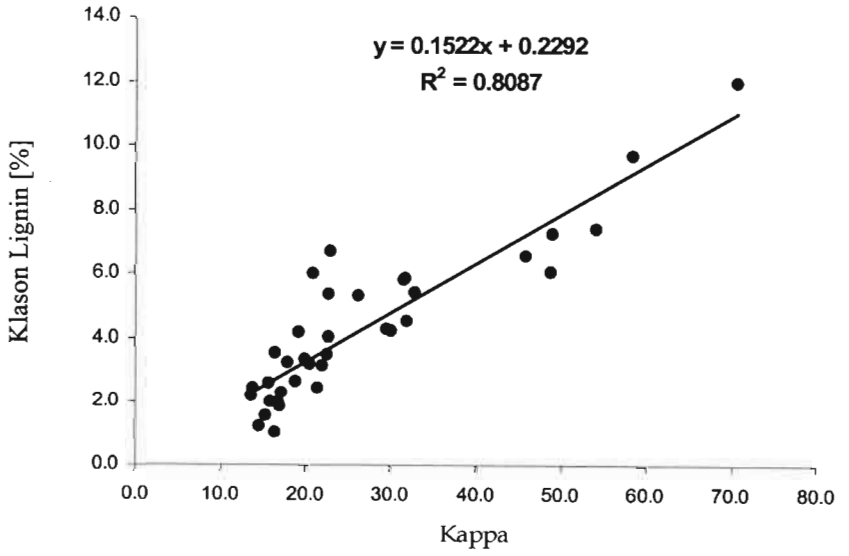


Fig. 5-6. Relationship between kappa & Klason lignin

5.3.3 Hemicelluloses

The degradation of carbohydrates during pulping is of significant importance since it is related to pulp yield (Saucedo *et al.* 2002, Yan & Krishnagopalan 2003) and is also believed to be related to the strength properties of pulp.

The results of the sugar analyses of pulp hydrolysate are shown in Fig. 5-7. It is important to note here that the percentage of each of the monosaccharides in the pulp is shown.

Both arabinose and galactose were present in very small amounts and decreased with increases in cooking time. The older sites had less of these monosaccharides than the younger sites. The difference in the amount of galactose among the sites became less marked at longer cooking times.

Mannose and xylose, which were present in fairly large quantities, remained at higher levels during cooking, though a slight decline in the longer cooking periods was evident. Since the amounts of these monosaccharides remained fairly high throughout the cooks, it can be concluded that the mannan and xylan polymers were most resistant to degradation during cooking. Kleppe (1970) states that softwood xylans are generally fairly stable to degradation during kraft pulping and that the reason for this has not been definitely established.

As a percentage of the total pulp yield, glucose increased with increasing cooking time. This is expected, as the cook proceeds, due to the loss of lignin and hemicelluloses.

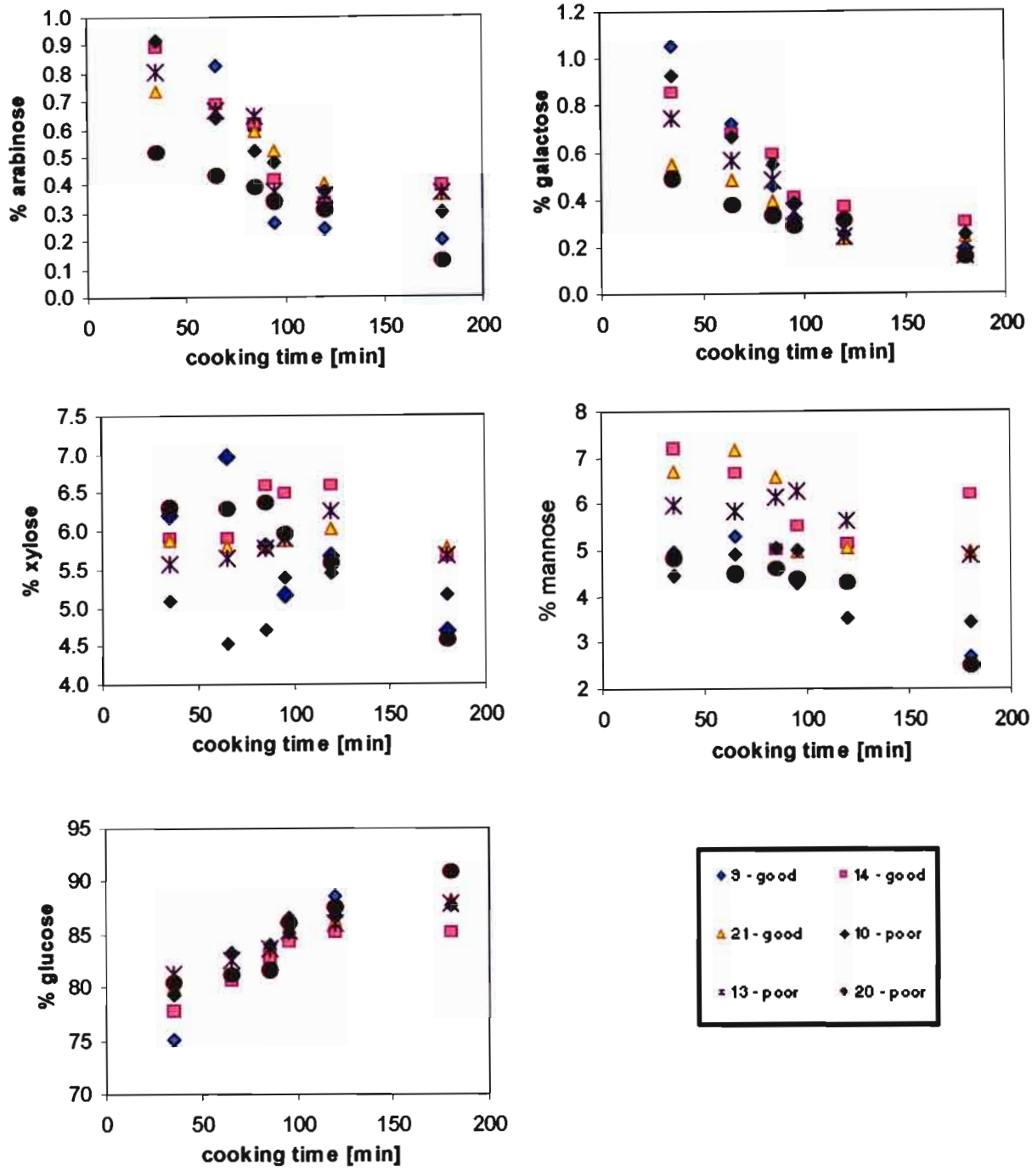


Fig. 5-7. Effects of tree age & site quality on the rate of change of hemicelluloses during pulping.

5.4 Variation of pulp anatomical properties

The results for the pulp physical properties that were obtained are presented below. These results were analysed for the changes in these properties with cooking time and for differences among compartments. It must be noted that since the Fibre Length Analyser that was used was not calibrated, only qualitative analysis of differences among the sites for the measured pulp properties could be made. Also, due to a different measurement method being

used for pulp compared to that used in the wood anatomy measurements, quantitative measurements of the differences in wood and pulp properties could not be made. Thus, only relative differences in the various properties among the sites in the wood properties compared to pulp were made. It is thus very important to carry out quantitative analysis to show differences among the various methods of measurement of pulp anatomical properties.

5.4.1 Fibre length

Fig. 5-8 shows the length weighted average fibre length as a function of cooking time.

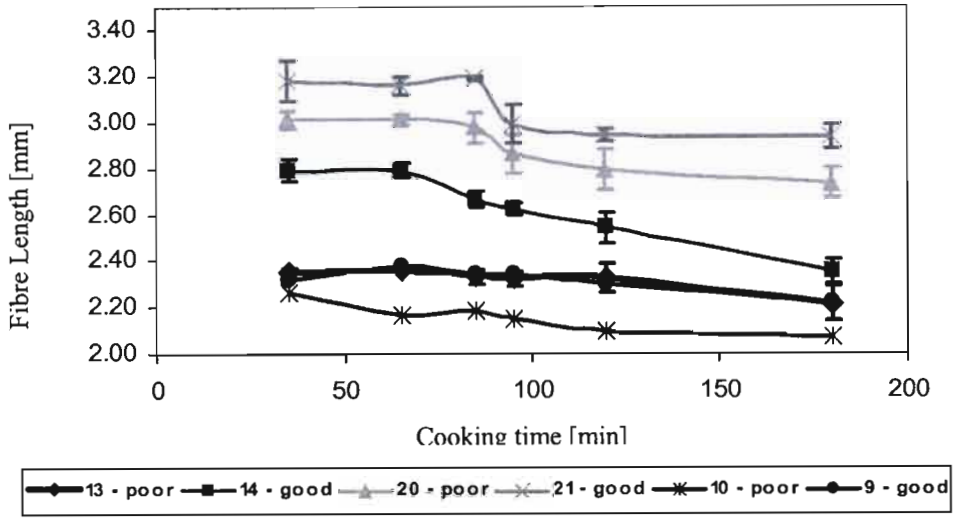


Fig. 5-8. Effects of tree age & site quality on the rate of change of fibre length during pulping.

The shortening of fibres with increased cooking times is according to expectation, due to the cleavage of polysaccharide chains by the cooking liquor. Fibre length shortening with cooking time was more severe for the older trees, with the fibre length of the younger pulps decreasing only very slightly as the cook proceeded. The pulps from the older trees had longer fibres than that of the younger trees. This increase in average fibre length with tree age agrees with the findings by Svedman *et al.* (1998), Goyal *et al.* (1999), Hatton (1997), Morris *et al.* (1993) and Kerr & Swann (1980). The good sites had longer fibres than the poor sites. The variation in fibre length at each cooking time, as indicated by the standard error bars, was greater for the older compartments than for the younger compartments. This is expected due to greater within-tree variation of fibre length in older material.

5.4.2 Cell wall thickness

Fig. 5-9 shows the variation of pulp cell wall thickness at the various stages of pulping for each of the six compartments.

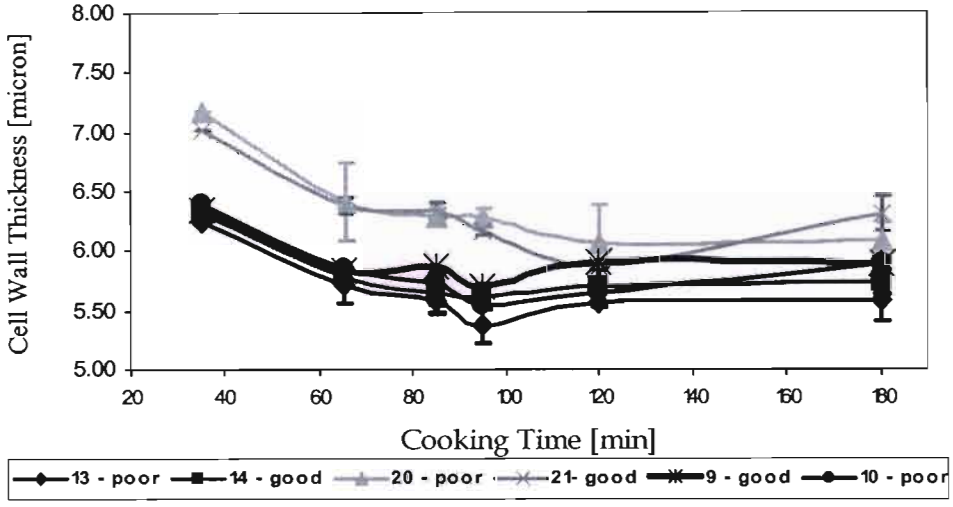


Fig. 5-9. Effects of tree age & site quality on the rate of change of cell wall thickness during pulping.

Cell wall thickness decreased with cooking time. This is expected due to the removal of lignin and the hemicelluloses from the fibre walls. Also, the primary cell wall of fibres is gradually removed as wood is pulped, which would result in the cell wall thickness of the fibres decreasing with increased pulping. The older material had the thickest cell walls, which was also the case in the wood anatomy analysis. The slight increase in the cell wall thickness of the fibres at the later stages of pulping could be indicative of the fibre swelling. Since lignin inhibits the permeation of water through the fibres, the low residual lignin content in the fibres at these later stages in the cook would allow more water to be absorbed thus resulting in fibre swelling.

An issue worth consideration is that whereas the method of measurement in the fibre analyser may be successfully used in the measurement of fibres with detectable lumens, fibres that collapse during pulping, to the extent that the two sides of their inner walls touch thus closing the lumen, would lead to failure of the above method for accurate measurement of cell wall thickness, or any of the other fibre cross section dimensions.

5.4.3 Fibre diameter

Fig. 5-10 shows the variation of fibre diameter with cooking time.

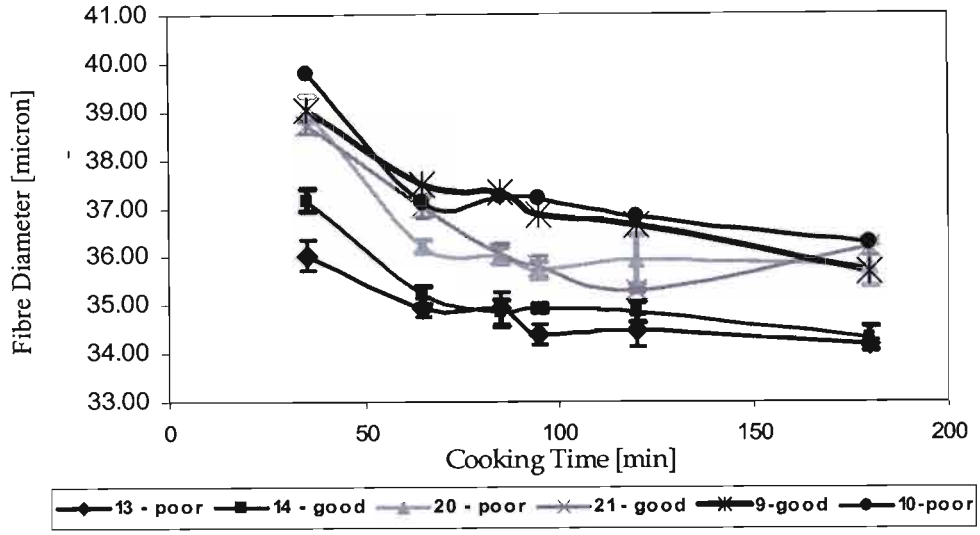


Fig. 5-10. Effects of tree age & site quality on the rate of change of fibre diameter during pulping.

The fibre diameter decreased as cooking time increases. The 13 and 14 year old sites had the smallest fibre diameter. The two oldest sites had a slightly lower fibre diameter than the two youngest sites. These variations in the pulp fibre diameter with age, compared to the wood fibre diameter variations with tree age, could be due to different rates of removal of the primary cell wall of the fibres.

As already mentioned, since the wood anatomical properties were measured using a different method (image analysis) to the pulp anatomical properties (Fibre Lab Analyser), the measured values obtained from these two methods cannot be compared directly, thus the percentage change in fibre diameter between wood and pulp fibres cannot be determined. However, relative differences in fibre diameter among the compartments can be found on wood and pulp separately. In wood, the fibre diameter of the 9-13 year old sites was on average lower than the older sites, whereas after pulping it can be seen that 9-10 year old sites had the largest fibre diameter. Thus, the rate of decrease in the fibre diameter of these oldest sites was greater than that of the 9-10 year old sites, which resulted in the slightly higher fibre diameter in the younger fibres in the final pulp. The 13 year old site however had the lowest fibre diameter, compared to all other sites, after pulping, as it did in wood. This would indicate that this site also underwent rapid degradation from its outer fibre walls. The 14 year old site had a fibre

diameter in wood that was comparable to the two oldest sites (i.e. the 20 and 21 year old sites). With pulping, its fibre diameter was lower than both these sites. This indicated that the primary cell wall of the 14 year old material underwent greater rate of removal than the oldest material.

However, as mentioned in section 5.4.2, there exists the possibility for discrepancies in the results obtained for collapsed fibres, which would be expected to hinder the measurement process.

5.4.4 Lumen diameter

Fig. 5-11 shows the variation of lumen diameter with cooking time for each of the six compartments. Lumen diameter was not measured, but calculated by subtracting twice the fibre cell wall thickness from the fibre diameter. Therefore, the aforementioned problem of collapsed fibres probably leading to incorrect measurements holds true here too.

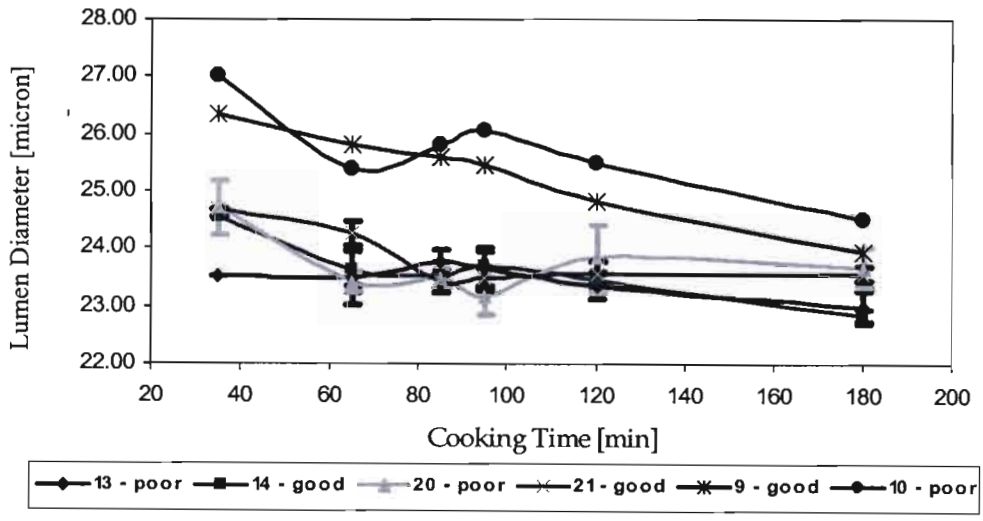


Fig. 5-11. Effects of tree age & site quality on the rate of change of lumen diameter during pulping.

The youngest trees had the largest lumen diameter and also showed the most significant decrease in lumen diameter as the cook proceeded. For the wood analysis, the opposite trend held true, with the younger sites having a smaller lumen than the older sites. This change could be explained by different rates of degradation of the cell walls of the different age trees.

As mentioned in section 5.4.2, since the wood anatomical properties were measured using a different method to the pulp anatomical properties, the actual values obtained from these two

methods cannot be compared directly, thus the percentage change in lumen diameter between wood and pulp cannot be found. However, inferences about differences in the lumen diameter of the compartments, relative to each other, can be made. The younger sites developed, with pulping, a larger lumen diameter than the older sites, compared to initially having smaller lumens than the older sites (in wood). This could indicate that the younger material underwent greater degradation from the inner walls of the fibres than the older sites. From the pulp fibre diameter analysis (section 5.4.3) it was inferred that the younger material underwent the slowest degradation of its primary cell wall. The results here could indicate a different mechanism of degradation of the fibre cell walls in the younger material, i.e. it appears that the younger sites lost material at a greater rate from the inside of the fibres than from the outer wall, whereas for the older material, the removal of the outer wall of the fibres occurred at a greater rate.

Another possible explanation of these results could be that the younger material underwent very little degradation from their inner walls compared to the older material.

5.4.5 Fines

The fines content of the pulp was determined using the Fibre Analyser. Fig. 5-11 shows the fines content as a function of cooking time.

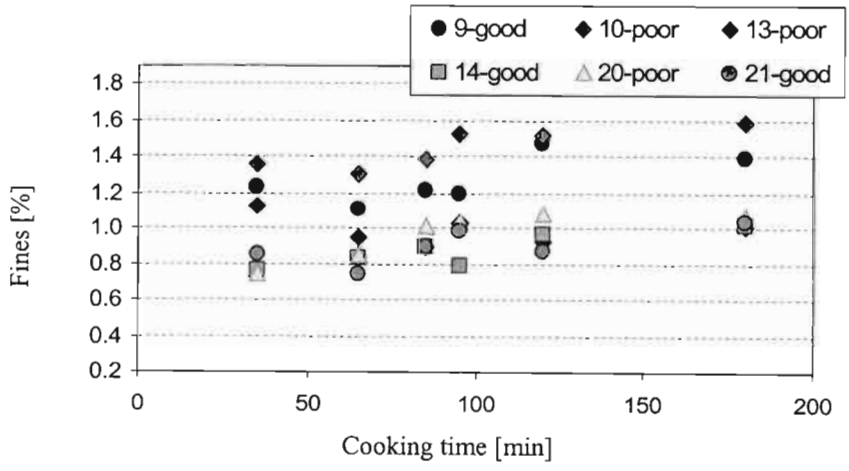


Fig. 5-12. Effects of tree age & site quality on the rate of change of fines during pulping.

There was a general increase in the amount of fines with increasing cooking time. This would be expected since pulping results in the progressive degradation of the polysaccharides, which would result in the generation of a larger amount of fines. The greatest increase in the fines produced by the various sites occurred at the longer cooking times. A possible reason for this could be that when enough lignin has been removed during pulping to allow for hydrophilic swelling of the fibre to occur, easier penetration of the cooking chemicals into the fibre would result. This, in turn would result in greater degradation of the hemicelluloses, thus the increase in the amount of fines at higher cooking times.

The younger material (i.e. the 9-10 year old sites) generated significantly more fines than the older material. Fines contribute positively towards bonding. This is because fines increase the amount of surface area available for bonding. Therefore, strength properties that are positively influenced by increased bonding (such as tensile strength) would benefit from the large amount of fines in these younger sites.

5.4.6 Muhlsteph ratio

Calculation of the Muhlsteph ratio is found in Chapter 2. It is used to give an indication of the collapsibility of fibres. The higher this ratio, the less collapsible the fibres would be. Fig. 5-12 shows the variation of the Muhlsteph ratio with cooking time for each of the six compartments.

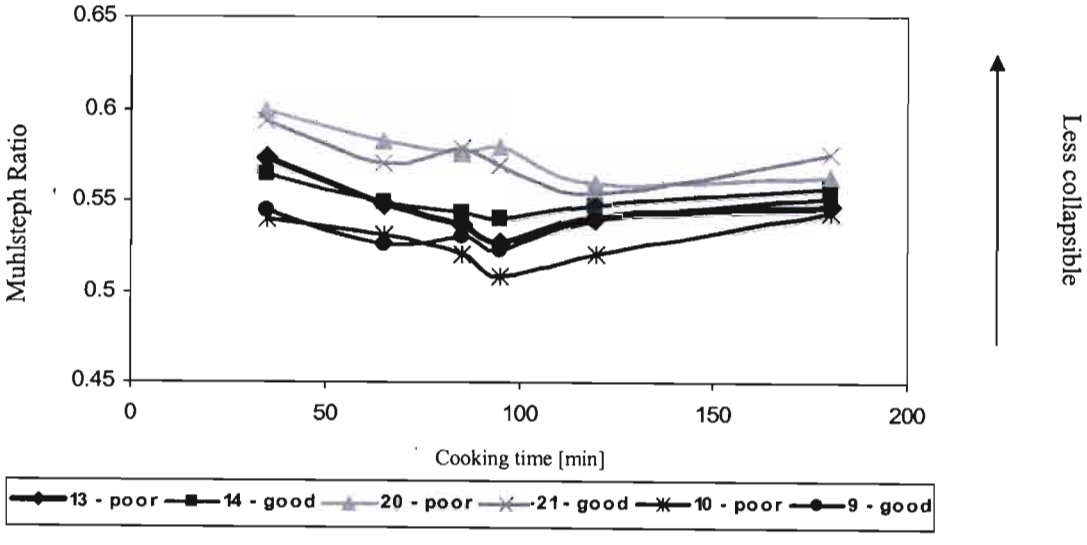


Fig. 5-13. Effects of tree age & site quality on the rate of change of the Muhlsteph ratio during pulping.

Fibres undergo collapse during pulping (Jones 1998). Thus as cooking time increases, the greater extent of fibre collapsibility was expected. Stephenson states that fibres in high yield pulps, obtained after shorter cooking times, are generally stiffer, thus less collapsible. At kappa 20-30 (i.e. the 65minute cooks), it can be seen that fibre collapse decreases with tree age.

5.4.7 Coarseness

Calculation of coarseness is found in Chapter 2. Fig. 5-13 shows the variation of pulp coarseness with cooking time for each of the six compartments.

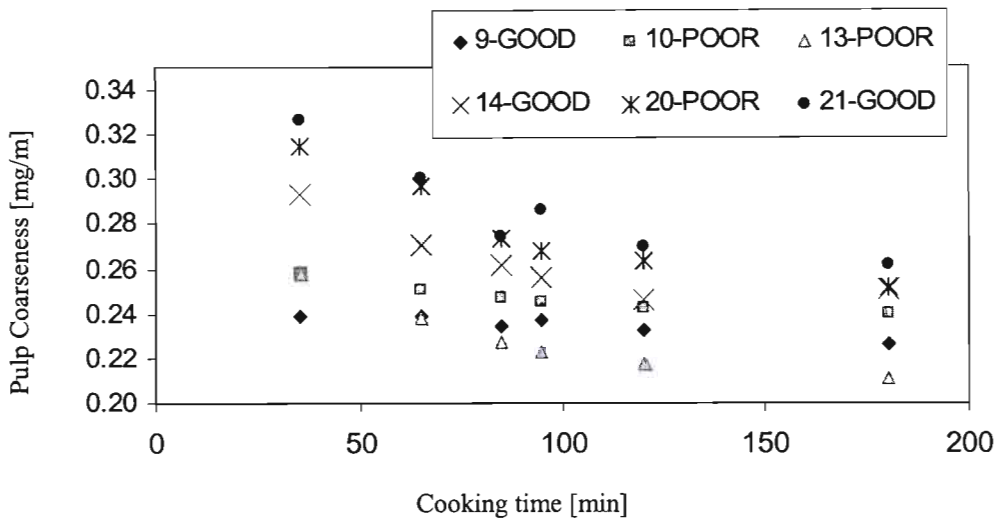


Fig. 5-14. Effects of tree age & site quality on the rate of change of coarseness during pulping.

Coarseness decreased with increased cooking. This is expected due to the progressive degradation of lignin and polysaccharides from the fibre wall during pulping causing the mass of material per length of fibre (i.e coarseness) to decrease. Since the pulp yield decreased with cooking due to the aforementioned reasons, pulp coarseness also decreased, since pulp yield was used in the calculation of coarseness (thus these variables were autocorrelated).

The older material had more coarse pulp fibres than the younger material. This would be expected since the older material had thicker cell walls (see section 5.4.2), thus a greater mass per length of fibre. The greatest differences in coarseness among the sites occurred at the shortest cooking time, with the sites approaching a similar value at the longest cooking time.

The younger material underwent the least change in coarseness during pulping, with the 9 year old site remaining essentially unchanged with increases in cooking time. The greatest and least decrease in coarseness, from the 35 minute-to-180-minute cooks, were obtained by the 20-and-21 year old sites (20%) and the 9 year old site (3%) respectively. The great extent of the decrease in coarseness (18%) of the 13 year old site, together with its relatively low coarseness (at the first cooking time) compared to the other older sites, resulted in its decrease with cooking time causing it to attain the lowest coarseness, compared to the other sites, from the 85 minute cook onwards.

5.5 Predicting pulp properties from wood measurements

The correlation table relating wood and pulp physical and chemical properties are found in Table D-2 [Appendix D]. This was performed over all cooking times collectively. Some of these results are discussed below.

Wood cellulose correlated well with other variables that were also strongly related to tree age. r-values between cellulose with fibre length and the Muhlsreph ratio were 0.89 and 0.81 respectively. Pulp fibre length correlated very well with all wood hemicellulose components measured. Here again, this is probably due to both fibre length and these chemical components being strongly affected by tree age. When considered across all cooking times, the extractives content of wood was very poorly correlated to any of the wood or pulp properties.

Correlations between wood chemical and physical properties, at each cooking time, are shown in Table 5-4. The table should be read horizontally, as it only shows the r-value between a wood variable and that variable in the pulp.

It can be seen that pulp lumen diameter could be predicted extremely well from measurements of this property that were made on wood. Predictions for xylose were moderately high, at the first thee cooking times. The prediction of cell wall thickness was only strong at the two shortest cooking times. The same holds true for galactose. Mannose and glucose could be predicted fairly well, only at the shortest cooking time. The negative r-values for mannose indicate that wood with a high mannose content resulted in pulp with low amounts of mannose. Very poor predictions for fibre diameter and arabinose existed.

Table 5-4: Correlation coefficients (r-values) between wood and pulp measurements, for each measured variable, at each cooking time.

Cooking Time [min] →	35	65	85	95	120	180
CWT	0.82	0.72	0.48	0.55	0.22	0.4
LD	-0.84	-0.9	-0.98	-0.96	-0.94	-0.81
FD	0.3	-0.04	-0.17	-0.03	-0.09	-0.05
Glucose	0.57	-0.3	-0.34	-0.17	-0.5	-0.22
Galactose	0.73	0.65	0.4	0.25	-0.08	0.17
Arabinose	-0.24	0.02	0.36	0.1	0.21	0.4
Mannose	-0.73	-0.54	-0.38	-0.33	-0.82	-0.58
Xylose	0.61	0.63	0.8	0.42	0.62	0.19

Pulp properties are expensive and time consuming to measure. Correlations between wood and pulp properties indicate that there may be methods for indirectly assessing these pulp properties.

5.6 Conclusions

- Pulp yield, at kappa 30, increased with tree age.
- The existence of strong correlations between wood cellulose content and pulp yield offers the possibility of determining the pulp yield potential of a large number of wood specimens, without having to resort to the time consuming and expensive process of laboratory pulping.
- The amount of active alkali consumed by older trees, to achieve a kappa number of 30, is less than that of younger trees.
- The polymers xylan and mannan appeared to be the most resistant to degradation during cooking.
- Older material had coarser fibres than younger material.
- Younger material generated more fines than older material.
- The older sites had longer and less collapsible fibres than the younger sites.

CHAPTER 6

Strength Properties

6.1 Introduction

Increasing the efficiency of use of our renewable resources has resulted in much research into optimising the potential of these resources. Since the various types of paper end-products have specific strength requirements, the ability of paper to satisfy these specific requirements will determine its quality. The wood raw material sets the upper quality limit achievable. The diversity of the incoming raw materials is one of the main factors that influence pulp quality. However, this variability of fibre properties can be turned into an advantage. Knowledge of how processing impacts on wood and pulp of various characteristics would allow for appropriate treatment of wood entering mills in order to satisfy the needs of the end-product. By classifying and segregating the wood raw material according to their properties ability to meet the end-product requirements, and allocating them to the appropriate type of processing, more efficient and productive utilisation of the fibre resource can be achieved.

Tree age is one of the most significant sources of pulp quality variation in mills. For instance, in softwoods, it is well known that very young material is incapable of achieving the high tear achieved by older material. This is due to the mature fibres having relatively larger amounts of cellulose in their thicker cell walls, which gives these fibres higher inherent strength. However, younger fibres are more flexible and are capable of achieving higher burst and tensile strengths. Thus in many respects, the pulp of younger wood show different but not necessarily poorer quality compared to older wood (depending on the end product requirements). By understanding how younger fibres react under various processes, optimisation of the strength potential of such material would be of great importance. If younger material can be appropriately treated to at least attain the required burst and tensile strength, then older material can be used for the purpose of providing high tear strength. It is important to note however that during refining there are limits for the potential for tear improvement whilst burst and tensile strength can be improved significantly with higher levels of refining (at a cost to tear strength). With this in mind, it can therefore be concluded that tear strength can often be the limiting factor. However, the potential benefits of using younger material to satisfy the needs of certain paper grades, which don't require high tear strength, are important. As the per capita demands of an expanding population increases, the future raw materials will depend heavily on obtaining wood from younger material. Under

these circumstances, younger wood with high tear strength is going to be important. Knowledge of the efficient utilisation of this younger material is thus essential. Since this study involved using material from a wide age range, which included material from above and below the rotation age (14 years), the influence of age on the development of strength properties under various processing conditions was investigated.

When the age of the material entering mills is unknown, as is often the case, understanding how the various measurable wood and pulp properties contribute towards the development of strength is required. Identification and quantification of the impact of those fibre characteristics that play a decisive role in determining the various strength characteristics would in such instances prove to be useful. Since the wood and pulp used in this study was extensively classified according to its chemical and physical properties, investigation of how these measured wood and pulp chemical and anatomical properties influenced the development of various handsheet strength properties, when subjected to various degrees of chemical and mechanical treatment, was examined.

The dilemma of how much mechanical and chemical treatment a specific type of pulp should be subjected to would obviously depend on the strength requirements of the end product. For example, for packaging papers, it is critical to use board of high tear strength, whereas for sack kraft, the main requirement is high stretch and tensile rupture energy. In this study, the processing treatments involved subjecting the pulps, from the various extents of pulping, to different amounts of mechanical treatment. The intention here was to determine the mechanisms governing the development or deterioration of the strength of the pulp from the various ages and sites, with different extents of mechanical treatment, and with different residual lignin content and chemical and physical properties.

6.2 The physical properties of handsheets at different kappa and beating levels.

Before analysis of the pulp strength properties, a discussion of the results for freeness and sheet density is given. The graphs for the change in strength properties, freeness and sheet density, for all cooking times and at the four levels of beating (1000, 2500, 4500, 6500 revolutions) are found in Fig. C-3 to C-19 [Appendix C].

Table 6-1 gives a summary of the average kappa number, for each compartment, of the pulps obtained after each cooking time. The results for kappa number have already been discussed.

However, this table was included since the residual lignin content (i.e. kappa number) is of great use to industry, where kappa is used in the control of the pulping process. Thus, it is of great use in analysing the pulp strength results.

Table 6-1. Table showing average kappa number of pulps at each cooking time.

Tree age → / Cooking time [min]	9	10	13	14	20	21
35	70.8	58.6	48.9	49.1	54.2	46.1
65	32.8	31.7	32.0	22.8	22.9	30.2
85	26.3	31.7	20.6	19.2	20.9	22.0
95	16.4	29.6	17.2	20.9	22.5	21.4
120	15.9	22.7	16.8	15.6	18.8	17.1
180	16.4	17.9	15.2	13.6	13.9	14.6

6.2.1 Variation in freeness (Fig. C-3 and Fig. C-11 [Appendix C])

The decrease in freeness with an increase in beating was entirely according to expectation (Stairs *et al.* 1996, Smook 1992, Muneri 1994, Mansfield *et al.* 1999), due to the freeness of pulp being related to the flexibility of fibres. Increased conformability of the fibres, which resulted from increased amounts of beating, would create a less open network of pulp fibres, which in turn would hinder the easy drainage of water.

The next observation was that, when considered at any beating level, higher cooking times resulted in a reduction in pulp freeness. This finding of low yield pulps being easier to refine than high yield ones was also observed by Ifju *et al.* (1975). The reason for this was possibly due to the residual lignin content in pulps (i.e. kappa), which has been shown in many studies to be a major factor affecting the rate of change of pulp properties upon refining (Ifju *et al.* 1975). Lignin hinders the permeation of water through the fibre. This prevents fibres from swelling and becoming more conformable and thus prevents the development of surfaces to be available for interfibre bonding (Clarke 1985). Therefore, high yield pulps (shorter cooks) would have higher freeness than low yield pulps, due to their stiff fibres not being able to conform to one another. At higher cooking times, when more of the lignin has been removed, the cellulose and hemicellulose in fibres are able to imbibe water more easily during beating, causing swelling and increased flexibility of the fibre, hence the observed lower freeness in these low yield pulps. Multiple regression analysis performed on freeness obtained after mild

and more harsh beating (i.e. 100 and 650 beating) across all cooking times supported this, as kappa, which can be used to give an indication of the residual lignin content, accounted for 27% of the variation and the Muhlsteph ratio about 7% of the variation after mild beating and at the highest beating level, kappa accounted for 72% of the variation in freeness.

The shortest cooked pulps (35 minutes) showed significant intersite differences in their refining potential after a short period of beating (100 beatings). It was therefore decided to consider the freeness results at this cooking time in more detail. It was seen that there were marked differences in freeness, among the compartments, with these differences becoming less marked at the highest beating level. There existed a general decrease in freeness with increasing tree age. It might be expected that thin-walled, flexible fibres would exhibit appreciably slower drainage characteristics than ones containing much latewood. However, the 20 year old site did not conform to this trend. What was interesting to note was that the 9 and the 20 year old sites, which were the two sites with relatively large amounts of earlywood, had higher freeness values than the other sites. By default, the 21 year old site had the smallest percentage of earlywood and was seen to have the lowest freeness. An R^2 value of 0.72 was obtained between the percentage of earlywood measured in wood and freeness, at 100 beating, for the 35 minute cooks. This indicated that a relation between the observed freeness and the percentage of earlywood could exist. This finding agrees with a study done on the response of earlywood and latewood fibres to beating, which showed that thin walled earlywood fibres would require appreciably more energy to refine than the latewood ones (Ifju *et al.* 1975). In that study, it was found that the mechanism of peeling of the cell wall in earlywood fibres and latewood fibres were different. In earlywood fibres, the primary and secondary cell wall layers that were removed during beating remained intact (SEM pictures in the aforementioned study revealed a "snake-skin" type of peeling of the fibre cell wall) whereas the latewood peelings disintegrated into fibrillar bundles. This difference in the peeling mechanism was seen to be responsible for greater reduction in freeness of latewood pulps, as fibrillar bundles would be more effective in hindering the drainage of water through the pulp, since the fibrils would occupy more of the gaps between the fibres. This could perhaps be the reason for the high earlywood content material, in this study, responding slower to beating than the pulps from wood with large amounts of latewood. However, SEM analysis was only carried out on handsheet samples, and not on wet pulp fibres prior to papermaking. Thus, the mechanism of removal of the cell walls could not be seen.

At the higher beating level, for the 35 minute cook, a decrease in freeness with increasing tree age was evident. The youngest material underwent the smallest change in freeness (16% and 13% for the 9 and 10 year old sites respectively). This result was in accordance with findings

from studies on the response of juvenile and mature wood fibres to beating, where younger material required more treatment before achieving freeness levels of older material. However, the 20 year old site still seemed to follow the behaviour typical of earlywood fibres as it had a relatively high freeness when compared to the other older sites, even though it underwent the greatest decrease in freeness (27%), with the increased beating. Drainage characteristics of pulps are influenced by a number of factors. Accompanying the increase in fibre flexibility with increasing beating, was the generation of fines. The results from multiple regression analysis indicated that at the higher level of beating for this cooking time, the amount of fines in the unrefined pulp contributed 79% to the observed variation in freeness.

With regard to the other cooking times, it was observed that at mild beating there were very small differences in freeness among the sites, with the greatest intersite differences in freeness occurring at the higher beating levels.

6.2.2 Variation of sheet density (Fig. C-4 and Fig. C-12 [Appendix C])

Increasing age had a negative impact on sheet density (r-values = -0.69, -0.64, -0.66 and -0.63, in order of increasing beating). This would be expected as the highly collapsible fibres of younger material would be more conformable to each other easily, thus promoting better sheet consolidation and denser mat of fibres when making the hand sheet.

One of the principle purposes of refining is to promote collapsibility and flexibility of the individual fibres, thus enhancing the paper properties. The increase in sheet density with increased amounts of beating was a direct consequence of the mechanical treatment, since with increased beating, fibres become more flexible and fines are usually generated, which would result in the formation of a more dense and compact sheet. Similar trends were obtained by Robertson (1991) for *P. patula* and by Wang & Braaten (1997) for spruce. The slight increase in sheet density with increased cooking time was also expected since increased cooking resulted in the fibres becoming more collapsible (see section 5.4.6). This increase in collapsibility of fibres would be expected to contribute positively to the strength of paper, as it would result in a greater surface area being available for interfibre bonding to occur. However, if the strength requirements for the end product can be met, bulkier sheets (i.e. paper with low sheet density) would be more economical for mills, as a less amount of fibres would be needed in such sheets. In bulky sheets (i.e. low density paper), in order to meet the grammage requirements of the end product, fillers would be used to fill the voids between the fibres. Bulky sheets are more absorbent and opaque and can be used in applications where these characteristics are needed.

Multiple regression results for sheet density showed that pulp fibre length alone accounted for about 47.5% and 59% of the variation at mild and harsh beating respectively. Fibre length could affect the degree of fibre packing since longer fibres entangle with one another. This would result in a less dense network of fibres in the paper (i.e. low sheet density) compared to the more compact arrangement of shorter fibres (i.e. high sheet density). At mild beating, the impact of fibre length not playing as significant a role as at more harsh beating could be due to the fact that after a short period of beating, fibres are still fairly stiff and fibre characteristics such as the residual lignin content would play a greater role. Once the amount of beating is increased and the flexibility of the fibres become enhanced, the negative effect of fibre entanglement and floc formation would become more apparent, thus fibre length would play an important role in these instances.

6.3 The strength properties of handsheets at different kappa and beating levels.

Different combinations of the various pulp fibre characteristics are expected to result in different rates of change of the pulp strength properties with increasing amounts of mechanical treatment. Added to this complexity is that beating increases the tensile-and-burst-strength of fibres whereas tear strength increases initially, and then deteriorates. Thus comparison of pulps at just one beating level would not be adequate in investigating these relationships.

It was decided to first discuss the maximum tear strength achievable for each site (which occurred at the mildest beating level) and the maximum achievable tensile-and-burst-strength by each of the sites (which occurred at the highest beating level). Even though these maxima would not necessarily yield the most optimum combination of strength properties for the pulp, it is of use to know what the maximum strength capabilities of pulps were, in order to establish some idea of what type of end-product each of the fibres would be best suited for.

This analysis is followed by a more in depth one (section 6.3.2), with the measured strength properties of the pulps at all beating levels and their change over cooking time being discussed. As previously mentioned, it was found in various studies that pulp around a kappa of 30 would produce highest strength compared to pulps of higher or lower kappa. Despite this, it was decided not to confine the analysis to any particular kappa but to provide a general discussion of the results obtained at the different lignin content pulps. Maximising pulp yield, but not at the expense of poor strength properties, would be of great economical value to

industry. The strength properties at the shorter cooking times (i.e. higher yield pulps) would be especially useful in analysing the younger material in this study, where longer cooking times would result in a considerably greater loss of yield and tear strength than in older material. Analysis of results from pulp with kappa numbers lower than 30 was also performed (despite the lower pulp yields at this stage of pulping), in order to determine if the optimum strength potential of the pulp from any of the sites occurred here.

Even though comparison of results at a fixed pulp property does not necessarily yield the optimum strength potential of the pulp, it is common practice in industry to do so. Therefore, an analysis of the strength results at constant freeness and constant sheet density was also performed (see Figs 6.1 – 6.9).

6.3.1 The maximum achievable strength properties

Firstly, the general trends of tear index decreasing with increased amounts of beating and the opposite holding true for tensile-and-burst-index was according to expectation (see Figs. C-13 to C-15 [Appendix C]). With tear strength, there was a general increase and then decrease with cooking time. This trend was followed for tensile-and-burst-strengths, although on the whole there was a general decrease in strength with increasing cooking time, which was probably due to the removal of hemicelluloses. With regard to zero-span, very erratic changes occurred as cooking time increased. The only pattern evident was that the older material showed generally higher zero-span strength than the younger material.

Before the analysis of the results at each cooking time and beating level a brief discussion of the maximum achievable strength properties for each site is presented below. Although these maximum values were not necessarily accompanied by the other strength properties also being high (i.e. the maximum tear strength may have been accompanied by extremely low tensile-and-burst-strengths and vice versa), it was still interesting to know the maximum strength capabilities of each of the sites.

Table 6-2 shows the maximum strength properties that were achievable for each site, together with the kappa number/s and the magnitude of the other strength properties at each of those maximum strength properties.

Table 6-2. Table showing maximum achievable strength properties for the six sites (freeness [in mL] shown in brackets next to kappa).

	Age	Max. Strength Achieved	Tear	Tensile	Burst	Zero-Span	Stretch	TEA	Kappa / (freeness)
	years		kN m²/kg	kN m/kg	MN/kg	kN	%	J/m²	
Tear									
	9	10.9	-	69	5.8	52	2	53.9	25-28 / (760)
	10	10.6	-	66	5.29	34	2.4	62	22-23 / (650)
	13	13.3	-	62	5	46	2.5	62	30-34 / (690)
	14	10.7	-	70-81	5.6-6.1	68-80	2.4-2.8	68-94	18-25 / (655)
	20	13.7	-	58	4.9	67	1.8	39	21-24 / (700)
	21	15	-	60-65	4.8-5.2	63-71	2.1-2.2	50-57	20-24 / (690)
Tensile									
	9	102	7.6-8.4	-	7-7.8	32-45	2.9-3.1	103-124	15-30 / (400)
	10	97	7.9-8.5	-	7-7.36	22-26	3-3.4	110-137	29-34 / (440)
	13	92	8.3-8.9	-	7.4-8	32	3.2-3.36	121	48-50 / (500), 19-21 / (395)
	14	99	8.8	-	7.7	65	3.1	124	19-22 / (350)
	20	91	8.3-10.29	-	6.7-8.32	40-78	3.1-3.27	116	17 / (320) -23 / (490)
	21	95	9-10.3	-	7.9-8.37	65-72	3-3.24	104-121	20-22 / (400) , 45-47 / (500)
Burst									
	9	7.7	7.6-7.7	69-80	-	37-45	3.06-3.1	113-120	15 / (480) -27 / (600)
	10	7.7	8.59	69	-	22	3.46	116	56-60 / (600)
	13	8	8.3	70	-	32	3.36	121	19-22 / (395)
	14	7.7	9.4	70-80	-	63-66	2.98	110	21 / (350) - 50 / (505)
	20	8.3	10.2	58	-	78	3.13	117	21-24 / (480)
	21	8.3	10.3-10.97	64-75	-	61-65	2.96-3.2	98-121	28-46 / (500)

a. MAXIMUM TEAR

When considering the results for tear, it was evident that the maximum tear for each compartment did not occur at the same kappa. Also, it was seen that a certain amount of delignification needed to occur before the maximum tear strength was achieved. The older material achieved higher maximum tear than the younger sites. According to Svedman *et al.* (1998), this is expected since the tear strength of paper is largely dependant on the strength and the length of the component fibres. From Fig. 5-10, it was found that the fibre length of the older sites were longer than the younger sites. Also, the older material had thicker cell walls than the younger material. Thicker walls are due to the deposition of large amounts of the middle layer of the secondary wall (Ifju *et al.* 1972). This provides fibres with high strength (Ifju *et al.* 1972). The longer and stronger fibres in older material would therefore appear to contribute positively towards their high tear strength. The SEM images (Appendix D3) for the 100 beating handsheet samples, at the 35 minute cook, clearly showed the larger amount of thicker and uncollapsed fibres in the older material than in the younger sites. It therefore appears that tear strength is positively impacted by a high proportion of thick walled, uncollapsed fibres.

It follows from the tear strength of fibres decreasing with increased amounts of beating that the maximum tear for any of the compartments would occur at the 100 beating level. In multiple regressions analyses performed for tear strength at 100 beatings, across all cooking

times and tree ages, fibre length and kappa number together accounted for 50% of the variation in the tear index, with fibre length contributing 33% towards the model developed. Kappa can be considered to indirectly give an indication of the strength of the fibres, since at longer cooking times (i.e. lower kappa), fibres are weakened due to degradation of hemicelluloses from their cell wall. This would impact negatively on the tear strength. Kappa could also give an indication of the rigidity of the fibres. Shorter cooking times would result in more rigid fibres. Longer cooks lead to greater fibre flexibility due to more lignin being removed and the hydrophilic swelling of fibres. Multiple regression carried out at kappa 20-30 (Table D-1 [Appendix D]), showed that irrespective of beating level, tear was most affected by the collapsibility of the fibres. Multiple regression analysis was also performed on each compartment separately, across all cooking times and at this lowest beating level (i.e. 100 beating). This was done to eliminate the impact of tree age on the results. The results are shown below in Table 6-3.

Table 6-3: Multiple regression results for tear index, at 100 beating, of each site separately[ξ].

AGE:	9	10	13	14	20	21
Adj. R^2 =		**47**	**64**	**51**	**95**	**80**
FL / FD				50		74
Fines						6
Pulp FL			64		57	
Pulp CWT					38	
Muhlsteph		47				
Adj. R^2 =			**25**	**46**	**73**	**44**
Pulp Arabinose						33
Pulp Mannose					73	11
Pulp Galactose				25		
Pulp Xylose				21		
Pulp Glucose			25			

Regression results using pulp anatomy

Regression results using pulp chemistry

The tear index of the 9 year old site could not be predicted. Firstly, it must be noted that kappa did not play a significant role in any of the models developed. However, fibre length proved to be a reasonably good predictor of tear for both the 13 and 20 year old sites. Collapsibility of the fibres, represented by the Muhlsteph ratio and the ratio of fibre length-to-diameter, offered some prediction of tear for the 10, 14 and 21 year old sites. For the 20 year old site, the impact of pulp chemistry was very evident, with pulp mannose alone accounting for a

[ξ] Individual components to the overall model are included to indicate their relative contribution to the model. This applies to all multiple regression results shown.

significant portion of the variation in tear (73%). In general, models developed using pulp anatomy proved to be better predictors of tear strength, as indicated by the high R^2 values in these models.

b. MAXIMUM TENSILE STRENGTH

It was seen that apart from the 13 year old site, the younger material achieved significantly higher tensile strength than the older material (Table 6-2). The younger material generated more fines than the older material (section 5.4.5). Fines are believed to increase strength properties which are dependant on interfibre bonding. This is due to the fines filling up the voids between the fibres and thus increasing the surface area available for interfibre bonding. It was also noted that the maximum tensile strength in certain sites was not achieved at only one kappa number. The 13, 20 and 21 year old sites bear testimony of this. These sites achieved their maximum tensile strength at a shorter cooking time, after which the tensile strength deteriorated, but then increased again later in the cook. Such irregularities could be due to a combination of a number of properties of the pulp that changed over cooking time and would influence the degree of bonding in the sheet. Some of these factors include pulp fibre length, the degree of beating and the residual lignin content. For the other sites, the maximum tensile strength peaked and then dropped with increased cooking. Multiple regression analysis was carried out at the 650 beating level, as the maximum tensile strength occurred there. The results indicated that only 30% of the variation could be accounted for by the Muhlsteph ratio and pulp cell-wall thickness, together. Multiple regression was then performed for each site separately, in order to determine the main drivers of tensile strength for each tree age. The results are shown in Table 6-4.

Table 6-4: Multiple regression results for tensile index, at 650 beating, of each site separately.

AGE:	9	10	13	14	20	21
Adj. R^2 =	**33**		**23**		**22**	**30**
Muhlsteph	33					
Pulp FL						30
Pulp FL / FD			23		22	
Adj. R^2 =	**35**			**39**	**72**	**26**
Pulp Mannose	18				37	
Pulp Arabinose	17					26
Pulp Galactose					6	
Kappa					29	
Pulp Xylose				39		

Regression results using pulp anatomy

Regression results using pulp chemistry

There were very weak predictions of tensile strength at this harsh beating level. Here, as in the tear analysis, fibre length and the ratio of fibre length to fibre diameter (which may give an indication of collapsibility) proved to be the main drivers of tensile strength. For the younger material (i.e. the 9 and 13 year old sites), collapsibility (as indicated by the Muhlsteph ratio and the ratio of fibre length-to-diameter) offered the best indicators of tensile strength. The tensile index for the 20 year old site could best be predicted using pulp chemistry. For this compartment, mannose again proved to be a good indicator of tensile strength, as it did for tear strength. Arabinose was the hemicellulose that was of some significance in predicting the tensile strength of the 21 year old site. This hemicellulose was also used in the model developed for tear for this site.

c. BURST

When considering burst, it must first be noted that the older material yielded higher maximum burst strength than the younger sites. However, it is interesting to note that the 13 year old site was able to achieve higher maximum burst strength than the 14 year old site, indicating a stronger site or genetic effect (since within the species *P. patula* various families exist). The kappa range at which the maximum burst strengths occurred was wide, ranging from 19 to 60. Thomson & Gustafson (2000) stated that other authors found that higher lignin content pulps were harder to bleach than low lignin content ones. Higher lignin pulps required more chemicals to achieve the same brightness end-point. Thus, high yield pulps are best suited for unbleached paper grades.

Multiple regression results for each compartment separately are shown in Table 6-5.
It was seen that reasonably good models existed for predicting burst index at 650 beating. Here again, fibre length proved to be a good indicator of pulp strength. This was true for the 9, 14 and 21 year old sites. It must be noted that these were all the good sites. Kappa and the ratio of fibre length-to-diameter were very influential variables in the models developed for the 13 and 20 year old sites respectively. For the 10 year old site, only pulp chemistry could predict burst to a significant degree, with glucose being the only predictor in the model developed and accounting for more than half the variation in burst. Mannose alone accounted for two thirds of the variation in burst in the 9 year old site. Glucose alone accounted for more than half the variation in burst for the 21 year old site. For the 20 year old site, xylose alone accounted for more than two thirds of the variation.

Table 6-5: Multiple regression results for burst index, at 650 beating, of each site separately.

AGE:	9	10	13	14	20	21
Adj. R^2 =	**70**		**72**	**90**	**89**	**58**
Pulp FL	70			64		58
Pulp FD			20		16	
Pulp CWT			7		8	
FL / FD					56	
Kappa			45	15	9	
Muhlsteph				11		
Adj. R^2 =	**63**	**48**	**50**	**66**	**69**	**70**
Pulp Mannose	63					10
Kappa			21			7
Pulp Glucose		48				53
Pulp Xylose				26	69	
Pulp Galactose				40		
Pulp Arabinose			29			

Regression results using pulp anatomy

Regression results using pulp chemistry

Multiple regression analysis carried out at kappa 20-30 (Table C-13 [Appendix C]) showed that wood collapsibility or pulp arabinose was the most influential variables at mild beating (i.e. 100 beating). At more harsh beating (i.e. 650 beating), wood coarseness or pulp cell wall thickness were able to predict burst very well.

The large impact of pulp chemistry in the prediction of burst index was clearly evident. This finding agrees with Stephenson, who stated that burst strength depends strongly on hemicellulose. Clarke (2000) stated that pentosans are a major constituent of the outer layers of fibre walls. Swollen hemicelluloses on the surface of fibres can take an active part in the formation of bonds between the fibres in the paper, by acting like glue. Therefore, more of this surface material present would result in a greater bonding ability. However, the evaluation of paper properties on the presence or absence of pulp hemicellulose content alone could be misleading, as the structural characteristics of fibres also have a large influence with regard to fibres during the paper making process. Therefore, research being done must take both the physical and chemical properties into account, so as to not obtain contradictory and confusing results.

6.3.2 Variation of strength properties with each cooking time and beating level

As cooking proceeds, more lignin is removed from the fibres. This allows for hydrophilic swelling of fibres. However, accompanying this delignification process is the progressive weakening of fibres due to the degradation of hemicelluloses and cellulose. In this study, a further variation with cooking time was the decrease in pulp fibre length. It was therefore difficult to separate the effects of fibre damage (due to both cooking and beating) and the impact of decreases in fibre length. However, possible reasons for the observed results are given.

a. TEAR (Figs. C5 and C-13 [Appendix C])

Dinwoodie (1966) stated that, for unbeaten fibres, fibre length is the main determinant of tear, whereas fibre strength is an additional significant variable in beaten pulp. Casey (1981) stated that in addition to fibre length two other factors need to be considered for tear viz. the number of fibres participating in the rupture of the sheet and the number and strength of fibre-to-fibre bonds.

Van den Akker (Alexander *et al,*1968, Dinwoodie 1965) proposed a theory to explain tear strength. It states that the sum of the work needed to pull fibres out from a sheet and the work required to rupture some of them, divided by twice the length of the line of tear, is equal to the average tearing force. The basic principle of this theory is based on the fact that the work needed to rupture a fibre is much less than the work needed to pull out a fibre from its bonded state, without damaging it. Therefore, in unbeaten pulp or at mild beating, since the interfibre bonds in the sheet are not strong, the work expended in the tear test would be expected to be used mainly in breaking these weak bonds rather than in rupturing the fibres. With more beating, the increased bonding results in more work being needed to produce tear failure due to increased frictional drag involved in pulling the fibres out of their bonded state. This shows up as an increase in tear strength, which is sometimes observed in the initial increase in tear strength with increased beating. Karenlampi (1996) stated that a fibre fails when the load needed to break a bond exceeds fibre strength. Thus, with increased beating, once a critical level of bonding is achieved, initiation of fibre failure results. Since, as mentioned, the work required to rupture a fibre is not great, this type of failure results in a lowering of tear strength. Therefore, at higher levels of beating, the greater amount and strength of interfibre bonds results in tear strength decreasing, due to tear failure mode being the fibre rupture rather than the breaking of interfibre bonds. These concepts will be referred to shortly when discussing the behaviour of tear with increases in cooking time and beating, for each of the compartments.

As already mentioned, tear index, in this study, decreased with increased beating. This suggests that the tear strengths observed perhaps fall in the region past the critical level of bonding, referred to by the Van den Akker theory. From the SEM images (Appendix D), clear signs of external fibrillation were evident at the 650 beating level, compared to the 100 beating level. This was due to increased amounts of beating resulting in the formation of fibrils. There are many authors who view fibrillation as being far from a key factor promoting strength development. Their argument is that accompanying the splitting of fibres to produce fibrils, is significant damage in other areas of the fibre. This damage is brought about by the serious fracture lines at the base of these fibrils that result when they break out from the fibres (Bolam 1965). If this is in fact true, then tear strength, which is highly dependant on the strength of fibres, would be adversely impacted at higher beating levels, thus its decrease with increased beating.

It must be noted that as much as the fibre strength needs to be preserved by using shorter cooking times, the shortest cooking time in this study (35 minutes) did not yield the highest tear strengths. Casey (1981) states that excessive lignin content (from undercooking) or degraded carbohydrates (from over cooking) have a negative impact on tear. This agrees with the findings in this study, as it was evident that limited delignification needed to occur in certain sites, in order for the tear strength to achieve its maximum value and there was also a rapid deterioration of tear at very long cooking times. Broderick *et al.* (1996) stated that it was found in one study that moderate pulping conditions initially increased tear by providing better bonding, but more pronounced chemical treatment eventually becomes detrimental to this property. This study supported this finding.

The most marked differences in tear among the sites, for any cooking time, occurred at the lowest beating level, with the older sites generally having higher tear strengths than the younger material (Fig. C-13 [Appendix C]). The older sites underwent greater decreases in tear with beating than the younger material. Goyal *et al.* (1999) also observed the increase in tear with age and the fact that the most marked differences in tear occurred at the lowest beating level. Tree age is the principal factor affecting fibre length, with wood from younger trees having shorter fibres than wood from older trees. In the present study, there existed a strong positive correlation between fibre length and age (r-value = 0.89). It would be interesting for further studies to use material where the effects of fibre length and age on strength properties can be separated, by perhaps using different species at the same age, but which have different fibre lengths. The initial pulp fibre length (before beating) was found to be strongly positively correlated with tear strength for all but the highest beating level (r-values = 0.70, 0.72, 0.72 and 0.58, in order of increasing beating). This result of fibre length

playing a greater role in unbeaten pulp agreed with Dinwoodie (1966). The positive r-values could be indicative of the older material, with longer fibres, having achieved higher tear strengths than the younger material.

There is a limit to which longer fibres contribute positively to paper strength (Britt 1966). Broderick *et al.* (1996) and Wangaard & Williams (1970) state that very long fibres can be detrimental to tear. On the one hand, whereas longer fibres are known to impart high tear strength to paper, very long fibres can entangle with one another and disrupts the uniformity of formation of the sheet. This in turn creates areas of weakness in the sheets. Therefore, the shortening of very long fibres should increase the uniformity of sheet formation and thus have a positive influence on the strength of the paper web. Broderick *et al.* (1996) stated that work by another author found fibre lengths above 2.17mm resulted in poor strength due to non-uniform sheet formation due to flocculation of the long fibres. The discussions that follow shortly, describing the tear results for each compartment separately, show the possible positive effect of shortening of fibres on tear strength. Again, it is stressed that research into separating the influence of age and fibre length on tear strength could help in gaining an understanding of the impact of each of these variables on tear. This would be useful in determining whether longer fibres actually contribute to higher tear or whether the length of fibres coupled with other morphological and chemical characteristics that may also increase with age are also key variables.

Broderick *et al.* (1996) stated that in one article, the authors found that coarser fibres produced high levels of tear resistance. However, Svedman *et al.* (1998) stated that work by other authors have shown that the correlation between fibre length and coarseness, within species, is very high. It was also stated in this article that the influence of each of these factors towards strength must be considered separately. James d'A Clark (1962) stated that as a consequence of the relationship between fibre length and coarseness, many of the effects in literature that are attributed to longer fibres may in fact be masked by, or are due to, the fibres being correspondingly coarser. Cluster analysis was performed on tear strength results, at kappa 30, across all sites together (Appendix D4). It was seen that tear strength, at all beating levels, was found in the same cluster that pulp coarseness was found in. This implies that both these variables exhibited similar patterns of change. Fibre length, however, was not in the same cluster as tear strength. This agrees with the aforementioned findings by Broderick *et al.* (1996), in which tear strength was accounted for by fibre coarseness and not fibre length.

It is also important to note that apart from very long fibres entangling with one another, these fibres would generally be expected to kink or curl far more easily than younger material. This

would probably be due to there being fewer stresses hindering the formation of these deformations (i.e. kinks and curls) in longer fibres than in shorter ones. The shortening of very long fibres would reduce the longer fibre content, and thus be expected to result in pulp with a lesser degree of fibre deformation than in pulp with a larger proportion of longer fibres. Kinks and curls not only would result in non-uniform sheet formation, but would also be areas of weakness in the sheet. Hence, fibre shortening might be expected to increase strength properties.

The development of tear strength, with cooking time and beating level, for each age was not the same. Thus a summary of the changes in tear that occurred for each of the compartments was made, with focus being made mainly on the impact of changes in fibre length, strength and interfibre bonding with increased cooking time and beating level.

9 years: At all levels of beating, tear increased to a maximum with increases in cooking time and then decreased with further increases in cooking time. The maximum tear for all but the 100 beating pulp samples achieved a peak in their tear index at the 65 minute cook. For the 100 beating level, tear continued to increase with increases in cooking time beyond 65 minutes, and achieved its maximum value at the 85 minute cook. From Fig. 5-8 it was seen that the pulp fibre length for this compartment decreased very slightly from the 65-to-85-minute cook.

10 years: For this site, tear showed a general increase followed by a decrease with increases in cooking time. The initial positive impact, possibly due to fibre shortening that occurred between the 85, 95 and 120 minute cooking times, on tear strength was evident only at the shorter beating levels (100 and 250 beating). For the 100 beating level, the positive impact of the decrease in fibre length that occurred seemed to outweigh the deterioration in strength that accompanied the longer cooking times, since tear continued to increase from 85 minutes to 120 minutes. However, for 250 beating, the decrease in fibre length only had a positive impact on tear between the 85 and 95 minute cooks, with the increased amount of beating at 120 minutes of cooking resulting in fibre damage, and this outweighing the positive effect of more uniform sheet formation. Thus, it can be deduced that, at shorter beating levels, tear strength appears to benefit from shortening of fibres. At higher beating levels, no observable benefit from fibre shortening was evident. It must be noted that it is within the boundaries of this study that it appeared that decreases in fibre length impacted positively on tear strength.

13 years: Here as well, tear increased to a maximum and then generally decreased with further cooking, at all beating levels. However, from Fig. 5-8, it was seen that very slight decreases in fibre length occurred from the 85 to 120 minute cooking times. The possible effect of this was seen most clearly in the tear strength increase from 85-to-120-minutes of

cooking, at 100 beating. The same explanation as the 10 year old site, at the 250 beating level, holds true as well.

14 years: It was evident that at the shortest beating level (100 beating), the possible positive effect of decreases in pulp fibre length only sufficiently compensated for losses in fibre strength with increased cooking. This was clearly seen in the tear strength of the fibres being maintained high and fairly constant from 35 to 120 minutes of cooking. However, the greater damage caused to the fibres at the longest cooking time (180 minutes) caused the tear strength to decrease. Tear showed an increase from the 85 minute cook to the 95 minute cook, at all beating levels, with this increase being less marked for the 100 beating level. From Fig. 5-8, it was seen that the pulp fibre length decreased form the 65 minute cook onwards. It can perhaps be assumed that the benefit of shortening of fibres to tear strength will only occur if sufficient shortening of longer fibres occurs in order to enhance sheet formation. Therefore the tear strength only improved after further fibre shortening occurred in the transition from 85 to 95 minutes of cooking, and not after 65 minutes of cooking. It must be noted that the 14 year old site had relatively long fibres compared to the younger material. Therefore, for this site, the higher amount of fibre shortening required before sheet formation was adequately improved to the extent that it would outweigh the negative effect of damage to the fibres, due to increased cooking and beating, would be expected.

20 years: Here, again the changes in fibre length appeared to impact on tear strength only at the shorter beating levels. At the two highest beating levels, the decrease in fibre length did not seem to outweigh the negative impact of fibre damage on tear strength. These results agree with the aforementioned concept by Dinwoodie (1966). At the two lowest beating levels, the decrease in fibre length from the 85 minute cook onwards resulted in higher tear strengths than at the previous cooking time. This increase in tear was more pronounced for the 100 beating than the 250 beating. Thus it can be seen that fibre shortening had a positive effect on tear for more stiff fibres than ones made more flexible by beating.

21 years: The same explanation for the results obtained for the 20 year old site would hold true here. The decreasing fibre length with increasing cooking time has a more positive effect on tear strength of more stiff fibres than ones that are more flexible due to increased beating. Fibre strength becomes the main contributor to tear at higher beating levels.

It is very evident in the foregoing discussion that when there was less bonding (i.e. at lower beating levels), variation in tear appeared to be strongly influenced by decreases in fibre length. Also, the shortening of fibres appeared to impact positively on tear strength. Cluster analysis was performed on tear strength results, at kappa 30, and at each beating level, for all sites collectively. The results are found in Appendix D4.

b. TENSILE STRENGTH (Figs. C-6 and C-14 [Appendix C])

As previously mentioned, tensile strength increased with increasing beating. This agrees with findings by Robertson (1991), Smook (1992), Muneri (1994), Brolin *et al.* (1995) and Law *et al.* (1999). Fig. C-6 [Appendix C] showed that there was a clear increase and then decrease in tensile strength with cooking. At the beginning of the cook, the removal of lignin contributes positively to the bonding ability of the fibres. With longer cooking times, the degradation of hemicelluloses would be expected to reduce fibre strength, thus the decrease in tensile strength.

Tensile strength is highly dependant on the amount and quality of fibre bonding (Casey 1981). Fibre length is also believed to play a role. Multiple regression results supported this, with fibre length playing a significant role in the prediction of tensile strength. Very long fibres entangle with one another very easily, thus resulting in poor sheet formation. In such sheets, due to low uniformity, there are greater areas of weakness. On the other hand, shorter fibres are able to mat together easily and due to greater area of contact between them, can form more interfibre bonds. This would contribute positively to the strength of the sheet. The SEM images (Appendix D), at the 650 beating level, clearly showed that the handsheets from older material, with longer fibres, were less compact compared to the younger material. Also, even though the fibres from the older sites were fully collapsed, they appeared to be less conformable. This probably is due to the older material having very thick walls, which make their fibres more rigid, compared to the fibres from the younger material, which are thin walled and more collapsible.

During the course of the cook, fibre length in each site decreased, with this decrease being more pronounced in the older sites. The cooking times where fibre length was decreased markedly were sometimes accompanied by increases in tensile strength. This could possibly be due to the aforementioned positive impact of decreases in fibre length on sheet formation. However, accompanying this positive effect of decreasing fibre length with increasing cooking time on tensile strength, was the fact that longer cooks resulted in the fibre losing more cellulose and hemicellulose. This would cause the fibres to become weaker. Since hemicelluloses are believed to play a key role in promoting interfibre bonding, degradation of these polymers would have an adverse effect on bonding. Therefore, whether tensile strength will be positively or negatively impacted on during the course of the cook will depend on the opposing factors of the degree of fibre damage and the degree to which the decrease in fibre length can improve the uniformity and bonding in the sheet. It will also be affected by the residual lignin content.

9 years: It was firstly noted that from the 35 minute cook to the 65 minute cook, there was an increase in tensile strength. At very short cooking times, much lignin would still be present in the fibres. Lignin hinders the imbibition of water into the fibres. This in turn would prevent fibres from swelling and becoming more conformable. After sufficient lignin was removed to allow water to enter the fibres, tensile strength increased due to an increased amount of fibre bonding. This increase in tensile strength from the shortest cooking time to the next highest cooking time (i.e. from 35 minutes to 65 minutes) was more pronounced for the shorter beating levels. This would be expected since higher amounts of beating results in even stiff undercooked fibres becoming more flexible, thus enhancing interfibre bonding. For 650 beating, with increasing cooking time the small changes in fibre length that occurred did not significantly improve the tensile strength of the fibres, but maintained it constant from 65 minutes to 120 minutes of cooking.

10 years: Here it was seen that the tensile strength, at all but the highest beating level, was maintained nearly the same over long periods of cooking (65 – 120 minutes). The increase in tensile strength from the 35 minute cook to the 65 minute cook, for the lowest beating level, could indicate that a certain amount of lignin needs to be removed to allow for fibres to imbibe water for fibre swelling to occur, and thus promote bonding.

13 years: The positive impact of decreases in fibre length (from 65 to 85 minutes) on tensile strength was clearly seen at all but the lowest beating level, where the tensile strength of the fibres decreased with increases in cooking time.

14 years: Here, the positive impact of decreases in fibre length was most marked at the two highest levels of beating. At the lowest beating level, no improvement in tensile strength was seen with increasing cooking time. It was also evident that rapid deterioration of tensile strength occurred after the maximum was achieved.

20 years: The decrease in fibre length from the 85 to 95 minute cooks resulted in tensile strength increasing at the shorter beating levels (100 and 250 beating), and remaining constant at the longer beating levels. Further decreases in fibre length, at the higher cooking times, improved the tensile strength only at the highest beating levels (450 and 650 beating).

21 years: The most marked increases in tensile strength due to decreasing fibre length occurred at the lower beating levels.

c. BURST (Figs. C-7 and C-15 [Appendix C])

The decrease in burst strength with increased beating (Fig. C-7) was in accordance with findings by Stairs *et al.* (1966), Robertson (1991), Smook (1992) and Law *et al.* (1999). Casey (1981) states that there are two factors that are responsible for bursting strength viz. fibre length and interfibre bonding, with the latter playing a greater role. Since bursting strength is a test of the weakest part of the paper, it is affected by the formation of the sheet. The negative impact of very long fibres on paper formation has already been discussed.

9 years: The impact of insufficient delignification at the 35 minute cook can be seen at the 100 beating level. A higher amount of beating at this cooking time was adequate to increase the flexibility of the fibres, and increase the burst strength. This was evident in the decrease in burst from the 35 to 65 minute cooks, for all beatings except the 100 beating level.

10 years: Here it can be seen that the highest burst strengths occurred at the shortest cooking time, at all levels of beating. The possible positive impact of the slight decrease in fibre length from 85 to 120 minutes of cooking, on burst could be seen as burst remaining fairly constant over this cooking period, especially at the higher levels of beating. Again it is stressed that the assumption of decreases in fibre length appearing to impact positively on burst strength are limited to the boundaries of this study. Another factor that could result in burst strength increasing could be the greater amount of lignin removed at the 120 minute cook, which would result in a greater ability for interfibre bonding to occur, thus the increase in burst strength.

13 years: The sudden increase in burst strength from the 65 to 85 minute cooks, at all beating levels, was probably indicative of the positive impact of the slight decrease in fibre length that occurred during these cooking times or the greater amount of interfibre bonding that would result from a greater amount of delignification. It was interesting to note that even at the highest cooking times (i.e. from the 120 to 180 minute cook), burst strength for this compartment did not deteriorate rapidly as it did for the other sites.

14 years: At the shortest cooking time, it appears that enough lignin was removed to allow for the sufficient interfibre bonding to occur, since the burst strength was at the maximum after this cooking time. From Fig. 5-8, it was seen that shortening of the fibres from this site occurred from the 65 minute cook onwards. The positive impact of this can be seen in the increase in burst up to a local maximum, for that beating level, at the 95 minute cooks. Thereafter, fibre deterioration and loss of hemicelluloses with increasing cooking time possibly outweighed the positive effects of decreasing fibre length.

20 years: Decreases in fibre length started occurring from the 65 minute cook. At the highest beating levels, these decreases in fibre length did not improve the burst strength with increasing cooking time. However, at the two lowest levels of beating, burst increased from 65 to 85 minutes of cooking, and then deteriorated rapidly for the shortest beating level, but

extremely slightly for the 250 beating level. Thus, it was evident that decreases in fibre length, accompanied by moderate beating, could reduce the rate of deterioration of burst with increased cooking.

21 years: From Fig. 5-8 it was seen that a large decrease in fibre length occurred, for this site, from the 85 to 95 minute cooks. Accompanying this decrease in fibre length was the marked increase in burst at the highest beating levels. However, further fibre shortening was not able to offset the decrease in fibre strength that occurred at high cooking times. The reduction in burst that occurred from the 95 minute cook onwards was indicative of this.

It was evident from the results obtained that changes in fibre length did not have as marked an impact on burst strength as it did on tear and tensile strength. Kibblewhite, Evans, Riddel (1997) found that burst was not influenced by fibre length.

d. ZERO-SPAN TENSILE STRENGTH (Figs. C-8 and C-16 [Appendix C])

From Fig. C-16 it was seen that the older material achieved higher zero-span strengths than the younger material. Increases in zero-span with beating have been noted in numerous studies (Britt & Yiannos 1964). Since it was not possible in this study to separate the effects of irreversible deformation[ξ], due to cooking time (chemical damage) and beating (mechanical damage), and reversible deformation (i.e. straightening of fibres during beating), a measure of fibre strength from these measurements could not be made. However, reversible damage could be used to explain the increases in zero-span with beating (Mohlin *et al.* 1996). This is due to beating straightening the fibres, mainly through the removal of angular folds and kinks (Page 1985), which are areas of weakness. Multiple regression carried out at kappa 20-30 (Appendix D1) at the 100 and 650 beating levels showed that wood cellulose proved to be an excellent predictor of zero-span at both beating levels, accounting for more than 80% of the variation in zero-span. Seth & Chan (1999) stated that pulp fibres derive their strength from the amount and condition of cellulose in the fibre walls. In the absence of information regarding the wood properties, the ratio of fibre length to fibre diameter in pulp would also prove to be a reliable indicator of zero-span, with it accounting for more than 70% of the variation, at both beating levels.

[ξ] The concepts of reversible and irreversible deformation are discussed in section 2.14.5.

6.4 Variation of strength properties [evaluated at constant freeness] with cooking time

Results were compared at a constant freeness of 500 CSF. Comparisons at this freeness value are generally made on softwood pulp. However, due to the pulps from the 35 minute cooks not attaining a freeness of 500 CSF, it was decided to perform separate analyses at a freeness of 620 CSF on these samples. Sections 6.4.1 to 6.4.7 discuss the change in sheet properties, interpolated at 500 CSF, as a function of cooking time (i.e. from the 65 minute cook to the 180 minute cook). Section 6.4.8 discusses the change in sheet properties, interpolated at 620 CSF, for the 35 minute cooks.

6.4.1 Variation in sheet density [500 CSF]

Fig. 6-1 shows the change in sheet density from the 65 minute cooks to the 180 minute cooks for each of the six compartments.

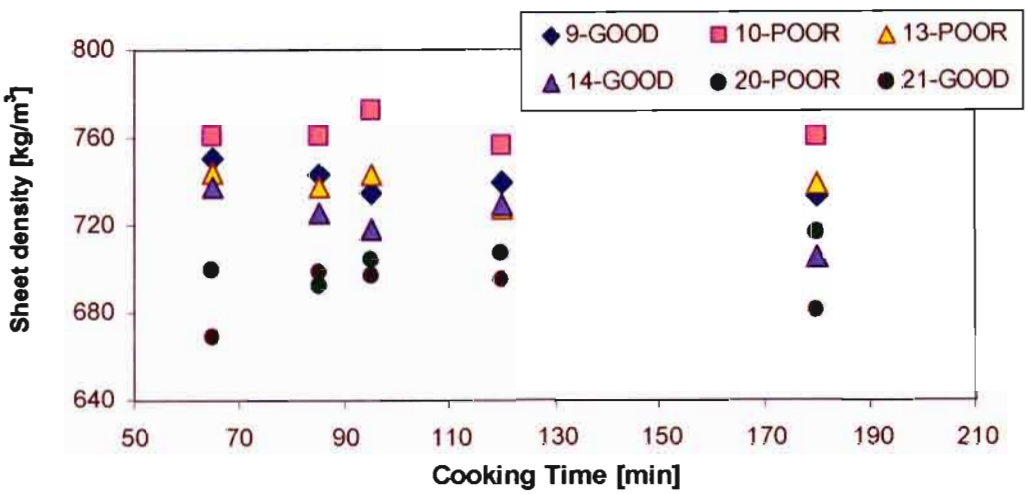


Fig. 6-1. Effect of cooking time on sheet density [500 CSF]

For each compartment, no clearly visible changes in sheet density occurred throughout the cooks. However, there existed marked differences due to tree age, with the younger sites having a significantly higher sheet density than the older sites. Hatton (1997) and Turner *et al.* (2000) and Rudie (1998) also observed the trend of decreasing sheet density with increasing age. From sections 5.4.2 and 5.4.6, it was observed that fibres from the younger sites had thinner cell walls and were more collapsible than those from the older sites. Various authors have shown that thin-walled fibres are more collapsible and are able to conform to one another thus forming a denser mat than less collapsible fibres would (Alexander *et al.* 1968, Smook 1992, Britt 1970). This would explain the higher sheet density that the younger sites exhibit.

Table 6-6: Multiple regression results for sheet density (500 CSF)

Adj. R^2 =	80	Adj. R^2 =	70
WTLD	60	% Cellulose	70
Wood Coarseness	10		
WTCollaps	10		
Adj. R^2 =	**90**	**Adj. R^2 =**	**80**
Pulp FL	80	FL / FD	80
Pulp Galactose	10		

When using only pulp properties to predict sheet density, multiple regression results indicated that fibre length or its ratio to fibre diameter, proved to be key variables in describing the observed trends, with each of these variables alone contributing 80% to the prediction model. The older material had considerably longer fibres than that of the younger sites. With the shorter fibres, less entanglement of the fibres occur, which results in more dense fibre mat during sheet formation, thus the high sheet density observed.

6.4.2 Variation in tear index [500 CSF]

Fig. 6-2 shows the change in the tear strength of the pulp samples, from each compartment, with cooking time.

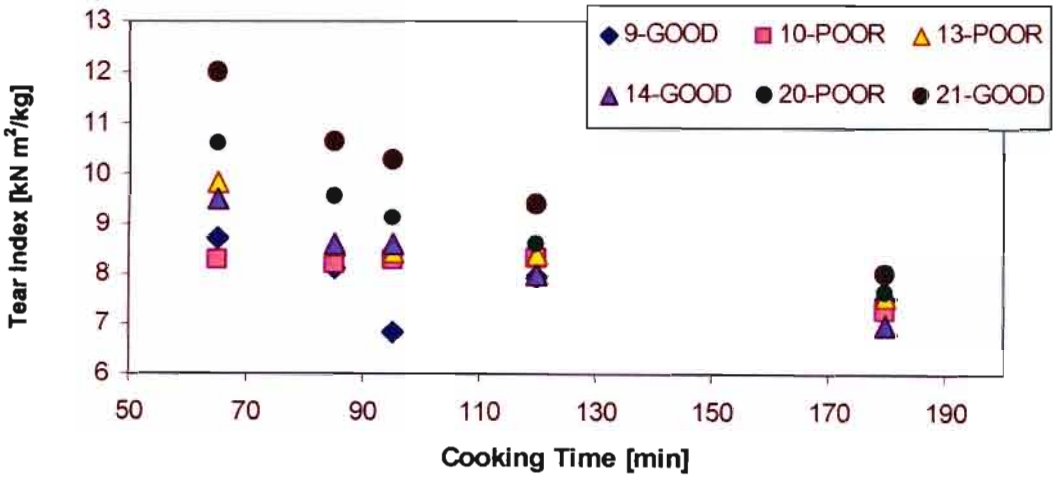


Fig. 6-2. Effect of cooking time on tear index [500 CSF]

It was seen that increasing cooking time had a deleterious effect on tear strength. This decrease in tear occurred at different rates for the various compartments. The rate of decrease of tear strength from the older sites was greater than that of the younger sites, where the tear

strength remained low and changed only slightly with cooking time. The differences in tear among the sites were greatest for the shorter cooking times and became less marked at the longer cooking times. This degradation in tear strength with increased cooking time and the increase in tear strength with tree age have also been observed by Clarke *et al.* (2002) and by Morris *et al.* (1993). Accompanying the loss of lignin, as cooking time increases, is the chemical attack and degradation of the polysaccharides in the fibre walls. Thus, the polysaccharides from the cell walls of fibres are progressively degraded and removed during pulping. This, in turn, results in the loss of fibre strength. Since tear strength is highly dependant on the strength of fibres, as cooking time increases the tear strength of pulp decreases. The results in this study indicate that older material is better suited to high yield pulping.

The oldest sites had the highest tear, at all cooking times. The thicker walls and longer fibres of older material are known to impart high tear strengths to the fibres. This increase in tear with increasing age is a well documented fact and was also observed in many studies (Turner *et al.* 2000, Hatton 1997, Morris 1993 and Clarke *et al.* 2002). Svedman *et al.* (1998) also found mature wood, with long, strong fibres to yield kraft pulp products with high tear strengths, at high yield.

Table 6-7: Multiple regression results for tear index (500 CSF)

Adj. R^2 =	30	Adj. R^2 =	20
Runkel	30	% Cellulose	20
Adj. R^2 =	80	Adj. R^2 =	70
Pulp FL	50	Pulp FL	50
Kappa	30	Yield	20
Adj. R^2 =	60		
Pulp Coarseness	50		
Pulp Arabinose	10		

Multiple regression analysis identified the pulp Runkel ratio (accounting alone for 30% of the variation in tear strength) and fibre length and pulp coarseness (each accounting alone for 50% of the variation in tear strength) as the key variables used to predict tear strength. Also, as shown in Fig. 5-8, the older sites had longer fibres than the younger sites. This could also contribute to the older sites having higher tear strength than the younger sites, since tear strength is also influenced by fibre length (Clarke 2000), with longer fibres generally

imparting higher tear strength, since longer fibres naturally provide more points of bonding and being pulled a longer average distance from within the fibre network that makes up paper. The multiple regression results for predicting tear strength from pulp properties supported this reasoning (see Table 6-7).

6.4.3 Variation in tensile index [500 CSF]

Fig. 6-3 shows the variation of tensile strength with cooking time.

The tensile strength of pulp from all compartments decreased with cooking time. Fibre strength is one contributor to the tensile strength of pulp (Stephenson 1950). Tensile strength is also highly dependant on the number and strength of the interfibre bonds (Stephenson 1950). As previously mentioned, fibres may become chemically degraded and weakened in the pulping process. These fibres would produce weak paper i.e. the fibre can be easily ruptured in the testing of the paper due to it being weak and is also unable to withstand the physical treatment of the beating action. Refining is an essential preliminary to paper manufacture, thus maintaining a high enough initial fibre strength is important.

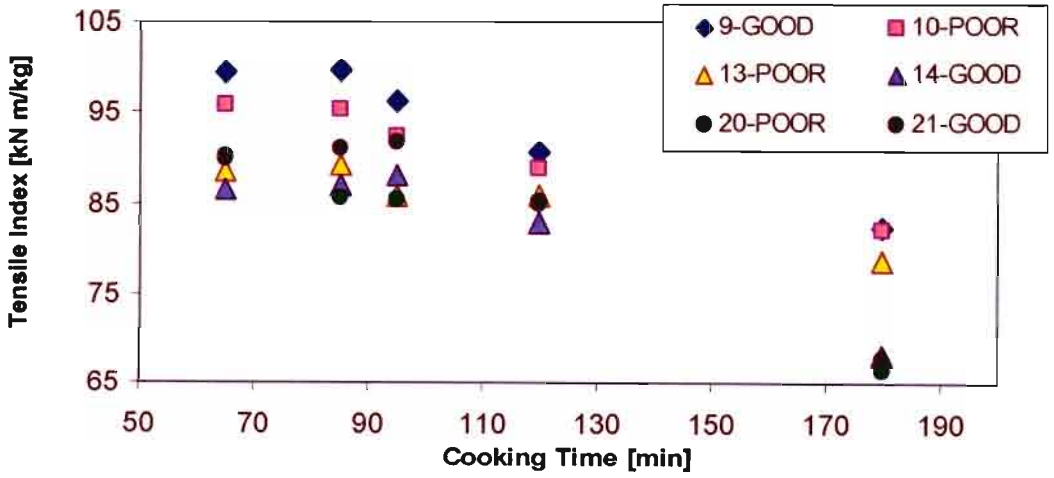


Fig. 6-3. Effect of cooking time on tensile index [500 CSF]

The impact of site quality was evident in the shorter cooking times, with the good sites having higher tensile strength than the poor sites. No marked differences in tensile strength could be seen at these cooking times. However, for the good sites, the tensile strength of the youngest material was higher than that of the older material.

The two youngest compartments (i.e. the 9 and 10 year old sites) exhibited higher tensile strength values than the other compartments. From the 65 minute cook to the 85 minute cook, no significant change in tensile strength was observed for any of the compartments. The greatest rates of change in tensile strength occurred at longer cooking times. At the longest cook, differences in tensile strength due to age became more evident, with the compartments separating into two distinct groups, with the three youngest sites having higher tensile strength than the three oldest sites. The deleterious effect of increasing age has on tensile strength was also observed by Morris *et al.* (1993), Hatton (1997), Britt (1970) and Turner *et al.* (2000). The high tensile strength exhibited by the younger compartments could be due to these sites having, on average, more collapsible fibres than the older sites. Since these younger fibres were more flexible, they would be able to conform to the surface of other fibres, thus increasing the available surface area for strong interfibre bonding to occur (Ivkovish 2000). It is believed that interfibre bonding in paper is the predominant determinant of tensile strength (Stephenson 1950), thus the higher tensile strengths shown by the younger sites.

Fibre length is also a contributor to the tensile strength of paper with longer fibres generally imparting higher tensile strength to the pulp. However, there is a limit to which longer fibres will be beneficial to paper strength, since too long fibres result in uneven sheet formation, with thick and thin areas. This has a negative impact on strength. This may be the reason for the older sites having, in general, lower tensile strength than the younger sites. An exception would be the 21 year old site, which, even though having had the longest fibres, came closer than the other compartments in achieving the strength properties shown by the two youngest sites.

Table 6-8: Multiple regression results for tensile index (500 CSF)

Adj. R^2 =	20	Adj. R^2 =	60
Wood Klason	20	Kappa	50
		Pulp LD	10

6.4.4 Variation of burst index [500 CSF]

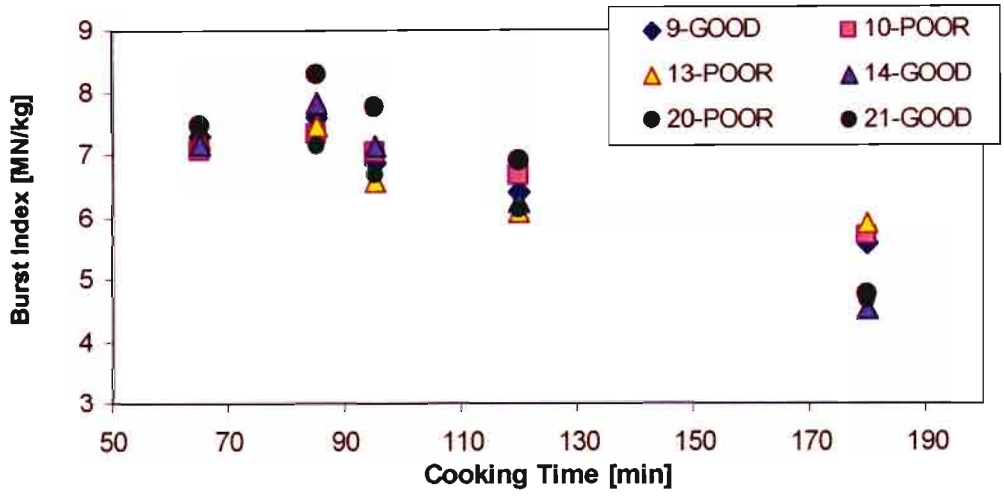


Fig. 6-4. Effect of cooking time on burst index [500 CSF]

All sites showed a decrease in burst strength with cooking time. Unlike tensile strength, at the shorter cooking times, less marked differences in burst among the compartments occurred. The good sites showed a slight peak after 65 minutes of cooking, and thereafter also steadily decreased as pulping proceeded. The behaviour of burst was very similar to that of tensile strength at the 180 minute cooks, where the impact of tree age became evident, with younger sites yielding higher strength. This similarity between tensile-and-burst-strength behaviour has been previously observed in pine species (Morris *et al.* 1993). This relationship is well documented for *Eucaluptus* species as well. Multiple regression results for burst strength indicated that 50% of the variation could be accounted for by pulp glucose. The impact of chemistry on burst strength was seen here again. No other regression models could be developed for burst.

6.4.5 Variation of zero-span [500 CSF]

Fig. 6-5 shows the variation in zero-span strength with cooking time.

Zero-span strength is generally used as an indication of fibre strength (Dinwoodie 1966). It is evident in Fig. 6-5 that the strength of fibres from the three youngest sites was considerably less than that of the three older sites. Britt (1964) stated that decreasing fibre length affects zero-span strength adversely. This agrees with findings here, as the younger sites were shown to have considerably lower fibre lengths than the older sites.

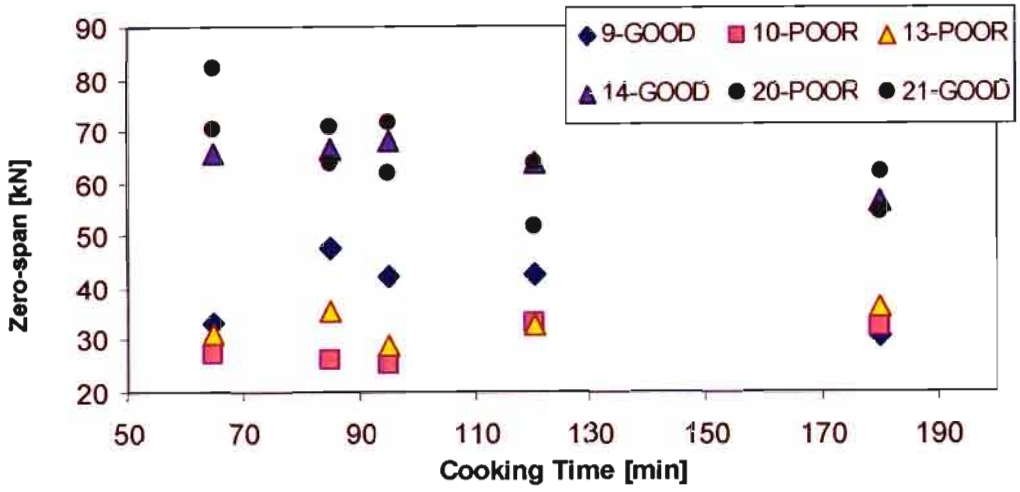


Fig. 6-5. Effect of cooking time on zero-span tensile strength[500 CSF]

The decrease in zero-span strength with cooking time was more pronounced in the older sites, with this strength property remaining virtually unchanged for the younger sites. The decrease in fibre strength with cooking time could be due to the degradation of hemicelluloses and, to a lesser degree, the degradation of cellulose from the cell walls of fibres, which in turn weakens the fibres. Multiple regression results for zero-span strength indicated that either the wood cellulose content or the ratio of pulp fibre length to diameter were able to predict zero-span best. Both these variables increased with tree age. The large amount of cellulose present in the older material would yield stronger fibres since cellulose is the main structural component of cell walls.

Table 6-9: Multiple regression results for zero-span tensile strength(500 CSF)

Adj. R^2 =	**80**	**Adj. R^2 =**	**80**
% Cellulose	80	WTFD	70
		WTLD	10
Adj. R^2 =	**60**	**Adj. R^2 =**	**70**
Pulp Coarseness	60	Pulp FL	70
Adj. R^2 =	**80**		
FL / FD	80		

6.4.6 Variation of stretch [500 CSF]

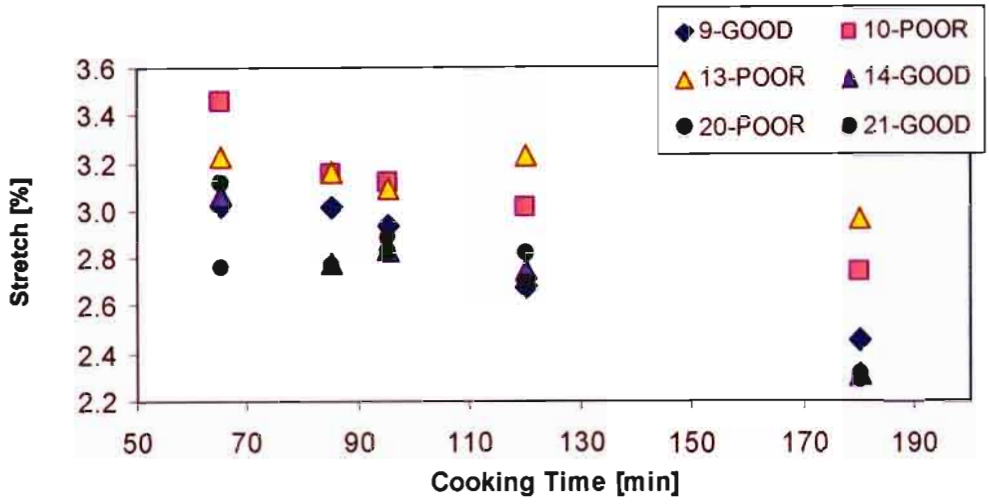


Fig. 6-6. Effect of cooking time on stretch [500 CSF]

The general trend was a decrease in stretch with longer cooking times and with increasing age. Hatton (1997) observed that juvenile wood pulps were more extensible than that of mature wood. It was evident (as shown in the figure above) that younger sites had higher stretch than older sites. As already mentioned, younger material is made up of a greater proportion of juvenile wood compared to older material. Also, the older material, in this study, had longer fibres than that of the younger sites. Broderick *et al.* (1996) also found longer fibres to have a negative effect on stretch. This difference in stretch due to age was most marked at the longest cooking time.

Table 6-10: Multiple regression results for stretch (500 CSF)

Adj. R^2 =	30	Adj. R^2 =	40
Wood Coarseness	20	% Cellulose	20
Kappa	10	Wood Klason	10
		Wood Xylose	10
Adj. R^2 =	**40**		
WTFD	30		
Kappa	10		
Adj. R^2 =	**50**	**Adj. R^2 =**	**30**
% Cellulose	20	Kappa	20
Pulp Glucose	20	Pulp Coarseness	10
Wood Klason	10		

6.4.7 Variation of TEA [500 CSF]

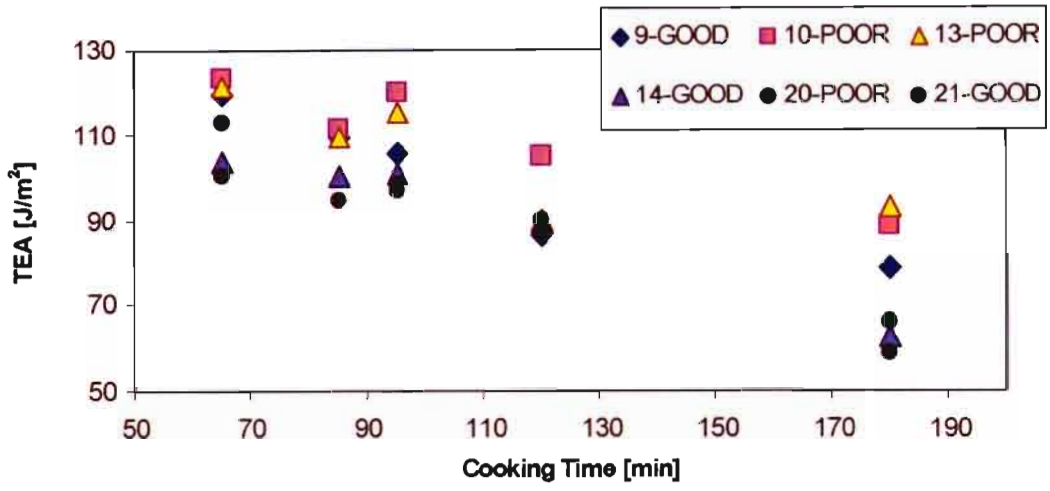


Fig. 6-7. Effect of cooking time on tensile energy absorbed (TEA) [500 CSF]

The general trend was a decrease in TEA with increases in cooking time. The younger sites had higher TEA than the older sites. This difference due to age became most marked at the longest cooking time as the sites separated into distinct groups with younger trees having higher TEA than the older ones. This behaviour of TEA was similar to that of burst index and tensile index. Morris *et al.* (1993) also observed that TEA at 500 CSF decreased with increasing age.

Table 6-11: Multiple regression results for TEA (500 CSF)

Adj. R^2 =	70	Adj. R^2 =	70
Kappa	60	Kappa	60
% Cellulose	10	Wood Coarseness	10
Adj. R^2 =	**80**		
Kappa	60		
Pulp CWT	10		
Yield	10		

6.4.8 Variation of strength properties at 620 CSF.

Fig. 6-8 shows the graphs of the strength properties (at 620 CSF) as a function of tree age.

- **Sheet density.** Very small differences in sheet density occurred among the compartments. The younger sites had slightly higher sheet density than the older sites. The same trend occurred with the results compared at 500 CSF, at the various other cooking times. The possible reasons for this trend have already been discussed in section 6.2.1. In summary, the reasons for this trend are due to the younger sites having shorter and more collapsible fibres than the older sites, thus the higher sheet density observed in these young sites.

- **Tear index.** Tear index increased with increasing age. Here again, the same trend occurred with the results at 500 CSF for the other cooking times. The reasons for tear increasing with tree age have already been discussed in section 6.2.2. Ultimately, tear strength is a function of the strength of the fibres. The older sites, which had thicker cell walls, would be able to withstand the degradation of the hemicelluloses from the walls of the fibres to a greater degree, than the thin walled younger fibres, in which the degradation of the hemicelluloses from the cell walls would show up dramatically in a loss in tear strength.

- **Tensile index.** The inverse relationship between tensile index and tree age was also found at the other cooking times, in the analysis at 500 CSF. Section 6.2.3 discusses possible reasons for this. This trend, being associated with the number and strength of interfibre bonds, is linked to fibre collapsibility, since greater surface area is available for interfibre bonding to occur in highly collapsed fibres. The younger sites, having highly collapsible fibres compared to the older sites (see section 5.4.6) would mean that due to the fibres conforming to one another, there would be a greater surface area available for interfibre bonding to occur, thus the observed high tensile strength. The oldest site strayed from the trend of decrease in tensile strength with increasing age. The effect of highly collapsible fibres having a positive influence on tensile strength did not hold true here, as this compartment had the least collapsible fibres. There are various other factors that could have contributed to this behaviour. Fibre length was shown to impact positively on tensile strength, thus the effect of this compartment having the longest fibres compared to the other compartments could be impacting positively on the tensile strength of this compartment. Also, the fibres from this compartment had thick cell walls.

- **Burst index.** Burst strength decreased with increases in tree age. Burst strength exhibited similar trends as those observed for tensile strength. Both these strength properties are dependant on the number and strength of the interfibre bonds. Thus, the same reasons for the trends observed for the comparison of tensile strength with age, can explain the results obtained here.

- **Tensile energy absorbed (TEA).** The findings here were similar to that of the TEA interpolated at 500 CSF for the other cooking times (section 6.4.4), with TEA decreasing with increasing age. The pattern observed here for differences in TEA with increasing age was the same as that obtained for tensile-and-burst-strength (sections 6.2.7 and 6.2.8 respectively).

- **Stretch.** There existed a general decrease in stretch with increasing age. There were very small differences in stretch, due to site quality, in the younger age range. However, some differences, due to the 20 year old site, exist in the older material.

- **Zero-span.** There existed a general increase in zero-span with tree age. Zero-span is believed to be a good indication of fibre strength. Older material, with their thicker cell walls and longer fibres would be expected to have higher inherent fibre strength. If in fact zero-span gives an indication of fibre strength, then the results of increasing fibre strength with increasing tree age would agree with that, since older material generally have stronger fibres than younger material.

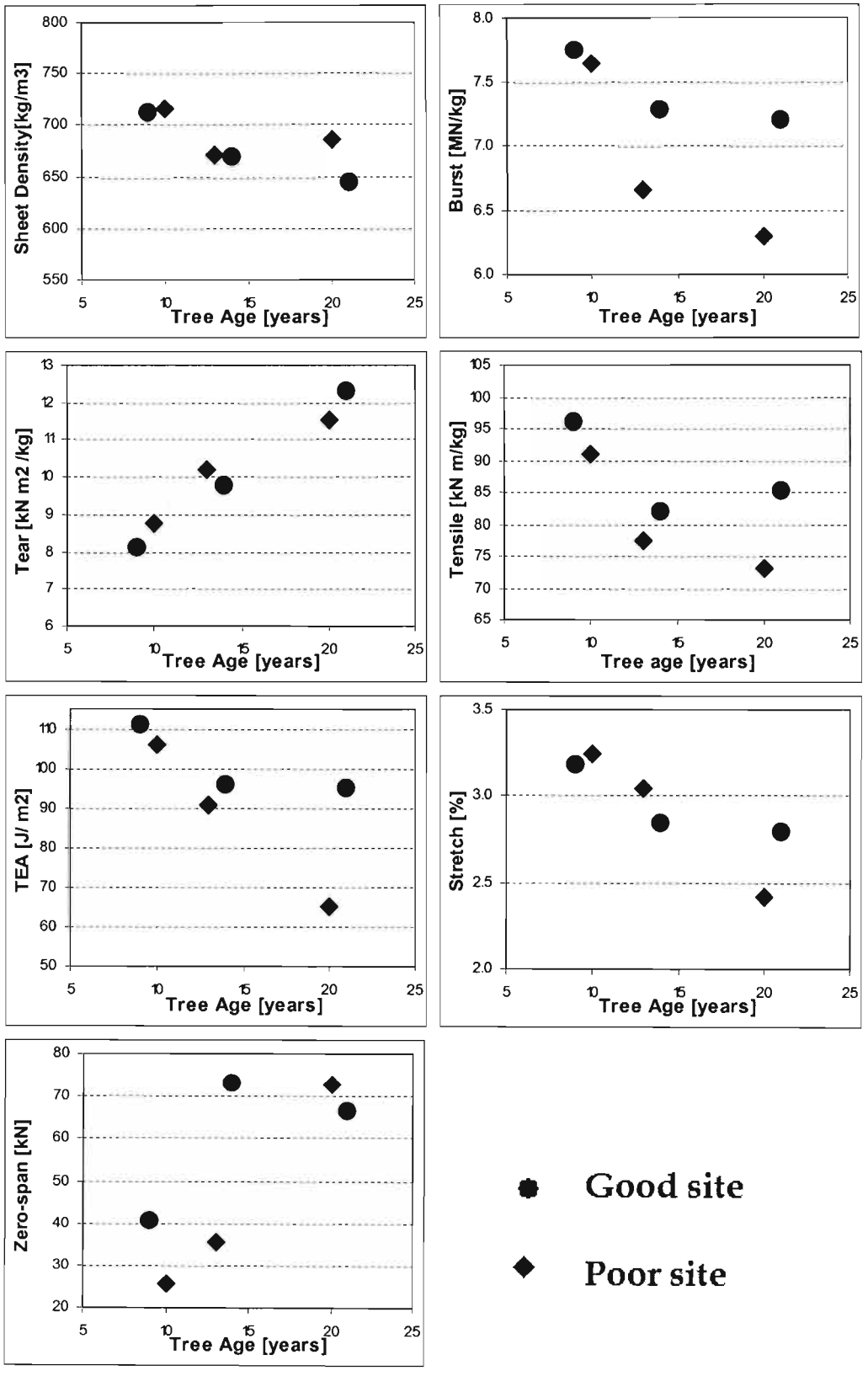


Fig. 6-8. Effects of tree age on pulp strength at 620 CSF

6.5 Variation of Strength Properties [at Constant Sheet Density] with Cooking Time

Fig. 6-9 shows that graphs of the strength properties, interpolated at constant sheet density, as a function of cooking time.

Freeness. No definite trend existed between freeness and cooking time. It was clearly evident that the older sites achieved lower freeness values than the younger sites. This behaviour would generally not be expected, since freeness depends to a significant degree on the collapsibility of fibres, and since the younger sites had more collapsible fibres, it would naturally be assumed these sites would have had lower freenesses, due to greater packing of the fibres. Also, the younger sites generated more fines than the older material (see section 5.4.5). This would be expected to result in the younger sites having a lower freeness than the older material as the fines would fill up the voids between the fibres, thus creating a highly dense network that poses much resistance to the passage of water through it. However, the reverse held true. This anomalous behaviour could be explained by the nature of the fines fraction, which, according to Corson (1999), influences the pulp drainage characteristics. It was found in that study that the fines of juvenile wood are more particulate and potentially faster draining than those of mature wood, which are more fibrillar and contribute more effectively to the reduction in freeness. Since younger material are made up of a greater proportion of juvenile wood than mature wood (Leggate *et al.* 1998), the aforementioned explanation could hold true for the higher freeness exhibited by the younger material.

Tear Index. Tear index decreased with increases in cooking time. This trend was expected and was also observed for the results for tear interpolated at constant freeness. Tear is strongly dependant on fibre strength, thus as cooking time increases fibre strength decreases due to the degradation of polysaccharides from the cell walls of the fibres, hence the decrease in tear with increasing cooking time. No clearly discernable trend due to age could be seen. However, at the shortest cooking time, the younger sites had a lower tear index than the older sites. The reverse held true at the longest cooking time. Also, for the longest cooking time, the poor sites in each age range had a higher tear index than the good sites in that age range.

Tensile Index. There existed a general decrease in tensile index with increases in cooking time. No definite trends due to tree age and site quality were evident.

Burst index. Burst index decreased with increases in cooking time. The two oldest sites clearly had higher burst strength than the younger sites, with these differences due to tree age becoming less marked at the longer cooking times. For the 21 year old site, the increase in burst from the 85-to-95 minute cook could be accounted for by the large decrease in fibre length that occurred between these cooking times. The positive impact of decreases in fibre length has already been thoroughly discussed in this chapter.

Zero-span tensile strength. Again, here it was seen that the older material had higher zero-span strengths than the younger material. The possible reasons for this have already been discussed.

Stretch. Stretch decreased with increases in cooking time. No definite trend with age was evident. The differences among the sites were most marked at the shorter cooking times, with them approaching a similar value at the highest cooking time.

TEA. All sites, except the 20 year old site, showed a decrease in TEA with increasing cooking time.

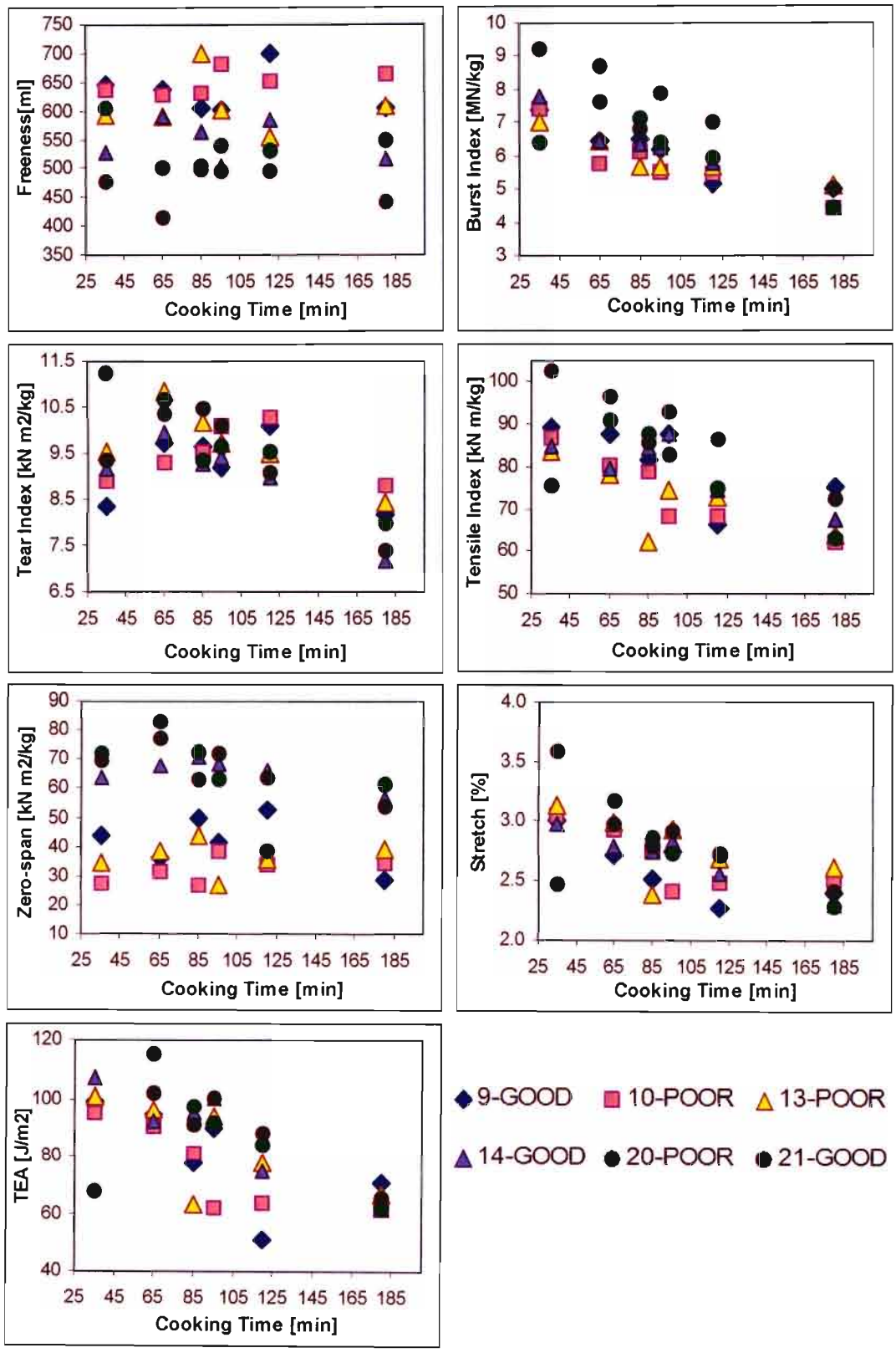


Fig. 6-9. Effects of cooking time on pulp strength at constant sheet density.

Table 6-12: Multiple regression results for strength results at constant sheet density.

Freeness			
R^2 =	**70**	R^2 =	**70**
WTLD	50	% Cellulose	70
EW Density	20		
R^2 =	**70**		
FL / FD	70		

Burst			
R^2 =	**70**	R^2 =	**50**
Yield	50	Kappa	30
Pulp FL	10	% Cellulose	20
Pulp Arabinose	10		
R^2 =	**50**		
Pulp Glucose	50		

Tensile			
R^2 =	**20**		
LW Density	20		
R^2 =	**40**	R^2 =	**50**
Pulp Coarseness	40	Pulp Glucose	30
		Pulp FL	20

Tear			
R^2 =	**20**	R^2 =	**30**
Yield	20	Yield	20
		Muhlsteph	10

Stretch			
R^2 =	**50**	R^2 =	**40**
Pulp Glucose	40	Kappa	30
Yield	10	Wood Glucose	10
R^2 =	**40**		
Kappa	30		
FL / FD	10		

Zero-span			
R^2 =	**70**	R^2 =	**70**
WTFD	60	% Cellulose	70
WTLD	10		
R^2 =	**70**	R^2 =	**70**
FL / FD	70	Pulp FL	70

TEA			
R^2 =	**30**	R^2 =	**38**
Pulp Coarseness	30	Pulp Glucose	38
R^2 =	**50**		
Yield	40		
Pulp FL	10		

6.6 Conclusions

- Older material achieved higher maximum tear and burst strength than the younger material, with increasing age negatively impacting on tensile strength. Therefore, when aiming to improve the quality control of pulp products, it is clear that kraft mills should segregate the incoming wood according to the age.

- The results in this study indicate that younger material can attain higher tensile strength than older material, though at the expense of very lower tear strengths. However, the tear strengths at these higher tensile strength values are comparable with, if not higher than, that obtained by hardwood species (Rampersadh 2005). The implications of this is that younger *P. patula* trees could be used for grades of paper where very high tear strength is not essential, but tensile strength is (e.g. tissue paper) and that older material can be used solely for the purpose of providing the high tear strength needed by certain paper grades (e.g. linerboard). Thus the results in this study indicate that by understanding the manner in which the fibres from very young material react under various process conditions, effective treatment of younger trees can result in the development of their optimum strength potential. However, the lower pulp yields attained by younger material are a limiting factor for their use.

- Low yield pulps (obtained by higher cooking times) were easier to refine than high yield pulps. Increasing cooking time had a deleterious effect on strength properties, when compared at constant freeness of sheet density. Both these factors have important implications when considering high yield pulping processes.

- At constant freeness or sheet density, older sites had higher tear and burst strength than the younger material. For tensile strength, the trends observed depend on whether the results are compared at constant freeness or sheet density. At constant sheet density, the younger material achieved higher tensile strengths, with the opposite holding true at constant sheet density. This has also been observed in a study by Clark (1990). The results also indicated that in applications where high tear strength is required, high yield pulping of older material should be used.

- Apparently, a minimum amount of mechanical work needs to be applied to pulps of widely differing morphology before fibre characteristics become important in determining drainage properties. The results shown at the 35 minute cooks bear out the above

conclusion, with pulps decreasing in freeness with decreasing percentage of earlywood. The youngest and oldest material showed the most significant differences in their refining potential at this cooking time.

- It is clearly evident that a decrease in fibre length with increased pulping had a marked positive influence on tear and tensile strength. It is a widely held view that increases in fibre length contributes positively to pulp strength. However, excessively long fibres can become liabilities, since they entangle easily with one another and result in uneven fibre distribution in the sheet. Fibre length and tree age, for any species, are very strongly positively correlated. The influence of each of these factors need to be considered separately, so that the positive contribution of stronger fibres of older material to pulp strength is not misinterpreted as longer fibres impacting positively to strength. Thus, there are two issues that need to be considered, viz. fibre coarseness and fibre length. The results from this study appear to indicate that relationships ascribed to fibre length may be related, at least in part, to some other variable that also is strongly related to age.

- Because of the great influence of fibre morphology and chemistry on refining rates and on the resultant strength properties, fibres of greatly differing chemical and anatomical characteristics should not be refined together if beating energy and pulp strength are to be optimised.

CHAPTER 7

Summary & Recommendations

The results from this study have demonstrated that tree age is a major determinant of wood properties in *P. patula*. Tree age played a more important role than site quality. It is recommended that, in future, as much information regarding the nature of the sites on which sampling material was obtained, be recorded.

The density and anatomical property profiles, from pith to bark, needs to be investigated in more detail in order to understand how the radial distribution of these properties influences the properties of the pulp produced. Using average values can be misleading, as various combinations of different values for any of the wood properties can result in the same average value.

It was concluded that most paper properties can be predicted with a high degree of accuracy from knowledge of wood or pulp fibre variables. This should be used by paper mills to allocate the wood to applications for which it is best suited.

Classification and segregation of the incoming raw materials arriving at pulp mills could help in controlling the ratio of juvenile and mature wood and therefore the quality of the pulp produced. The results indicated that older material are best suited for those end-products that require very high tear strength. Younger material produced very high tensile strengths, and tear strengths that were comparable to hardwoods. Therefore, younger material can, at least in part, be used in applications similar to which hardwoods are used. However, the disadvantages of using younger material are many. These include lower pulp yields and higher cooking chemical consumption. Therefore, determining whether the use of younger softwood material in mills would be economically viable should be considered in more detail.

The results indicate that for optimum pulp yield, trees of age greater than 20 years should be harvested. From the point of view of production economy, this may not however be economically viable for the foresters. Therefore, there needs to be a trade-off between wood yield (i.e. the mean annual increment) and pulp yield.

The excellent relationships obtained for prediction of whole-tree estimates of wood density and anatomical properties from results obtained at breast height are promising for optimising this non-destructive sampling technique. Breast height analyses can also be used by mills for classification of wood from various sites.

Industry requires a minimum freeness level for machine runnability. Therefore, it is common practise to compare results at a certain freeness level. However, if there is a requirement for revealing the full potential of fibres, then comparisons should not be limited to this single condition. Instead, pulps within a freeness range that is acceptable to ensure machine runnability should be analysed for the optimum strength that meets the end-products requirements.

Fibre deformation (i.e. kink and curl) is a very important property that can probably explain some of the confusing and contradictory results found in literature. In future, fibre deformations should be studied more extensively, with tools for quantifying the various types of deformation being developed. The MorFi fibre analyser can measure kinks in pulp samples. However, methods need to be developed for other types of deformations (such as curl, folds etc). This would especially useful for the zero-span tensile test, where the possible effects of fibre deformations on strength are evident. Unless fibres are straight, the zero-span test will not reflect their strength (Seth & Chan 1999). Measurement of other strength properties may also be sensitive to fibre deformation. Thus, more research needs to be done on rectifying this problem, either by quantifying the various types of deformations in order to apply a correction factor to the measured strength values or by straightening fibres prior to making handsheets for strength tests.

Future work that separates the influence of fibre length and tree age on strength properties may be useful. Many of the strength properties that are ascribed to longer fibres may in fact be due to some other property that varies with age (e.g. coarseness).

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APPENDIX A

Sampling Methodology

Trees grow both vertically and radially. In forestry, the measure of site index is related to tree height growth rate. Diameter at breast height is another good indicator of site quality and age relations. In sites where conditions are favourable for high growth rates, both radial and vertical growth would be high. The site index measurement basically determines the mean height of the thickest trees (widest diameter trees) in a certain sampling plot. Younger trees would generally be shorter than older ones. This would result in the site index measurement of younger material being lower than older material, which would make site quality comparisons among sites of different ages very complicated. To alleviate this problem, equations have been developed to determine site index of sites as it would be/have been at a certain age (referred to as base age). These equations basically apply a correction factor for the site index that was calculated using the chosen base age and the current age of the site. This allows for direct comparisons of site index to be made among sites of varying ages.

- **Selection of Sites**

A short list of all possible sites that satisfied the requirements in the project design was made from the compartment listings provided by Sappi and Mondi. All sites that were under investigation in this study were from Sappi.

In order to validate the site index measurements indicated in the compartment listings, the sites in the shortlist were visited and a rapid site-index assessment was firstly made. This procedure is described below.

- At the site, a plot of approximately 15m in radius was randomly chosen.
- Within the chosen plot, the 15 trees which have the thickest diameter compared to the other trees within the plot were selected.
- The heights of these trees were measured using the vertex and transponder. The average of these tree heights was calculated.
- Using the equation below, the site index of that site was calculated. This equation is known as the Chapman-Richards 2-parameter difference equation developed for *Pinus patula* grown in the KwaZulu-Natal Midlands Region (Naidu 2003).

Equation A1:

$$Site\ \ Index\ \ (HD_2) = HD_1 \times \left[\frac{1 - e^{(b_1(age_2))}}{1 - e^{(b_1(age_1))}} \right]$$

Where

Site Index (HD_2)	= Dominant Height at age 20
HD_1	= Mean dominant height (of 20 thickest trees)
e	= base of natural log
b_1	= -0.02955
age_1	= Stand age
age_2	= 20

This preliminary calculation of site index was performed for all the sites in the short-list. From the site index values obtained, the sites that best suited the requirements of the project design were identified.

Once the sites that would be the focus of this study were identified, a more accurate calculation of site index was then performed on each of these sites. The following enumeration procedure was performed within the same plot at each of the chosen compartments, in order to determine site-index for that plot.

- All trees that lay on the border of the plot of 15m in radius were marked.
- The heights and diameter at breast height of all the trees in that plot, including those on the border of the plot was measured.
- The mean height of 20% of the total number of trees measured that were the thickest was found and was used to calculate the site index (at base age 20) for that compartment, using equation A1.

- **Obtaining Samples**
- For each compartment, from the plot in which the site-index calculation was made, 20 trees were randomly chosen. Breast-height (1.3m from the base) on these trees was marked off.
- These trees were felled.
- The total tree height (N.B. include the length of the uncut stump) was measured. This was done easily by measuring the tree height from the mark at breast height to the top of the tree and then adding 1.3m.
- The height of the tree to a diameter of 7cm was measured (this is the total merchantable stem height).
- 1m intervals along the length of the tree were marked to the point of 7cm diameter. 2cm thick discs were cut at these markings. These discs were used for pulping studies.
- For analysis of wood anatomical, discs at breast height, 35% and 65% of the tree height (from the base to 7cm diameter) were also sampled. One 2cm thick disc was sampled at each of these heights.
- The discs were appropriately labeled and transported to the CSIR Forestry and Forest Products Research Center.

Appendix B

Equipment & Equations Used

B1. Wood properties

- **Equipment**

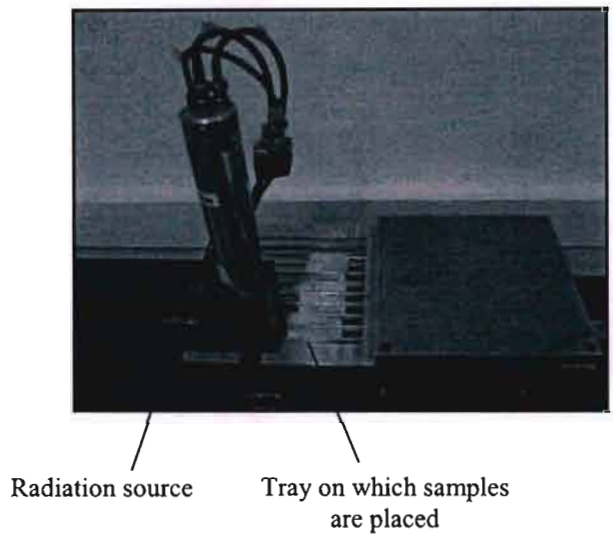


Fig. B-1. Wood densitometer system.

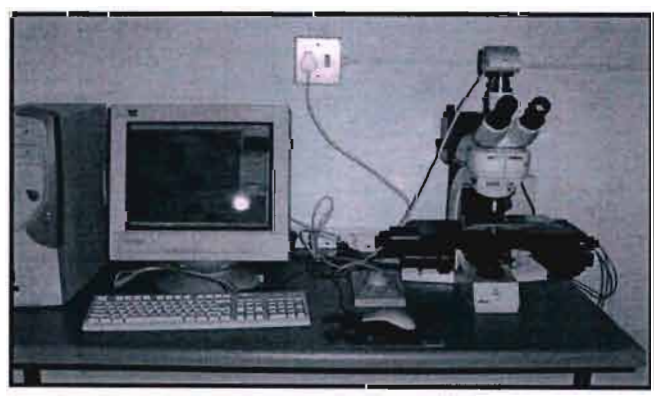
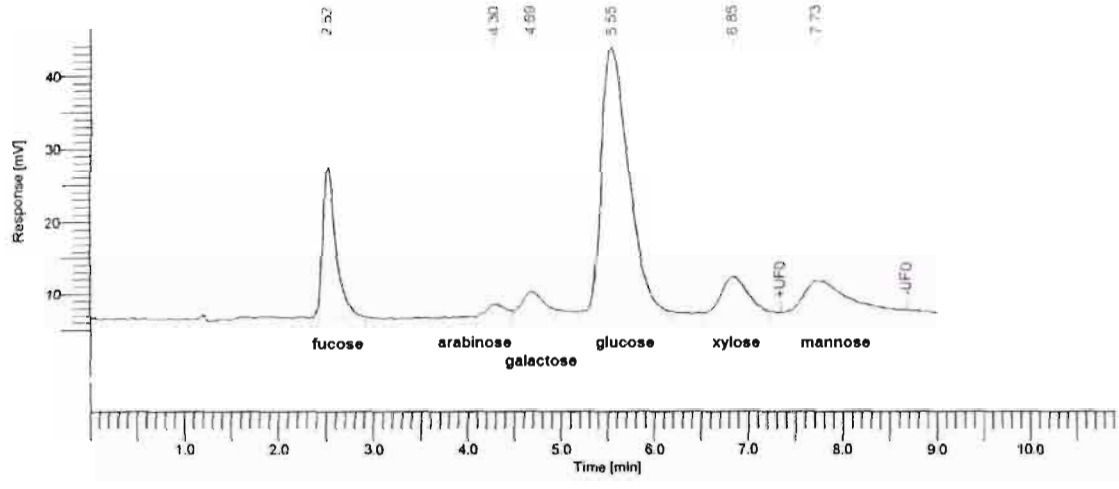


Fig. B-2. Image analysis equipment.

Fig. B-3. HPLC



ffp report

Peak #	Component Name	Time [min]	Area [µV·s]	Height [uV]	Raw Amount
1	Fucose	2.517	201422.00	20810.65	----------
2		4.297	18278.13	1523.11	0.02
3		4.687	37784.87	2691.24	0.04
4		5.553	720600.00	36494.78	0.72
5		6.848	93321.00	4984.74	0.09
6		7.733	130708.24	4299.94	0.13
			1202114.24	70804.46	1.00

Fig. B4. Chromatogram obtained from HPLC

- **HPLC**

High performance liquid chromatography was the method used to analyse the filtrate produced after acid hydrolysis of pulp and wood samples. The five monosaccharides that make up the hemicelluloses are arabinose, galactose, glucose, mannose and xylose. The position of the peaks obtained for these monosaccharides are shown in Fig. B4. The method of using an internal standard, fucose in this study, was used in the analysis. Standards of known concentration of each of the monosaccharides were run first in order to plot a calibration graph that related the area under the peaks of each of the monosaccharides to their concentration. These calibration graphs were used to evaluate the concentration of the monosaccharides from the chromatograms obtained for the wood and pulp samples.

B2. Pulping properties

• Standardisation of cooking liquor

- Total Alkalinity (TA)

10.0 ml of the cooking liquor was transferred into a 250 ml Erlenmeyer flask, together with 100 ml of deionised water. A few drops of phenolphthalein indicator were added. This solution was titrated with 1.0 N hydrochloric acid until colourless (Reading A). A few drops of methyl orange was added to the colourless solution and titrated further until the solution turned red (Reading B).

TA (as Na_2O, g/L) = Reading B x 3.1

- Active alkalinity (AA) & Sulphidity (S)

10.0 ml of the cooking liquor was transferred into a 250 ml Erlenmeyer flask and well mixed with 100 ml of deionised water and 50 ml of a 10% barium chloride solution. A few drops of phenolphthalein indicator were added. The solution was titrated with 1.0 N hydrochloric acid until colourless (Reading C). This solution was thereafter used to determine the sulphidity of the cooking liquor. A few drops of formaldehyde was added to the resultant colourless solution which was thereafter further titrated with 1.0 N hydrochloric acid until the end-point was reached (Reading D).

AA (as Na_2O, g/L) = [(B – ((A – C) x 2))] x 3

S (as Na_2O, g/L) = (D – C) x 6.2

% S = (S / TA) x 100

- **Calculations for quantity of reagents to use to obtain the required pulping conditions**

- The amount, in grams, of cooking liquor to use for each cook depends on the percent of active alkali charge. In this study, this was chosen to be 22%.
  (% AA x oven dry mass of chips) / 100 = Z (g)
  The oven dry mass of chips used was 800g.

- The equivalent volume of this amount of liquor is:
  Vol. of Liquor (ml) = (Z x 1000ml/L) / AA (g/L)
- The total volume of liquid (i.e. water and cooking liquor) used depends on the liquid to solid ratio (L:S), which was chosen to be 5:1 in this study.
  Total liquid volume (ml) = (L:S) x oven dry mass of chips

  Thus the amount of water to be added can be calculated as follows:
  Vol. of water (ml) = Total liquid volume – Vol. of liquor – moisture present in chips

- **Equipment and equations used for pulping**

The digester is made from stainless steel. A degassing step is included in the pulping cycle in order to remove gases that are not condensable in water.

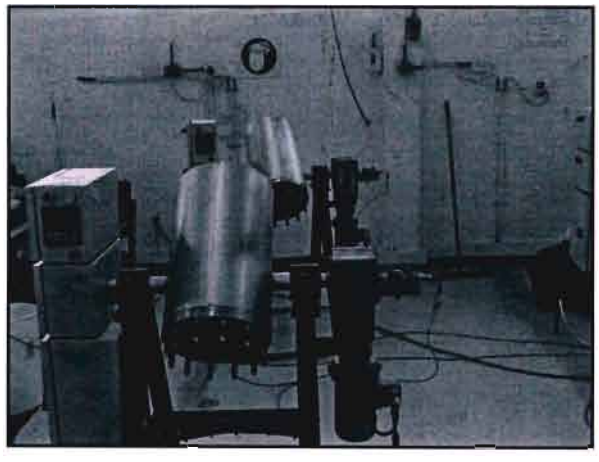


Fig. B5. Rotating batch digester.

The H-factor

The concept of the H-factor is based on the assumption that the Arrhenius equation satisfactorily describes the temperature dependence of pulping reaction rates. The Arrhenius equation can be written in the form

$$\ln k = b - \frac{a}{T}$$

where k = reaction rate constant

T = temperature

and a and b are constants.

The reaction rate at 100°C was arbitrarily taken as unity, with rates at other temperatures being scaled to this standard. The constants a and b were found to be 16113 and 43.2 respectively. The relative reaction rate at any other temperature (in the Kelvin temperature scale) is thus given by:

$$k_r = \ln^{-1}\left(43.20 - \frac{1611}{T}\right)$$

The area under a plot of relative reaction rate vs. time (in hours), for a kraft cook, was then designated the H-factor, i.e.

$$H - factor = \int_0^t e^{43.2 - \frac{16113}{T}} dT$$

B3. Pulp physical and strength properties

- Basis Mass

The average mass of the six handsheets to be used in the analyses was determined. Assuming the moisture content of a handsheet is 7%, the oven-dry basis mass is calculated as follows:

$$Basis\ mass\,(g/m^2) = \frac{0.93 * Average\ basis\ dry\ mass\ (g)}{Area\ of\ sheet\ (m^2)}$$

Area of sheet = $(\pi \times r^2)$, with radius (r) of a handsheet being 0.1m.

- Sheet Density

An instrument called a micrometer was used to determine the thickness of the six handsheets. Sheet density was calculated as follows:

$$Sheet\ density\,(kg/m^3) = \frac{Basis\ mass\ (kg/m^2)}{Bulk\ thickness\ (m)}$$

- Burst/ Tear/ Tensile Index

In order to calculate strength values from the measurement obtained from the instrument, the following formulae were used:

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

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

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

- Zero-span tensile strength

$$ZEROSPAN\ TENSILE\ (N) = \frac{Average\ Zero\,span\,Tensile\ Strength\ (N) \times 60 g/m^2}{Basis\ Mass\ (g/m^2)}$$

Table C-1: Wood density results

Age	SI	Tree#	WMD (dbh)	WMD (35%)	WMD (65%)	Ht (7cm)	r(BH)	r(35%)	r(65%)	r1	r2	V1	V2	V3	WTD	Extracted Density
years			g/cm^3	g/cm^3	g/cm^3	m	m	m	m	m	m	m^3	m^3	m^3	g/cm^3	g/cm^3
13	poor	1	0.43	0.37	0.39	9.40	0.10	0.08	0.07	0.09	0.07	0.05	0.05	0.005	0.40	0.40
13	poor	2	0.39	0.34	0.36	12.00	0.09	0.08	0.06	0.09	0.07	0.07	0.06	0.004	0.37	0.37
13	poor	3	0.39	0.36	0.37	11.30	0.14	0.11	0.08	0.12	0.09	0.13	0.09	0.007	0.38	0.38
13	poor	4	0.49	0.43	0.37	11.20	0.11	0.09	0.07	0.10	0.08	0.08	0.07	0.005	0.46	0.46
13	poor	5	0.50	0.37	0.37	9.80	0.10	0.08	0.07	0.09	0.07	0.05	0.05	0.004	0.43	0.43
20	poor	1	0.46	0.37	0.37	20.00	0.14	0.12	0.09	0.13	0.10	0.30	0.20	0.009	0.42	0.42
20	poor	2	0.37	0.36	0.41	20.20	0.18	0.14	0.11	0.16	0.12	0.47	0.29	0.012	0.37	0.36
20	poor	3	0.48	0.37	0.41	21.20	0.16	0.13	0.10	0.14	0.11	0.38	0.25	0.010	0.44	0.43
20	poor	4	0.42	0.38	0.38	19.90	0.15	0.12	0.10	0.14	0.11	0.35	0.23	0.010	0.41	0.40
20	poor	5	0.44	0.38	0.36	19.30	0.13	0.12	0.09	0.13	0.11	0.29	0.21	0.008	0.42	0.41
14	good	1	0.41	0.36	0.35	17.49	0.12	0.11	0.08	0.12	0.10	0.21	0.15	0.007	0.39	0.38
14	good	2	0.41	0.37	0.35	20.40	0.14	0.12	0.10	0.13	0.11	0.32	0.23	0.010	0.39	0.39
14	good	3	0.42	0.40	0.36	13.25	0.08	0.07	0.05	0.07	0.06	0.06	0.05	0.003	0.41	0.41
14	good	4	0.43	0.34	0.36	17.27	0.11	0.15	0.08	0.13	0.11	0.24	0.21	0.007	0.39	0.38
14	good	5	0.42	0.39	0.39	19.35	0.13	0.12	0.10	0.13	0.11	0.28	0.22	0.010	0.41	0.40
21	good	1	0.46	0.44	0.43	20.15	0.16	0.14	0.11	0.15	0.12	0.40	0.30	0.013	0.45	0.45
21	good	2	0.51	0.51	0.38	25.00	0.16	0.15	0.11	0.15	0.13	0.56	0.41	0.014	0.50	0.50
21	good	3	0.42	0.40	0.40	21.80	0.11	0.09	0.07	0.10	0.08	0.19	0.12	0.005	0.41	0.41
21	good	4	0.45	0.38	0.38	19.30	0.19	0.15	0.12	0.17	0.13	0.50	0.32	0.014	0.42	0.42
10	poor	1	0.51	0.44	0.42	9.20	0.11	0.09	0.07	0.10	0.08	0.07	0.06	0.005	0.47	0.47
10	poor	2	0.44	0.43	0.38	6.28	0.09	0.08	0.06	0.08	0.07	0.02	0.03	0.004	0.43	0.42
10	poor	3	0.45	0.42	0.38	9.90	0.10	0.07	0.06	0.08	0.06	0.05	0.04	0.004	0.43	0.43
10	poor	4	0.41	0.40	0.37	7.98	0.09	0.08	0.06	0.09	0.07	0.04	0.04	0.004	0.40	0.40
10	poor	5	0.40	0.35	0.36	8.35	0.12	0.10	0.07	0.11	0.09	0.07	0.06	0.006	0.38	0.37
9	good	1	0.41	0.35	0.33	11.90	0.11	0.09	0.07	0.10	0.08	0.09	0.07	0.004	0.38	0.38
9	good	2	0.46	0.39	0.36	11.80	0.07	0.06	0.05	0.06	0.05	0.04	0.03	0.003	0.43	0.42
9	good	3	0.47	0.40	0.39	11.65	0.10	0.08	0.06	0.09	0.07	0.07	0.05	0.003	0.44	0.44
9	good	4	0.41	0.35	0.38	12.40	0.14	0.08	0.06	0.11	0.07	0.12	0.06	0.003	0.39	0.38
9	good	5	0.39	0.33	0.33	13.70	0.10	0.08	0.06	0.09	0.07	0.09	0.06	0.004	0.36	0.36

Table C-2: Wood anatomy results

Age	SI	Tree #	WMCWT 35%	WMCWT 65%	WMCWT-bh	WT-CWT	WMFD35	WMFD65	WMFD-bh	WT-FD
years			mm	mm	mm	mm	mm	mm	mm	mm
13	poor	1	3.62	3.65	2.70	3.17	40.50	40.23	34.49	37.52
13	poor	2	3.79	3.26	3.25	3.50	37.52	36.33	34.52	35.95
13	poor	3	3.29	3.32	3.95	3.66	38.68	36.19	30.00	33.71
13	poor	4	4.57	3.32	4.55	4.52	37.03	36.42	33.51	35.12
13	poor	5	3.56	3.57	4.61	4.09	36.25	37.18	33.69	34.99
20	poor	1	4.35	3.66	4.98	4.71	41.28	42.13	37.50	39.09
20	poor	2	4.10	4.71	4.45	4.32	42.34	40.31	40.87	41.41
20	poor	3	5.05	4.33	4.96	4.99	41.81	40.83	37.35	39.12
20	poor	4	3.95	2.69	4.35	4.17	40.03	38.39	38.67	39.19
20	poor	5	3.81	4.29	3.92	3.88	32.92	37.68	34.08	33.66
14	good	1	4.06	3.36	4.83	4.48	38.79	38.62	37.95	38.31
14	good	2	4.32	3.57	4.18	4.23	42.46	40.11	39.05	40.49
14	good	3	3.43	3.64	3.64	3.55	34.88	36.82	34.05	34.49
14	good	4	3.30	3.27	4.23	3.79	41.08	39.11	39.03	39.98
14	good	5	4.58	4.34	4.04	4.28	38.35	36.29	37.06	37.60
21	good	1	4.62	4.70	3.35	3.90	38.02	37.58	36.01	36.87
21	good	2	4.85	3.98	6.07	5.53	38.22	41.30	38.30	38.31
21	good	3	3.24	4.49	4.29	3.89	38.06	36.55	36.84	37.30
21	good	4	4.59	3.52	4.35	4.43	38.02	38.32	36.78	37.29
10	poor	1	4.66	4.77	4.29	4.47	36.60	38.18	37.89	37.33
10	poor	2	5.18	4.11	4.58	4.86	39.11	45.54	37.05	38.70
10	poor	3	3.45	3.19	3.58	3.50	36.83	38.24	34.97	35.92
10	poor	4	3.59	3.43	3.93	3.73	36.71	36.78	33.89	35.43
10	poor	5	3.93	4.14	3.49	3.72	37.85	37.81	32.54	35.19
9	good	1	2.90	2.78	3.33	3.14	38.24	39.61	34.43	36.12
9	good	2	3.34	2.60	3.16	3.22	37.29	36.73	32.96	35.06
9	good	3	3.47	3.28	3.14	3.28	37.29	35.44	33.19	34.87
9	good	4	3.14	4.16	3.26	3.24	36.65	36.64	37.10	36.95
9	good	5	3.37	3.48	3.41	3.39	39.64	40.53	39.77	39.74

cont...

Table C-2 continued

Age	SI	Tree #	LD35%	LD65%	LD-bh	WT-LD	Runk 35%	Runk 65%	Runk- bh	WT-Runk	Coll35%	Coll65%	Coll-bh	WT-Coll
years			mm	mm	mm	mm								
13	poor	1	33.27	32.93	29.08	37.52	0.26	0.25	0.21	0.23	15.45	14.04	21.20	18.23
13	poor	2	29.94	29.81	28.02	35.95	0.28	0.24	0.26	0.27	12.00	13.02	14.65	13.39
13	poor	3	32.10	29.54	22.09	33.71	0.23	0.24	0.39	0.32	16.37	13.55	8.11	11.62
13	poor	4	27.90	29.79	24.41	35.12	0.37	0.25	0.42	0.39	8.12	13.64	7.38	7.90
13	poor	5	29.14	30.04	24.46	34.99	0.27	0.28	0.44	0.36	11.81	13.18	7.34	9.61
20	poor	1	32.58	34.81	27.54	39.09	0.30	0.23	0.40	0.36	9.57	12.76	7.21	8.24
20	poor	2	34.14	30.89	31.97	41.41	0.29	0.35	0.33	0.31	11.86	7.63	9.89	10.59
20	poor	3	31.70	32.18	27.42	39.12	0.38	0.31	0.43	0.41	7.53	10.17	7.19	7.37
20	poor	4	32.13	33.02	29.96	39.19	0.32	0.18	0.35	0.34	14.48	20.32	10.26	12.07
20	poor	5	25.31	29.09	26.25	33.66	0.35	0.34	0.34	0.34	9.31	8.90	9.54	9.43
14	good	1	30.66	31.89	28.30	38.31	0.30	0.23	0.39	0.35	11.02	14.24	7.39	9.03
14	good	2	33.81	32.97	30.68	40.49	0.28	0.23	0.30	0.29	9.81	12.01	9.64	9.75
14	good	3	28.03	29.55	26.76	34.49	0.28	0.28	0.31	0.29	14.71	12.99	12.22	13.32
14	good	4	34.49	32.56	30.58	39.98	0.22	0.25	0.32	0.28	17.47	16.57	10.46	13.77
14	good	5	29.19	27.61	28.99	37.60	0.34	0.36	0.31	0.33	7.63	8.64	10.42	9.18
21	good	1	28.78	28.17	29.30	36.87	0.40	0.41	0.26	0.32	8.93	8.76	15.02	12.37
21	good	2	28.52	33.35	26.16	38.31	0.40	0.28	0.55	0.49	7.86	12.10	5.11	6.35
21	good	3	31.57	27.57	28.26	37.30	0.23	0.40	0.35	0.30	14.97	9.91	10.40	12.14
21	good	4	28.84	31.29	28.07	37.29	0.38	0.28	0.36	0.36	8.64	14.70	9.29	9.13
10	poor	1	27.29	28.64	29.30	28.39	0.38	0.37	0.34	0.36	7.65	6.76	8.91	8.26
10	poor	2	28.74	37.33	27.89	28.98	0.43	0.31	0.41	0.41	6.39	10.09	8.21	7.41
10	poor	3	29.93	31.86	27.81	28.91	0.23	0.22	0.30	0.27	14.26	17.16	13.67	14.10
10	poor	4	29.54	29.92	26.03	27.96	0.25	0.24	0.32	0.28	12.38	13.26	9.75	11.23
10	poor	5	29.99	29.52	25.56	27.75	0.23	0.33	0.30	0.27	18.17	10.87	13.18	15.34
9	good	1	32.45	34.05	27.78	29.84	0.20	0.18	0.26	0.24	23.42	23.97	14.37	18.29
9	good	2	30.60	31.53	26.64	28.62	0.25	0.20	0.27	0.25	15.03	25.97	15.45	15.64
9	good	3	30.35	28.88	26.91	28.32	0.27	0.26	0.37	0.32	16.25	15.43	10.60	12.96
9	good	4	30.36	28.32	30.57	30.46	0.24	0.36	0.26	0.26	16.75	9.18	17.62	17.19
9	good	5	32.91	33.57	32.96	32.95	0.22	0.22	0.31	0.27	15.87	13.59	21.70	19.09

Table C-3: Wood chemistry results

Age	SI	Arabinose	Galactose	Glucose	Xylose	Mannose	Klason	Cellulose	Extractives
years		%	%	%	%	%	%	%	%
9	good	1.31	3.49	46.50	5.51	13.43	28.62	43.28	1.37
9	good	1.21	3.43	46.63	5.22	13.74	28.49	42.71	1.32
9	good	1.15	3.51	46.75	5.53	13.66	28.05	42.55	1.35
10	poor	0.84	4.57	45.95	4.38	14.77	28.16	43.03	1.40
10	poor	0.96	4.29	46.14	4.54	14.33	28.32	42.26	1.38
10	poor	0.98	4.24	45.97	4.53	13.91	28.59	42.91	1.42
13	poor	1.49	2.77	49.25	5.36	10.32	29.98	43.10	0.45
13	poor	1.34	2.85	49.11	5.19	10.69	30.01	42.73	0.29
13	poor	1.63	2.79	49.21	5.31	10.44	29.96	43.26	0.37
14	good	1.71	2.58	48.50	5.79	9.71	30.00	44.26	1.65
14	good	1.43	2.37	48.62	5.76	9.53	30.50	44.39	1.64
14	good	1.40	2.22	49.07	5.72	9.48	30.60	44.21	1.67
20	poor	1.32	2.32	48.20	5.61	10.68	30.02	44.47	0.76
20	poor	1.30	2.12	49.37	4.95	9.74	30.56	44.68	0.75
20	poor	1.28	1.70	48.73	5.38	10.34	30.87	44.58	0.77
21	good	1.79	2.56	48.95	5.80	10.10	30.02	45.00	0.87
21	good	1.42	2.37	49.38	5.55	9.49	30.64	43.87	0.93
21	good	1.50	1.96	48.97	5.71	10.20	30.79	44.81	0.90

Table C-4: Pulp anatomy results

Age	SI	Cooking Time	Pulp FL	Pulp FD	Pulp CWT	Pulp LD	Fines	Mulhsteph	FL/FD	Pulp coarseness
years		min	mm	mm	mm	mm	%			mg/m
9	good	35	2.40	39.40	6.15	27.10	1.48	0.53	60.91	0.24
9	good	35	2.40	39.40	6.15	27.10	1.48	0.53	60.91	0.24
9	good	35	2.40	39.40	6.15	27.10	1.48	0.53	60.91	0.24
9	good	65	2.37	37.47	5.83	25.80	1.08	0.53	63.35	0.24
9	good	65	2.37	37.47	5.83	25.80	1.08	0.53	63.35	0.24
9	good	65	2.37	37.47	5.83	25.80	1.08	0.53	63.35	0.24
9	good	85	2.34	37.33	5.87	25.60	1.21	0.53	62.77	0.23
9	good	85	2.34	37.33	5.87	25.60	1.21	0.53	62.77	0.23
9	good	85	2.34	37.33	5.87	25.60	1.21	0.53	62.77	0.24
9	good	95	2.34	36.87	5.70	25.47	1.20	0.52	63.56	0.24
9	good	95	2.34	36.87	5.70	25.47	1.20	0.52	63.56	0.23
9	good	95	2.34	36.87	5.70	25.47	1.20	0.52	63.56	0.24
9	good	120	2.30	36.63	5.90	24.83	1.48	0.54	62.78	0.23
9	good	120	2.30	36.63	5.90	24.83	1.48	0.54	62.78	0.23
9	good	120	2.30	36.63	5.90	24.83	1.48	0.54	62.78	0.23
9	good	180	2.22	35.70	5.88	23.93	1.39	0.55	62.09	0.22
9	good	180	2.22	35.70	5.88	23.93	1.39	0.55	62.09	0.22
9	good	180	2.22	35.70	5.88	23.93	1.39	0.55	62.09	0.23
10	poor	35	2.35	39.43	6.32	26.80	1.36	0.54	59.59	0.26
10	poor	35	2.35	39.43	6.32	26.80	1.36	0.54	59.59	0.26
10	poor	35	2.35	39.43	6.32	26.80	1.36	0.54	59.59	0.26
10	poor	65	2.17	37.10	5.85	25.40	1.30	0.53	58.49	0.25
10	poor	65	2.17	37.10	5.85	25.40	1.30	0.53	58.49	0.25
10	poor	65	2.17	37.10	5.85	25.40	1.30	0.53	58.49	0.25
10	poor	85	2.18	36.80	5.58	25.63	1.39	0.51	59.15	0.25
10	poor	85	2.18	36.80	5.58	25.63	1.39	0.51	59.15	0.25
10	poor	85	2.18	36.80	5.58	25.63	1.39	0.51	59.15	0.25
10	poor	95	2.11	36.43	5.51	25.40	1.53	0.51	57.93	0.25
10	poor	95	2.11	36.43	5.51	25.40	1.53	0.51	57.93	0.24
10	poor	95	2.11	36.43	5.51	25.40	1.53	0.51	57.93	0.25
10	poor	120	2.11	36.57	5.62	25.33	1.51	0.52	57.79	0.24
10	poor	120	2.11	36.57	5.62	25.33	1.51	0.52	57.79	0.24
10	poor	120	2.11	36.57	5.62	25.33	1.51	0.52	57.79	0.24
10	poor	180	2.07	36.27	5.88	24.50	1.59	0.54	57.08	0.24
10	poor	180	2.07	36.27	5.88	24.50	1.59	0.54	57.08	0.24
10	poor	180	2.07	36.27	5.88	24.50	1.59	0.54	57.08	0.24

cont...

Table C-4 continued

Age	SI	Cooking Time	Pulp FL	Pulp FD	Pulp CWT	Pulp LD	Fines	Mulhsteph	FL/FD	Pulp coarseness
years		min	mm	mm	mm	mm	%			mg/m
20	poor	35	3.01	39.03	7.17	24.70	0.75	0.60	77.20	0.31
20	poor	35	3.01	39.03	7.17	24.70	0.75	0.60	77.20	0.31
20	poor	35	3.01	39.03	7.17	24.70	0.75	0.60	77.20	0.33
20	poor	65	2.89	35.97	6.32	23.33	0.85	0.58	80.35	0.29
20	poor	65	2.89	35.97	6.32	23.33	0.85	0.58	80.35	0.31
20	poor	65	2.89	35.97	6.32	23.33	0.85	0.58	80.35	0.30
20	poor	85	2.82	35.77	6.15	23.47	1.24	0.57	78.84	0.27
20	poor	85	2.82	35.77	6.15	23.47	1.24	0.57	78.84	0.28
20	poor	85	2.82	35.77	6.15	23.47	1.24	0.57	78.84	0.27
20	poor	95	2.81	35.70	6.00	23.70	1.53	0.56	78.80	0.27
20	poor	95	2.81	35.70	6.00	23.70	1.53	0.56	78.80	0.27
20	poor	95	2.81	35.70	6.00	23.70	1.53	0.56	78.80	0.27
20	poor	120	2.74	35.53	5.95	23.63	0.87	0.56	77.11	0.26
20	poor	120	2.74	35.53	5.95	23.63	0.87	0.56	77.11	0.26
20	poor	120	2.74	35.53	5.95	23.63	0.87	0.56	77.11	0.26
20	poor	180	2.69	34.87	6.00	22.87	0.88	0.57	77.06	0.26
20	poor	180	2.69	34.87	6.00	22.87	0.88	0.57	77.06	0.25
20	poor	180	2.69	34.87	6.00	22.87	0.88	0.57	77.06	0.25
21	good	35	3.18	38.70	7.02	24.67	0.96	0.59	82.26	0.32
21	good	35	3.18	38.70	7.02	24.67	0.96	0.59	82.26	0.33
21	good	35	3.18	38.70	7.02	24.67	0.96	0.59	82.26	0.33
21	good	65	3.16	37.03	6.38	24.27	0.68	0.57	85.42	0.30
21	good	65	3.16	37.03	6.38	24.27	0.68	0.57	85.42	0.30
21	good	65	3.16	37.03	6.38	24.27	0.68	0.57	85.42	0.30
21	good	85	3.08	36.10	6.22	23.67	0.90	0.57	85.41	0.27
21	good	85	3.08	36.10	6.22	23.67	0.90	0.57	85.41	0.28
21	good	85	3.08	36.10	6.22	23.67	0.90	0.57	85.41	0.27
21	good	95	2.99	35.80	6.17	23.47	0.98	0.57	83.61	0.29
21	good	95	2.99	35.80	6.17	23.47	0.98	0.57	83.61	0.28
21	good	95	2.99	35.80	6.17	23.47	0.98	0.57	83.61	0.29
21	good	120	2.92	35.33	5.95	23.43	0.85	0.56	82.74	0.27
21	good	120	2.92	35.33	5.95	23.43	0.85	0.56	82.74	0.27
21	good	120	2.92	35.33	5.95	23.43	0.85	0.56	82.74	0.27
21	good	180	2.84	36.00	6.08	23.83	1.06	0.56	78.98	0.26
21	good	180	2.84	36.00	6.08	23.83	1.06	0.56	78.98	0.26
21	good	180	2.84	36.00	6.08	23.83	1.06	0.56	78.98	0.26

Table C-4 continued

Age	SI	Cooking Time	Pulp FL	Pulp FD	Pulp CWT	Pulp LD	Fines	Mulhsteph	FL/FD	Pulp coarseness
years		min	mm	mm	mm	mm	%			mg/m
20	poor	35	3.01	39.03	7.17	24.70	0.75	0.60	77.20	0.31
20	poor	35	3.01	39.03	7.17	24.70	0.75	0.60	77.20	0.31
20	poor	35	3.01	39.03	7.17	24.70	0.75	0.60	77.20	0.33
20	poor	65	2.89	35.97	6.32	23.33	0.85	0.58	80.35	0.29
20	poor	65	2.89	35.97	6.32	23.33	0.85	0.58	80.35	0.31
20	poor	65	2.89	35.97	6.32	23.33	0.85	0.58	80.35	0.30
20	poor	85	2.82	35.77	6.15	23.47	1.24	0.57	78.84	0.27
20	poor	85	2.82	35.77	6.15	23.47	1.24	0.57	78.84	0.28
20	poor	85	2.82	35.77	6.15	23.47	1.24	0.57	78.84	0.27
20	poor	95	2.81	35.70	6.00	23.70	1.53	0.56	78.80	0.27
20	poor	95	2.81	35.70	6.00	23.70	1.53	0.56	78.80	0.27
20	poor	95	2.81	35.70	6.00	23.70	1.53	0.56	78.80	0.27
20	poor	120	2.74	35.53	5.95	23.63	0.87	0.56	77.11	0.26
20	poor	120	2.74	35.53	5.95	23.63	0.87	0.56	77.11	0.26
20	poor	120	2.74	35.53	5.95	23.63	0.87	0.56	77.11	0.26
20	poor	180	2.69	34.87	6.00	22.87	0.88	0.57	77.06	0.26
20	poor	180	2.69	34.87	6.00	22.87	0.88	0.57	77.06	0.25
20	poor	180	2.69	34.87	6.00	22.87	0.88	0.57	77.06	0.25
21	good	35	3.18	38.70	7.02	24.67	0.96	0.59	82.26	0.32
21	good	35	3.18	38.70	7.02	24.67	0.96	0.59	82.26	0.33
21	good	35	3.18	38.70	7.02	24.67	0.96	0.59	82.26	0.33
21	good	65	3.16	37.03	6.38	24.27	0.68	0.57	85.42	0.30
21	good	65	3.16	37.03	6.38	24.27	0.68	0.57	85.42	0.30
21	good	65	3.16	37.03	6.38	24.27	0.68	0.57	85.42	0.30
21	good	85	3.08	36.10	6.22	23.67	0.90	0.57	85.41	0.27
21	good	85	3.08	36.10	6.22	23.67	0.90	0.57	85.41	0.28
21	good	85	3.08	36.10	6.22	23.67	0.90	0.57	85.41	0.27
21	good	95	2.99	35.80	6.17	23.47	0.98	0.57	83.61	0.29
21	good	95	2.99	35.80	6.17	23.47	0.98	0.57	83.61	0.28
21	good	95	2.99	35.80	6.17	23.47	0.98	0.57	83.61	0.29
21	good	120	2.92	35.33	5.95	23.43	0.85	0.56	82.74	0.27
21	good	120	2.92	35.33	5.95	23.43	0.85	0.56	82.74	0.27
21	good	120	2.92	35.33	5.95	23.43	0.85	0.56	82.74	0.27
21	good	180	2.84	36.00	6.08	23.83	1.06	0.56	78.98	0.26
21	good	180	2.84	36.00	6.08	23.83	1.06	0.56	78.98	0.26
21	good	180	2.84	36.00	6.08	23.83	1.06	0.56	78.98	0.26

Table C-5 continued

Age	SI	Cooking Time	Yield	AA Cons	Kappa	Klason	pulp arabinose	pulp galactose	pulp glucose	pulp xylose	pulp mannose
years		min	%	%		%	%	%	%	%	%
13	poor	35	50.20	83.25	48.20	5.95	0.82	0.84	81.47	5.87	5.28
13	poor	35	49.01	82.29	48.80	6.21	0.74	0.60	80.89	5.53	6.72
13	poor	35	51.61	81.56	49.68	6.10	0.86	0.79	81.51	5.34	5.91
13	poor	65	45.51	84.66	30.00	4.69	0.61	0.54	82.51	5.90	5.35
13	poor	65	46.53	84.40	34.76	4.09	0.68	0.63	82.67	5.63	6.37
13	poor	65	47.02	84.25	31.14	4.79	0.71	0.52	82.48	5.44	5.84
13	poor	85	43.45	85.23	21.63	3.10	0.60	0.50	83.95	5.87	6.21
13	poor	85	44.01	85.15	20.88	3.50	0.67	0.46	83.60	5.96	6.14
13	poor	85	45.51	85.04	19.21	3.05	0.65	0.49	83.56	5.52	6.13
13	poor	95	43.49	85.16	17.50	2.32	0.41	0.39	85.57	5.52	6.57
13	poor	95	43.85	85.25	17.17	2.21	0.39	0.35	85.01	6.10	6.83
13	poor	95	42.87	85.33	16.90	2.43	0.32	0.30	85.59	6.08	5.34
13	poor	120	41.78	85.66	16.79	2.10	0.37	0.16	86.76	6.07	5.34
13	poor	120	42.50	85.99	16.78	2.02	0.35	0.33	85.19	6.51	5.78
13	poor	120	42.50	85.84	16.90	2.00	0.37	0.23	86.12	6.17	5.76
13	poor	180	41.64	87.34	15.22	1.89	0.37	0.16	86.90	6.08	5.20
13	poor	180	40.88	87.63	15.50	1.12	0.37	0.16	88.89	5.58	4.32
13	poor	180	40.74	88.95	15.02	1.78	0.37	0.16	88.07	5.39	5.08
14	good	35	50.54	76.87	48.72	7.65	0.96	0.90	77.35	5.21	7.40
14	good	35	50.66	76.33	49.95	7.14	0.86	0.85	78.12	6.05	7.11
14	good	35	50.23	78.00	48.50	7.02	0.84	0.81	77.95	6.45	7.02
14	good	65	46.42	80.74	25.00	5.97	0.66	0.63	80.23	6.48	6.49
14	good	65	46.58	82.10	21.83	5.02	0.69	0.69	80.56	5.99	6.59
14	good	65	46.80	81.00	21.58	5.19	0.72	0.71	81.21	5.23	6.89
14	good	85	45.07	83.55	20.61	4.98	0.59	0.49	82.42	6.74	5.19
14	good	85	44.92	81.40	18.36	3.60	0.64	0.69	83.49	6.41	5.50
14	good	85	45.07	81.90	18.68	3.92	0.63	0.59	83.15	6.59	4.29
14	good	95	43.75	81.05	19.54	3.15	0.43	0.56	84.98	6.79	4.93
14	good	95	44.21	81.27	21.63	3.89	0.44	0.33	83.58	6.57	5.15
14	good	95	44.36	84.00	21.50	3.01	0.39	0.33	84.20	6.08	6.41
14	good	120	42.52	82.41	15.59	2.53	0.33	0.22	85.15	6.99	5.11
14	good	120	42.15	81.91	15.79	2.76	0.35	0.49	85.17	6.42	5.34
14	good	120	42.60	82.10	15.50	2.49	0.32	0.39	84.98	6.39	4.98
14	good	180	43.28	83.57	14.16	2.23	0.39	0.30	85.20	5.65	6.19
14	good	180	42.94	84.76	13.97	2.12	0.30	0.29	86.12	5.42	5.89
14	good	180	43.21	86.00	12.72	1.98	0.29	0.27	86.09	5.39	5.75

continued...

Table C-5 continued

Age	SI	Cooking Time	Yield	AA Cons	Kappa	Klason	pulp arabinose	pulp galactose	pulp glucose	pulp xylose	pulp mannose
years		min	%	%		%	%	%	%	%	%
20	poor	35	51.01	76.55	54.28	7.35	0.56	0.50	80.77	6.30	4.99
20	poor	35	51.16	76.04	53.22	7.56	0.49	0.49	79.98	6.40	4.88
20	poor	35	53.56	76.65	55.20	7.23	0.50	0.47	80.56	6.23	4.56
20	poor	65	47.42	80.74	23.85	6.95	0.40	0.33	81.11	6.31	4.41
20	poor	65	50.47	81.23	23.93	6.70	0.48	0.39	81.23	6.21	4.39
20	poor	65	48.95	82.02	21.00	6.52	0.41	0.41	81.30	6.29	4.62
20	poor	85	44.99	83.25	18.48	5.90	0.38	0.35	81.67	6.48	4.75
20	poor	85	45.31	83.60	24.07	6.20	0.42	0.33	81.55	6.30	4.44
20	poor	85	44.69	83.16	20.20	6.01	0.37	0.32	81.98	6.29	4.56
20	poor	95	44.25	84.75	20.79	3.80	0.34	0.35	85.46	5.73	4.37
20	poor	95	44.20	84.56	22.39	3.21	0.34	0.21	86.48	6.16	4.35
20	poor	95	44.08	85.60	24.26	3.50	0.33	0.28	86.23	5.98	4.39
20	poor	120	43.59	85.26	19.25	2.98	0.30	0.30	87.34	5.54	4.22
20	poor	120	43.24	85.19	17.01	2.01	0.31	0.32	87.98	5.63	4.34
20	poor	120	43.33	86.20	20.11	3.05	0.30	0.30	87.15	5.51	4.25
20	poor	180	42.55	86.59	15.00	2.50	0.10	0.16	90.73	4.32	2.61
20	poor	180	40.86	86.90	13.53	2.15	0.17	0.17	91.67	4.17	2.49
20	poor	180	40.75	87.29	13.08	2.80	0.11	0.11	89.94	5.19	2.28
21	good	35	51.75	79.76	46.80	6.90	0.79	0.55	80.15	5.85	6.36
21	good	35	52.05	77.02	45.88	6.23	0.74	0.56	79.98	5.88	6.89
21	good	35	52.16	80.40	45.54	6.59	0.69	0.52	80.05	5.89	6.79
21	good	65	47.37	80.57	27.80	4.37	0.63	0.51	81.81	5.84	7.21
21	good	65	47.99	80.33	32.19	4.23	0.66	0.48	81.15	5.80	7.25
21	good	65	48.26	78.93	30.50	4.15	0.68	0.44	81.56	5.78	6.95
21	good	85	43.32	82.95	23.80	3.30	0.62	0.39	83.49	5.75	6.87
21	good	85	43.88	80.58	20.97	3.05	0.59	0.36	83.98	5.89	6.60
21	good	85	43.64	80.69	21.33	3.12	0.57	0.41	83.84	5.76	6.18
21	good	95	45.68	81.95	22.10	2.80	0.56	0.28	85.55	5.94	5.06
21	good	95	45.25	83.82	20.59	2.20	0.56	0.31	86.16	5.89	4.86
21	good	95	45.55	82.50	21.65	2.46	0.45	0.28	85.86	5.78	4.96
21	good	120	42.73	83.58	17.27	1.95	0.44	0.21	86.78	5.89	5.41
21	good	120	42.80	84.35	17.86	1.82	0.36	0.24	86.22	6.22	4.57
21	good	120	43.20	85.60	16.13	1.85	0.41	0.25	86.51	5.96	5.09
21	good	180	41.49	89.90	15.22	1.23	0.36	0.35	87.97	6.18	4.72
21	good	180	41.96	90.24	14.48	1.05	0.32	0.16	88.35	6.06	4.90
21	good	180	41.25	88.32	14.00	1.35	0.40	0.19	88.22	5.09	5.30

Table C-5 continued

Age	SI	Cooking Time	Yield	AA Cons	Kappa	Klason	pulp arabinose	pulp galactose	pulp glucose	pulp xylose	pulp mannose
years		min	%	%		%	%	%	%	%	%
20	poor	35	51.01	76.55	54.28	7.35	0.56	0.50	80.77	6.30	4.99
20	poor	35	51.16	76.04	53.22	7.56	0.49	0.49	79.98	6.40	4.88
20	poor	35	53.56	76.65	55.20	7.23	0.50	0.47	80.56	6.23	4.56
20	poor	65	47.42	80.74	23.85	6.95	0.40	0.33	81.11	6.31	4.41
20	poor	65	50.47	81.23	23.93	6.70	0.48	0.39	81.23	6.21	4.39
20	poor	65	48.95	82.02	21.00	6.52	0.41	0.41	81.30	6.29	4.62
20	poor	85	44.99	83.25	18.48	5.90	0.38	0.35	81.67	6.48	4.75
20	poor	85	45.31	83.60	24.07	6.20	0.42	0.33	81.55	6.30	4.44
20	poor	85	44.69	83.16	20.20	6.01	0.37	0.32	81.98	6.29	4.56
20	poor	95	44.25	84.75	20.79	3.80	0.34	0.35	85.46	5.73	4.37
20	poor	95	44.20	84.56	22.39	3.21	0.34	0.21	86.48	6.16	4.35
20	poor	95	44.08	85.60	24.26	3.50	0.33	0.28	86.23	5.98	4.39
20	poor	120	43.59	85.26	19.25	2.98	0.30	0.30	87.34	5.54	4.22
20	poor	120	43.24	85.19	17.01	2.01	0.31	0.32	87.98	5.63	4.34
20	poor	120	43.33	86.20	20.11	3.05	0.30	0.30	87.15	5.51	4.25
20	poor	180	42.55	86.59	15.00	2.50	0.10	0.16	90.73	4.32	2.61
20	poor	180	40.86	86.90	13.53	2.15	0.17	0.17	91.67	4.17	2.49
20	poor	180	40.75	87.29	13.08	2.80	0.11	0.11	89.94	5.19	2.28
21	good	35	51.75	79.76	46.80	6.90	0.79	0.55	80.15	5.85	6.36
21	good	35	52.05	77.02	45.88	6.23	0.74	0.56	79.98	5.88	6.89
21	good	35	52.16	80.40	45.54	6.59	0.69	0.52	80.05	5.89	6.79
21	good	65	47.37	80.57	27.80	4.37	0.63	0.51	81.81	5.84	7.21
21	good	65	47.99	80.33	32.19	4.23	0.66	0.48	81.15	5.80	7.25
21	good	65	48.26	78.93	30.50	4.15	0.68	0.44	81.56	5.78	6.95
21	good	85	43.32	82.95	23.80	3.30	0.62	0.39	83.49	5.75	6.87
21	good	85	43.88	80.58	20.97	3.05	0.59	0.36	83.98	5.89	6.60
21	good	85	43.64	80.69	21.33	3.12	0.57	0.41	83.84	5.76	6.18
21	good	95	45.68	81.95	22.10	2.80	0.56	0.28	85.55	5.94	5.06
21	good	95	45.25	83.82	20.59	2.20	0.56	0.31	86.16	5.89	4.86
21	good	95	45.55	82.50	21.65	2.46	0.45	0.28	85.86	5.78	4.96
21	good	120	42.73	83.58	17.27	1.95	0.44	0.21	86.78	5.89	5.41
21	good	120	42.80	84.35	17.86	1.82	0.36	0.24	86.22	6.22	4.57
21	good	120	43.20	85.60	16.13	1.85	0.41	0.25	86.51	5.96	5.09
21	good	180	41.49	89.90	15.22	1.23	0.36	0.35	87.97	6.18	4.72
21	good	180	41.96	90.24	14.48	1.05	0.32	0.16	88.35	6.06	4.90
21	good	180	41.25	88.32	14.00	1.35	0.40	0.19	88.22	5.09	5.30

Table C-6: 100 beating strength results

Age	SI	Cooking Time	Sheet Dens	burst	tear	tensile	tea	stretch	z-span	freeness
years		min	kg/m^3	MN/kg	kN m^2/kg	kN m/kg	J/m^2	%	N	mL
9	good	35	108.33	5.60	9.30	71.00	65.19	2.40	53.40	720.00
9	good	35	109.57	5.69	9.99	66.43	67.86	2.33	64.88	725.00
9	good	35	108.43	5.52	9.17	69.56	58.12	2.38	60.31	719.32
9	good	65	115.13	6.43	10.18	86.36	89.82	2.63	29.76	682.07
9	good	65	111.09	6.28	10.20	82.08	84.53	2.65	31.74	661.71
9	good	65	114.33	6.01	9.51	74.79	60.55	2.17	45.57	643.22
9	good	85	110.88	5.54	10.87	66.74	38.60	1.93	48.63	651.88
9	good	85	110.50	5.94	10.94	71.96	54.44	2.09	55.43	658.03
9	good	85	111.24	5.92	10.73	66.98	68.87	2.26	52.00	680.00
9	good	95	110.07	5.70	10.51	84.93	79.54	2.48	47.18	654.87
9	good	95	111.16	6.00	10.64	78.49	66.49	2.54	30.72	662.02
9	good	95	111.87	5.33	9.41	76.41	74.30	2.55	36.70	678.42
9	good	120	116.11	5.30	11.05	69.64	63.91	2.47	49.85	654.43
9	good	120	122.15	5.14	9.31	60.59	47.38	2.21	54.55	644.61
9	good	120	117.78	5.78	9.78	79.68	57.24	2.41	48.33	640.44
9	good	180	110.04	4.62	9.52	66.98	76.93	2.49	22.04	659.07
9	good	180	113.88	4.65	9.38	65.31	52.90	2.18	29.58	653.34
9	good	180	110.40	3.62	8.37	62.40	41.21	2.16	25.00	684.39
10	poor	35	108.50	6.67	9.49	70.64	60.93	2.35	30.05	707.42
10	poor	35	110.39	7.00	9.52	66.95	50.07	2.17	28.32	682.73
10	poor	35	109.45	6.50	9.52	68.78	55.50	2.50	30.10	677.00
10	poor	65	113.25	5.07	10.43	72.07	74.41	2.75	32.60	686.02
10	poor	65	111.52	5.04	10.13	67.09	62.95	2.51	33.07	643.70
10	poor	65	110.86	5.25	10.10	76.49	75.14	2.56	29.58	668.42
10	poor	85	110.23	5.42	10.29	65.54	57.41	2.39	26.44	683.40
10	poor	85	110.24	5.98	10.07	79.01	81.43	2.67	26.49	659.94
10	poor	85	111.90	5.20	9.54	66.85	56.55	2.53	26.05	674.63
10	poor	95	117.99	5.32	10.42	62.02	50.48	2.26	32.15	657.95
10	poor	95	118.77	5.68	9.81	73.81	85.35	2.28	33.13	638.92
10	poor	95	117.22	5.30	10.63	62.30	51.16	2.25	44.48	668.20
10	poor	120	116.73	5.36	10.73	66.95	73.94	2.69	29.75	636.68
10	poor	120	115.11	5.47	10.37	64.46	54.55	2.31	41.11	657.12
10	poor	120	115.03	5.03	10.63	67.85	58.06	2.37	31.16	645.58
10	poor	180	115.65	4.43	9.44	60.01	62.26	2.64	41.82	668.73
10	poor	180	114.23	3.95	8.92	51.98	43.99	2.44	39.72	653.15
10	poor	180	116.12	4.48	8.54	62.08	63.34	2.34	36.78	657.49

continued...

Table C-6 continued

Age	SI	Cooking Time	Sheet Dens	burst	tear	tensile	tea	stretch	z-span	freeness
years		min	kg/m^3	MN/kg	kN m^2/kg	kN m/kg	J/m^2	%	N	mL
13	poor	35	97.62	5.49	12.23	61.70	80.41	2.89	35.83	670.99
13	poor	35	100.83	5.74	11.42	64.11	44.15	2.35	36.60	678.45
13	poor	35	99.23	5.60	11.78	62.89	62.28	2.89	36.23	680.55
13	poor	65	105.93	4.70	13.70	59.47	59.30	2.64	46.99	679.16
13	poor	65	105.92	5.07	13.67	64.73	66.53	2.45	45.59	684.16
13	poor	65	107.52	5.24	12.58	61.06	60.55	2.59	46.71	678.63
13	poor	85	112.51	5.61	10.03	59.82	62.96	2.44	42.33	665.79
13	poor	85	120.68	5.57	10.67	57.81	58.00	2.30	45.00	641.23
13	poor	85	119.88	5.52	11.20	55.80	53.04	2.13	43.53	655.23
13	poor	95	107.26	4.68	11.73	57.93	68.48	2.70	27.64	687.34
13	poor	95	109.68	4.74	10.82	56.48	67.27	2.60	30.01	680.70
13	poor	95	112.10	4.80	11.00	59.59	66.06	2.53	29.81	682.23
13	poor	120	104.20	4.63	12.43	57.55	48.83	2.24	41.41	643.36
13	poor	120	106.73	4.86	11.74	60.39	53.29	2.32	36.90	650.07
13	poor	120	101.67	4.40	13.44	54.71	44.34	2.14	45.92	642.50
13	poor	180	111.90	4.24	9.09	49.56	46.88	2.38	41.97	666.12
13	poor	180	112.35	4.70	9.05	52.00	47.90	2.40	43.71	656.99
13	poor	180	112.12	4.47	9.07	50.78	47.39	2.39	40.23	656.23
14	good	35	106.91	6.80	10.18	80.78	85.18	2.69	81.20	675.48
14	good	35	107.75	7.01	10.18	79.63	89.54	2.77	82.24	681.91
14	good	35	105.15	6.96	10.91	78.48	93.90	2.84	81.63	689.81
14	good	65	108.67	5.77	11.12	72.61	82.80	2.74	69.27	640.00
14	good	65	105.72	5.29	10.34	67.21	68.08	2.63	74.36	667.97
14	good	65	107.20	5.83	10.79	69.91	75.44	2.67	71.83	655.23
14	good	85	109.23	5.81	9.95	81.56	94.44	2.80	81.00	650.45
14	good	85	108.27	5.76	10.66	80.08	93.20	2.79	80.43	641.87
14	good	85	108.61	5.97	11.10	83.04	95.68	2.80	81.15	645.23
14	good	95	109.90	5.98	10.88	74.76	83.88	2.68	67.98	661.03
14	good	95	110.05	6.21	10.81	71.80	68.31	2.52	68.44	649.56
14	good	95	110.20	6.23	10.74	68.84	52.74	2.24	68.93	654.21
14	good	120	110.19	4.94	9.97	69.09	73.59	2.50	77.76	665.79
14	good	120	110.46	5.14	10.42	64.15	58.50	2.23	67.33	651.69
14	good	120	110.65	5.34	10.87	59.21	43.41	1.97	64.35	662.96
14	good	180	105.70	3.41	9.36	52.67	36.52	2.02	62.19	650.89
14	good	180	108.01	4.13	9.19	58.12	64.12	2.47	69.64	648.37
14	good	180	105.12	3.32	8.28	54.45	42.41	2.01	68.42	651.51

continued...

Table C-6 continued

Age	SI	Cooking Time	Sheet Dens	burst	tear	tensile	tea	stretch	z-span	freeness
years		min	kg/m^3	MN/kg	kN m^2/kg	kN m/kg	J/m^2	%	N	mL
20	poor	35	102.51	5.67	12.55	63.09	47.86	2.08	78.25	700.99
20	poor	35	103.13	5.63	13.56	57.77	50.42	2.17	76.06	717.28
20	poor	35	103.80	5.69	13.10	60.43	49.14	2.11	77.14	700.56
20	poor	65	109.91	4.90	13.70	58.05	38.91	1.80	67.62	707.23
20	poor	65	111.65	5.00	13.55	59.50	39.20	1.82	66.90	680.12
20	poor	65	108.44	4.80	13.85	56.60	38.62	1.79	68.34	683.75
20	poor	85	105.00	5.80	11.97	58.50	50.00	1.95	69.56	700.20
20	poor	85	102.00	5.51	11.75	56.77	50.38	2.02	71.52	695.50
20	poor	85	105.50	5.56	12.19	60.23	49.62	2.00	70.54	720.00
20	poor	95	103.68	4.86	13.15	55.10	41.03	1.75	71.90	678.11
20	poor	95	102.19	5.32	13.10	67.47	59.53	2.26	75.61	656.81
20	poor	95	102.93	5.39	13.14	63.18	50.28	2.47	70.38	665.56
20	poor	120	105.00	4.32	11.40	53.33	41.83	2.01	27.15	660.00
20	poor	120	108.09	4.30	11.50	51.06	42.17	2.03	25.80	671.05
20	poor	120	107.91	4.35	11.30	55.60	42.00	2.05	28.50	676.00
20	poor	180	107.66	3.09	9.12	47.59	38.26	1.97	52.28	696.43
20	poor	180	107.80	3.20	9.05	50.10	39.00	1.98	50.00	680.00
20	poor	180	107.52	2.98	9.19	45.08	37.52	1.96	54.56	674.60
21	good	35	103.16	6.18	14.16	80.76	78.38	2.39	61.65	676.68
21	good	35	103.97	5.69	13.37	72.33	51.07	2.09	65.47	679.76
21	good	35	102.97	5.84	13.48	72.62	61.00	2.33	53.99	672.61
21	good	65	99.58	5.31	14.31	64.96	80.33	2.55	67.94	651.39
21	good	65	101.00	5.29	15.61	62.85	44.22	2.14	60.23	655.50
21	good	65	101.28	5.29	14.39	64.19	53.32	2.26	62.35	650.20
21	good	85	102.74	5.06	14.36	66.34	63.63	2.34	72.18	672.62
21	good	85	103.78	4.55	15.80	49.68	34.16	1.89	71.06	671.19
21	good	85	104.89	4.80	14.96	64.30	52.39	2.13	72.62	679.69
21	good	95	102.37	5.29	13.98	69.36	79.48	2.52	70.07	674.28
21	good	95	99.30	5.18	15.55	61.14	50.53	2.17	61.44	683.60
21	good	95	102.70	5.20	15.72	64.61	42.85	1.95	57.58	677.01
21	good	120	103.65	5.12	11.78	61.50	56.48	2.36	64.14	678.77
21	good	120	102.34	5.17	12.51	66.94	64.03	2.40	60.82	676.33
21	good	120	102.88	4.69	13.24	52.74	36.52	2.05	63.07	670.20
21	good	180	99.94	3.93	10.60	55.21	47.00	1.90	52.59	679.96
21	good	180	104.00	3.63	10.84	46.18	25.26	1.71	60.22	678.01
21	good	180	101.19	3.36	9.92	47.26	32.27	1.82	55.58	679.54

Table C-7: 250 beating strength results

Age	SI	Cooking Time	Sheet Dens	burst	tear	tensile	tea	stretch	z-span	freeness
years		min	kg/m^3	MN/kg	kN m^2/kg	kN m/kg	J/m^2	%	N	mL
9	good	35	112.71	7.14	8.27	81.72	78.50	2.56	53.11	682.93
9	good	35	111.22	7.38	8.66	71.19	71.04	2.52	53.61	700.00
9	good	35	112.62	6.77	8.80	74.45	68.82	2.59	50.00	699.44
9	good	65	118.59	6.45	9.79	99.19	123.18	3.00	31.10	626.52
9	good	65	119.28	6.92	9.58	97.27	124.80	3.10	43.01	630.00
9	good	65	119.81	6.42	9.64	88.00	90.25	2.94	38.29	600.00
9	good	85	120.08	6.47	8.90	76.82	68.39	2.49	41.63	600.00
9	good	85	118.62	6.58	8.73	88.75	86.88	2.71	44.12	609.24
9	good	85	119.46	6.47	9.48	88.99	94.23	2.86	53.48	630.00
9	good	95	120.85	6.84	8.60	97.80	109.82	2.95	49.29	593.75
9	good	95	120.58	6.92	9.44	89.14	103.64	3.12	39.97	611.77
9	good	95	120.42	5.75	8.06	89.05	101.03	2.74	38.00	600.00
9	good	120	121.07	6.39	8.42	88.62	90.13	2.75	42.31	595.65
9	good	120	122.90	5.79	7.98	82.14	87.43	2.74	42.46	561.64
9	good	120	122.07	6.63	8.10	90.92	76.32	2.70	52.42	574.28
9	good	180	118.26	5.84	7.65	86.15	90.00	2.78	23.10	598.79
9	good	180	120.10	5.92	7.75	86.82	78.85	2.53	27.90	598.72
9	good	180	120.88	5.19	6.75	77.54	84.76	2.44	32.61	614.77
10	poor	35	110.65	7.30	9.18	86.17	73.60	2.62	37.73	680.00
10	poor	35	112.62	7.28	9.17	85.70	93.21	3.05	36.12	670.78
10	poor	35	110.73	7.25	9.14	84.25	84.43	2.80	37.00	661.50
10	poor	65	119.10	6.28	8.65	87.36	116.86	3.16	34.33	650.10
10	poor	65	118.31	6.27	8.48	83.94	88.63	2.97	32.00	624.52
10	poor	65	118.91	6.04	8.39	85.87	105.43	3.09	36.66	641.69
10	poor	85	120.54	6.56	8.77	75.58	87.10	3.03	27.71	659.17
10	poor	85	121.87	6.66	8.60	89.01	90.67	2.83	27.83	629.19
10	poor	85	121.93	6.58	8.51	86.84	91.29	2.79	25.81	632.28
10	poor	95	121.13	6.41	9.15	79.23	92.74	2.86	31.54	617.06
10	poor	95	121.19	6.46	9.08	90.02	98.77	3.18	34.19	596.67
10	poor	95	121.78	6.25	9.15	82.28	89.31	2.89	40.17	623.42
10	poor	120	126.59	6.60	8.98	81.15	94.15	2.89	26.18	590.90
10	poor	120	125.30	6.59	8.15	86.33	97.72	2.91	43.56	600.50
10	poor	120	124.18	6.53	8.37	81.11	81.47	2.76	30.80	602.06
10	poor	180	122.76	5.11	7.53	71.15	61.96	2.49	26.70	610.10
10	poor	180	123.57	5.32	8.30	84.12	83.51	2.67	16.32	585.34
10	poor	180	122.76	5.24	7.88	76.45	97.42	2.87	24.47	647.49

continued...

Table C-7 continued

Age	SI	Cooking Time	Sheet Dens	burst	tear	tensile	tea	stretch	z-span	freeness
years		min	kg/m^3	MN/kg	$kN\ m^2/kg$	kN m/kg	J/m^2	%	N	mL
13	poor	35	110.32	6.78	10.58	78.97	112.41	3.50	38.69	635.99
13	poor	35	109.31	6.75	10.55	76.45	98.96	3.43	34.39	639.35
13	poor	35	108.29	6.86	10.49	73.93	85.51	2.92	35.83	629.33
13	poor	65	114.00	5.93	11.67	72.31	94.16	2.92	42.74	653.96
13	poor	65	114.31	6.50	11.78	68.44	63.06	2.75	44.98	663.36
13	poor	65	114.50	6.36	10.71	79.65	92.28	2.96	43.05	647.09
13	poor	85	119.24	7.06	8.52	89.28	110.00	3.25	40.93	627.08
13	poor	85	119.82	6.98	8.36	87.86	107.72	3.37	37.83	599.23
13	poor	85	120.39	6.91	8.23	83.80	95.90	2.72	34.73	600.54
13	poor	95	113.46	5.47	10.52	75.40	104.00	3.34	19.85	644.03
13	poor	95	114.87	5.61	9.45	77.09	97.16	3.15	22.92	641.52
13	poor	95	116.28	5.75	9.40	78.81	90.29	2.91	25.98	644.52
13	poor	120	121.33	6.00	8.10	74.94	78.23	2.53	37.11	596.29
13	poor	120	122.54	5.89	7.89	68.64	68.93	2.50	37.58	588.22
13	poor	120	120.12	6.08	7.99	81.24	87.53	2.56	38.50	598.23
13	poor	180	118.50	5.61	8.05	71.96	71.34	2.66	35.20	608.89
13	poor	180	117.10	5.35	8.17	70.10	73.10	2.70	37.76	623.62
13	poor	180	117.80	5.48	8.11	71.03	72.22	2.68	36.48	615.20
14	good	35	112.58	7.16	9.64	81.88	88.70	2.73	75.44	655.38
14	good	35	111.53	7.19	9.55	83.77	96.72	2.95	80.18	641.93
14	good	35	113.64	7.10	9.55	80.35	88.20	2.73	72.83	660.00
14	good	65	122.00	6.64	9.23	80.95	103.42	2.81	58.74	630.43
14	good	65	121.70	6.63	9.28	86.22	104.31	2.93	65.87	620.00
14	good	65	121.85	6.62	9.27	87.20	103.88	2.88	62.32	640.85
14	good	85	121.60	6.60	8.50	87.79	82.60	2.97	61.74	601.80
14	good	85	119.85	6.26	8.86	78.68	77.20	2.66	62.20	592.04
14	good	85	118.09	5.92	8.97	79.14	76.00	2.21	62.66	588.65
14	good	95	115.32	7.17	9.38	89.36	112.12	2.71	79.36	607.52
14	good	95	112.40	6.67	9.91	76.06	80.63	2.66	74.61	597.69
14	good	95	113.20	6.54	10.34	87.94	84.19	2.67	71.47	600.23
14	good	120	115.48	6.09	9.07	73.47	66.37	2.40	67.92	623.77
14	good	120	116.80	6.04	8.05	69.98	73.22	2.57	61.97	602.18
14	good	120	117.92	6.01	9.06	77.85	79.97	2.65	61.58	607.77
14	good	180	113.09	4.57	7.47	67.28	57.03	2.22	57.44	591.78
14	good	180	110.20	4.32	7.45	58.66	53.82	2.25	53.42	601.01
14	good	180	113.09	4.32	7.47	66.97	64.27	2.32	57.49	593.88

continued...

Table C-7 continued

Age	SI	Cooking Time	Sheet Dens	burst	tear	tensile	tea	stretch	z-span	freeness
years		min	kg/m^3	MN/kg	kN m^2/kg	kN m/kg	J/m^2	%	N	mL
20	poor	35	116.91	6.02	11.71	69.00	57.67	2.32	71.17	687.14
20	poor	35	115.31	5.63	12.58	68.57	42.79	1.99	75.79	680.18
20	poor	35	116.11	6.04	12.16	69.44	50.23	2.35	73.48	690.85
20	poor	65	112.68	5.83	13.25	77.07	92.43	2.91	82.94	640.50
20	poor	65	112.60	5.96	13.35	78.54	92.71	2.93	85.38	615.20
20	poor	65	115.73	5.70	13.15	75.60	92.15	2.89	80.50	632.37
20	poor	85	111.08	6.29	10.86	65.71	59.66	2.32	71.16	670.81
20	poor	85	110.59	5.64	11.34	69.32	73.70	2.51	69.86	660.00
20	poor	85	110.84	5.97	11.10	67.53	66.68	2.43	70.51	681.61
20	poor	95	112.98	5.79	10.57	77.73	73.52	2.33	70.03	637.22
20	poor	95	115.78	5.34	11.74	71.50	73.91	2.46	65.69	632.12
20	poor	95	110.19	5.57	12.20	74.60	73.73	2.41	67.87	633.57
20	poor	120	119.63	6.07	9.98	65.77	81.42	2.67	31.02	649.39
20	poor	120	114.49	5.73	10.24	69.27	63.05	2.39	35.87	620.00
20	poor	120	115.88	5.90	9.74	68.95	72.25	2.56	33.50	619.70
20	poor	180	116.78	5.12	8.17	64.05	73.07	2.58	60.09	626.00
20	poor	180	116.90	5.25	8.29	64.60	72.64	2.62	58.98	610.00
20	poor	180	116.66	4.99	8.05	63.50	73.50	2.55	61.20	589.37
21	good	35	107.17	7.32	13.69	90.77	112.33	2.87	62.78	648.07
21	good	35	105.27	6.70	12.57	75.68	86.15	2.79	66.59	671.22
21	good	35	105.88	7.46	12.31	78.59	78.33	2.64	68.84	658.00
21	good	65	109.66	6.51	14.20	78.15	75.90	2.54	72.46	599.07
21	good	65	110.05	6.18	13.37	72.51	68.65	2.44	74.92	605.00
21	good	65	110.45	5.85	12.54	66.87	65.00	2.35	70.00	588.26
21	good	85	109.79	6.58	11.72	75.93	78.07	2.66	66.26	622.67
21	good	85	110.51	6.18	11.88	73.00	72.13	2.58	60.76	626.95
21	good	85	111.24	5.78	12.04	70.08	66.16	2.53	57.27	611.75
21	good	95	107.08	6.80	11.48	82.87	87.19	2.67	78.41	640.56
21	good	95	106.51	6.16	12.82	80.80	68.81	2.45	84.56	639.63
21	good	95	106.79	6.49	12.15	81.82	78.00	2.56	81.49	654.96
21	good	120	110.50	5.80	9.78	72.00	67.32	2.50	62.00	640.05
21	good	120	111.67	5.98	9.40	78.86	70.00	2.46	65.72	640.90
21	good	120	111.08	5.89	9.59	75.43	68.66	2.48	63.86	639.50
21	good	180	110.87	4.75	8.02	62.49	52.51	2.09	54.52	621.25
21	good	180	109.87	4.93	8.11	62.51	47.23	2.08	55.39	605.15
21	good	180	111.87	4.57	7.96	62.44	50.74	2.11	53.62	611.20

Table C-8: 450 beating strength results

Age	SI	Cooking Time	Sheet Dens	burst	tear	tensile	tea	stretch	z-span	freeness
years		min	kg/m^3	MN/kg	$kN\ m^2/kg$	kN m/kg	J/m^2	%	N	mL
9	good	35	117.57	7.32	8.05	85.50	95.15	2.94	39.48	645.26
9	good	35	119.10	7.45	8.34	93.41	100.20	3.11	40.26	657.19
9	good	35	117.58	7.55	8.23	91.09	103.46	3.19	40.84	660.00
9	good	65	124.43	7.42	8.65	103.51	129.02	3.12	27.31	551.26
9	good	65	124.94	7.39	8.65	101.31	120.00	3.08	33.85	560.00
9	good	65	126.43	7.02	8.51	99.33	115.90	2.92	37.27	570.00
9	good	85	120.87	7.40	7.34	100.03	112.97	2.79	57.71	519.96
9	good	85	121.91	7.68	8.23	101.18	102.72	2.92	45.61	538.04
9	good	85	124.43	7.41	9.30	102.30	129.37	3.16	59.65	540.00
9	good	95	123.26	7.58	7.34	100.03	112.97	2.79	57.71	519.96
9	good	95	123.53	6.91	7.26	93.60	104.24	3.13	42.00	510.00
9	good	95	124.32	6.09	6.75	97.37	93.25	2.75	55.03	490.50
9	good	120	123.19	6.80	8.25	93.87	95.31	2.73	34.73	460.00
9	good	120	124.15	6.70	7.58	104.61	97.43	2.59	32.00	475.00
9	good	120	123.67	6.74	7.93	99.25	96.37	2.57	45.68	468.85
9	good	180	122.50	5.57	7.41	86.07	84.85	2.45	36.07	500.00
9	good	180	123.98	6.15	7.64	86.94	84.35	2.59	42.45	474.94
9	good	180	124.10	5.69	6.58	82.59	76.13	2.37	32.00	475.50
10	poor	35	113.19	8.01	8.90	90.11	102.16	3.09	31.34	658.42
10	poor	35	115.32	7.33	8.93	86.45	68.29	2.82	21.63	626.64
10	poor	35	114.42	7.67	8.89	90.17	110.95	3.10	25.00	641.77
10	poor	65	121.31	6.44	8.19	97.39	122.78	3.49	29.00	560.11
10	poor	65	123.82	6.95	8.61	86.93	110.03	3.51	34.44	553.63
10	poor	65	123.12	6.36	8.66	87.11	100.63	3.16	24.79	550.12
10	poor	85	125.40	7.05	8.41	85.40	109.00	3.21	20.93	545.75
10	poor	85	124.24	7.25	8.20	87.85	107.10	3.28	27.78	575.15
10	poor	85	125.65	6.86	8.20	95.11	110.74	3.18	30.90	560.20
10	poor	95	127.38	7.19	8.41	85.40	109.00	3.21	20.93	545.75
10	poor	95	128.21	7.12	8.23	93.43	116.00	3.39	24.24	543.88
10	poor	95	128.45	6.92	7.74	90.48	108.73	2.67	24.41	527.97
10	poor	120	126.57	6.87	8.04	91.91	118.23	3.09	31.99	480.00
10	poor	120	126.07	7.08	7.97	86.87	100.76	3.10	36.21	470.00
10	poor	120	126.97	6.92	7.30	100.24	104.88	3.15	34.33	471.07
10	poor	180	129.40	6.09	6.74	84.01	94.06	2.81	39.17	511.11
10	poor	180	129.23	5.81	6.81	80.41	83.32	2.71	39.71	479.94
10	poor	180	131.06	6.00	6.80	90.48	107.41	2.77	19.94	518.51

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Table C-8 continued

Age	SI	Cooking Time	Sheet Dens	burst	tear	tensile	tea	stretch	z-span	freeness
years		min	kg/m^3	MN/kg	kN m^2/kg	kN m/kg	J/m^2	%	N	mL
13	poor	35	117.35	6.95	9.30	79.69	99.68	3.17	35.64	616.03
13	poor	35	120.44	6.98	9.07	80.53	73.37	2.89	35.31	622.39
13	poor	35	118.21	7.07	9.09	80.10	86.54	3.00	36.00	620.35
13	poor	65	114.96	6.75	11.12	80.17	104.08	3.27	40.05	588.69
13	poor	65	116.12	7.08	10.99	83.81	99.47	3.04	36.48	585.11
13	poor	65	120.17	6.90	9.96	84.73	116.22	3.27	36.13	567.03
13	poor	85	122.22	8.01	9.11	83.91	115.02	3.18	25.01	529.21
13	poor	85	123.08	7.94	8.34	96.74	111.68	3.18	37.84	529.45
13	poor	85	123.94	7.90	8.01	93.62	110.89	3.19	35.25	529.58
13	poor	95	120.77	6.45	9.11	83.91	115.02	3.18	25.01	529.21
13	poor	95	122.28	6.34	8.78	87.73	107.51	2.92	22.96	528.67
13	poor	95	123.80	6.23	8.43	86.37	100.00	2.81	29.88	528.26
13	poor	120	125.73	6.27	7.76	85.64	105.63	3.31	30.64	522.84
13	poor	120	125.88	6.09	8.02	78.35	94.74	3.03	31.76	522.08
13	poor	120	125.57	6.48	7.81	92.90	116.52	3.38	29.52	521.65
13	poor	180	125.90	6.17	7.73	84.70	104.90	3.09	37.04	518.61
13	poor	180	127.11	5.85	7.49	82.70	103.90	3.05	35.60	517.67
13	poor	180	126.50	6.01	7.61	83.70	104.40	3.07	36.32	518.20
14	good	35	113.57	7.51	9.21	84.47	100.26	2.99	60.21	608.77
14	good	35	112.11	7.40	9.76	83.32	97.00	2.79	65.57	581.62
14	good	35	112.75	7.51	9.48	82.63	98.50	2.87	68.04	590.45
14	good	65	123.45	6.70	9.95	84.60	75.95	2.54	67.79	552.61
14	good	65	125.67	7.15	9.26	84.98	104.15	2.75	65.47	529.22
14	good	65	121.24	6.59	9.60	86.45	113.39	2.94	75.26	510.00
14	good	85	125.57	6.73	8.67	96.95	129.45	3.05	66.10	482.33
14	good	85	124.01	7.00	8.25	86.95	101.93	2.36	64.02	474.01
14	good	85	122.45	7.80	7.90	83.15	82.34	2.60	67.76	476.25
14	good	95	122.81	7.68	8.67	96.95	129.45	3.05	66.10	482.33
14	good	95	114.07	7.29	8.34	82.97	97.78	2.94	63.91	478.13
14	good	95	120.68	7.27	8.93	88.93	83.70	2.63	66.89	481.23
14	good	120	124.51	6.22	7.69	76.34	78.72	3.15	62.69	528.05
14	good	120	122.83	6.19	7.30	81.45	90.84	2.50	64.51	530.56
14	good	120	121.50	6.19	8.14	86.56	102.93	3.08	60.84	500.23
14	good	180	125.28	4.99	5.88	72.37	68.66	2.28	52.63	470.39
14	good	180	121.51	4.82	6.43	69.91	68.84	2.39	49.29	480.66
14	good	180	122.03	4.55	6.41	76.00	75.63	2.46	53.95	475.63

continued...

Table C-8 continued

Age	SI	Cooking Time	Sheet Dens	burst	tear	tensile	tea	stretch	z-span	freeness
years		min	kg/m3	MN/kg	kN m2/kg	kN m/kg	J/m2	%	N	mL
20	poor	35	121.47	6.69	11.04	82.64	76.07	2.59	75.11	600.10
20	poor	35	118.81	6.15	11.17	74.18	67.52	2.52	67.94	590.15
20	poor	35	120.13	6.65	11.09	76.08	71.81	2.57	71.53	588.75
20	poor	65	117.51	6.92	10.50	89.98	104.24	3.10	83.20	530.00
20	poor	65	115.45	6.99	10.35	87.46	105.76	3.00	87.60	518.50
20	poor	65	114.00	7.06	10.65	92.50	105.00	2.96	85.40	532.60
20	poor	85	118.41	7.26	9.08	86.07	104.24	2.88	67.74	550.60
20	poor	85	115.63	6.25	9.69	85.48	79.99	2.46	76.25	550.00
20	poor	85	112.85	6.53	9.56	83.80	90.13	2.95	77.32	572.85
20	poor	95	118.32	6.54	9.08	86.07	104.24	2.88	67.74	550.60
20	poor	95	118.49	6.13	9.60	79.71	86.43	2.66	60.81	562.63
20	poor	95	118.41	6.32	9.34	82.89	95.35	2.77	62.16	555.94
20	poor	120	120.11	6.66	9.01	88.51	117.20	3.15	53.21	536.00
20	poor	120	117.13	6.61	8.16	82.22	85.52	2.73	50.43	490.00
20	poor	120	121.76	6.62	8.59	84.56	101.36	3.03	51.82	482.55
20	poor	180	121.63	5.17	7.02	77.09	76.87	2.37	78.62	470.00
20	poor	180	121.10	5.35	7.06	79.08	76.74	2.35	77.64	420.00
20	poor	180	122.16	5.26	6.98	75.10	77.00	2.39	79.60	421.72
21	good	35	106.08	7.45	12.56	89.85	94.60	2.84	71.51	616.86
21	good	35	108.77	7.37	12.41	92.72	108.37	2.99	77.96	599.36
21	good	35	108.43	7.97	11.40	88.69	121.28	3.14	76.39	602.23
21	good	65	112.32	7.73	11.70	84.97	89.23	2.75	85.33	501.23
21	good	65	110.34	7.91	12.19	89.80	88.58	2.72	83.96	527.96
21	good	65	111.33	8.09	11.22	94.60	87.90	2.71	84.00	500.27
21	good	85	114.28	6.42	11.72	93.44	101.18	2.78	70.22	552.90
21	good	85	115.07	6.99	10.81	98.40	110.06	2.88	63.63	547.62
21	good	85	115.08	6.76	10.00	85.06	85.12	2.70	65.98	528.67
21	good	95	112.46	8.06	11.72	93.44	101.18	2.78	70.22	552.90
21	good	95	113.27	8.01	11.68	91.88	95.67	2.80	66.35	543.70
21	good	95	114.08	8.12	12.06	90.35	90.16	2.80	62.47	573.29
21	good	120	114.11	7.00	9.90	83.36	79.00	2.55	68.90	541.41
21	good	120	111.90	7.18	9.88	84.60	77.88	2.51	65.50	534.51
21	good	120	113.00	7.09	9.89	83.98	78.44	2.53	67.20	540.00
21	good	180	115.16	5.09	7.58	74.82	65.87	2.43	56.98	492.74
21	good	180	114.87	5.14	7.37	74.40	69.26	2.57	53.64	470.29
21	good	180	115.45	5.04	7.82	75.24	62.45	2.27	60.32	478.56

Table C-9: 650 beating strength results

Age	SI	Cooking Time	Sheet Dens	burst	tear	tensile	tea	stretch	z-span	freeness
years		min	kg/m^3	MN/kg	$kN\ m^2/kg$	kN m/kg	J/m^2	%	N	mL
9	good	35	117.26	7.49	7.93	96.15	115.00	3.19	42.10	615.23
9	good	35	119.84	7.86	8.50	100.97	120.00	3.39	45.64	595.00
9	good	35	118.30	7.68	8.19	96.61	111.58	3.05	38.05	610.50
9	good	65	126.51	7.54	8.96	102.50	124.60	3.16	27.75	426.28
9	good	65	127.88	7.69	8.45	101.47	132.69	3.10	32.37	430.00
9	good	65	128.84	7.58	7.90	99.47	115.52	2.95	37.35	415.00
9	good	85	125.95	7.68	7.65	95.86	102.09	2.99	42.03	460.00
9	good	85	125.84	7.95	8.00	99.50	114.80	3.08	49.83	450.00
9	good	85	124.28	7.83	7.69	109.41	123.97	3.11	45.00	475.34
9	good	95	126.44	7.97	7.75	106.88	131.99	3.34	39.00	366.86
9	good	95	126.33	7.79	7.67	102.93	128.26	3.21	38.68	385.00
9	good	95	128.37	6.79	7.44	102.35	100.90	2.84	34.88	375.00
9	good	120	127.93	6.98	7.35	98.88	119.56	3.18	42.92	345.00
9	good	120	127.40	7.07	7.73	101.81	98.08	2.74	34.04	339.00
9	good	120	126.87	7.14	8.11	104.74	92.34	2.90	38.00	355.35
9	good	180	130.13	6.40	7.23	94.21	90.56	2.43	30.42	339.03
9	good	180	129.89	6.37	7.02	91.85	93.33	2.72	38.67	320.00
9	good	180	131.50	5.81	6.23	86.94	73.72	2.32	28.32	298.00
10	poor	35	123.22	8.13	8.39	92.30	109.00	3.37	23.10	613.54
10	poor	35	122.85	7.47	8.61	95.36	134.74	3.72	22.38	594.91
10	poor	35	124.18	7.49	8.76	91.95	106.06	3.28	22.71	585.78
10	poor	65	127.81	6.77	8.66	97.99	139.95	3.58	27.00	500.00
10	poor	65	126.03	7.30	8.34	93.46	120.76	3.47	29.00	470.50
10	poor	65	127.30	7.17	8.47	94.91	106.53	3.13	23.53	501.18
10	poor	85	125.18	7.29	8.42	93.46	115.49	3.18	27.97	475.93
10	poor	85	126.45	7.19	8.57	94.89	104.97	3.06	24.97	469.50
10	poor	85	127.89	7.58	7.55	101.32	110.01	3.00	19.93	470.00
10	poor	95	132.52	7.39	7.92	100.28	140.62	2.97	22.85	449.62
10	poor	95	131.92	7.55	8.08	101.51	144.00	3.72	23.85	394.56
10	poor	95	133.13	7.14	7.76	95.21	128.00	3.09	21.82	449.75
10	poor	120	131.54	7.16	8.15	95.90	147.20	3.41	28.09	410.00
10	poor	120	129.44	7.13	7.74	91.94	113.90	3.23	40.23	400.00
10	poor	120	129.66	7.03	7.26	104.09	120.17	3.16	28.48	415.11
10	poor	180	130.18	6.27	7.03	87.65	103.31	3.11	35.12	393.73
10	poor	180	130.66	6.09	6.58	85.96	82.80	2.66	36.47	376.93
10	poor	180	129.30	6.12	6.82	96.08	107.85	2.82	30.66	401.51

continued...

Table C-9 continued

Age	SI	Cooking Time	Sheet Dens	burst	tear	tensile	tea	stretch	z-span	freeness
years		min	kg/m^3	MN/kg	kN m^2/kg	kN m/kg	J/m^2	%	N	mL
13	poor	35	121.16	7.62	9.25	95.35	150.39	3.48	30.88	533.41
13	poor	35	123.14	7.32	8.80	94.21	107.18	3.05	34.63	531.41
13	poor	35	121.68	7.22	8.80	93.00	105.65	3.13	32.58	532.11
13	poor	65	124.29	7.00	10.30	84.54	144.15	3.45	35.26	507.15
13	poor	65	122.62	6.71	10.56	81.27	90.97	2.83	30.01	500.64
13	poor	65	124.06	7.09	9.59	90.18	112.31	3.04	29.56	498.31
13	poor	85	124.92	8.02	8.56	95.79	128.09	3.32	35.07	425.69
13	poor	85	125.20	8.00	8.34	94.19	121.57	3.36	32.80	400.29
13	poor	85	125.49	8.10	8.11	92.59	115.05	3.40	30.53	400.25
13	poor	95	124.57	6.79	8.46	85.40	136.61	3.40	32.48	435.09
13	poor	95	131.04	7.34	7.49	89.59	123.52	3.24	29.35	449.02
13	poor	95	126.45	7.00	7.54	92.01	120.00	2.96	33.95	442.50
13	poor	120	126.40	6.71	6.80	86.24	104.62	3.24	27.03	373.11
13	poor	120	126.13	6.47	6.81	89.60	104.34	3.19	24.31	350.88
13	poor	120	126.68	6.94	7.40	82.88	104.90	3.27	29.75	352.12
13	poor	180	127.40	6.19	6.50	91.32	111.70	3.24	35.78	382.31
13	poor	180	128.08	6.91	6.70	89.40	113.50	3.30	33.84	355.57
13	poor	180	127.74	6.55	6.60	90.36	112.60	3.27	31.90	355.60
14	good	35	116.01	7.93	9.32	84.66	108.54	3.10	67.93	520.00
14	good	35	114.64	7.51	9.60	85.14	116.35	2.98	65.60	507.05
14	good	35	115.21	7.89	9.47	82.78	105.11	2.88	67.14	510.00
14	good	65	128.00	7.61	9.02	91.61	121.53	3.08	62.45	434.88
14	good	65	120.24	7.88	9.83	90.62	104.98	2.87	62.67	440.00
14	good	65	124.69	7.20	9.42	84.41	101.46	2.97	66.35	429.75
14	good	85	127.58	7.65	7.33	91.46	134.60	3.52	63.19	370.55
14	good	85	124.53	7.25	7.88	95.76	98.86	2.82	57.81	375.34
14	good	85	126.05	7.45	7.60	93.61	116.73	2.96	67.41	366.84
14	good	95	122.64	8.08	9.01	110.07	160.42	3.45	66.39	340.12
14	good	95	120.44	7.60	8.96	86.89	103.62	3.01	68.17	359.29
14	good	95	119.95	7.55	8.64	100.76	108.91	2.97	61.09	354.56
14	good	120	125.60	6.45	6.62	95.80	95.96	2.66	64.09	410.23
14	good	120	125.66	6.61	7.28	95.31	102.05	2.77	63.26	401.23
14	good	120	125.72	6.79	7.95	86.99	108.11	3.16	62.43	386.09
14	good	180	128.55	5.06	5.70	75.47	55.54	2.35	55.52	331.04
14	good	180	122.85	4.95	5.99	77.02	70.64	2.40	50.38	323.56
14	good	180	127.53	5.07	5.78	80.60	83.11	2.48	51.39	314.24

continued...

Table C-9 continued

Age	SI	Cooking Time	Sheet Dens	burst	tear	tensile	tea	stretch	z-span	freeness
years		min	kg/m^3	MN/kg	$kN\ m^2/kg$	kN m/kg	J/m^2	%	N	mL
20	poor	35	115.96	6.78	9.91	84.43	83.62	2.63	64.38	515.60
20	poor	35	116.53	7.22	10.22	81.42	87.47	2.74	74.71	510.73
20	poor	35	116.24	7.00	10.05	82.94	85.56	2.70	69.53	520.25
20	poor	65	117.36	8.32	10.29	90.67	117.54	3.13	78.85	462.50
20	poor	65	117.90	8.09	10.19	92.36	117.10	3.15	81.71	475.46
20	poor	65	116.82	8.55	10.39	88.98	117.98	3.11	75.99	462.25
20	poor	85	114.88	7.83	9.88	85.93	103.64	2.88	68.84	450.06
20	poor	85	115.92	7.21	9.07	88.50	94.82	2.70	65.71	440.00
20	poor	85	115.40	7.52	9.46	88.03	99.23	2.80	67.26	460.12
20	poor	95	118.12	7.07	8.28	91.61	107.00	2.97	59.60	467.36
20	poor	95	115.87	6.83	9.30	83.12	92.49	2.84	60.60	449.67
20	poor	95	117.00	6.95	8.79	87.35	99.76	2.92	60.64	452.32
20	poor	120	122.24	6.39	8.85	87.20	111.50	3.18	46.41	347.10
20	poor	120	122.65	7.14	7.45	94.21	121.28	3.36	38.86	339.48
20	poor	120	122.82	6.75	8.71	90.69	116.39	3.27	37.11	319.20
20	poor	180	131.80	5.06	6.24	77.49	75.25	2.35	56.99	300.00
20	poor	180	132.00	5.14	6.09	79.78	74.50	2.33	57.00	250.00
20	poor	180	131.59	4.98	6.39	75.20	76.00	2.38	56.98	237.50
21	good	35	116.39	8.41	10.93	89.83	128.38	3.38	58.21	523.72
21	good	35	113.11	8.40	10.30	103.99	125.14	3.15	68.48	518.65
21	good	35	111.77	8.30	9.75	91.65	112.12	3.19	68.78	525.62
21	good	65	109.55	7.90	10.82	88.89	98.20	2.93	54.55	400.23
21	good	65	114.14	8.21	10.98	90.24	108.06	3.19	68.94	415.00
21	good	65	111.84	8.49	11.11	91.62	89.90	2.77	62.00	425.00
21	good	85	122.09	6.39	10.16	85.51	98.84	2.85	63.64	400.23
21	good	85	120.14	7.11	9.61	99.24	110.21	2.98	60.74	424.93
21	good	85	121.71	7.14	9.27	88.81	93.39	2.96	64.00	403.20
21	good	95	118.90	7.90	9.04	93.84	110.00	3.10	79.74	430.26
21	good	95	120.51	7.87	9.16	93.52	91.00	2.77	65.70	432.26
21	good	95	119.71	7.94	8.80	94.15	112.20	3.17	72.72	460.77
21	good	120	120.16	7.28	8.65	90.89	99.68	2.91	62.20	434.56
21	good	120	119.50	6.90	8.68	91.88	100.86	2.93	63.40	412.56
21	good	120	120.81	7.66	8.62	89.90	98.50	2.90	61.00	415.00
21	good	180	122.41	5.22	6.56	78.27	77.33	2.66	51.16	293.51
21	good	180	122.08	5.48	6.99	78.30	81.39	2.72	51.73	307.43
21	good	180	122.74	4.96	6.13	78.24	73.27	2.60	50.58	309.56

Table C-10: Results interpolated at 500 csf

Age	SI	Cooking Time	Sheet density	Burst	Tear	Tensile	TEA	Stretch	Z-span
years		min	kg/m^3	MN/kg	kN m^2/kg	kN m/kg	J/m^2	%	N
13	poor	65	744.64	7.25	9.82	88.43	121.58	3.23	31.25
13	poor	85	737.87	7.46	8.57	89.24	109.48	3.16	35.80
13	poor	95	742.79	6.59	8.45	85.88	115.36	3.10	28.82
13	poor	120	727.60	6.08	8.40	85.71	89.55	4.15	32.71
13	poor	180	738.31	5.87	7.55	78.66	92.43	2.96	36.28
20	poor	65	699.40	7.48	10.58	90.11	112.94	3.11	82.29
20	poor	85	691.75	7.14	9.56	85.52	94.47	2.77	70.84
20	poor	95	703.79	6.66	9.13	85.23	96.85	2.83	61.78
20	poor	120	706.63	6.11	8.59	85.20	89.94	2.82	51.63
20	poor	180	716.17	4.63	7.65	66.42	65.72	2.31	61.96
21	good	65	668.73	7.45	12.02	89.83	100.22	2.76	70.55
21	good	85	698.31	8.28	10.63	91.00	94.45	2.76	63.71
21	good	95	697.16	7.77	10.27	91.61	98.41	2.88	71.45
21	good	120	694.58	6.90	9.39	84.92	86.36	2.70	63.95
21	good	180	680.91	4.74	7.99	67.65	58.83	2.29	54.49
10	poor	65	760.83	7.08	8.30	95.81	123.09	3.47	27.25
10	poor	85	760.55	7.33	8.19	95.18	111.55	3.15	26.34
10	poor	95	773.26	7.04	8.27	92.45	119.74	3.12	25.41
10	poor	120	755.96	6.69	8.31	88.62	104.72	3.02	33.34
10	poor	180	760.41	5.68	7.29	81.86	88.39	2.74	32.40
14	good	65	737.75	7.15	9.52	86.50	103.78	2.88	65.69
14	good	85	725.18	7.83	8.59	86.98	100.26	2.77	66.44
14	good	95	717.84	7.13	8.61	88.06	100.83	2.84	68.13
14	good	120	729.60	6.23	8.01	82.96	88.87	2.75	63.94
14	good	180	705.55	4.50	7.02	68.18	62.43	2.31	56.41
9	good	65	750.76	7.30	8.74	99.25	119.50	3.02	33.45
9	good	85	743.69	7.60	8.14	99.47	109.30	3.02	47.59
9	good	95	734.71	6.86	6.83	96.11	105.63	2.94	42.45
9	good	120	739.23	6.42	7.97	90.53	86.50	2.68	42.69
9	good	180	733.23	5.57	7.53	82.26	78.39	2.46	31.08

Table C-10: Results interpolated at 620 csf

Age	SI	Cooking Time	Sheet density	Burst	Tear	Tensile	TEA	Stretch	Z-span
years		min	kg/m^3	MN/kg	kN m^2/kg	kN m/kg	J/m^2	%	N
9	good	35	712.28	7.74	8.12	96.00	111.22	3.19	40.54
14	good	35	668.49	7.28	9.78	82.09	96.12	2.85	73.21
21	good	35	645.02	7.20	12.33	85.15	95.15	2.79	66.63
10	poor	35	715.48	7.64	8.75	90.96	105.82	3.24	25.39
13	poor	35	670.11	6.66	10.19	77.56	90.67	3.04	35.32
20	poor	35	685.06	6.30	11.52	73.06	65.22	2.41	72.75

Table C-12: Results interpolated at 700 kg/m^3

Age	SI	Cooking Time	free	Burst	Tear	Tensile	TEA	Stretch	Z-span
years		min	mL	MN/kg	kN m^2/kg	kN m/kg	J/m^2	%	N
13	poor	35	593.10	7.01	9.55	83.59	100.75	3.13	34.69
13	poor	65	590.56	6.43	10.85	77.73	96.18	2.98	38.64
13	poor	85	699.96	5.67	10.16	62.15	63.27	2.39	43.79
13	poor	95	600.56	5.70	9.73	74.38	93.89	2.93	27.12
13	poor	120	554.55	5.67	9.50	72.60	77.49	2.69	35.69
13	poor	180	608.88	5.12	8.42	63.90	66.42	2.62	38.95
20	poor	35	605.23	6.41	11.24	75.48	68.00	2.47	71.91
20	poor	65	501.45	7.64	10.65	90.74	115.24	3.17	83.23
20	poor	85	503.66	7.14	9.34	87.41	97.14	2.85	72.33
20	poor	95	539.26	6.37	9.66	82.59	91.85	2.73	63.39
20	poor	120	530.62	5.94	9.54	74.75	83.90	2.72	38.53
20	poor	180	548.98	4.42	7.99	62.97	61.74	2.28	61.13
21	good	35	478.24	9.23	9.36	102.43	143.21	3.58	69.73
21	good	65	415.34	8.73	10.36	96.42	102.07	2.97	77.28
21	good	85	498.15	6.83	10.48	85.59	90.87	2.78	63.26
21	good	95	496.53	7.90	10.10	93.01	100.20	2.91	72.12
21	good	120	495.16	6.99	9.08	86.51	88.26	2.72	64.00
21	good	180	443.15	5.00	7.39	72.32	65.53	2.42	53.88
10	poor	35	637.19	7.41	8.92	86.79	95.07	3.05	27.32
10	poor	65	628.23	5.79	9.32	80.52	90.40	2.92	31.77
10	poor	85	632.52	6.16	9.54	78.56	80.97	2.76	26.88
10	poor	95	682.00	5.50	10.10	68.00	61.99	2.41	38.56
10	poor	120	650.79	5.46	10.27	68.22	63.81	2.49	34.16
10	poor	180	663.08	4.45	8.80	61.93	61.30	2.51	34.28
14	good	35	527.14	7.77	9.16	84.87	106.96	2.97	63.75
14	good	65	589.08	6.43	9.96	79.61	92.16	2.79	67.85
14	good	85	563.54	6.34	9.29	84.33	95.06	2.74	70.67
14	good	95	504.18	6.26	9.42	87.80	100.25	2.83	68.24
14	good	120	583.88	5.80	9.00	74.07	74.73	2.55	65.87
14	good	180	514.75	4.44	7.15	67.20	61.43	2.30	56.98
9	good	35	646.56	7.37	8.35	89.40	99.07	3.00	44.09
9	good	65	636.64	6.47	9.72	87.81	94.40	2.72	35.99
9	good	85	605.31	6.50	9.65	81.73	77.47	2.51	49.80
9	good	95	602.34	6.21	9.20	87.50	89.61	2.74	41.40
9	good	120	700.00	5.16	10.08	66.06	51.12	2.27	52.86
9	good	180	603.69	5.03	8.17	74.87	70.50	2.40	28.59

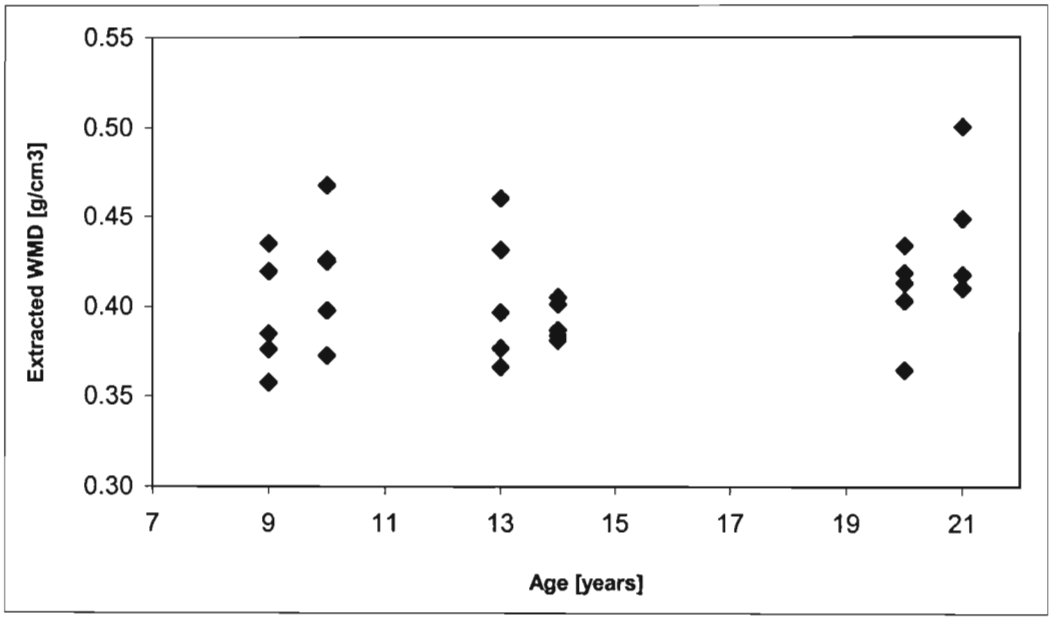
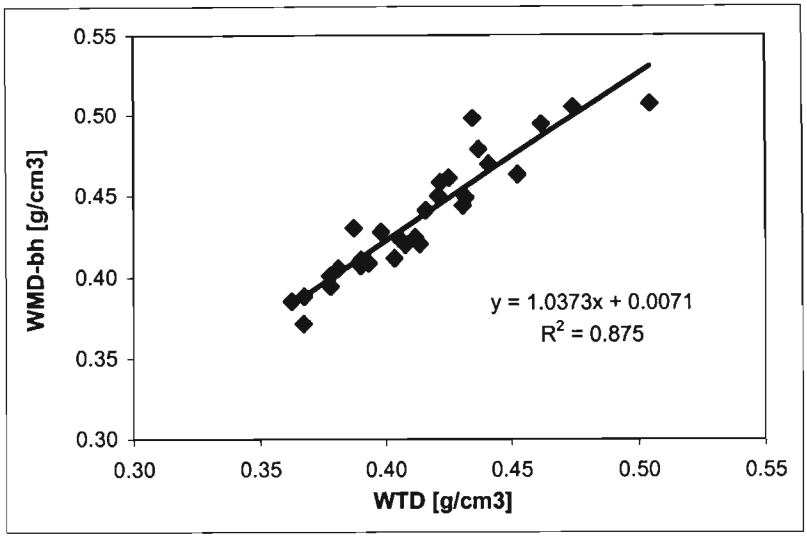
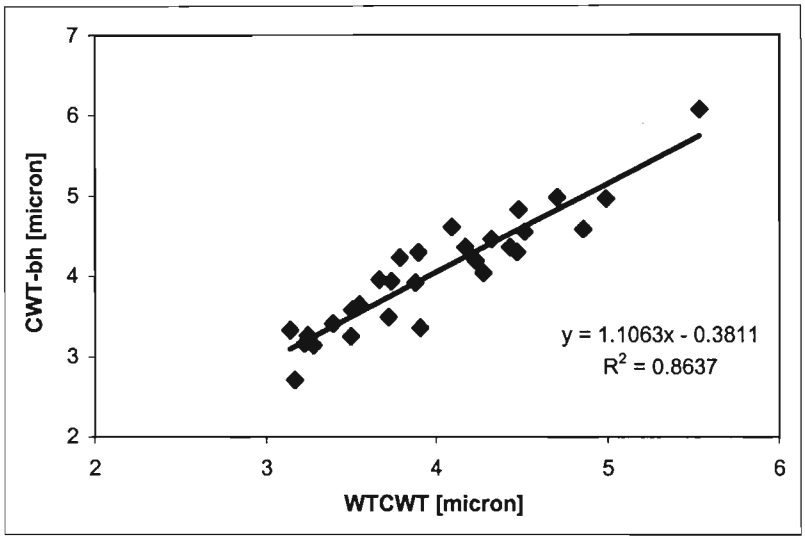


Fig. C-2: Graphical representation of extracted wood density data.





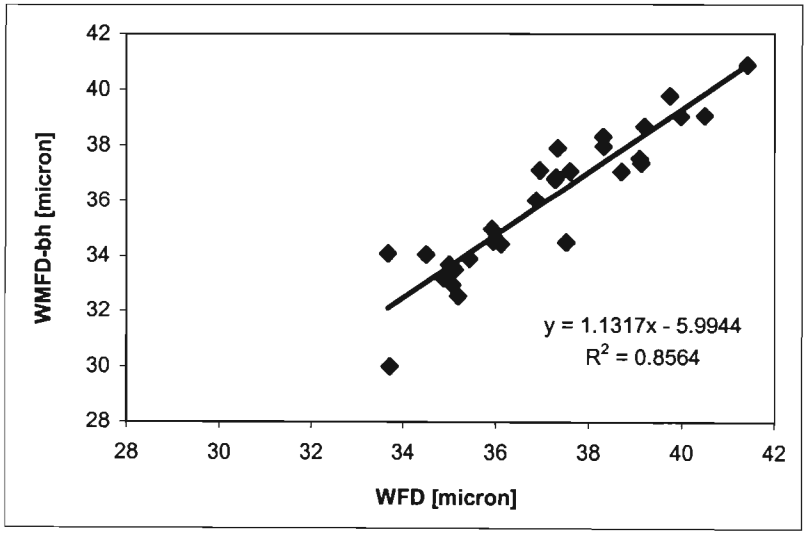


Fig. C-1: Breast height predictions of whole-tree estimates of wood properties.

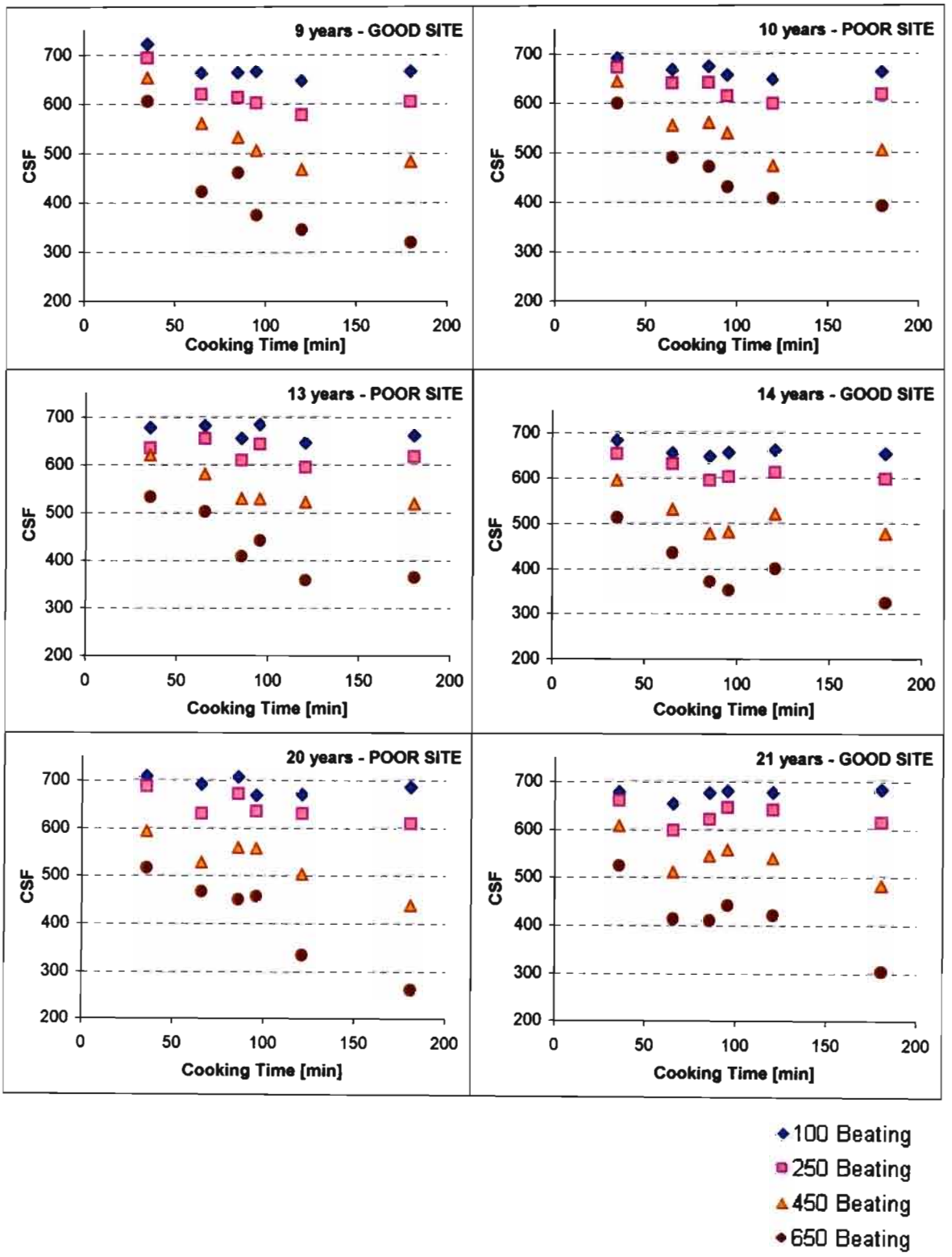


Fig. C-3: Freeness as a function of cooking time.

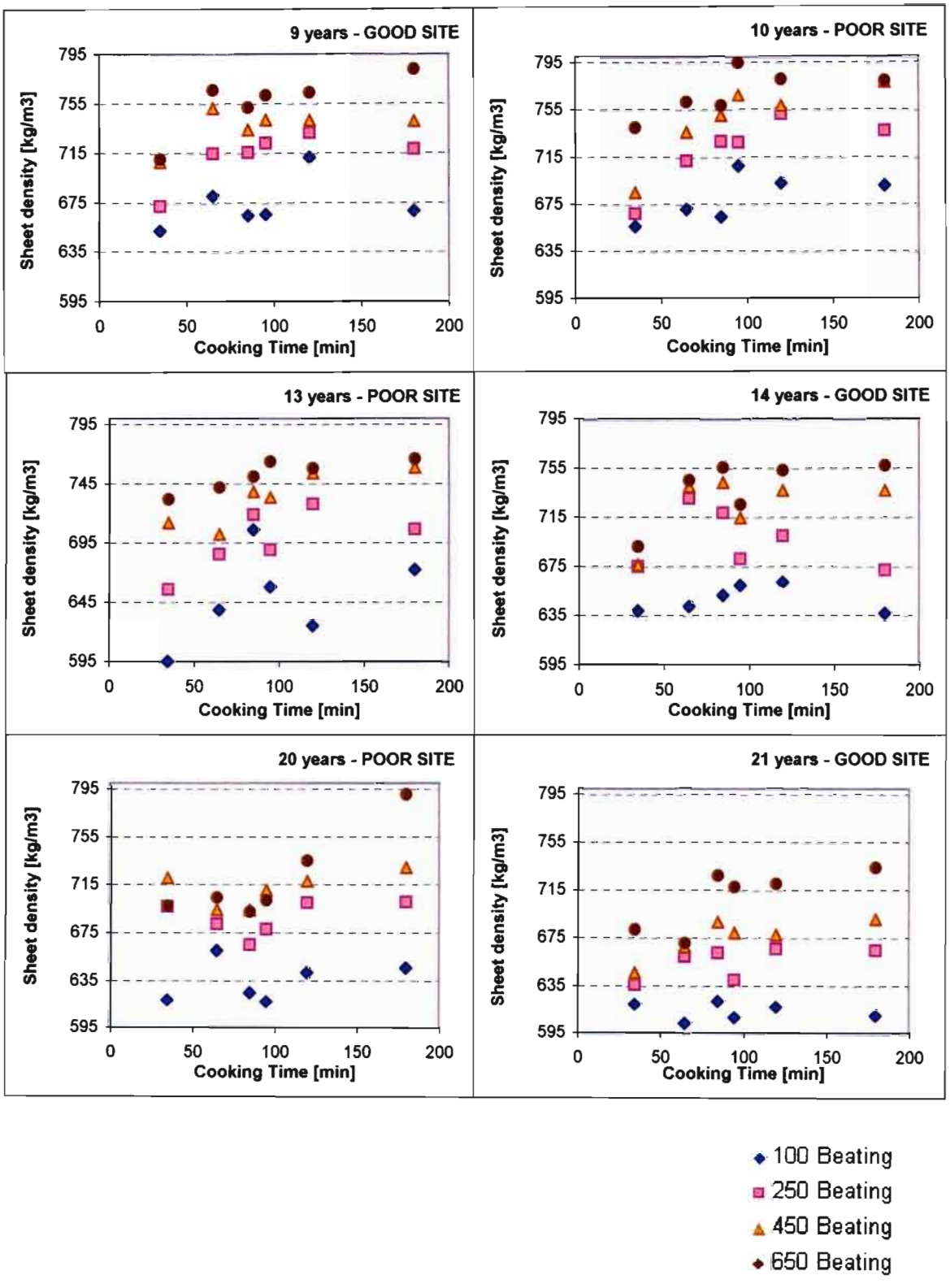


Fig. C-4: Sheet density as a function of cooking time.

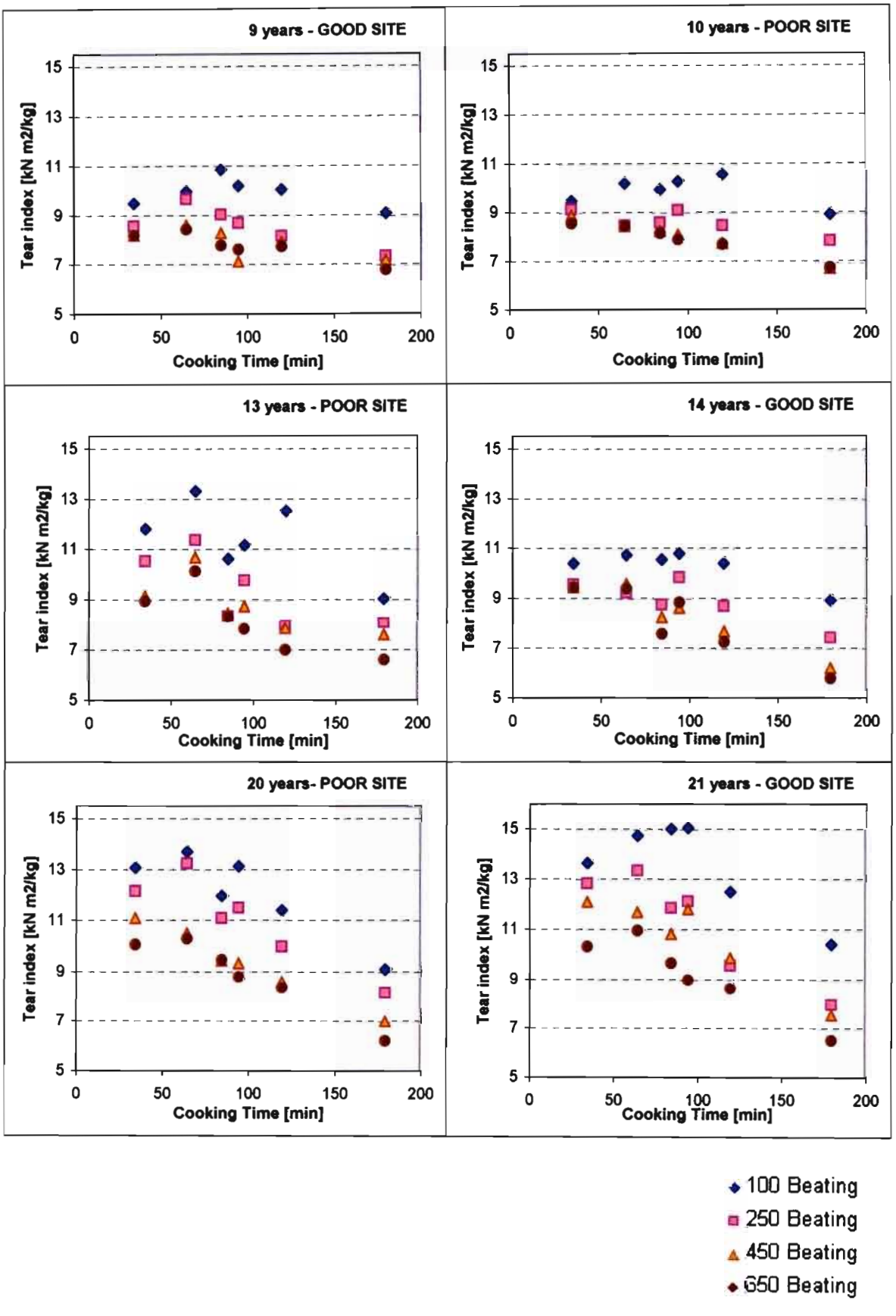


Fig. C-5: Tear index as a function of cooking time.

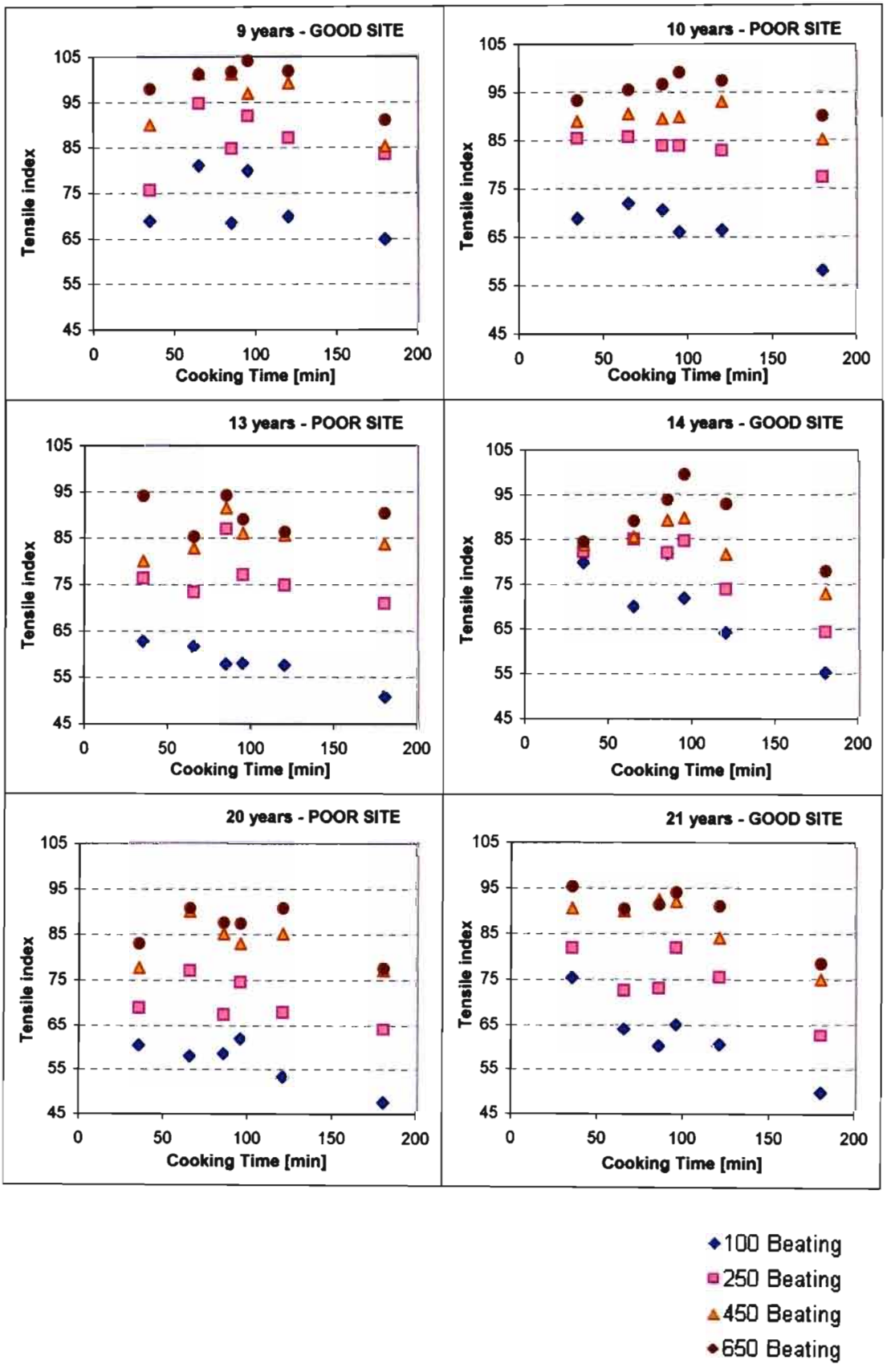


Fig. C-6: Tensile index as a function of cooking time.

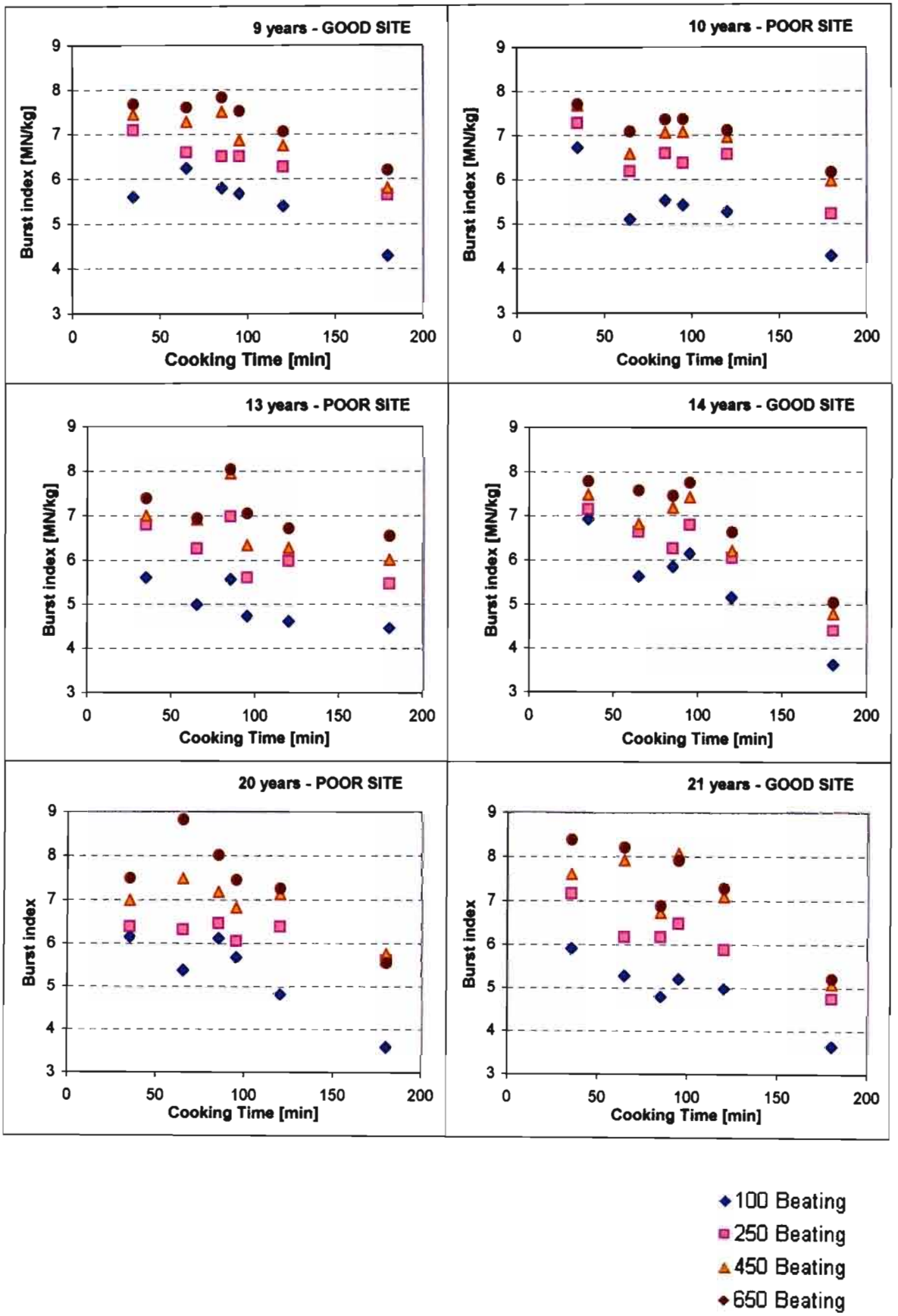


Fig. C-7: Burst index as a function of cooking time.

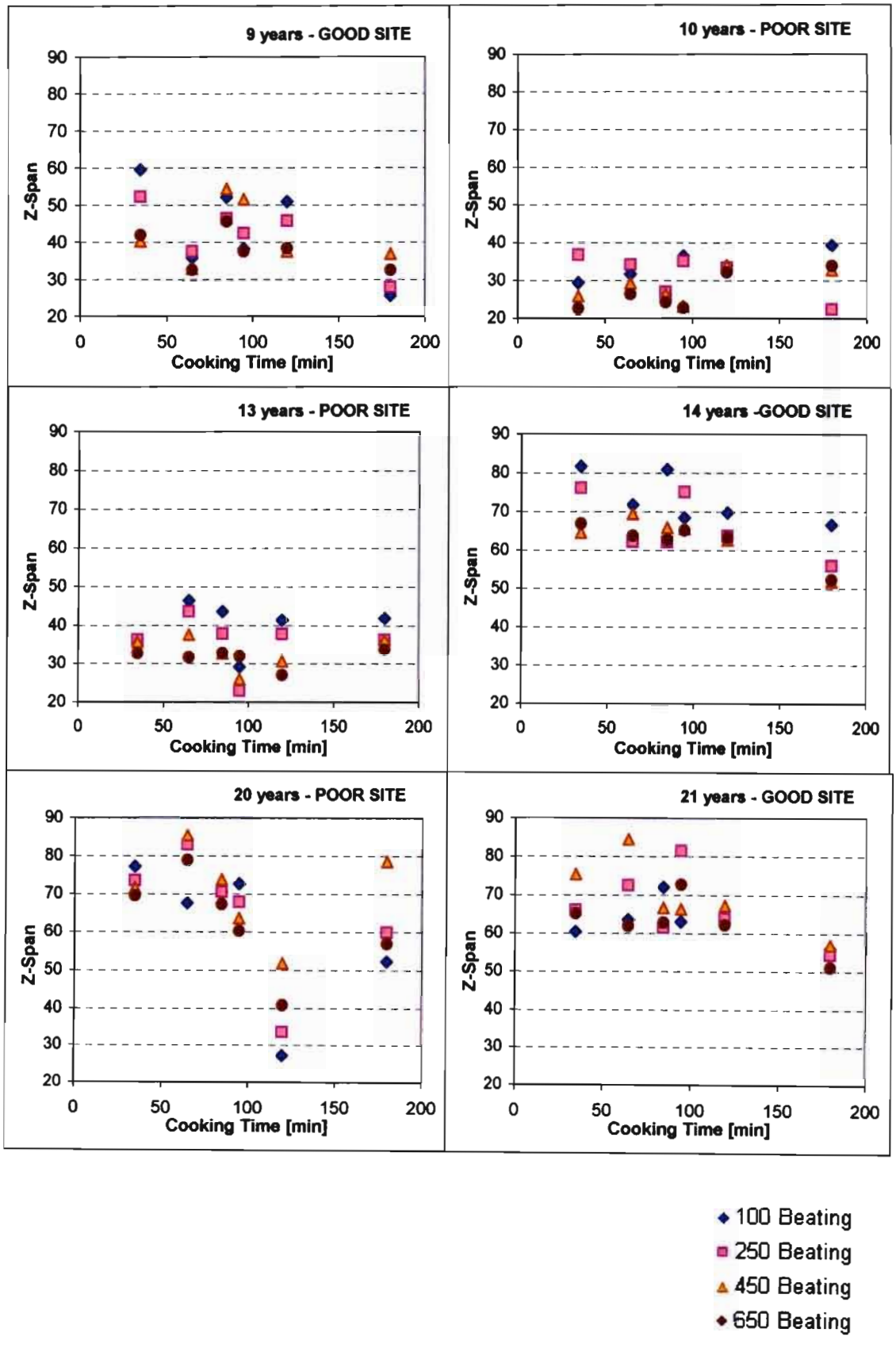


Fig. C-8: Zero-span as a function of cooking time.

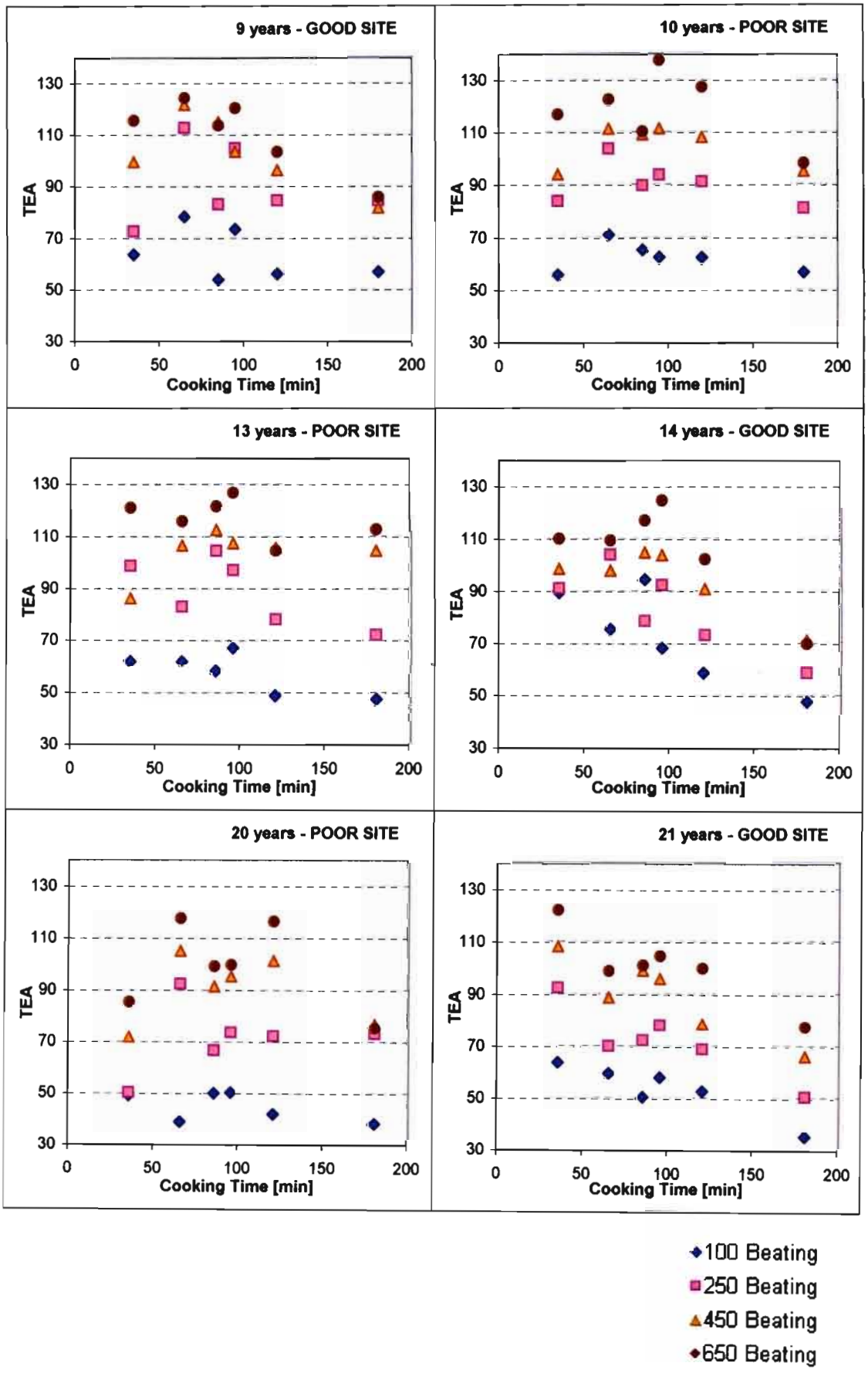


Fig. C-9: TEA as a function of cooking time.

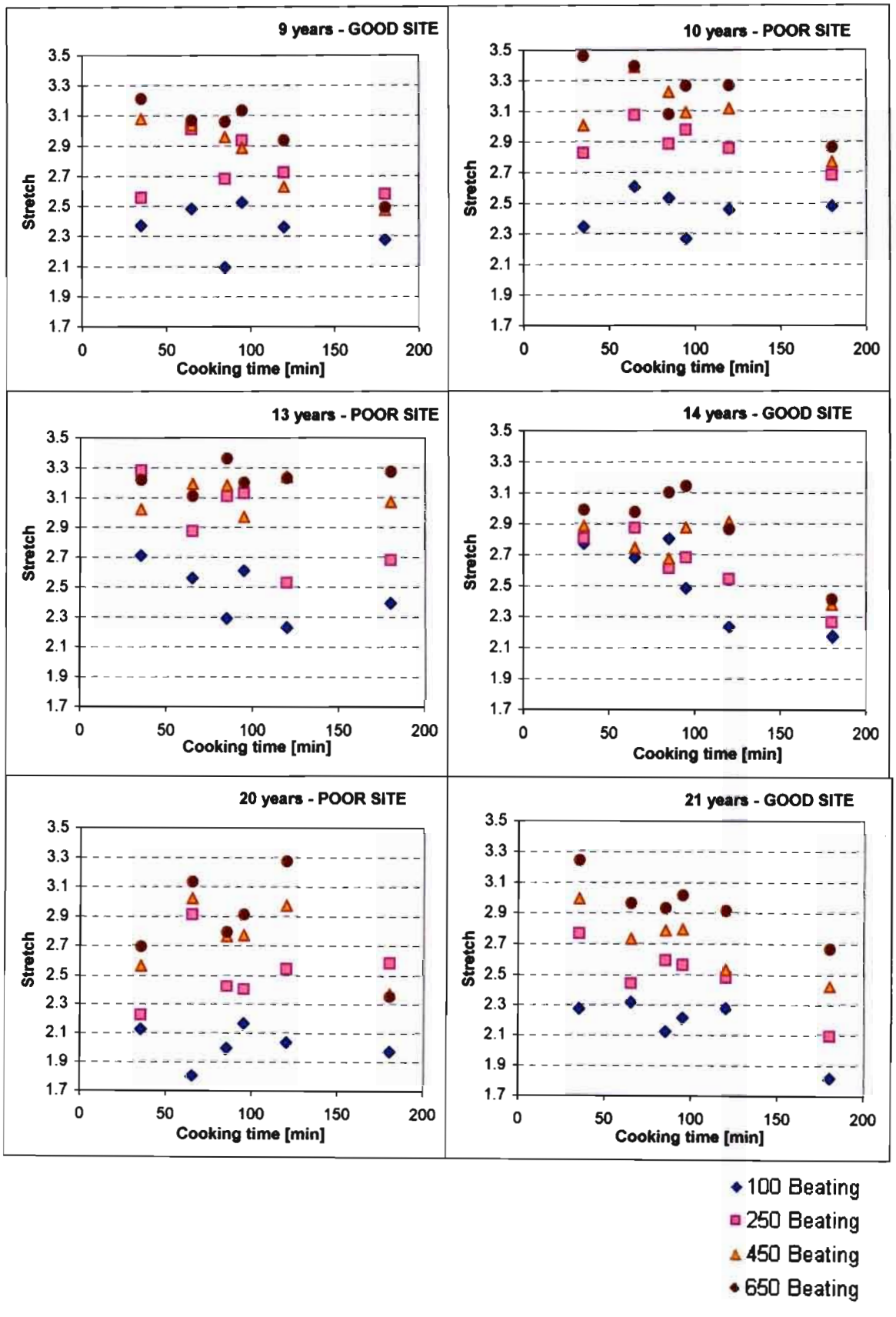


Fig. C-10: Stretch as a function of cooking time.

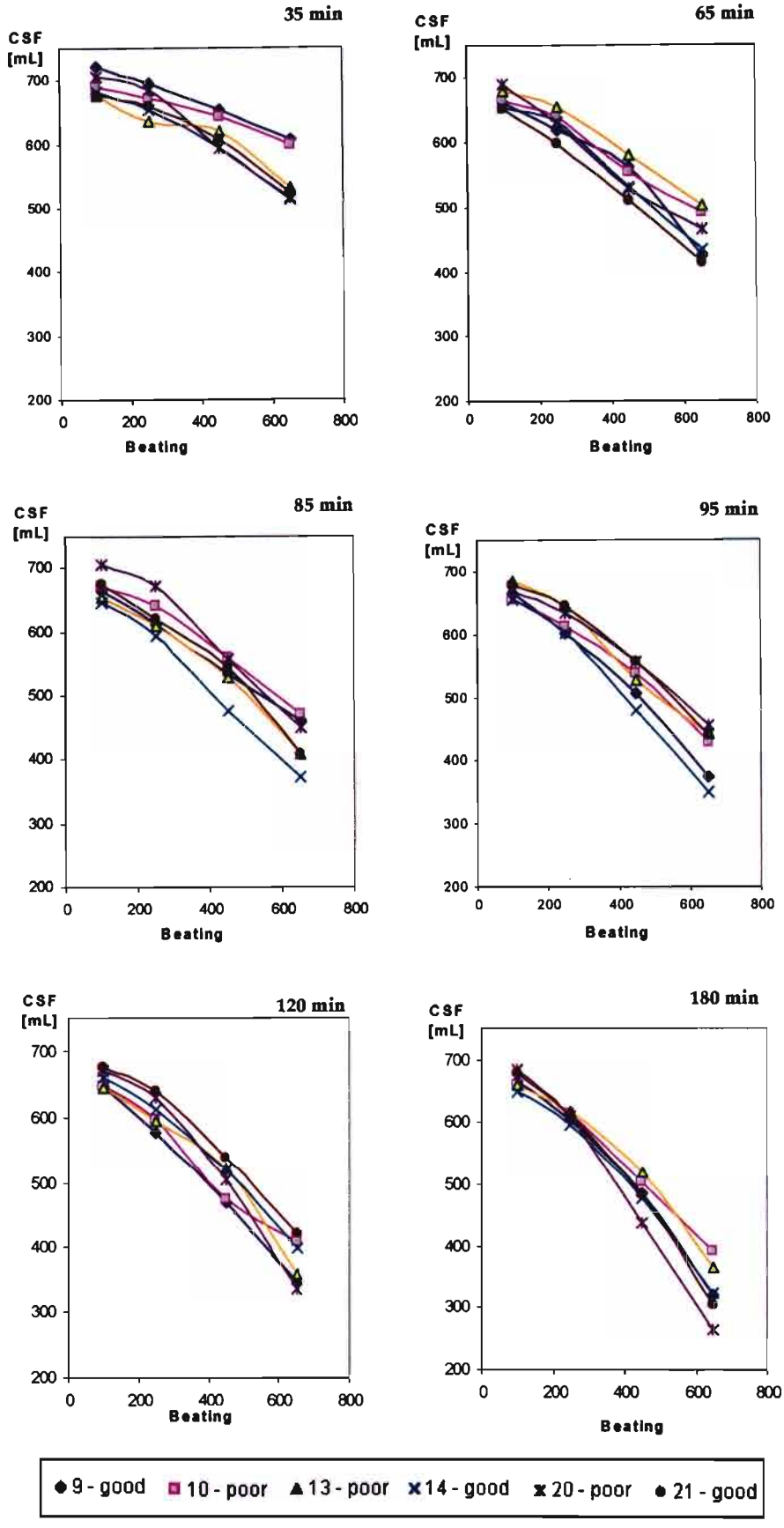


Fig. C-11: Freeness as a function of beating

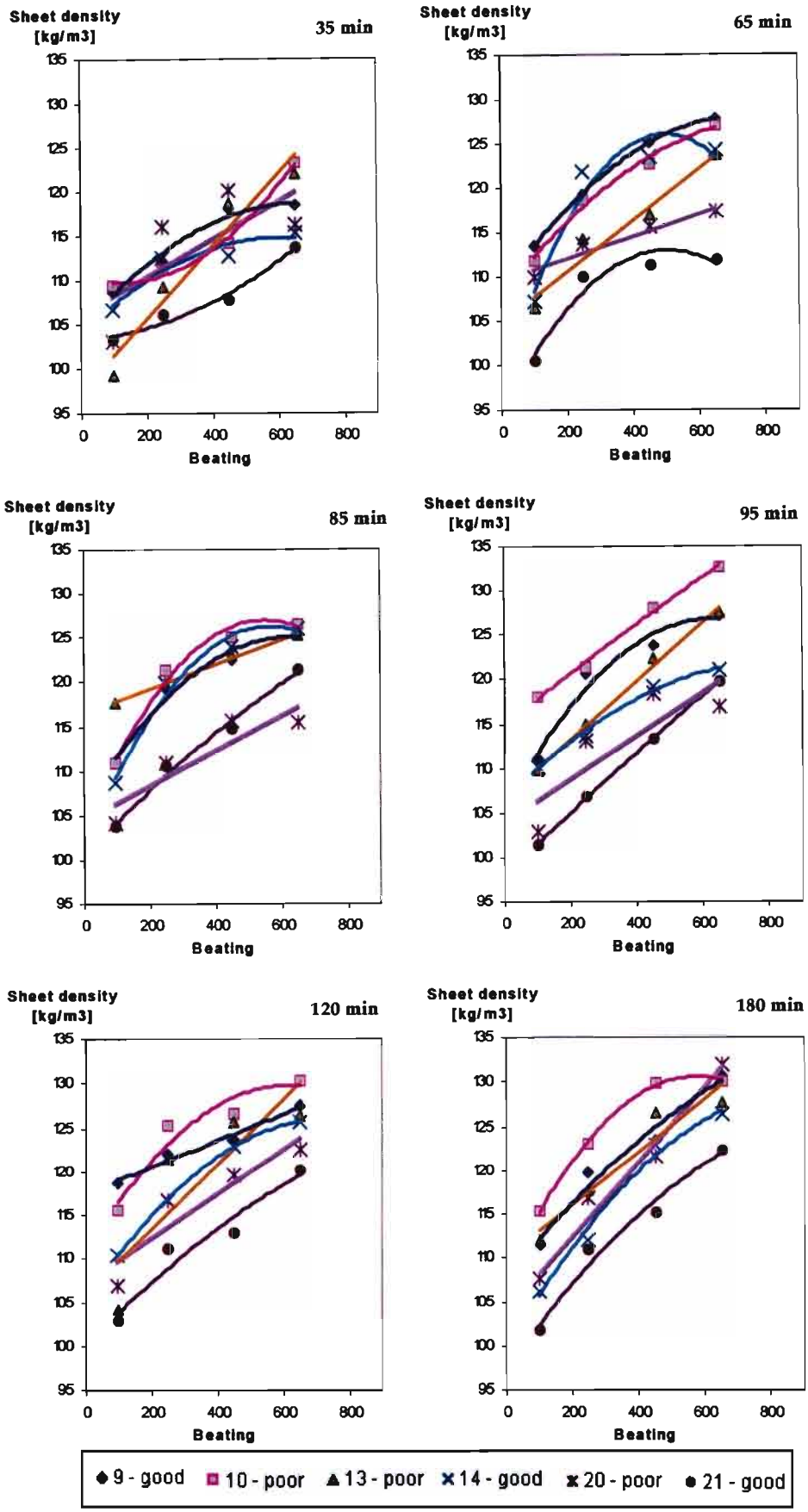


Fig. C-12: Sheet density as a function of beating

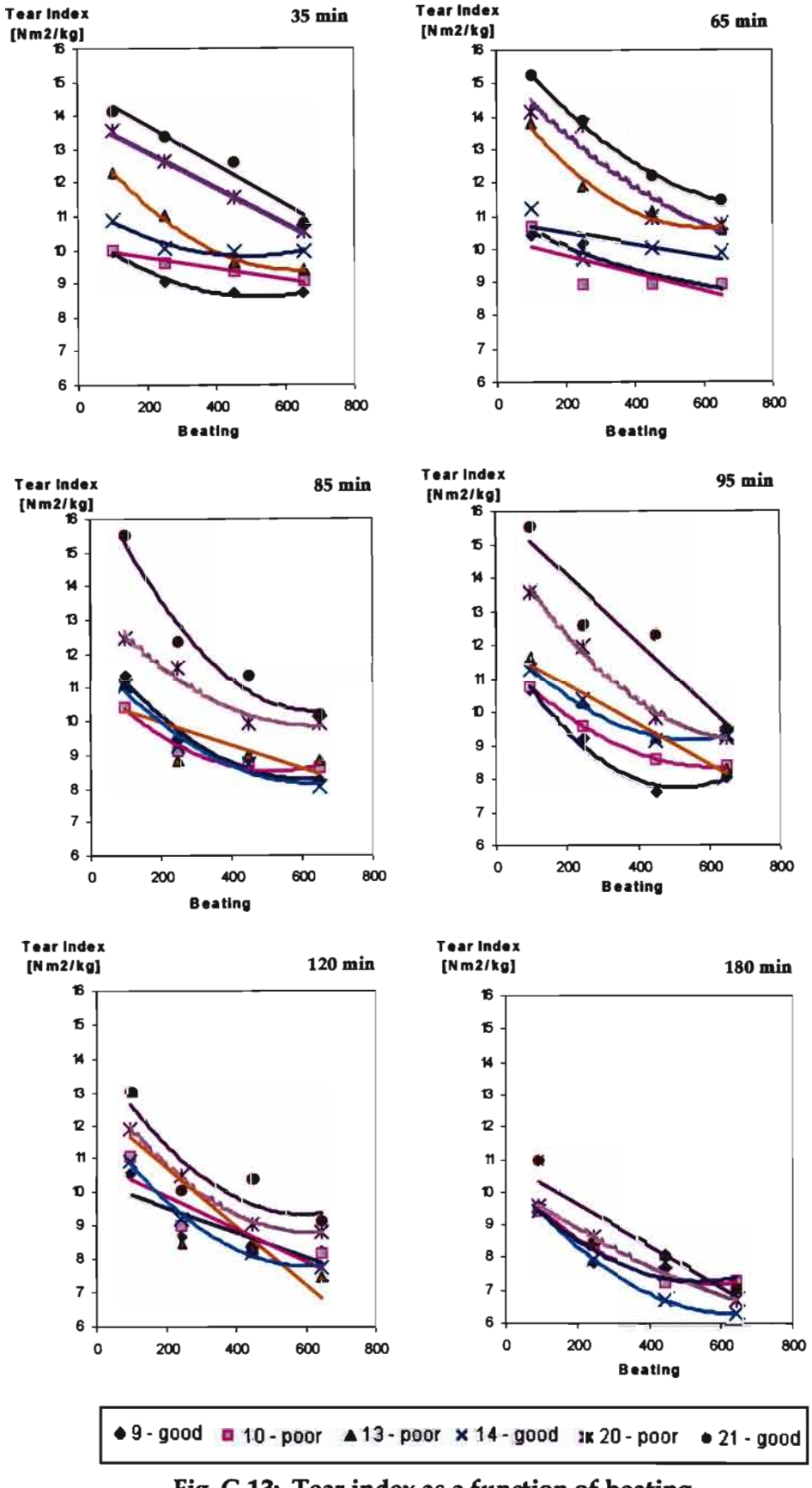


Fig. C-13: Tear index as a function of beating

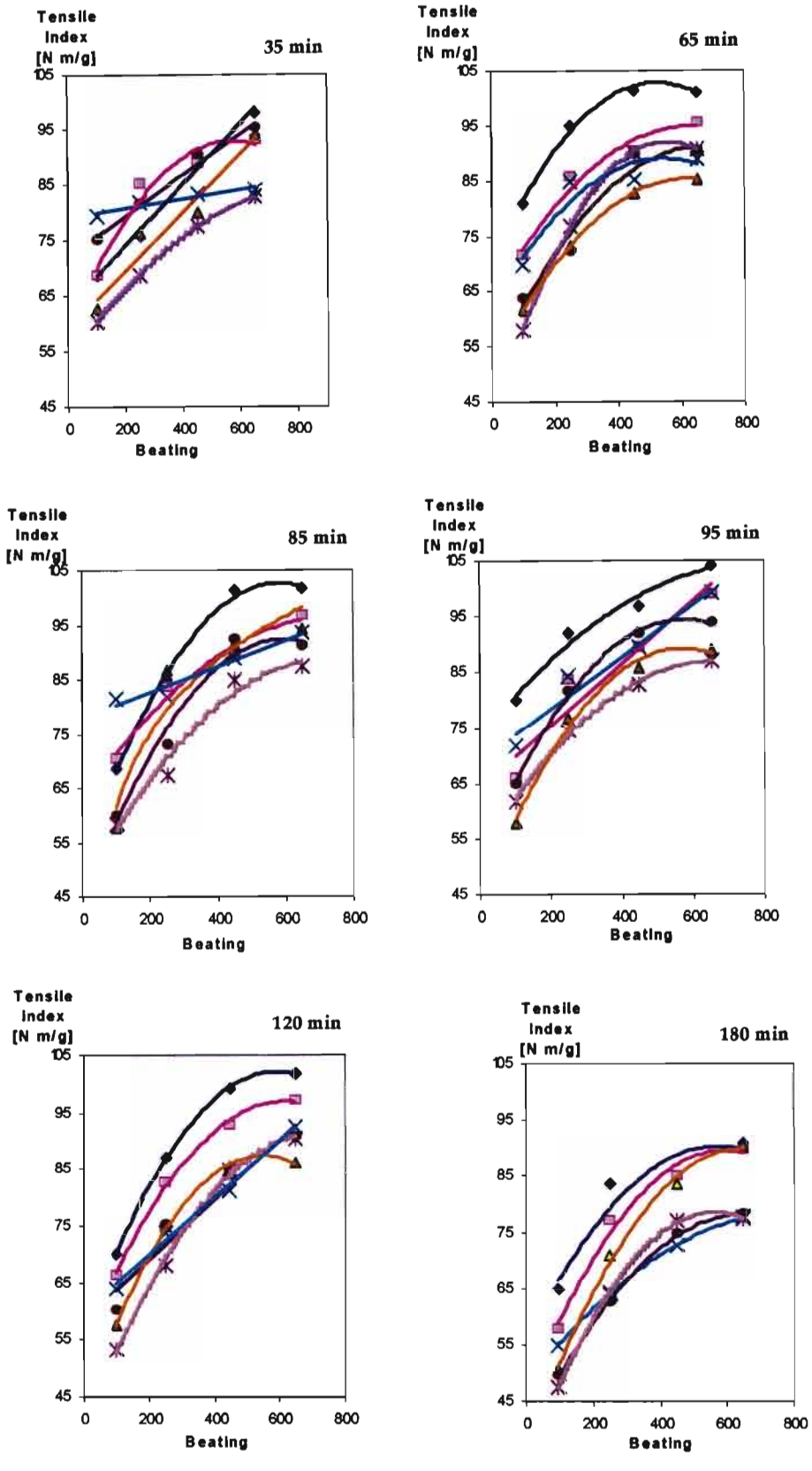


Fig. C-14: Tensile index as a function of beating

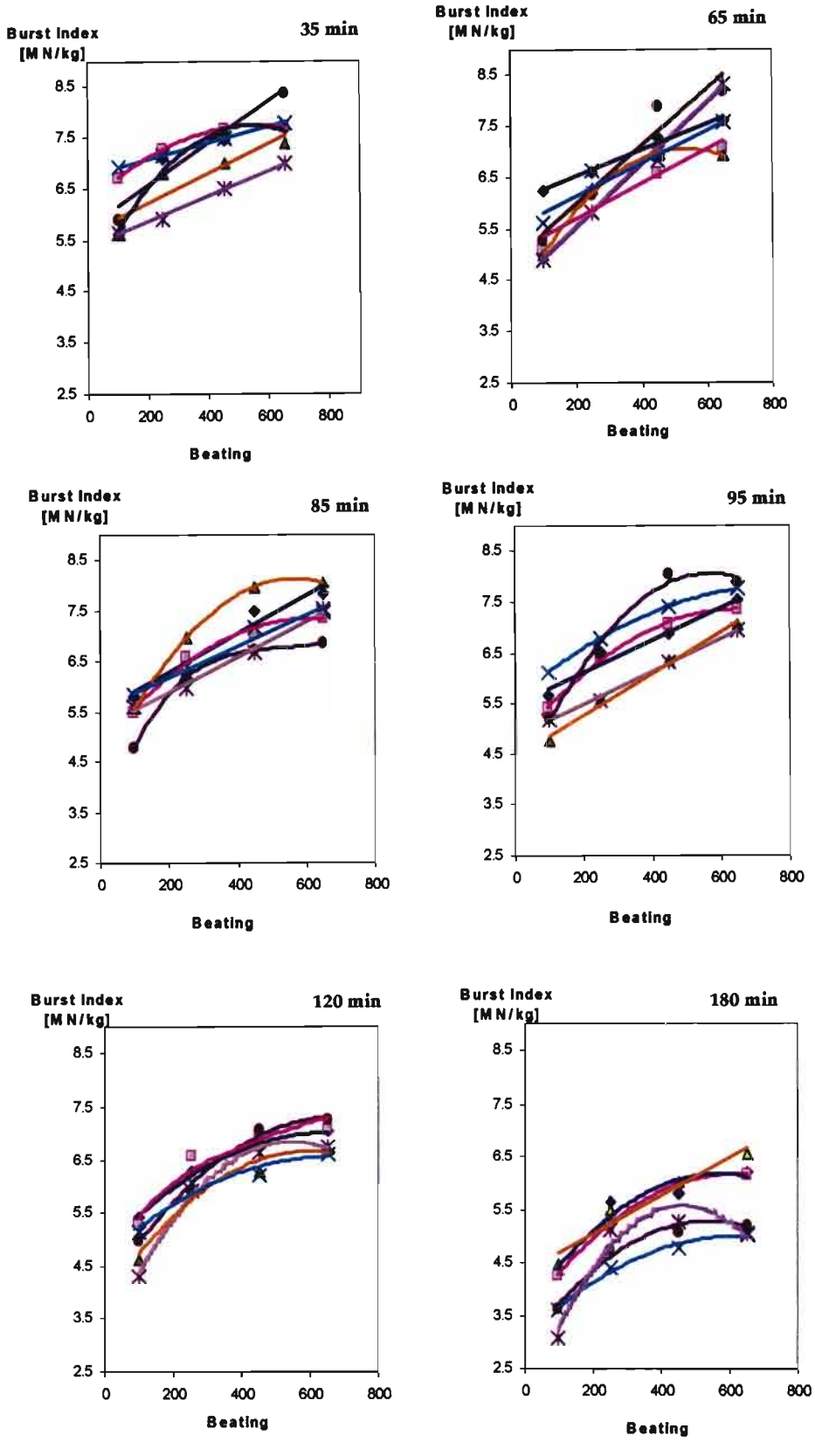


Fig. C-15: Burst index as a function of beating

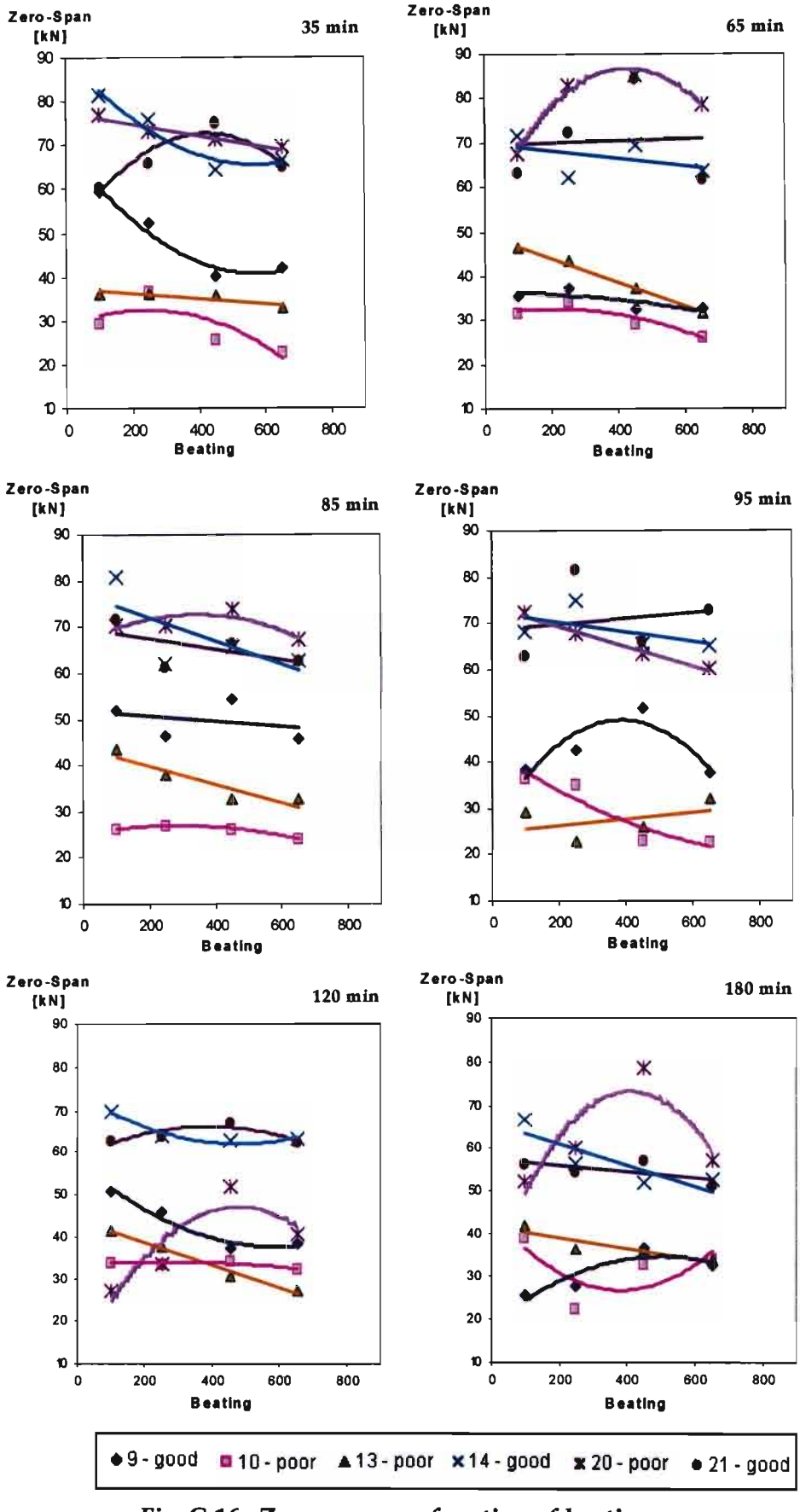


Fig. C-16: Zero-span as a function of beating

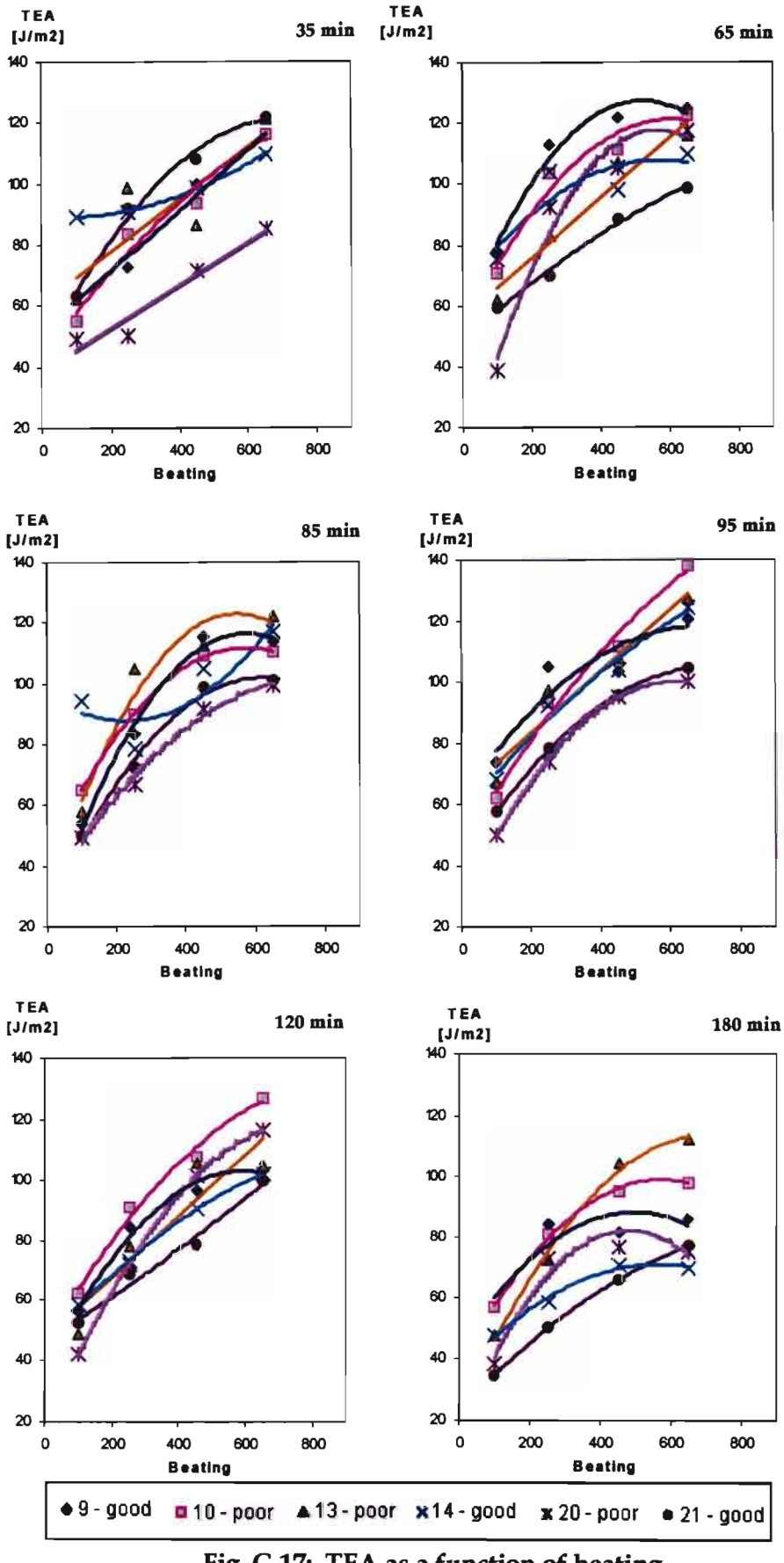


Fig. C-17: TEA as a function of beating

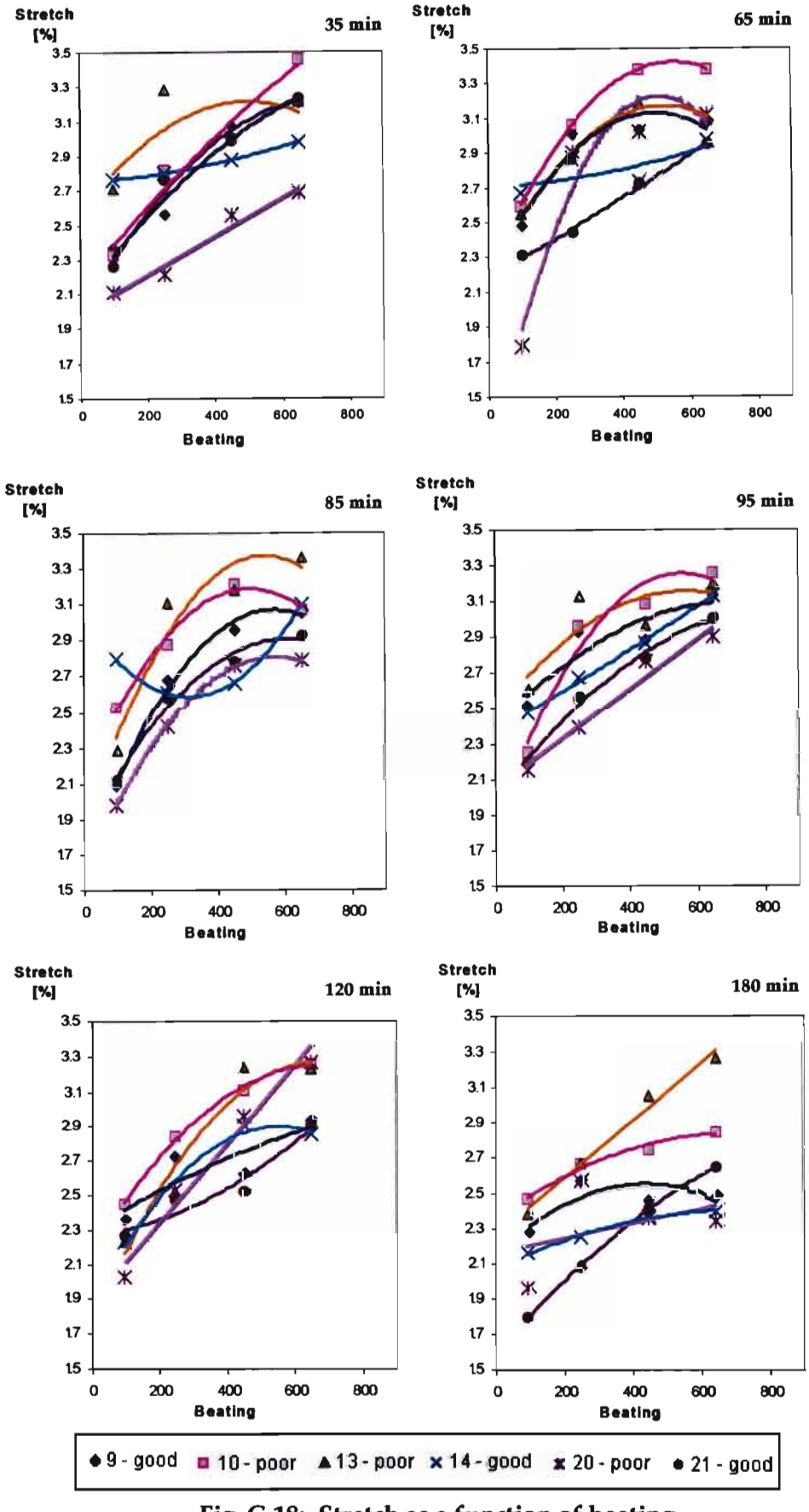


Fig. C-18: Stretch as a function of beating

Table D-1. Multiple regression results at kappa 30.

Tear 100B	
R^2	93
Wood Runkel	66
Wood CWT	15
Wood LD	12

Tensile 100B	
R^2	56
Wood Coll	56

Z-Span 100B	
R^2	94
Wood Cellulose	85
Wood Mannose	4
Wood Glucose	5

Burst 100B	
R^2	87
Wood Coll	56
Wood FD	16
% EW	15

Tear 100B	
R^2	88
Wood Glucose	58
Wood Extractives	14
Wood Cellulose	16

Tensile 100B	
R^2	82
Wood Coll	56
Wood Extractives	26

Z-Span 100B	
R^2	94
Wood LD	87
Wood Extractives	7

Burst 100B	
R^2	83
Wood Coll	56
Wood Coarseness	16
Wood CWT	11

Tear 100B	
R^2	95
Wood Runkel	66
Wood Extractives	20
Wood Xylose	9

Tensile 100B	
R^2	79
Pulp Galactose	65
Pulp FD	14

Z-Span 100B	
R^2	83
FL / FD	83

Burst 100B	
R^2	80
Pulp Arabinose	61
Pulp Glucose	19

Tear 100B	
R^2	70
Muhlsteph	70

Tensile 650B	
R^2	79
Wood LD	42
LW Density	22
Wood Density	15

Z-Span 650B	
R^2	94
Wood FD	79
Wood LD	15

Burst 650B	
R^2	82
Wood Cellulose	52
Wood Klason	13
Wood Galactose	13
Wood Extractives	4

Tear 650B	
R^2	88
Wood Runkel	60
Wood LD	16
Wood CWT	12

Tensile 650B	
R^2	70
Wood Glucose	57
Wood Xylose	13

Z-Span 650B	
R^2	87
Wood Cellulose	87

Burst 650B	
R^2	80
LW Density	52
Wood LD	22
EW Density	6

Tear 650B	
R^2	
Wood Klason	70
Wood Density	11
Wood Extractives	7

Tensile 650B	
R^2	79
Wood Mannose	51
Wood Xylose	19
Wood LD	8

Z-Span 650B	
R^2	95
Wood Cellulose	87
% EW	8

Burst 650B	
R^2	79
Wood Coarseness	57
% EW	13
Wood Xylose	9

Tear 650B	
R^2	84
Muhlsteph	70
Pulp Mannose	9
Pulp Coarseness	5

Tensile 650B	
R^2	83
Pulp LD	66
Pulp Glucose	8
Pulp Mannose	9

Z-Span 650B	
R^2	92
FL / FD	78
Pulp Mannose	14

Burst 650B	
R^2	85
Pulp CWT	67
Pulp Glucose	18

continued...

Table D-1. continued

Freeness 100B	
R^2	47
EW Density	20
Wood Runkel	14
% EW	13

TEA 100B	
R^2	56
Wood Runkel	35
% EW	21

Stretch 100B	
R^2	77
Wood Runkel	22
% EW	55

Sheet Density 100B	
R^2	88
% EW	65
Wood Xylose	12
Wood Extractives	11

Freeness 100B	
R^2	40
Pulp Mannose	24
Pulp LD	16

TEA 100B	
R^2	64
Pulp Galactose	64

Stretch 100B	
R^2	56
Pulp Galactose	56

Sheet Density 100B	
R^2	82
Pulp Mannose	58
Pulp Arabinose	24

Freeness 650B	
R^2	92
EW Density	59
Wood Density	29
Wood Collapsibility	4

TEA 650B	
R^2	20
% EW	20

Stretch 650B	
R^2	41
Wood Xylose	41

Sheet Density 650B	
R^2	86
WT Runkel	74
Wood Xylose	12

Freeness 650B	
R^2	62
Pulp Glucose	43
Pulp FD	19

TEA 650B	
R^2	34
Pulp Mannose	34

Stretch 650B	
R^2	30
Fines	30

Sheet Density 650B	
R^2	73
Muhlsteph	73

Table D-2: Correlation table showing r-values between wood and pulp properties, across all cooking times together

	Wood Klason	Wood Arab	Wood Galac	Wood Gluc	Wood Xyl	Wood Mann	extrac-tives	cellul-ose	%EW	EW dens	LW dens	WTD	WTC WT	WT FD	WT LD	WT Runk	WT Coll	Wood coarse	Yield	AA Cons	Kappa	Klason	Pulp Arab	Pulp Gal	Pulp Gluc	Pulp Xyl	Pulp Man	Pulp FL	Pulp FD	Pulp CWT	Pulp LD	Mulhste ph
Wood Arab	0.82	1.00																														
Wood Galac	-0.94	-0.83	1.00																													
Wood Gluc	0.95	0.90	-0.91	1.00																												
Wood Xyl	0.67	0.89	-0.80	0.70	1.00																											
Wood Mann	-0.98	-0.89	0.94	-0.97	-0.75	1.00																										
extractives	-0.41	-0.35	0.37	-0.57	-0.03	0.36	1.00																									
cellulose	0.89	0.62	-0.87	0.73	0.61	-0.83	-0.12	1.00																								
%EW	-0.55	-0.48	0.28	-0.49	-0.21	0.53	0.05	-0.51	1.00																							
EW dens	0.30	0.35	-0.32	0.18	0.46	-0.26	0.23	0.59	-0.50	1.00																						
LW dens	0.05	0.07	-0.20	-0.07	0.31	0.02	0.20	0.41	-0.02	0.86	1.00																					
WTD	0.17	0.09	-0.02	0.12	-0.09	-0.07	-0.23	0.32	-0.64	0.70	0.54	1.00																				
WTCWT	0.69	0.24	-0.50	0.49	0.07	-0.56	-0.20	0.81	-0.67	0.46	0.24	0.59	1.00																			
WTFD	0.53	0.20	-0.59	0.28	0.41	-0.47	0.34	0.81	-0.14	0.47	0.46	0.00	0.60	1.00																		
WTLD	0.99	0.82	-0.97	0.93	0.73	-0.98	-0.34	0.89	-0.44	0.28	0.07	0.05	0.62	0.60	1.00																	
WTRunk	0.68	0.33	-0.53	0.56	0.11	-0.55	-0.44	0.76	-0.65	0.52	0.34	0.75	0.94	0.42	0.59	1.00																
WTColl	-0.70	-0.25	0.48	-0.54	-0.01	0.59	0.24	-0.74	0.70	-0.27	-0.01	-0.47	-0.97	-0.51	-0.63	-0.88	1.00															
Wood coarse	0.54	0.22	-0.50	0.30	0.28	-0.42	0.12	0.85	-0.49	0.80	0.70	0.60	0.84	0.80	0.52	0.79	-0.70	1.00														
Yield	0.18	0.12	-0.21	0.14	0.16	-0.17	0.00	0.23	-0.04	0.13	0.13	0.02	0.15	0.23	0.20	0.13	-0.12	0.20	1.00													
AA Cons	-0.71	-0.59	0.64	-0.63	-0.52	0.71	0.05	-0.68	0.51	-0.30	-0.04	-0.10	-0.52	-0.49	-0.71	-0.44	0.53	-0.45	-0.64	1.00												
Kappa	-0.34	-0.38	0.40	-0.36	-0.40	0.38	0.08	-0.27	0.03	-0.04	0.01	0.17	-0.04	-0.20	-0.38	-0.03	0.05	-0.06	0.55	-0.19	1.00											
Klason	-0.21	-0.41	0.22	-0.31	-0.33	0.26	0.21	-0.09	0.18	-0.15	-0.04	-0.12	0.05	0.15	-0.19	-0.06	-0.06	0.04	0.69	-0.32	0.75	1.00										
Pulp Arab	-0.01	0.13	0.07	0.03	0.06	-0.03	0.07	-0.06	-0.26	0.11	-0.05	0.13	-0.04	-0.16	-0.04	-0.03	0.02	-0.06	0.57	-0.45	0.75	0.58	1.00									
Pulp Gal	-0.15	-0.09	0.19	-0.16	-0.05	0.11	0.30	-0.16	-0.05	-0.07	-0.16	-0.15	-0.14	-0.05	-0.14	-0.23	0.10	-0.14	0.58	-0.40	0.75	0.72	0.88	1.00								
Pulp Gluc	-0.16	-0.14	0.11	-0.13	-0.11	0.17	-0.08	-0.13	0.18	-0.02	0.09	0.04	-0.10	-0.11	-0.16	-0.04	0.13	-0.06	-0.77	0.67	-0.66	-0.79	-0.83	-0.82	1.00							
Pulp Xyl	0.45	0.54	-0.49	0.47	0.56	-0.51	-0.04	0.35	-0.16	0.12	-0.02	-0.17	0.06	0.23	0.48	0.04	-0.07	0.08	0.29	-0.52	-0.02	0.10	0.35	0.23	-0.52	1.00						
Pulp Man	0.41	0.55	-0.28	0.48	0.36	-0.47	-0.14	0.23	-0.57	0.16	-0.18	0.18	0.17	-0.10	0.36	0.19	-0.23	0.03	0.42	-0.65	0.31	0.17	0.68	0.52	-0.69	0.44	1.00					
Pulp FL	0.77	0.64	-0.81	0.67	0.65	-0.71	-0.21	0.89	-0.42	0.71	0.61	0.45	0.66	0.65	0.77	0.72	-0.54	0.80	0.42	-0.69	-0.07	0.01	0.13	-0.02	-0.26	0.38	0.31	1.00				
Pulp FD	-0.65	-0.60	0.54	-0.71	-0.39	0.70	0.32	-0.34	0.34	0.29	0.56	0.29	-0.21	-0.07	-0.64	-0.14	0.36	0.11	0.26	0.29	0.59	0.49	0.28	0.31	-0.19	-0.24	-0.19	-0.06	1.00			
Pulp CWT	0.31	0.16	-0.41	0.19	0.26	-0.21	-0.15	0.56	-0.06	0.65	0.78	0.51	0.46	0.49	0.31	0.57	-0.28	0.70	0.40	-0.28	0.09	0.16	0.03	-0.11	-0.11	0.02	-0.10	0.74	0.40	1.00		
Pulp LD	-0.87	-0.74	0.82	-0.87	-0.57	0.88	0.43	-0.68	0.40	-0.06	0.16	0.02	-0.49	-0.36	-0.87	-0.48	0.55	-0.28	0.06	0.47	0.58	0.43	0.28	0.40	-0.15	-0.27	-0.15	-0.49	0.85	-0.14	1.00	
Mulhsteph	0.74	0.55	-0.79	0.66	0.53	-0.68	-0.37	0.81	-0.28	0.50	0.46	0.35	0.62	0.57	0.74	0.69	-0.53	0.67	0.25	-0.47	-0.29	-0.15	-0.15	-0.32	0.02	0.18	0.01	0.82	-0.23	0.80	-0.70	1.00
Pulp Coarseness	0.51	0.24	-0.49	0.31	0.30	-0.42	0.09	0.78	-0.41	0.69	0.61	0.49	0.73	0.74	0.50	0.69	-0.61	0.88	0.63	-0.66	0.21	0.35	0.22	0.16	-0.41	0.21	0.22	0.83	0.21	0.75	-0.20	0.66

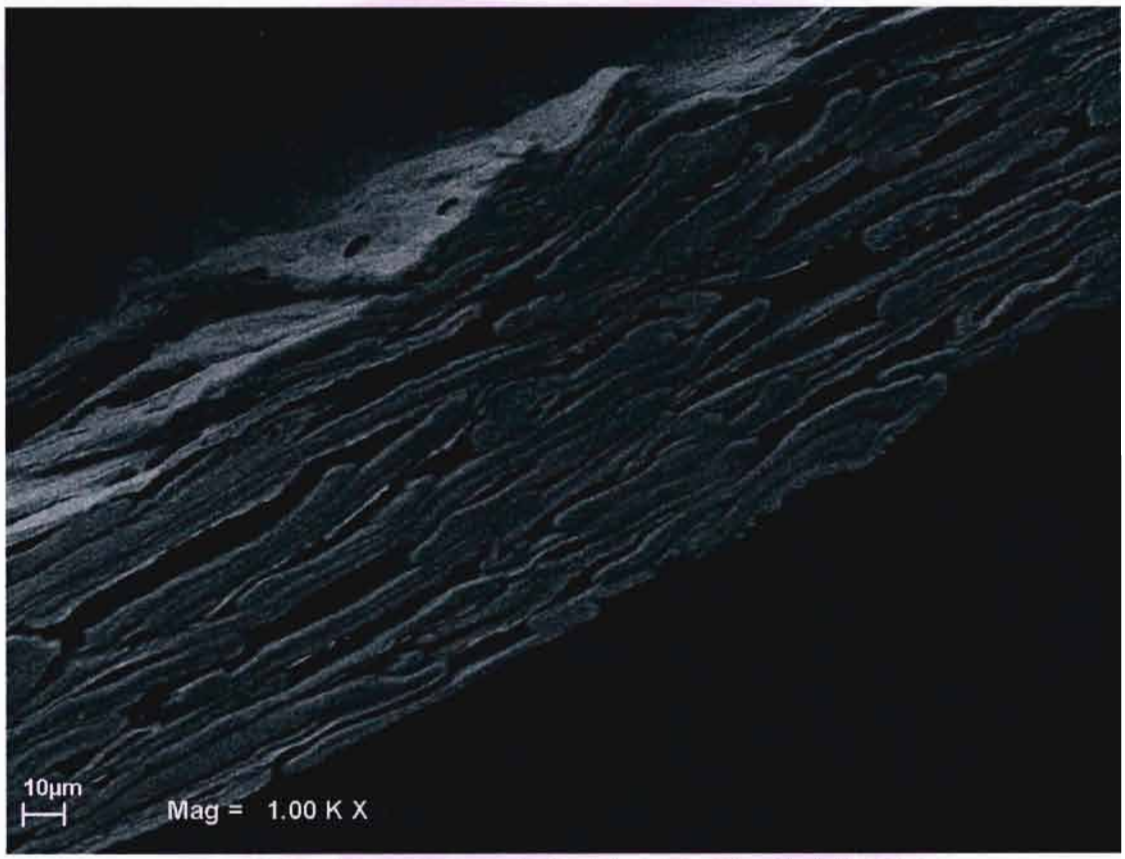


Fig. D-1a. 9 years - good site (35 minutes – 100 beating)

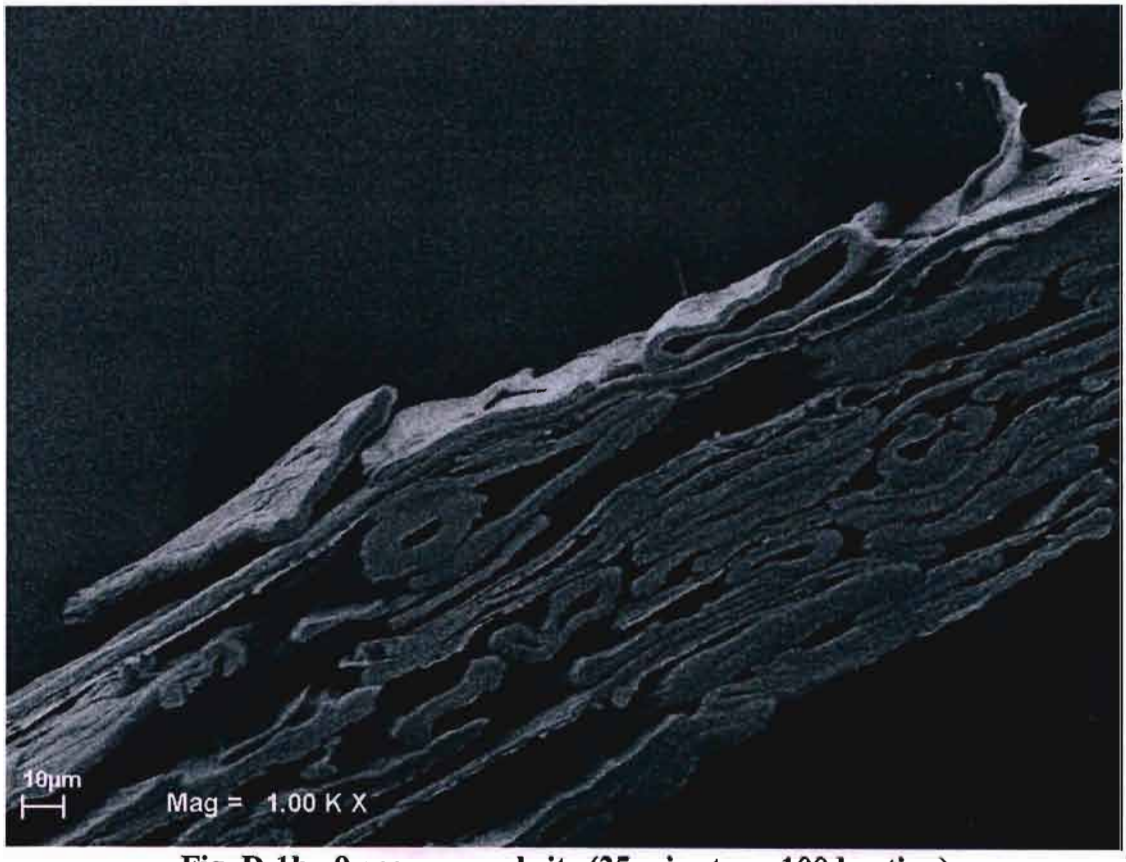


Fig. D-1b. 9 years - good site (35 minutes – 100 beating)

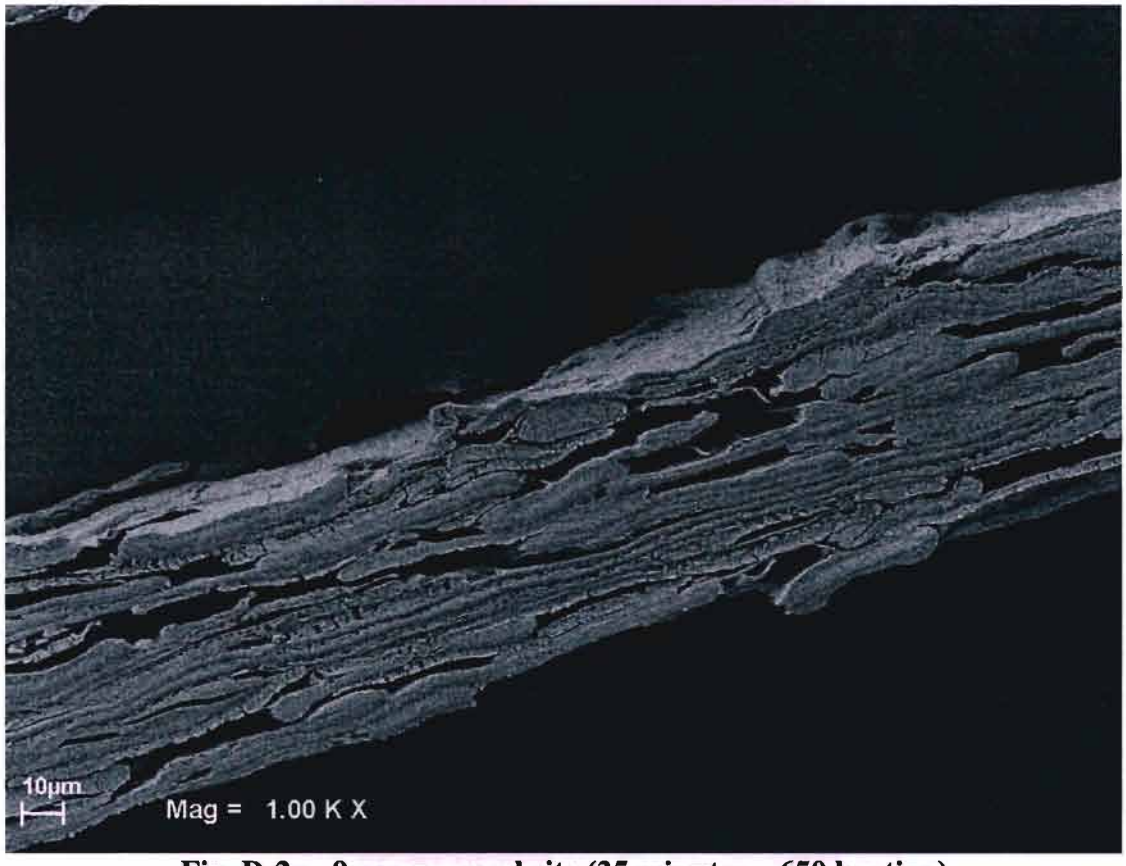


Fig. D-2a. 9 years - good site (35 minutes – 650 beating)

Fig. D-2b. 9 years - good site (35 minutes – 650 beating)

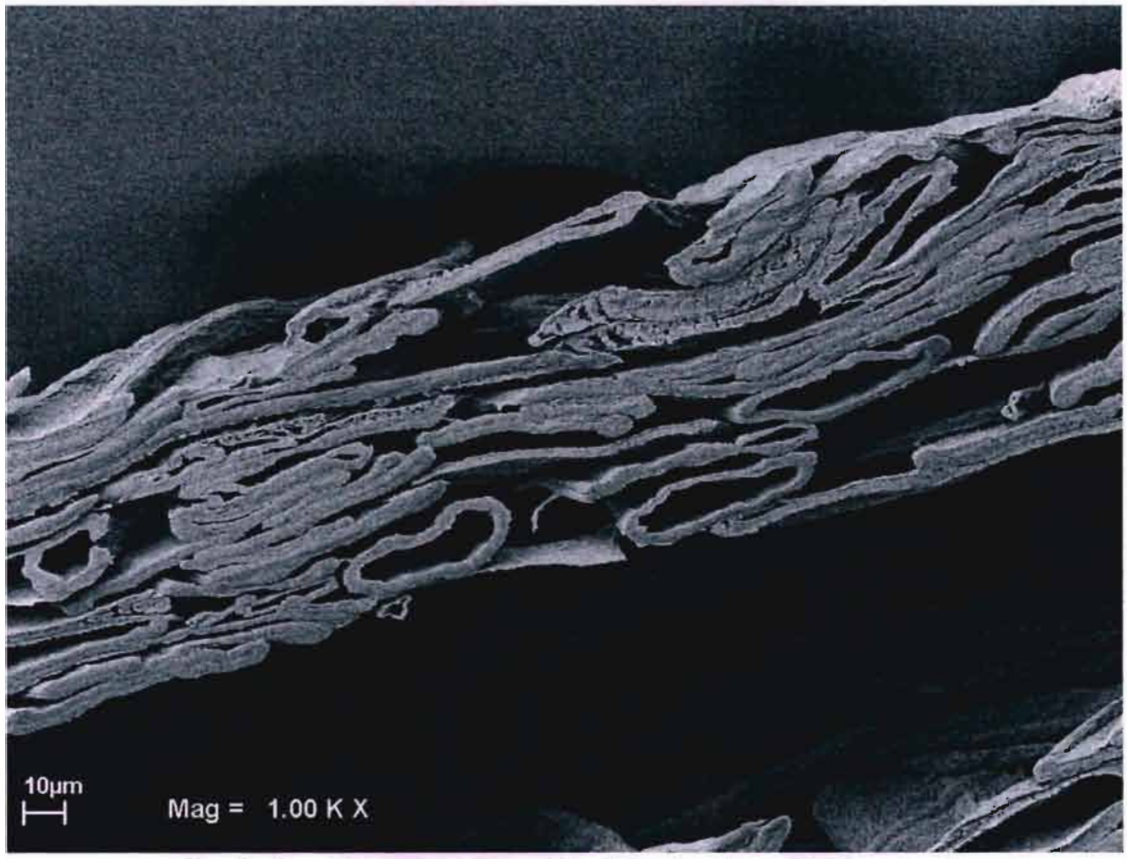


Fig. D-3a. 10 years - poor site (35 minutes – 100 beating)

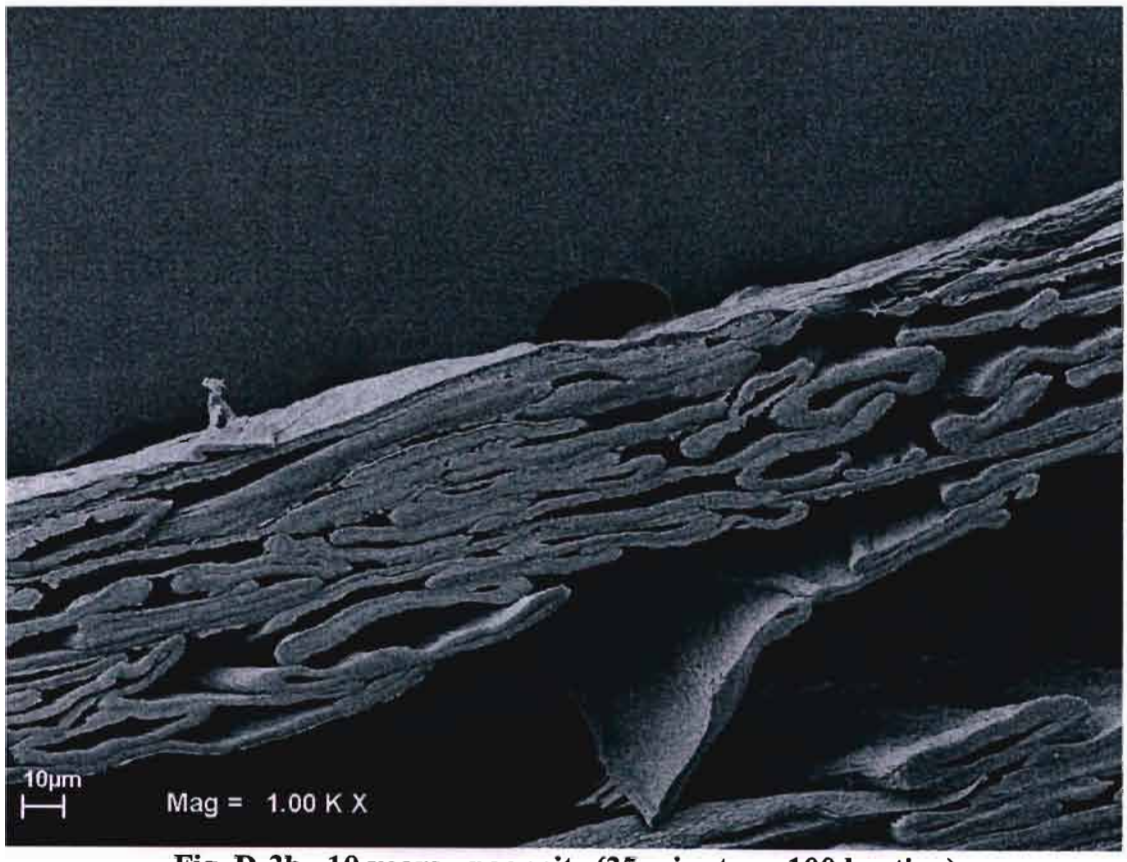


Fig. D-3b. 10 years - poor site (35 minutes – 100 beating)

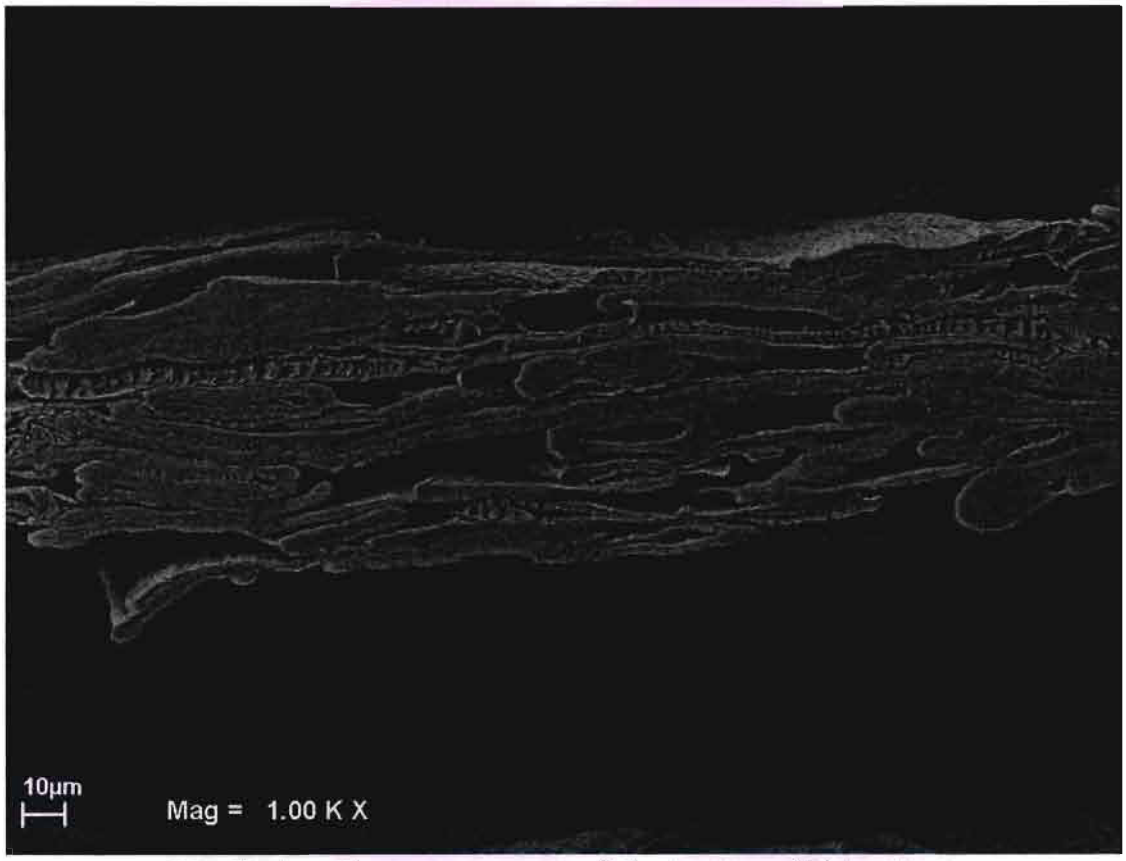


Fig. D-4a. 10 years - poor site (35 minutes – 650 beating)

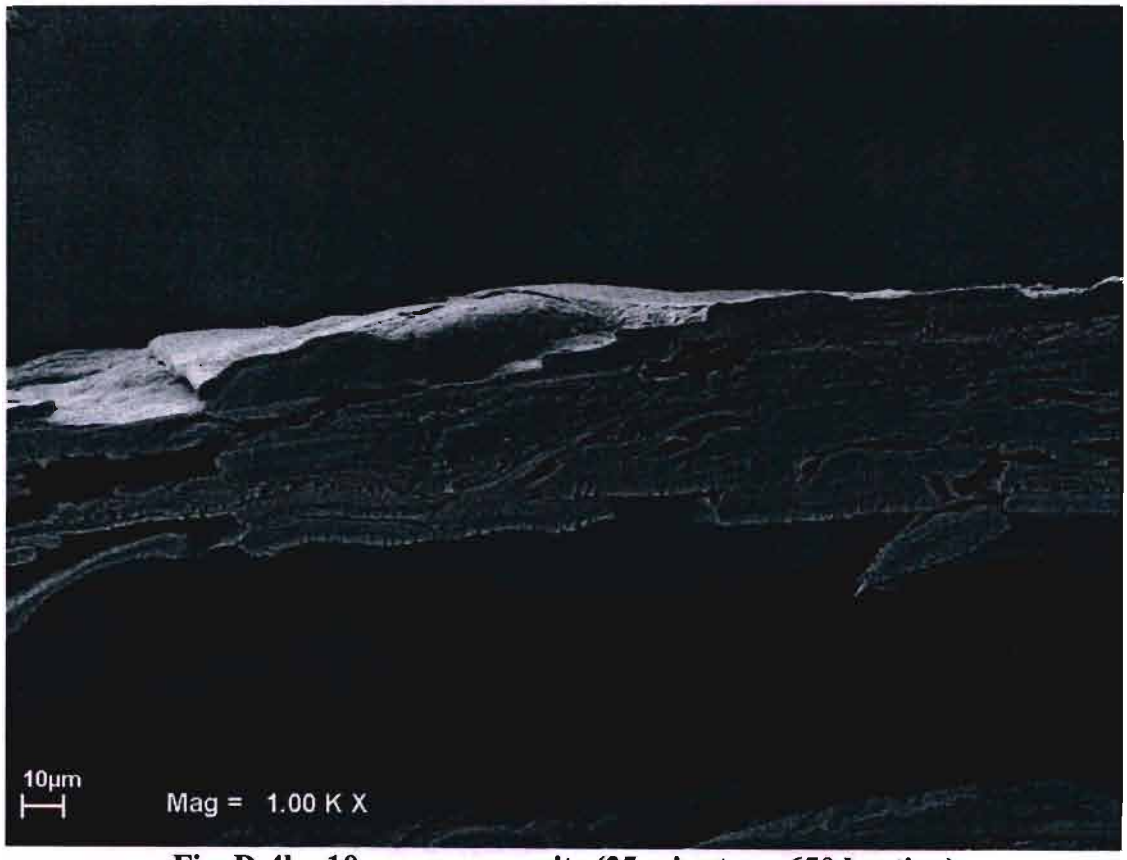


Fig. D-4b. 10 years - poor site (35 minutes – 650 beating)

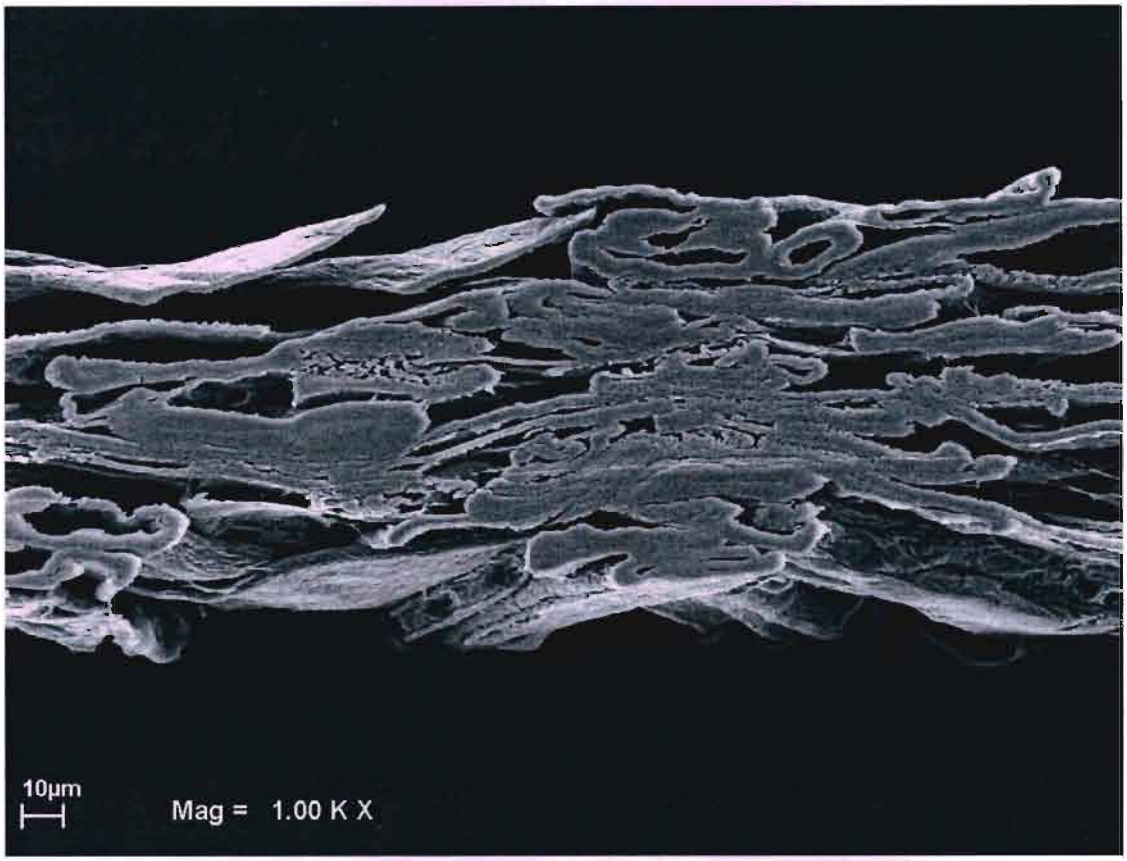


Fig. D-5a. 13 years - poor site (35 minutes – 100 beating)

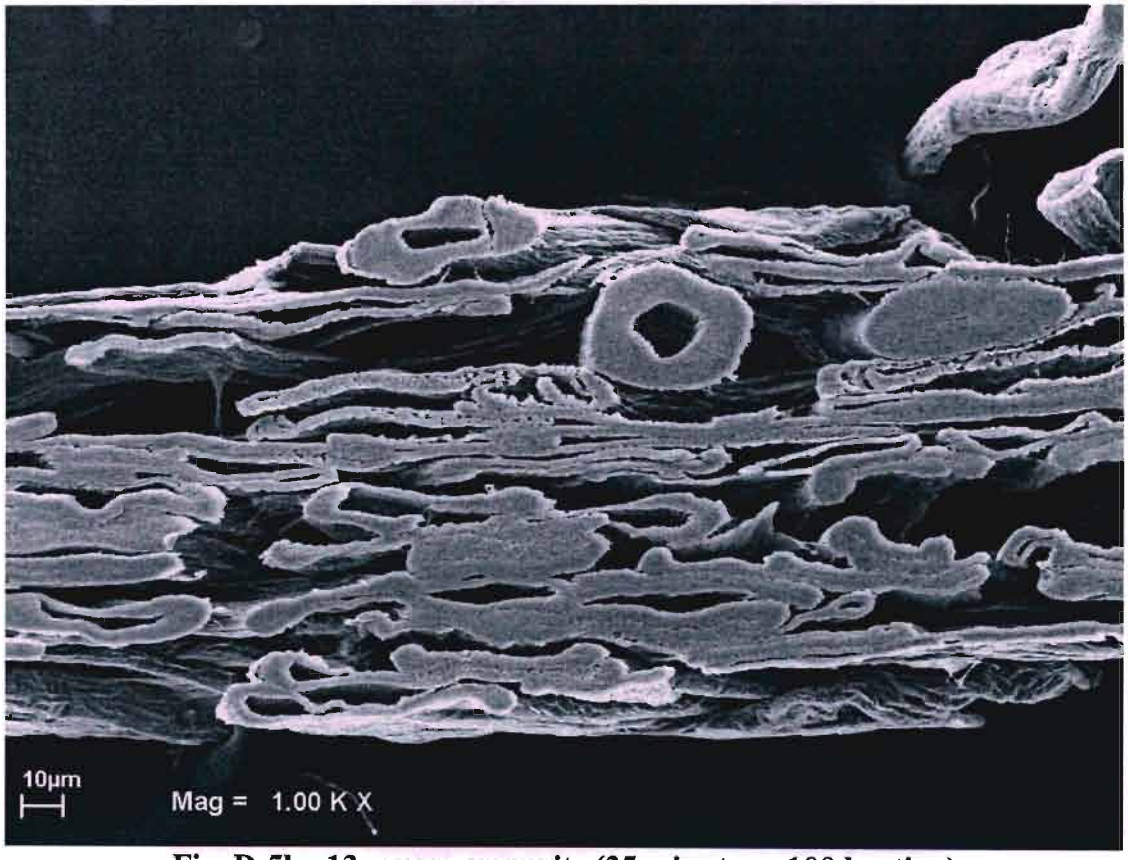


Fig. D-5b. 13 years - poor site (35 minutes – 100 beating)

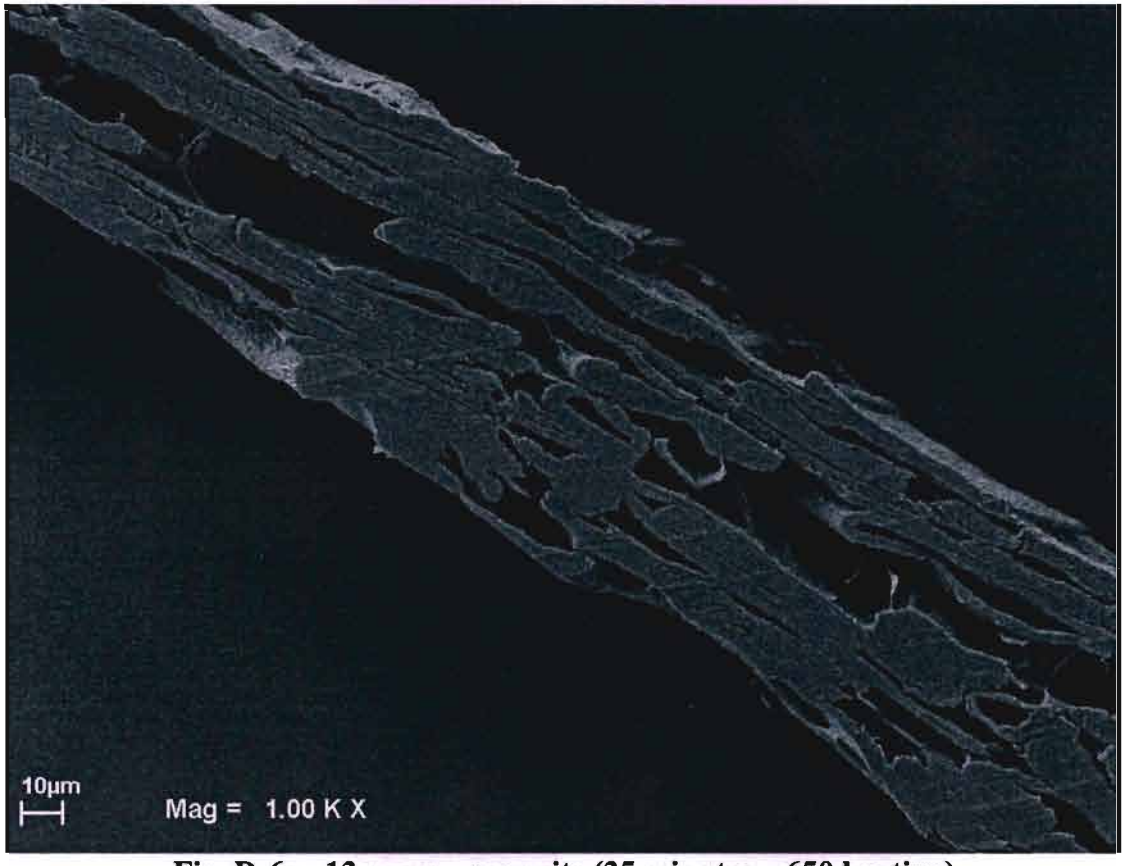


Fig. D-6a. 13 years - poor site (35 minutes – 650 beating)

Fig. D-6b. 13 years - poor site (35 minutes – 650 beating)

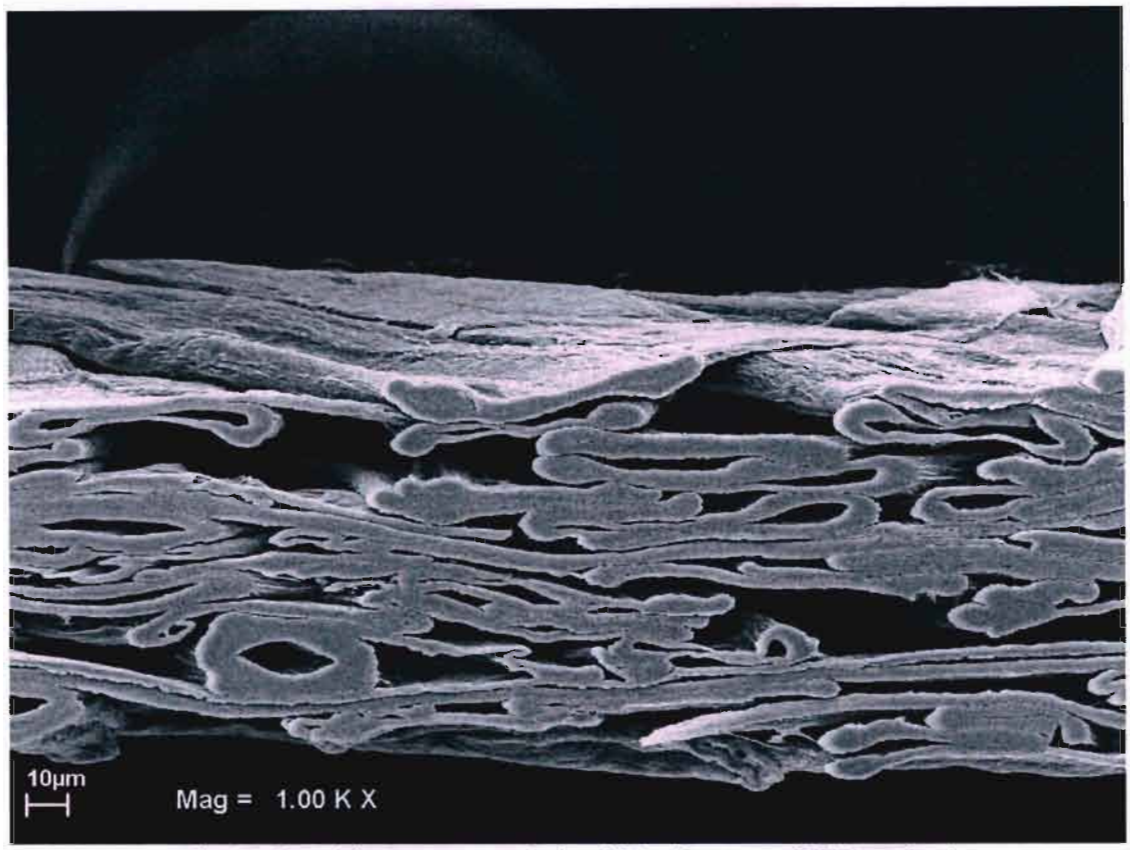


Fig. D-7a. 14 years - good site (35 minutes – 100 beating)

Fig. D-7b. 14 years - good site (35 minutes – 100 beating)

Fig. D-8 a. 14 years - good site (35 minutes – 650 beating)

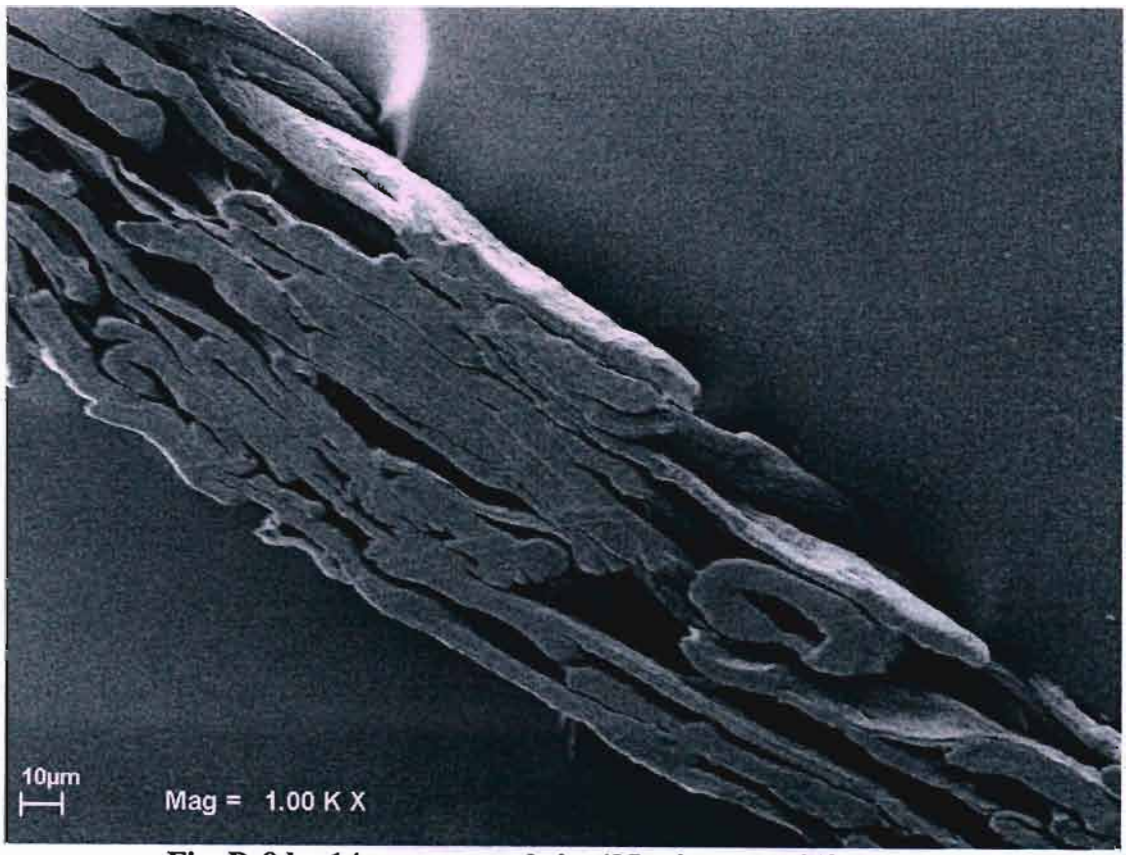


Fig. D-8 b. 14 years - good site (35 minutes – 650 beating)

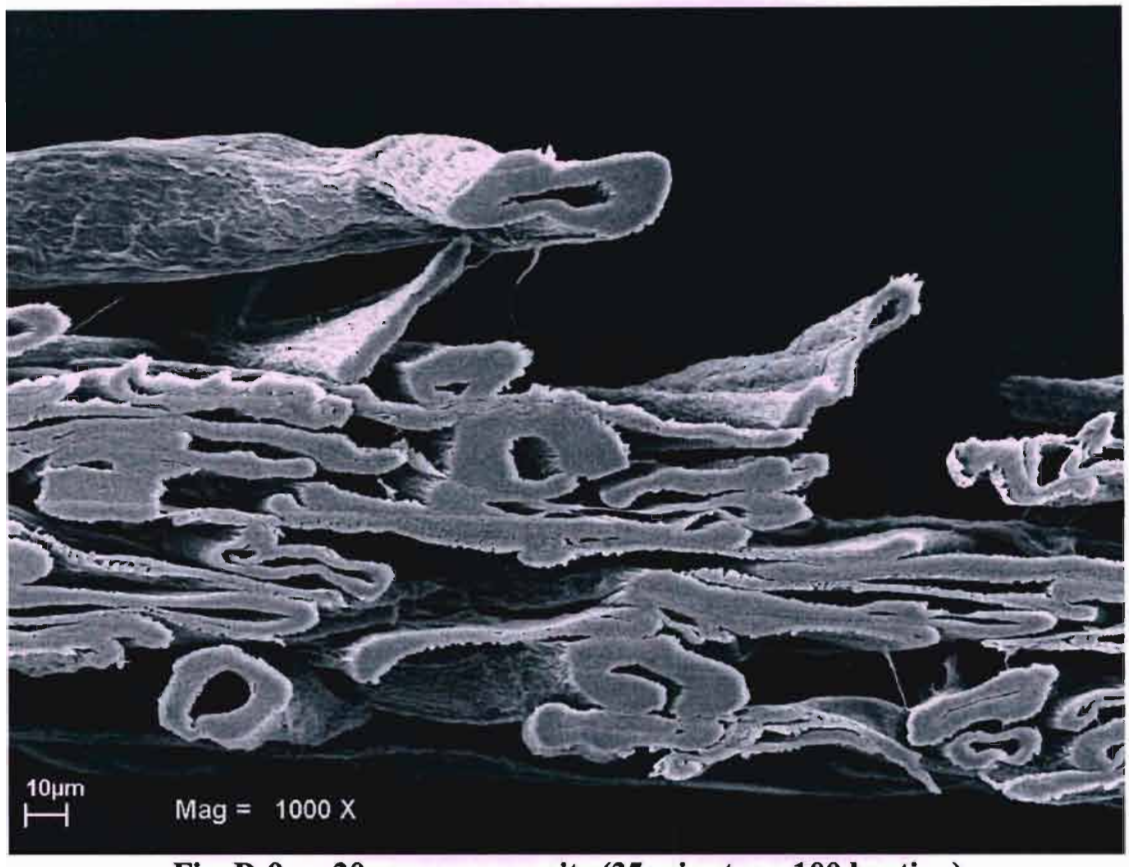


Fig. D-9 a. 20 years - poor site (35 minutes – 100 beating)

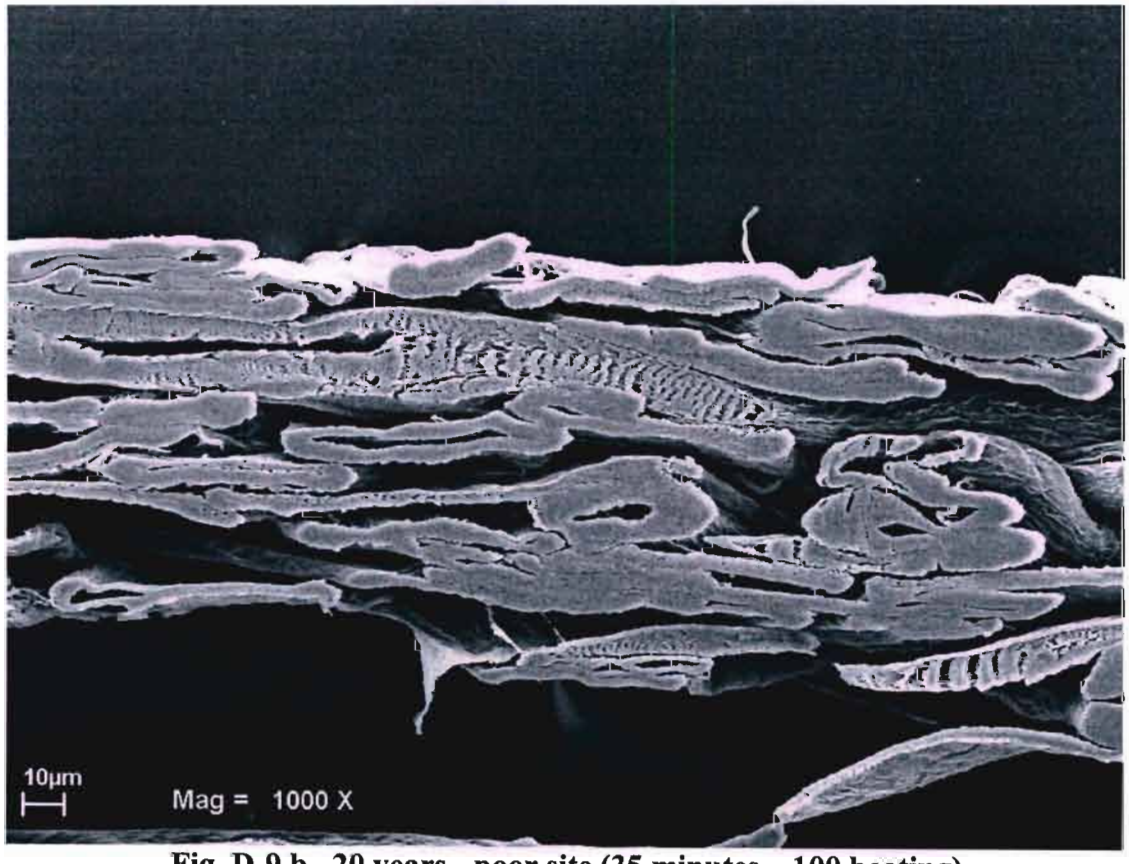


Fig. D-9 b. 20 years - poor site (35 minutes – 100 beating)

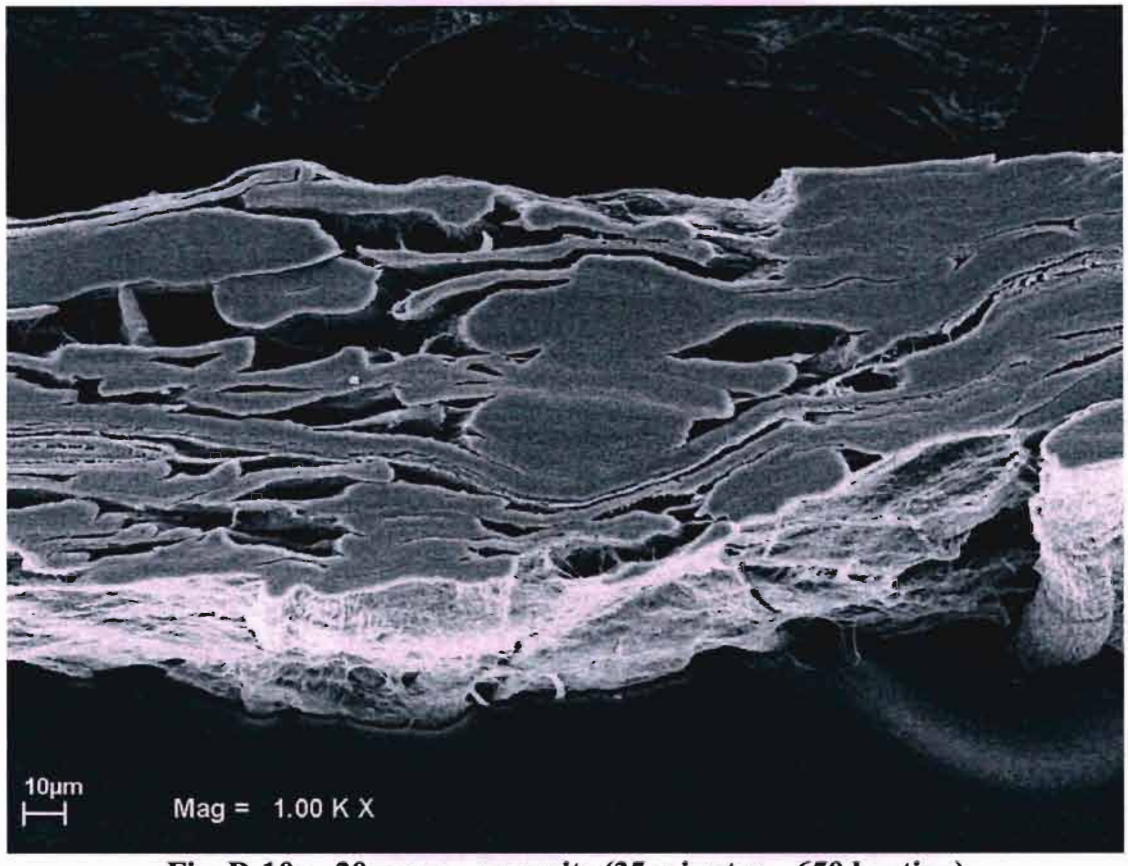


Fig. D-10a. 20 years - poor site (35 minutes – 650 beating)

Fig. D-10b. 20 years - poor site (35 minutes – 650 beating)

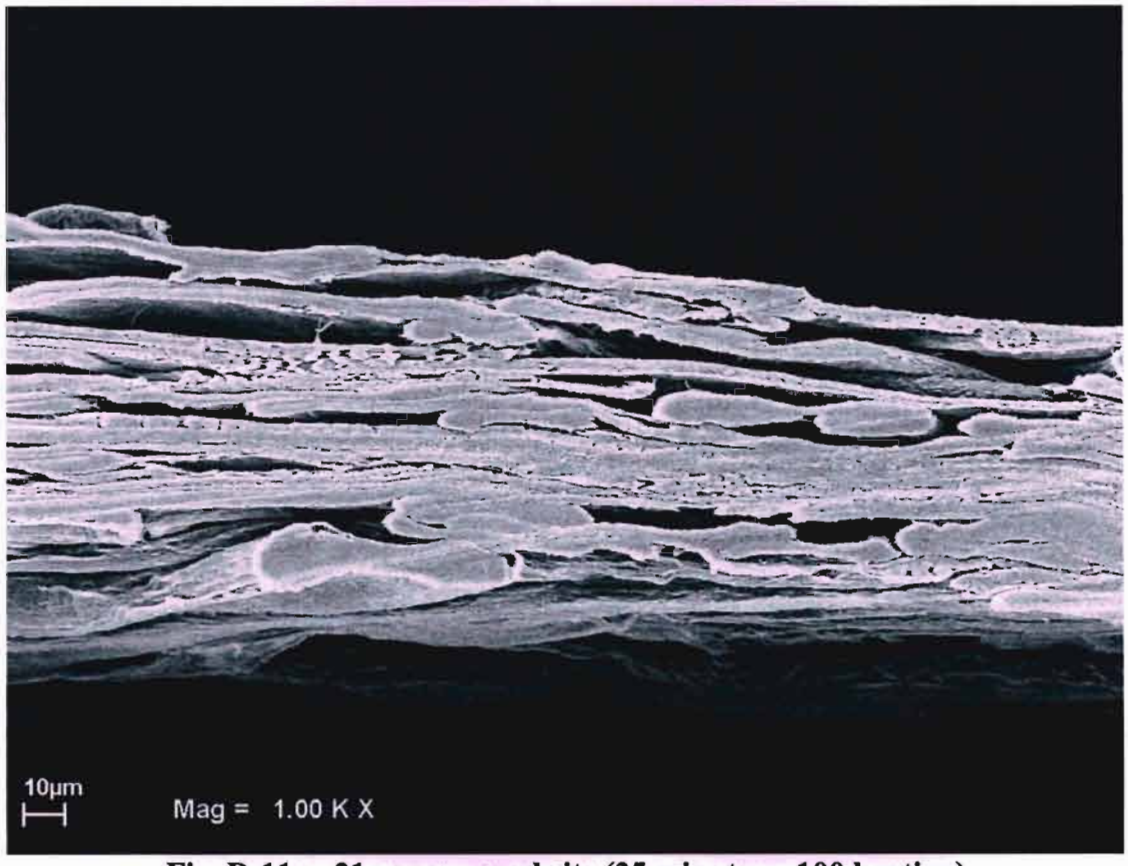


Fig. D-11a. 21 years - good site (35 minutes – 100 beating)

Fig. D-11b. 21 years - good site (35 minutes – 100 beating)

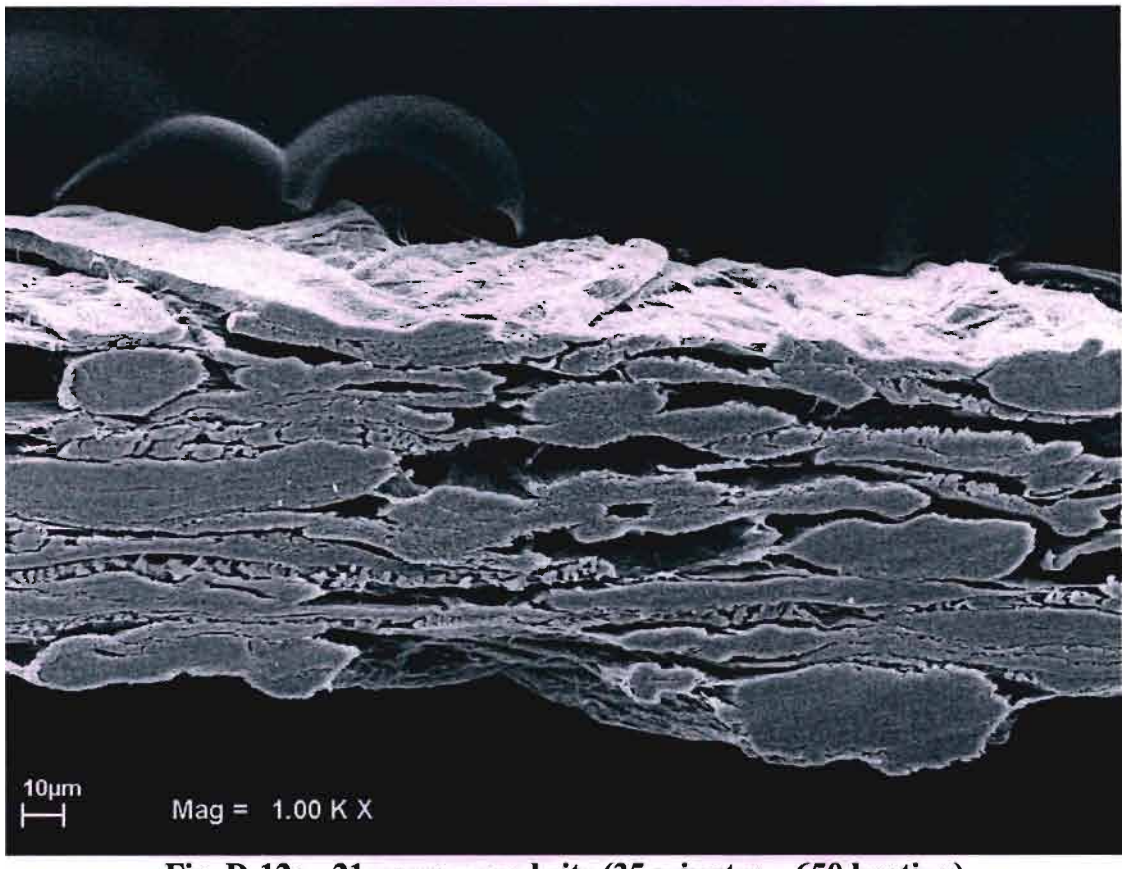


Fig. D-12a. 21 years - good site (35 minutes – 650 beating)

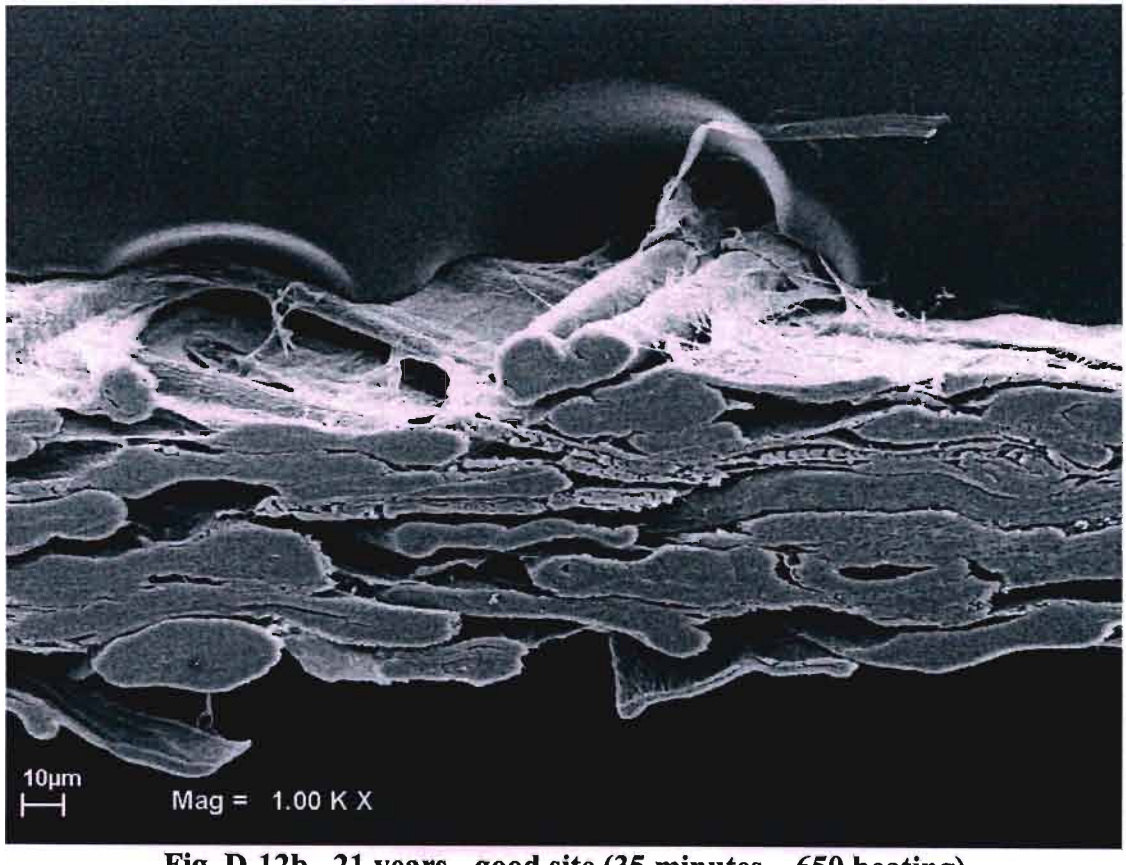


Fig. D-12b. 21 years - good site (35 minutes – 650 beating)

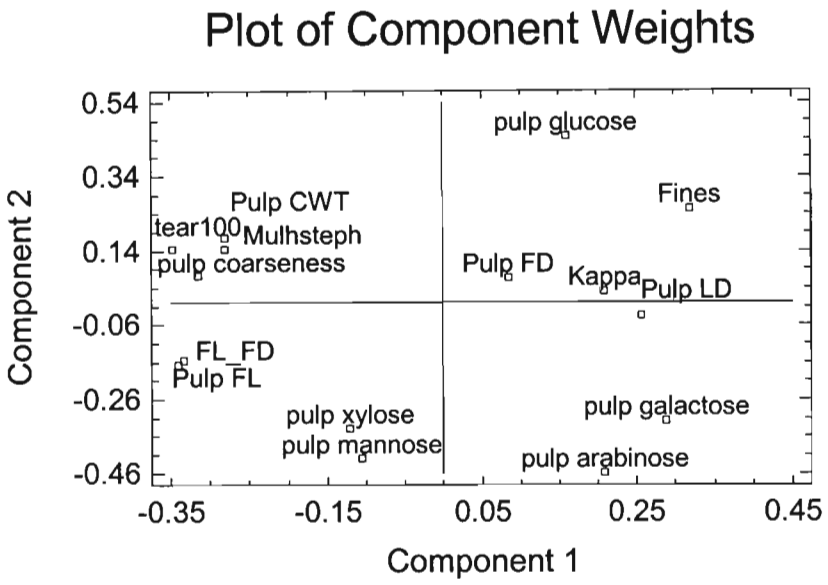


Fig. D-13. Results with tear at 100 beating.

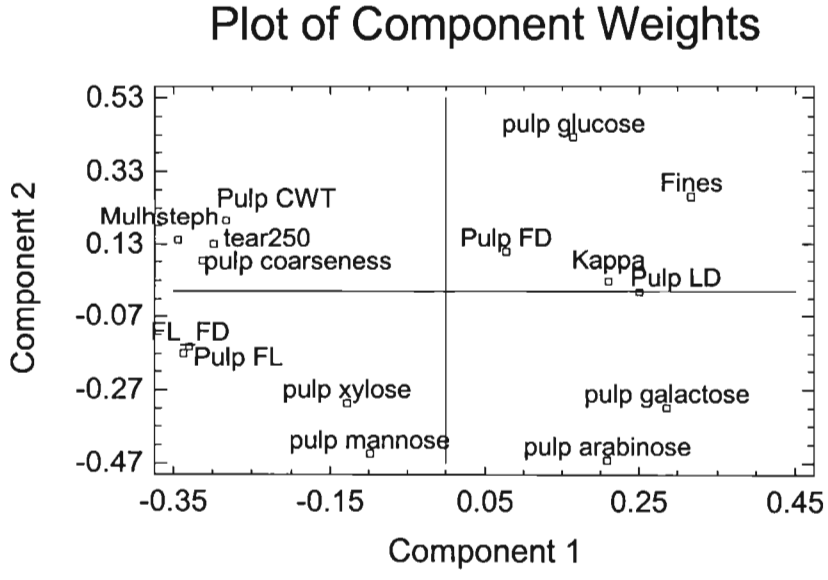


Fig. D-14. Results with tear at 250 beating.

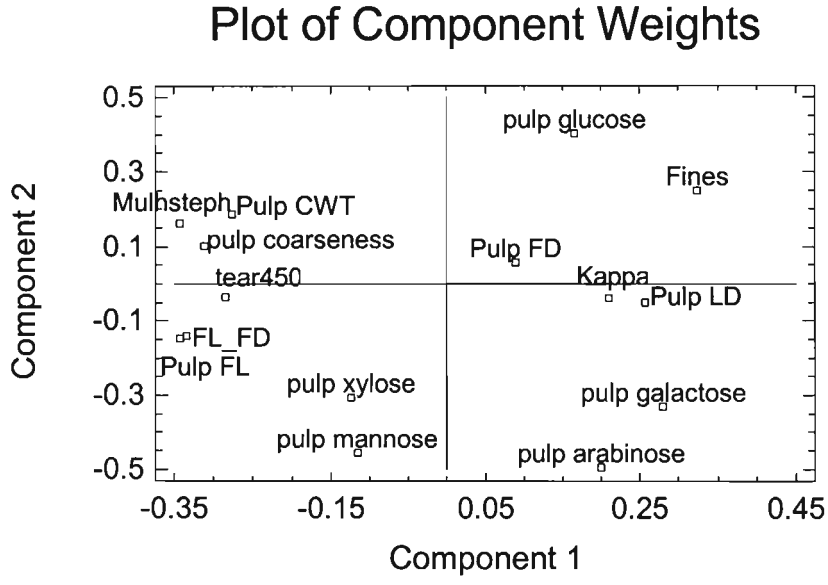


Fig. D-15. Results with tear at 450 beating.

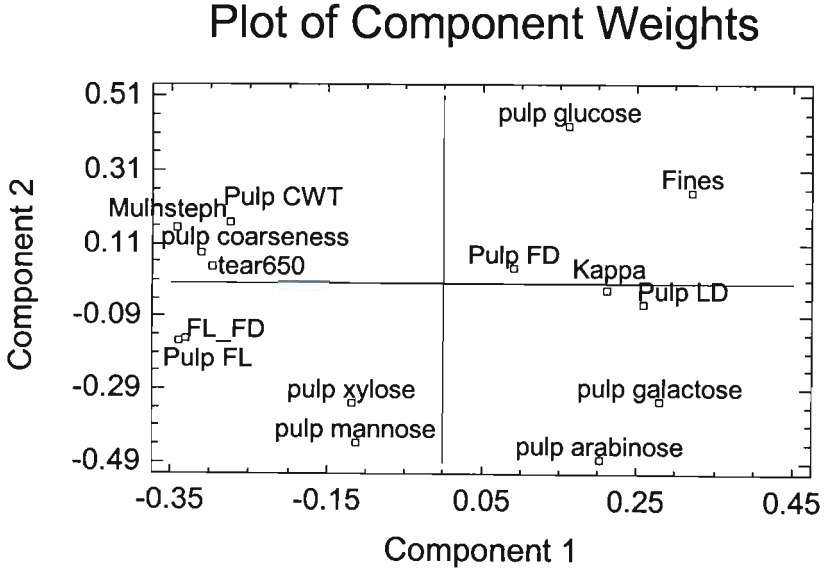


Fig. D-16. Results with tear at 650 beating.