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Clonal variation in the solid wood properties of eucalyptus

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CLONAL VARIATION IN THE SOLID WOOD PROPERTIES OF *Eucalyptus*

A Thesis submitted to the University of Wales for the Degree of *Philosophae Doctor* in Wood Science

by

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Esta tese é dedicada à minha esposa Zoraia

e às minhas filhas Marina e Taís.

Também, com saudades, dedico esta tese à minha mãe Maria da Penha.

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Abstract

The main objective of this study was to determine variations of density, mechanical and anatomical properties of *Eucalyptus* wood from the point of view of solid wood utilisation. The relationships between these traits have been studied.

The genetic material used was twenty-six eight-years-old clones of *E. grandis* × *E. urophylla* hybrids, planted over four experimental sites installed in Brazil.

The intra-clonal variation of basic density was found to be very low. The variations between clones were statistically significant for all density and mechanical properties and for anatomical characteristics. Except for wall thickness the between-site variations were statistically significant for all properties.

Clone × interaction studies suggested that the interactions were complex for all characteristics and in most cases it was not possible to predict a wood property produced on one site from its value at another site. Except for resilience, grain angle and microfibril angle, estimates of broad sense heritability for all properties studied were relatively high.

Wood from inner, intermediate and outer regions of the log was statistically different for all characteristics studied. In the radial direction of the log different patterns of wood variation were observed depending on the characteristic. However, from basal to top bolt the difference was normally relatively small and for some properties not significant.

Relationships between properties revealed that the microfibril angle was negatively correlated with fibre dimensions. The best correlation observed was between microfibril angle and fibre length: however, none of the correlations resulted in a significant coefficient. The prediction of the nominal density using fibre dimensions as predictors showed that 50 % of its variation may be significantly determined by wall thickness, 40 % by lumen diameter and 19 % by fibre diameter. In general the best predictor for the mechanical properties (compression strength parallel to grain, modulus of rupture - MOR and modulus of elasticity - MOE) was the nominal density. The anatomical traits were more influential for MOR and MOE than for compression strength parallel to the grain. Only MOE was significantly predicted by microfibril angle.

The wide range of variations between clones and between sites means that it should be possible to select clones which will produce solid wood suitable for different end uses.

CONTENTS

1 INTRODUCTION

1.1 *Eucalyptus* in the World

Eucalyptus was named in 1788 by a French magistrate and botanist, Charles Louis L'Héritier de Brutelle (L'Héretier, 1788, cited by Eldridge *et al.*,1993). His Latin description was based on a specimen collected on Bruny Island, Tasmania, probably in 1777 on James Cook's third expedition (Eldridge *et al.*, 1993).

About 500 species and subspecies are recognised as belonging to the *Eucalyptus* genus (Pryor and Johnson, 1971). This large natural variability, associated with fast growth, adaptability to different environments, possibilities of genetic improvement and good performance in plantations, characterise the reasons that have made *Eucalyptus* one of the most important trees for commercial applications in the world (Figure 1.1).

Although it is widely spread, Brazil and India together are responsible for 68 % of the 12.3 million hectares of *Eucalyptus* plantation in the world (Pandey, 1995; Gerard, 1994). The remaining areas are distributed among about 60 countries in Africa, Asia, America and Europe (Pandey, 1995; Gerard, 1994). According to Gerard (1994) two to four more million hectares are to be established by the year 2000. Figure 1.2 illustrates the proportional distribution of the genus in the world.

A mean annual increment of 10-15 $m^3.ha^{-1}$ per year of stem wood is commonly obtained from the already large areas of eucalypt plantations in temperate and tropical regions (Jacobs, 1981). The performance in a particular environment is the result of the interaction of that species' genetic make-up with climatic, edaphic and other physical and biological factors (Eldridge *et al.* 1993)

1.2 *Eucalyptus* in Brazil

When introduced to Brazil, in the early 20^{th} century, *Eucalyptus* was planted to supply firewood for fuel for trains. Progressively, it became an industrial wood to

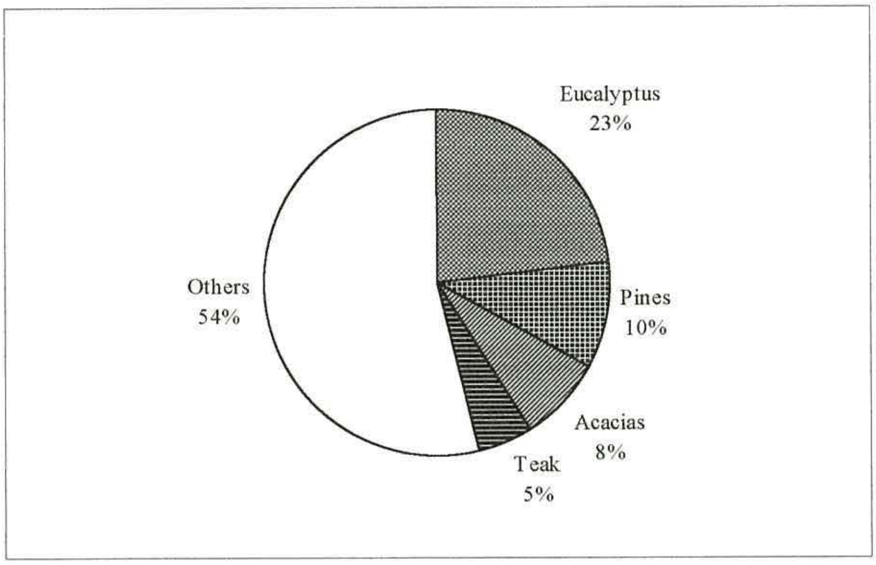


Figure 1.1 Areas (%) planted with trees in the tropical regions of the world.

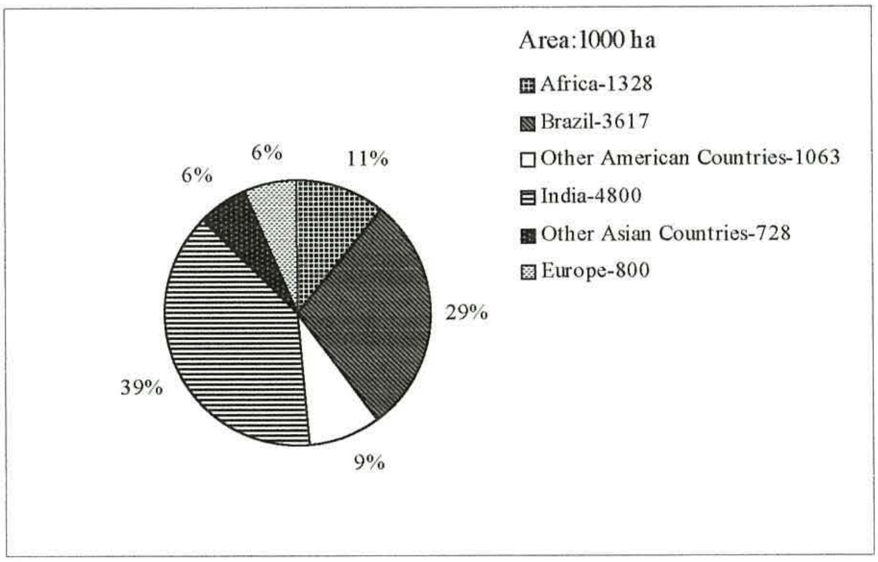


Figure 1.2 Distribution of *Eucalyptus* in the world (Total area: 12336000 ha).

the extent that in the 1960s/70s private companies, using governmental subsidies, promoted a large program of reforestation in the country. It has been estimated that a total area of approximately four million hectares is cultivated with *Eucalyptus* species in Brazil (Souza,1992; Pandey,1995). The main species utilised are *E. grandis, E. urophylla, E. saligna, E. camaldulensis, E. tereticornis,* and *E.*

cloeziana. Unfortunately there is no consistent survey existing in terms of the area, yield and quality of the stands by species, hybrids or clones. These trees, due to their fast growth, are normally short-rotated (around seven years) producing a large proportion of juvenile wood, in contrast to the higher levels of mature wood produced by *Eucalyptus* grown in Australia: a result of this is, for example, values for the mechanical properties of Brazilian-grown *E. grandis* wood were markedly lower than those reported for Australian-grown material (Della Lucia and Vital, 1980). It was suggested that this difference was associated with the lower density of the Brazilian-grown material (0.39 $g.cm^{-3}$) c.f. 0.72 $g.cm^{-3}$ as reported for Australian-grown material (Hillis, 1984).

Equally important to the reported expansion of the planted areas is the increased production obtained using new techniques of genetic selection and new forestry traits in replanted areas. In Brazil, large areas reforested during the 1970's have now been substituted by new genetic material, which gives better performance both in the plantation and in industry. Results obtained in large scale plantations by Aracruz Celulose S.A., for example, have assured continual reduction in the specific consumption of wood (i.e., the required amount of wood to produce one ton of pulp). The specific consumption in 1993 was 16 % less than that obtained by that enterprise some 20 years before (Bertolucci and Penchel, 1993). Exceptionally good results have occasionally been presented in the literature, but they have referred to experimental or specific conditions rather than the common or average cases generally found in the country. In support of this view Eldridge *et al.* (1993) relate that small sample plots of eucalypts aged 6-8 years in East and West Africa, Brazil and Papua New Guinea have grown at rates of 70-90 $m^3.ha^{-1}$ per year. The average yield of large scale eucalypt plantations in Brazil however ranged from 18 to 20 $m^3.ha^{-1}$ per year (Pandey, 1995). Assuming a wood basic density (oven dry mass/green volume) of about 500 $kg.m^{-3}$ and a total area of about 3.6 million ha the potential yield of the Brazilian eucalypt plantation is of the order of 30 million tons of dry wood per year. This figure may be higher if the area of 4.5 million hectares as reported by Souza (1992) is considered.

1.3 Traditional Uses of *Eucalyptus* Wood in Brazil

To date, the genetic selection of fast grown *Eucalyptus* cultivated in Brazil has been mainly directed towards pulp and paper and/or charcoal for steel production. For pulp the main desirable wood parameters searched for have been low density, specific fibre dimensions and chemical composition. For charcoal the parameters have been high density, associated with calorific value. Importantly, it was not relevant if these trees produced high levels of growth stresses, high grain angle, a tendency to collapse on drying or low mechanical strength, since these characteristics are not crucial for either pulp or charcoal production.

However, this timber also has possibilities of use as solid wood in structures, furniture, tools and others. This has been demonstrated by Acosta (1995) and Malan (1995) where emphasis was directed towards investigation of mechanical properties.

Some significant characteristics of short rotation, fast growing *Eucalyptus* wood which differentiate it from other wood are high intensity of growth stresses, high extension of juvenile wood and a tendency to collapse during drying. As these characteristics can be genetically manipulated (Zobel and Van Buijtenen, 1989), the possibility of achieving a higher quality of *Eucalyptus* for use as solid material exists.

1.4 New Utilisation of *Eucalyptus* as Solid Wood in Brazil

The economic and social development of Brazil will expand wooden raw-material requirement to supply diversified necessities, mainly for building and for furniture, in addition to the demands already existing. On the one hand, tropical timber from the Amazon jungle, despite its large potential availability faces ecological and infra-structural limitations to logging (the present timber production is not sufficient to meet the demand). On the other hand, as earlier described, extensive areas have been reforested with high quality *Eucalyptus* (Figure 1.3) whose main destination is presently limited to pulp and paper or charcoal for steel production. These products confront periodical market difficulties, which push the forest owners to look for new outlets for the raw material, either in the domestic or foreign market. Within this context, *Eucalyptus* sawn timber assumes an important role in terms of trade. The first wave of this tendency has already started, with important Brazilian companies, individually or in joint-ventures, producing sawn wood. Among them, can be cited: Aracruz Celulose S.A., Caf Florestal S.A., Duratex S.A., Florestas Rio Doce S.A., Flosul S.A., Klabin Fabricadora de Papel e Celulose S.A.. There is no reliable information about the volume of *Eucalyptus* sawn timber annually produced in Brazil, but it is sharply increasing, mainly of *E. grandis* and hybrids with *E. grandis*. However, information appertaining to investment in new sawmills and expansions of already installed sawmills indicate volume of between 100 000 and 150 000 m^3 per year, starting at 1999.

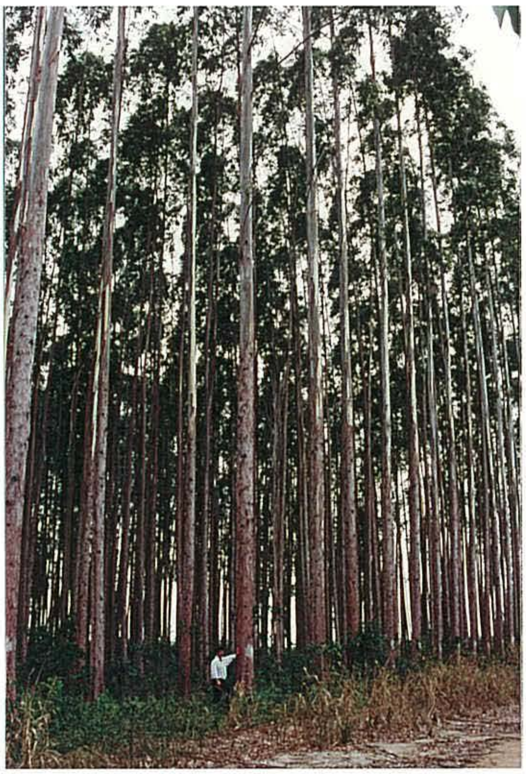


Figure 1.3 Fast grown, high quality 14 year-old *Eucalyptus grandis* hybrid trees produced in Brazil.

Also, the prospects for wood quality improvement is substantial, since the selection of new genetic material to be planted considers the requirement for solid wood production, and as silvicultural techniques directed towards timber production start to be adopted (pruning and thinning for example). In this particular context it is important to note that a more demanding selection of the matrix trees is not necessarily incompatible with the traditional uses: on the contrary, the production of an appropriate tree for solid wood production may also enhance its quality for pulp and paper, charcoal etc., depending on the origin of the material.

1.5 Outline of the Thesis

In the next chapter (Chapter 2) a literature review is presented concerning mechanical properties of wood and their interaction with other wood properties, mainly anatomical and density. The emphasis will be on *Eucalyptus* wood, but studies using other genera will also be considered, mainly when they contribute importantly to an understanding of the phenomena investigated in the thesis and when any research supports the insufficiency of studies on *Eucalyptus*. In addition, aspects relating to variations in wood properties will be mentioned.

In the subsequent chapter (Chapter 3), the material and methods used in the experimental work will be described. They involve the genetic characterisation, environmental characterisation, sampling in the field, sampling within log, and physical, mechanical and anatomical testing. Also, statistical methods for data analysis will be described.

In Chapter 4 a basic investigation of wood basic density will be described. The importance of this chapter is in the fact that basic density is one of the most utilised indices of *Eucalyptus* wood quality, mainly when this wood is used for pulp or charcoal production. In this case, the results may be used as comparison to earlier studies on *Eucalyptus* wood. In addition, this chapter will provide an indication of the clone-site interaction on basic density, this being important with regard to other studies of interaction discussed in this thesis.

One of the main objectives of the thesis is presented in Chapter 5. In this chapter within tree, inter-clonal and inter-site variations in the nominal density and mechanical properties will be presented and discussed. In the following chapter, the same material and sources of variation will be studied in relation to the grain angle of the timber. In Chapter 7 are presented intra-tree, interclonal and environmental variations associated with the fibre morphology of *Eucalyptus* wood, including fibre length, diameter, lumen diameter and wall thickness. In Chapter 8, the same material and source of variations will be studied in relation to microfibril angle. In addition the relationship between the microfibril angle and the fibre morphology will be examined.

Chapter 9 concerns the main subject of this thesis, that is the relationships between the mechanical properties and the anatomical characteristics of *Eucalyptus* wood. Thus, the influence of the anatomical characteristics (and also of density) on several mechanical properties will be analysed. Finally, Chapter 10 summarises the main conclusions found in this study and presents possibilities for further work which might provide more accurate answers to several questions posed in the thesis.

Since a frequent preoccupation of wood scientists and technologists concerns variation of wood properties, in this thesis 26 genotypes, four well-characterised sites and a within-tree sampling were utilised. In the face of this level of variation on the several properties studied, the format chosen for the thesis is that different properties are consecutively presented and statistically analysed (using a similar method). In spite of the resulting repetitive format it was decided that this was the best way to represent the variation associated with each property or group of properties.

2 LITERATURE REVIEW

The relationships between the mechanical properties of wood and other properties have been investigated for a long time, but the scientific approach was only initiated in the late XIX century. Since then most studies have been directed towards wood produced in regions of temperate climate: in Europe, North America, Australia and Japan. In tropical regions, only recently have more consistent studies been carried out on this subject, which indicates the necessity of emphasising research on this subject. Hence, this review will aim to show the level of development of investigations on some important mechanical properties of the wood and their relations with other wood properties, mainly wood density, and with anatomical structure both at the level of the fibre and the microfibril. Considering that knowledge in this area is very dispersed, the discussion wherever possible will be associated with *Eucalyptus* wood, the main object of the study.

2.1 Mechanical Properties

Timber is one of the few materials which possesses high toughness as well as high stiffness, and this unique combination of properties accounts for many of the specialised applications of timber (Dinwoodie, 1975). Mechanical properties of wood are its fitness and ability to resist applied or external forces (Record, 1914), which means any force outside a given piece of material tending to deform it in any manner. These properties are fundamental to define the use of wood for structural and building purposes, and innumerable other uses of which furniture, vehicles, implements, and tool handles are a few common examples.

From the point of view of mechanical properties, the morphological structure of wood is often described in terms of the "Reinforced Matrix Theory" (Fengel and Wegener, 1984). Accordingly, strands of high tensile strength microfibrils (cellulose) are embedded in a plastic matrix of non-cellulosic polysaccharides (hemicelluloses) and their derivatives, and lignin (Wardrop, 1971). In this structure, crystalline cellulose is the strength-creating agent, whereas non-crystalline cellulose, lignin and extractives add to the elasticity. Hemicelluloses are a presumably tangentially oriented coating of lamellae on microfibrils, promoting the surface interaction with lignin and resulting in a formation of "lignin-hemicellulose gel" (Kerr and Goring, 1975). The structure is to a great extent comparable with reinforced concrete (Glasser, 1990, cited by Verkasalo, 1992). The main differences are the discontinuity and unknown extent of the microfibrils beyond the boundaries of the particular cell wall layer, and their rare alignment with the longitudinal fibre axis. Some authors provide a different interpretation of the wood chemical components. Booker and Sell (1998) stated that hemicellulose acts as the cement, and lignin acts like the rock and sand filler in reinforced concrete.

A more important issue for the elasticity is the wide range of microfibrillar angles of the different layers. In particular, the microfibril angle of the S_2 layer is crucial, because the other layers are very thin compared with that layer and because their microfibrillar orientation is unfavourable for longitudinal stiffness (Cave, 1969). For conifers a reduction in a microfibril angle from 35 to 10 degrees resulted in a fourfold increase in the longitudinal modulus of elasticity (Cave, 1968).

By its turn, the mechanical functions of the cell wall layers in the living tree have been summarised by Booker and Sell (1998) as follows.

- The S_3 layer: strengthens the cell against collapse (i.e. implosion caused by water tension), and resists transwall fracture in the transverse directions.
- The S_2 layer: in the stem carries the weight, as well as the tension and compression forces generated by the wind, and strongly resists transwall crack propagation in the axial direction. Also, is part of an energy absorption mechanism at the cellular level with the CML (compound middle lamellae) layer that controls wind damage.
- The S_1: limits the maximum shear forces in the CML during axial compression, by limiting the maximum diameter increase of the S_2 layer, and prevents intrawall cracks from developing into transwall cracks.
- Combined S_3, S_2 and S_1: creates extra resistance against buckling and collapse.

- The CML layer: resists delamination of the double cell walls (intrawall checking) and prevents internal checking, and forms part of the mechanism of vibration energy absorption.

The Reinforced Matrix Theory has been criticised because lignin is believed to add to the ultimate strength, moreover elasticity (Boyd, 1982). It was hypothesised that strength and elasticity depend rather on the interactions of the crystalline and non-crystalline regions. Consequently, the relative alignment of cellulose, hemicelluloses and lignin would be essential to the mechanical properties.

Various factors affecting the mechanical properties, such as moisture content, temperature, wood density, rate of applied load and others, are of fundamental importance when acting associated to the wood. They reduce the high theoretical mechanical strength of the wood substance. In addition, different growth defects also tend to decrease the magnitude of mechanical properties of wood. Cross grain, knots, reaction wood, and checks, are among the most common defects. Moreover, miscellaneous defects, such as material separation, deposits, abnormal growth, and insect and fungus injuries occur (Bodig and Jayne, 1982). In accordance with a safety approach, Desch and Dinwoodie (1993) recommend that before using a particular piece of wood in a structural application a measure of the variability for each of the strength properties should be required, associated with some grading of the timber into different quality classes.

2.1.1 Elasticity

The modulus of elasticity in bending, together with the modulus of rupture, are the most important mechanical properties of structural wood (Verkasalo, 1992), and in consequence they are the most usual parameters used to express the effects of static strain in a wood structure (Bodig and Jayne, 1982). Elasticity in bending is of commercial importance because it is the criterion for stress grading structural lumber (Verkasalo, 1992). The elasticity of a material can be described by its modulus of elasticity (MOE), which is the constant of proportionality between the stress and the strain, assuming a linear relationship exists between the two up to the "limit of proportionality" (Breese, 1992). Above this limit plastic deformation or failure will occur (Kolmann and Côté, 1968). In wood there is no yielding of stress as in steel - if deformations increase, structural wooden members may fail rapidly. Thererore, the relations between elastic deformation and stresses within certain limits of stresses are of great importance (Kolmann and Côté, 1968).

Wood follows the Hooke's law which states that the strain ε is proportional to the stress

$$\varepsilon = \alpha\sigma \text{, where}$$

$$\varepsilon = \frac{\text{Elongation}}{\text{Original length}} = \frac{\Delta l}{l} = \text{relative elongation (strain),}$$

σ= stress in MPa; α= material constant and $\alpha = \frac{\varepsilon}{\sigma}$ is the compliance, i.e., the strain per unit of stress. In technical literature normally the reciprocal value $1/\alpha$ = MOE is used. In a wooden beam, for example, MOE is also called the Young's modulus (E) - its calculation takes into account component dimensions. It expresses that hypothetical stress (MPa) by which a rod would be extended to double its initial length (Kollmann and Côté, 1968). The weakness of this definition is evident since the tensile strength for most material is much lower than the modulus of elasticity (Kollmann and Côté, 1968). The moduli of elasticity in tension, compression, and bending of wood are approximately equal, but the elastic limit is considerably lower for compression than for tension (Kollmann and Côté, 1968).

The elastic constant by static test can be determined for longitudinal tension and compression, and for bending. Deformation and load readings are taken and recorded for reasonable load increments until the maximum load is reached (Kollmann and Côté, 1968). The values are then plotted and a line is drawn through the points (Kollmann and Côté, 1968). The modulus of elasticity in bending can be calculated from the straight part of the load-deflection curve.

2.1.2 Crushing Strength and Stress in Wood Columns

The maximum crushing strength plays an important role in the utilisation of wood as a building and construction material (Kollmann and Côté, 1968). The tests of short wood columns (blocks) or even of cubes, are easily carried out (Kollmann and Côté, 1968). The results elucidate a characteristic mechanical property and permit conclusions on the biological quality of the wood, and to some extent on its strength (Kollmann and Côté, 1968). The maximum crushing strength parallel to the grain reaches, on average, for air dry wood only about 50 % of the tensile strength along the grain (Kollmann and Côté, 1968). The different behaviour of wood in compression and tension may be explained by its fibrous structure (Kollmann and Côté, 1968). Tightly wedged and cemented fibres sustain very high tensile stresses. In compression probably an early buckling of individual fibres occurs starting the failure (Kollmann and Côté, 1968).

The maximum compression strength of wood can be determined parallel or perpendicular to the grain. To obtain the strength value is sufficient to divide the maximum applied load by cross sectional area of the specimen.

2.1.3 Bending Strength (Modulus of Rupture)

The understanding of the mechanical behaviour of a beam requires attention on the composition of the stresses that act on it. Material on the concave or compression face of a beam will be shortened or strained in compression, while material on the convex or tension face will be lengthened or strained in tension (Gordon, 1991). If the material obeys Hooke's law the distribution of stress and strain across any section of the beam will be a straight line, and there will be some point '0' at which the longitudinal stress, and strain is neither tensile nor compressive, but is zero (Gordon, 1991). This point lies on what is called the 'neutral axis' of a beam.

The difference between the tensile strength and the crushing strength of wood determines the characteristic behaviour of a wood beam in bending (Kollmann and Côté, 1968). On average the ratio of bending strength to crushing strength amounts to 1.75 for common European pinewood in the air-dry condition (Kollmann and Côté, 1968). This quotient is not a ratio of exact breaking stresses because, following the usual standardised tests, the so-called bending strength is computed using Navier's formula (Kollmann and Côté, 1968). It is based on the assumption that the stresses are distributed linearly and symmetrically over the cross section of the bent beam. This assumption is justified for isotropic and homogeneous beams but for the anisotropic wood beams only up to the proportional limit (Kollmann and Côté, 1968). This is the reason why the term "modulus of rupture" is accepted as a criterion of strength, although it is not a true stress (Kollmann and Côté, 1968).

The modulus of rupture is normally determined by the testing of small wood beams under static centre loading. In this case a beam supported at two points is centrally loaded up to the failure. During a complete bending test deflection readings are automatically recorded. To calculate the modulus of rupture, the recorded maximum load is applied in a formula which taken in account the span (l), the width (w) and the height (h) of the specimen.

2.1.4 Janka Hardness

For the anisotropic, heterogeneous, hygroscopic wood, the hardness value is more than doubtful (Kollmann and Côté, 1968). Hardness may have more than one meaning but here it will be considered as the resistance to indentation, normally determined by the Janka test: whereby a steel hemisphere, 1.12 cm in diameter is completely forced into the wood. There is no distinction between side hardness on a radial or a tangential face, but only between side and end hardness (Kollmann and Côté, 1968). The data obtained from indentation tests have a purely comparative significance, but so long as this is understood the data serve a practical purpose in certain circumstance (Desch and Dinwoodie, 1993). The utilisation of wood in flooring or furniture represents typical cases where indentation resistance is an important characteristic.

2.1.5 Resilience or Work to limit of Proportionality or Toughness

Resilience is the amount of work done upon a body in deforming it. Within the elastic limit it is also a measure of the potential energy stored in the material and represents the amount of work the material would do upon being released from a state of stress (Record, 1914). According to Gordon (1991) the quality of being able to store strain energy and be deflected elastically under load without breaking is called resilience, and it is a very valuable characteristic in a structure.

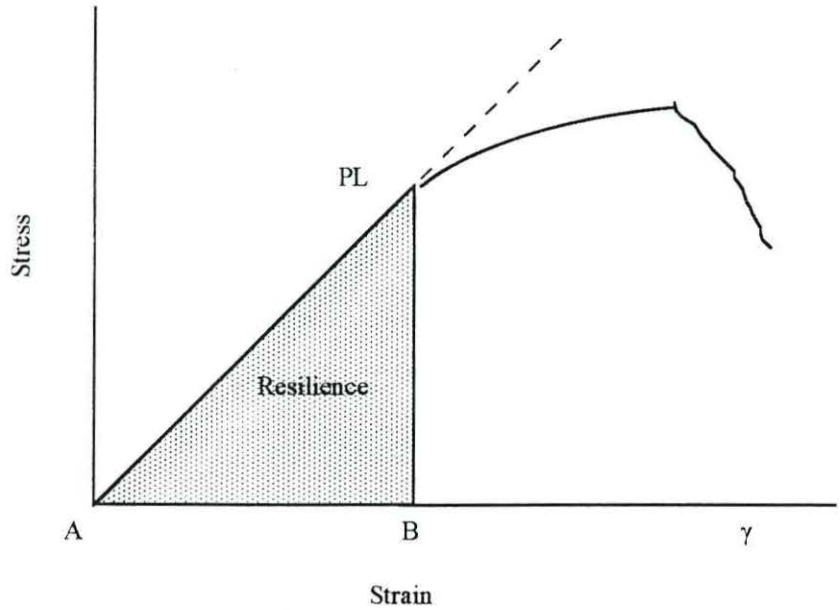


Figure 2.1 Characteristics of the stress-strain curve for wood.

If the elastic limit is taken as the apex of the triangle (Figure 2.1), the area of the triangle will represent the elastic resilience of the specimen. This amount of work can be applied repeatedly and is perhaps the best measure of toughness of the wood as a working quality though it is not synonymous with toughness (Record, 1914). It is easier to understand the importance of the resilience when comparing the force required to break a uniform rope by pulling on it (Gordon, 1991). The steady force or pull required to break a long string will indeed be the same as that needed to break a short one. However, the long string will stretch further before it breaks and it will therefore require more energy to break it, even though the force which is applied and the stress which is in the material remain the same (Gordon, 1991). Put it in a slightly different way, a long string will cushion a sudden blow by stretching elastically under the load, so that the transient forces and stresses which result are reduced (Gordon, 1991).

2.2 Performance of the Mechanical Properties in Relation to Anatomical Properties

The factors that have effect on mechanical properties in wood can be generally classified as those related to wood structure, and those related to environmental conditions of testing, such as moisture content, temperature, chemical treatment, and time-dependent effects. Only the factors related to the wood structure will be discussed in this review, since the environmental factors are supposed to be under control. This is in accordance with the standards testing methods applied to determine the mechanical properties.

Alexiou *et al.* (1991) suggest that factors beyond basic density and moisture content, such as the gross anatomy of the wood or ultrastructure of the cell wall, determine the elastic limit of *E. pilularis* wood. They related that the strain at the limit of proportionality (LP) under tension, in contrast to other properties also studied presented no significant correlation with basic density, either below or above the fibre saturation point (approximately 30 % of moisture content), and only a weak correlation with moisture content below the fibre saturation. Similar results were reported for compression perpendicular to the grain in the radial and tangential directions for the same species (Alexiou, 1994). The relationship between the ultramicroscopic anatomical characteristics of wood and its mechanical behaviour is scarcely studied if the considered wood is *Eucalyptus*.

2.2.1 Wood Fibre Morphology

The structural variability of wood in terms of its anatomical elements complicates an understanding of these effects on the mechanical properties of the wood. In hardwoods which presents a wider complexity than softwoods, such discussion becomes even more arduous. Thus, in this review, the emphasis will be placed on the fibres, which represents the main component of the wood of broadleaved trees.

The proportion of the various cells varies greatly between species so that, for example, in the angiosperms the volume of the xylem occupied by the fibres may range between 25 % in *Erytrhina* and 70 % in *Eucalyptus* (Wardrop, 1964). Wilkes (1988) gathering information provided by some authors (Dadswell, 1972; Hillis, 1972; Wilkes and Abbot, 1983; Bamber, 1985) summarised the various cell types of *Eucalyptus* as follows.

- Fibres (fibre-tracheids): 10 - 20 μm in diameter; 0.8 - 1.3 mm long and occupying > 60 % wood volume;
- Vessels: solitary and diffuse, 80 - 180 μm in diameter, 10 - 20 % wood volume;
- Rays: 1 - 3 seriate, < 20 cell high, 10 - 20 % wood volume;
- Vasicentric tracheids: < 2 % wood volume.

Robinson (1920) was the first researcher to describe with details the microscopic features of mechanical strains in timber and the bearing of these on the structure of the cell-wall in plants. In his sense the mechanical properties of wood depend primarily on the behaviour of the substance of the cell-walls, and only secondarily on the arrangement of the individual cells and tissues in the wood. He also adds that wood is a mechanical structure the qualities of which depend even more on the material of construction, that is the cell wall substance, than on the distribution of material in the structure. Other authors cited by Robinson (1920) had already made some statements relating anatomical aspects to the mechanical properties of wood or ligno-cellulosic materials.

Amongst them, Thill (1900) reported that the form of the fracture depended on the medullar rays acting as places of lower resistance. Jaccard (1910) (also referred to by Robinson) studied both the wood of dicotyledons and of conifers and concluded that there is no specific type of rupture common to all woods and, contrary to Thill (1900), that the fracture bears no relation to medullar rays. The rupture is determined by points of least resistance in the wood, the pits in the walls of the tracheids and fibres, forming such points of weakness. Fulton (1912) related that the initial cause of failure in oak, pitch pine, ash and box lies in the medullar rays. This failure is attributed to an initial set caused by the natural sinuous displacement of the fibres in a tangential plane round the medullar rays, and by the lack of cohesion between the fibres and the medullar rays.

The relationship between fibre length and strength is not very well understood. However it is known that the cell length is important in determining strength but it is not directly proportional to the length of the cells: rather it has been shown that a minimum length of the cell is necessary in order to ensure sufficient overlap with the cell above and below it in order to transfer stress from one cell to the next (Desch and Dinwoodie, 1993). Thus, although the stronger woods are frequently associated with increased cell length, it should be appreciated that it is not the cell length as such is the direct cause of the increase strength; rather the increased length is the consequence of other factors causing increased strength (Desch and Dinwoodie, 1993).

The great importance of the length of the fibre for wood utilisation and also in explaining behaviour, both physical or mechanical, has been a matter of discussion by many authors. According to Amidon (1981) fibre length is an important factor in controlling the resistance of paper, mainly under shearing. However, Zobel and van Buijtenen (1989) note that there is a threshold value of cell length where increasingly longer cells have little effect on the quality of the product. In addition they consider that improved technology has overcome cell length limitations to some degree, and as an example *Eucalyptus* wood is now being used to make good grades of papers (short fibre is typical for *Eucalyptus* wood).

In *Eucalyptus*, aspects of fibre morphology, such as fibre diameter, affect the processing of wood for paper making (Amidon, 1981) for composite products and for preserved timber products (Hudson *et al*,1998). In pulp studies the fibre diameter influences the coefficient of cell rigidity[1], the coefficient of cell flexibility[2] and the Runkel's ratio[3]. However, studies relating to these coefficients will not be discussed in this work. Also, the behaviour of the fibre diameter is important in

[1] Coefficient of cell rigidity = Cell wall thickness/Fibre diameter
[2] Coefficient of cell flexibility = Lumen diameter/Fibre diameter
[3] Runkel's ratio = Double cell wall thickness/Fibre diameter

explaining variations in density (Malan,1991) and strength properties (Nasroun and Elzaki, 1987) due the combined effects of an increase in fibre diameter and a decrease in lumen size.

Wall thickness and fibre diameter are the fibre characteristics that often have the most bearing on the density and mechanical properties of wood. Timber strength in general is related to the percentage of fibres present, but this may be much modified by the proportion of cell wall in individual fibres (Chalk, 1983). This is not simply a matter of the thickness of the wall, since it is recognised that during the specialisation of the fibre the dominant factor affecting the proportion of cell wall is the elongation of the cell by intrusive growth, which reduces the lumen without affecting wall thickness (Chalk, 1983). Density depends on wall material per unit area, but sometimes the influence of wall thickness is outweighed by fibre diameter. The actual density (specific gravity) of the cell wall material (wood substance) based on measurements carried out by Stamm (1964) has an almost constant value. The specific gravity of the cell wall substance is considered to be 1.46 when determined by helium displacement and 1.54 when determined in water.

The lumen diameter indicates the size of the cavities of the fibres. A direct and obvious inference is that the higher is the lumen diameter, the lower will the wood density be. Also, liquid movement will be favoured by a wider-lumen wood. Most of the discussion relating specifically to the lumen diameter can be inferred from the results in the literature for fibre diameter and fibre wall thickness. Possibly, more common are discussions concerning the coefficient of flexibility, since this parameter, which describes the relative cell dimension, explains more adequately the relationship between the fibre morphology and the quality of the pulp. The lumen diameter depends on the fibre diameter and the fibre wall thickness, so frequently these parameters have been indirectly associated with the lumen diameter.

In spite of the fact that cell wall thickness often presents a high correlation with density, according to Zobel and Van Buijtenen (1989) few studies have been made directed solely at variations in wall thickness; most of these relating to changing the proportion of thick-walled cells, via control of latewood percentage or the amount of thin-walled juvenile wood by changing rotation ages. In view of the importance of wood density to the physical and mechanical properties of timber, surprisingly little attention has been paid to variation in the transverse dimensions or frequency of libriform fibres in hardwoods (Rao *et al.*, 1997). According to Chalk (1983) there is some evidence that the fibre wall thickness increases from the pith outwards, but there seem to be little quantitative information on within-tree variation of these fibre dimensions in *Eucalyptus*.

In *E. grandis* fibre length, diameter and fibre wall thickness increase rapidly with increasing distance from the pith, levelling off after about 8 to 15 years (Bhat *et al.*, 1990; Malan and Gerischer, 1990). These results were similar to those found in *E. grandis* wood, fibre length and basic density, since they also increased from pith to bark, but lumen diameter was reduced in the same direction (Bamber and Humphreys, 1963). The authors stated that neither basic density nor fibre length were related to growth rate. Later Bamber *et al.* (1982) found for the same species that juvenile wood density and fibre dimension of fast-grown trees were similar to those of controls, but vessels were smaller and less numerous and ray volume greater in the fast-grown trees. They suggested that fast growth thus appears to have affected the physiologically active but not the mechanical cells.

The variation of the fibre characteristic in the longitudinal direction in the stem presents an auxiliary contribution to the understanding of the wood property as a whole. Thus, it has been shown that height in tree has little effect on fibre length, while fibre diameter increases with height in tree to about mid-height followed by a decrease higher up (Taylor, 1973; Bhat *et al.*, 1990).

The effects of fibre variations on the variation of mechanical properties are scarcely discussed. However many inferences have been drawn through the effect of the fibre on the specific gravity or density as previously discussed. Some direct relations are eventually found in the literature.

Choi and Cote (1990) related that under axial compression, strain profiles showed that deformation in wood was not uniform but was closely related to its morphology. These authors found that both fusiform rays and uniseriate rays caused disturbance in the deformation field; the influence of the uniseriate rays was not as great as that of the fusiform rays, which are larger. Thus, local disturbance in the deformation field appeared to be the main source of local failure and the main factor in the complete failure of specimens. The results suggest that local disturbance might be determined by the size, location and arrangement of rays, the angle of initial fibre bending and the mechanical properties of the fibres. The propagation of complete failure was gradual and appeared to follow the adjacent local failures (Choi and Cote, 1990).

The relations between wood anatomical structure and both mechanical properties and specific gravity of eight broad-leaved species grown in Sudan, including *Eucalyptus camaldulensis*, were investigated by Nasroun and Elzaki (1987). Through regression analysis it was shown that the most significant parameters influencing specific gravity and all the mechanical properties studied (compression and shear strengths, and hardness) were: volume fraction of total cell wall material, fibre length, and fibre diameter. Also, specific gravity was related to the volume fraction of rays, and hardness and shear strength to volume fraction of fibres. The fractional wall volume and wall thickness of fibres increase rapidly with age as a result of the combined effect of an increase in fibre diameter and a decrease in lumen size, which most probably accounts for most of the radial variation in wood density (Malan, 1991).

In spite of the fact that *Eucalyptus* is the main hardwood genus researched, some other trees deserve consideration. For instance, a study of *Tectona grandis* revealed that an increased number of pits per fibre had a definite weakening effect on tensile strength; fibre-wall volume and mean thickness of individual fibre-walls had a rough relation to that property; compressive strength was usually determined by the abundance of parenchyma cells and length and aggregation of vessel members were more resistant to compression; bending strength was related to the frequency of fibres, distribution of soft elements, and aggregation of vessels. Also, information on softwoods relating to this subject is available. As an example, maximum crushing strength parallel to grain, relative density and tracheid lengths studied by Kaya and Smith (1993) in *Pinus resinosa* wood increased from pith to bark and varied with height above ground.

The idea that fibre structure varies in response to environment was supported by the observed variation in wood properties within and between trees of *E. regnans* in a study in which the close relations between measurements of longitudinal growth strain and stress, modulus of elasticity, basic density, volumetric shrinkage, fibre characteristics and stem form also were demonstrated (Nicholson *et al.*,1975).

The effect of growth rate is either too small and/or inconsistent to be of any practical importance, judging from the coefficient of determination (Malan,1991). Also in other eucalypts the effect of growth rate on the wood anatomy was found to be minimal (Wilkes and Abbott, 1983). Bhat *et al* (1990) found the correlation of rate of growth with density and fibre length to increase with the age of the wood.

2.2.2 Grain Angle

Grain angle (or spiral grain) represents the deviation of the wood grain from the direction parallel to the axis of the stem. Some slight grain angle may be considered as normal in the stems, but occasionally the deviation from parallel is large, resulting in an obvious spiralling grain pattern (Haygreen and Bowyer, 1982). Interlocked is a more complex grain pattern, but one which has been widely accepted as being directly related to spiral grain because it has the appearance of reversal of spiral direction at more or less regular growth increments across a stem radius (Harris, 1989).

The most common effects of grain angle on wood properties and uses are (Harris, 1989):

i) shrinkage following drying which causes warping in sawn timber, roundwood and plywood;

ii) reducing values of sawn timber strength;

iii) reducing the conversion rate of logs.

Also electrical and thermal conductivity properties are affected due the anisotropic behaviour of wood (Harris, 1989). Planning of such lumber to a high quality surface may also be difficult (Haygreen and Bowyer, 1982) or, depending on the intensity, require further sanding.

In an isotropic material the elastic constants and strength properties are the same in all directions, but in anisotropic materials, like crystals and wood, the elastic constants and other mechanical properties vary with the direction relative to the grain (Kollmann & Côté, 1968). Strength properties of wood are strongly anisotropic, the greatest differences being between properties measured "along the grain" and "across the grain". The ratio of tensile strength parallel to, compared with perpendicular to the grain, varies among 25:1 for green wood and 45:1 for air-dried material. In compression, the difference is not so marked, being only six to ten times greater parallel to the grain than perpendicular to it (Boas, 1933 cited by Harris, 1989).

In trees spiral grain functions as an adaptation to improve torsional strength when they are twisted by prevailing winds (torque) when the direction of the spirality is the same as the direction of the prevailing torque (Skatter and Kucera, 1997). Wind blown beeches in Scotland are often found to exhibit this spiral grain phenomenon (Mattheck and Kubler, 1995).

Although stiffness is affected very slightly by sloping grain, longitudinal compression, static bending and longitudinal tension are all markedly lowered with the effect being most significant under tensile stressing. Thus, at an angle to the grain of 15° the tensile strength, static bending and longitudinal compression are reduced to 45, 70 and 80 % of their respective strengths in straight-grained material (Desch and Dinwoodie, 1993).

In tension, bending and compression, loss of strength amounts to 10 % for grain angles somewhere between 5° and 10° (Kollmann and Côté, 1968). However, the recommendations from selected references show that there is some diversity of opinion amongst workers dealing with different species, and this emphasises the difficulty of generalising about wood properties (Harris, 1989).

Strong radial and vertical patterns in spiral grain were established for *Pinus radiata* grown in New Zealand (Cown *et. al.*,1991). According to their results, the most pronounced deviations from vertical grain were in the inner 10 growth rings (corewood zone), where the left-hand angles averaged 4.7° was sufficient to cause significant problems in processing and marketing through drying degrade, strength loss and movement in service. Outside this zone, angles were generally less and showed a higher proportion of right-hand spirals.

The effect of grain angle on bending properties was investigated on *E. marginata* wood by Kloot and Schuster (1958). Their results showed a significant linear trend of both modulus of rupture and modulus of elasticity on grain.

For some timbers the ratio of strength properties parallel and perpendicular to the grain is relatively small (Harris,1989). According to him, tests of *E. diversicolor* studied by Langlands (1936) and of *E. marginata* by Kllot and Schuster (1958) showed that strengths of these timbers were relatively insensitive to sloping grain. Ratios for modulus of rupture parallel and perpendicular to the grain were only 5:1 for *E. diversicolor* and 7:1 for *E. marginatta*.

No significant difference between provenances were detected for spirality in *E. nitens* wood but it decreased rapidly from 0 m (12°) to 4.8 m (3°) where it remained constant with increasing height in the tree (Purnell, 1988). Spirality was not consistently correlated between sampling points within the tree. It appeared to be independent and was not correlated with any other trait measured (density, moisture content, splitting, collapse, taper).

Interlocked grain is often observed in radially sawn *E. grandis* boards, giving it an attractive striped figure (Malan, 1995). However, if the grain angle in the alternating spiral grained zones deviates more than 4-5 from vertical axis of the board, it is difficult to obtain a smooth surface except by sanding (De Villers,1973).

The research on grain angle of *Eucalyptus* wood and its relationships on other properties is very limited. When considering fast-grown *Eucalyptus* in Brazil, there is no such study available.

2.2.3 Microfibrillar Angle

The cellulose, hemicellulose and lignin come together in a unit known as the microfibril, which is of indefinite length and some 10 x 5 ηm in cross section (1ηm = 0.000001 mm), distributed in a crystalline and non-crystalline regions along the length of the microfibril (Desch and Dinwoodie, 1993). The crystalline core of cellulose (the 'fibre'), as seen within cross section of the microfibril, is first surrounded by a semi-crystalline sheath of hemicellulose and the non-crystalline cellulose, and then on the outside by a sheet of lignin, these two sheets comprising the 'matrix' (Desch and Dinwoodie, 1993).

In a contribution about the diameter of microfibrils from sulphite pulps, Jayme and Koburg (1959) stated that the diameter of microfibrils in the cells of various hardwood species (beech, chestnut, poplar, birch and *Eucalyptus*) in the form of wood pulps ranged from 90 to 230 Å and thus were distinctly smaller than those of spruce wood with 210 to 290 Å. They suggested that the wide deviations of the diameter within the same species were caused by varying growth conditions. In this study, *Eucalyptus* wood microfibril breadth diameter ranged from 120 to 200 Å, while the microfibrils could be followed for lengths of 1-2 μ without finding any definite end (Jayme and Koburg, 1959).

Microfibril angle is defined as the angle that the helical windings of the cellulose chains within the fibre wall make with the fibre axis (Stuart and Evans, 1995). Generally, the orientation of microfibril in the S_2 layer in angiosperms ranges from about 5° to 20° from the axial, whereas the comparable range for gymnosperms is from about 10° to 30° (Boyd, 1980).

The within-tree variation of microfibril angle in the S_2 layer of the secondary wall has deserved the attention of some workers. For instance, the longitudinal variation of microfibril was investigated by Donaldson (1993) working with three groups of distinct progenies of *Pinus radiata*. He found that the microfibril angles within the corewood at breast height were different between groups while outerwood values were comparable. Angles at 18 m height were similar to those at breast height except for one progeny (Donaldson, 1993). In a previous work (Donaldson, 1992) showed that microfibril angle of the same specie showed a curvilinear decline from pith to bark, which was more pronounced at the butt end of the stem. Moreover, microfibril angle declined rapidly with height within the tree, reaching more or less constant values at heights above 7 metres, followed by small increases in the corewood of the top log (Donaldson, 1992).

The microfibrillar angle of the S_2 layer represents an important ultra-microscopical feature that influences other wood properties, especially for solid wood products, where the microfibril orientation has a major effect on the stability of the wood upon drying and following manufacture (Zobel and Van Buijtenen, 1989). Also, in clear straight-grained wood both the longitudinal tensile strength and the stiffness have been shown to be markedly affected by the microfibrillar angle: as the angle to the vertical axis increases so the tensile strength and stiffness quickly decreases, however the remaining strength properties appear to be only lightly affected by the angle of orientation of the microfibrils (Desch and Dinwoodie, 1993).

Long cells with steep microfibril angles make stronger and more stable boards; this is one of the reasons that juvenile wood of loblolly pine is weak and somewhat unstable (Pearson and Gilmore,1980; cited by Zobel and Van Buijtenen, 1989). Tensile strength of East-Liaoning oak wood (*Quercus liaotungensis*) was closely related to microfibrillar angle and specific gravity was not always a good estimator of strength (Zhang and Zhong, 1992).

Bending stiffness has been shown for wood of Sitka spruce (*Picea sitchensis*), UK grown, to be strongly and inversely related to microfibril angle (Cockaday, 1992). In his study non linear models accounted for up 67 % of variability but the relationships with density were either very poor or not significant. Furthermore, multiple regressions involving non-linear functions of microfibril angle, growth rings from the pith and density accounted for up to 77 % of the variability of bending stiffness. In a similar study Downes *et al.* (1993) relate that variation in microfibril angle and lignin content was sufficient to account for 81 % of the bending strength of segments of living stems from two-years-old, fast growing *Pinus radiata*. A positive correlation between both of these variables and elasticity was also evident.

The stiffness (longitudinal Young's modulus) of fast grown softwood trees increases by a factor of 3 to 5, going outward from pith, during the first 30 years of growth (Cave and Walker,1994). According to the authors the only mechanism that has been proposed that can account for this is a change in the microfibril angle of the S_2 layer of the tracheid wall. There appear to be sufficient variations in microfibril angle between trees to justify selection of clones[4] to yield stiffer timber (Cave and Walker,1994).

According to Hirakawa and Fujisawa (1996) the S_2 microfibril angle generally declined with height in a tree, but the variation patterns and the height at which constant values were reached differed among cultivars and between clones of sugi (*Cryptomeria japonica*).

The variation pattern of the S_2 microfibril angles of latewood tracheids from pith to bark was almost the same in six clones of *Cryptomeria japonica*, but the angles in

[4] The term "clone" refers to a group of propagules that are genetically identical. Such a group normally comprises the original tree (ortet) and the vegetative propagules from it (ramets) (Harris, 1989).

the region of mature wood were different among individual clones even if the growth rates were nearly equal (Hirakawa and Fujisawa,1995). These results suggested to the authors that the S_2 microfibril angle might be controlled genetically. The Young's moduli in bending of clear small specimens had close correlations with specific gravity and the S_2 microfibril angle (Hirakawa and Fujisawa, 1995).

The importance of microfibril angle studies on the mechanical properties of *Eucalyptus* wood has been reported by some workers, but such studies are relatively rare in the literature. The variation of the microfibril angle between 0° and 27° (average = 9.5°) found by Bailleres *et al.* (1995) are similar to that of some species as *Eucalyptus rubida*, *Tulipera liriodendron* and *Magnolia obovata* (Okuyama *et al.*, 1990; Yoshida *et al.*, 1992) which do not present a G-layer. Results of studies on microfibril angle by several authors are presented in the Table 2.1. The microfibrillar angles of branches of *E. rubida* are smaller where tensile growth stresses are larger (Yoshida *et al*, 1992).

The effect of the microfibril angle on other wood properties of *Eucalyptus* is rarely reported in the literature. An exception was the work conducted by Boyd (1977) that describes the relationship between the microfibril angle and the shrinkage of wood from leaning *E. regnans*, *E. siebiri* and also in *Pinus radiata*. His data indicated that shrinkage increases progressively as fibre morphology changes from the mean representative of normal wood, and approaches that of reaction wood. In that case, the absence of a thick lignified S_2 layer, and of its usual moderating effect is most significant. There is a correspondingly big increase in longitudinal shrinkage attributable to the large microfibril angle in the S_1 (Boyd, 1977). The gelatinous layer in tension wood fibres apparently does not contribute significantly to longitudinal shrinkage, but on the other hand, it does not substantially impede a severe shrinkage tendency generated in S_1. The relative numbers and morphological characteristics of the lignified fibres in tension wood tissue determine the extent of moderation of the relatively extreme longitudinal shrinkage tendencies generated in the tension wood fibres.

Table 2.1 Microfibril angles (MFA) in *Eucalyptus* wood

Microfibril angle	Method	Specie	Remarks	Author
10° - 20°	X-ray Diffraction	*E. nitens*	MFA decreases from pith to bark and is smaller for latewood than earlywood	Stuart and Evans (1995)
0° - 27° 9.5° (mean)	Production of microfissures in the cell wall followed by contrast of coloration.	*Eucalyptus* (hybrids)	Negative correlation between the level of the residual growth stress and MFA of S_2 layer	Bailleres *et al.* (1995)
3.5° (tension wood) 22.5° (normal wood)	Polarised light microscopy	*E. camaldulensis*	Tension wood is characterised by a small MFA	Baba *et al.* (1996)
10° - 30°	X-ray Diffraction	*E. rubida*	MFAs decrease from the base to the extremity of the branch. Large tensile stress in the branch result in small MFA.	Yoshida *et al.* (1992)
7° (mean for the minimum) 10° (mean for the maximum)	X-ray Diffraction	*E. regnans*	Highly significant within-tree corre-lation between growth strain and MFA both in normal and in tension wood.	Boyd (1980)

2.3 Sampling and Analysis in Genetic Studies of Wood

The quantity and complexity of sampling needed to integrate within-tree and tree-to-tree studies can be formidable. The usual method of selecting which trees should be sampled is to choose and measure only the trees in the dominant and codominant crown classes: if intermediate and/or suppressed trees are sampled, wood properties may vary considerably from the more vigorous trees (Zobel and Jett, 1995). Furthermore dominant and codominant trees make up the bulk of the timber produced on an area (usually more than 80 %) and inclusion of intermediate or suppressed trees would require a larger sample if unreliable results are to be avoided (Zobel and Jett, 1995). However, the number of trees sampled depends on the uniformity of the stands.

Freese (1970) recommends the use of a formula based on the variance of a pre-sampling to estimate the number of trees. According to Zobel and Jett (1995) if a rooted cutting population is used 10 trees are required. However Hamza and Lewark (1992), working with four *Eucalyptus* species in Tanzania, reported at the 95 % confidence interval that the number of samples from a stand could be reduced from 20 to 5 to produce average values. In a study of the optimisation of statistical efficiency in clonal tests, with the goal of maximising genetic gain, the consequences of trade-offs between the number of ramets per clone (i.e., the accuracy of evaluating genotype means) and the number of clones tested (i.e., the selection intensity), when the total number of trees tested was held constant was examined (Muranty *et al.*,1996). According with their results the accuracy of genotype evaluation increases with the number of ramets per clone and tends to a maximum, which is the R^2 obtained using the complete data set (16 ramets). However, using 6 or 8 ramets resulted in only 3 to 10 % less than the maximum accuracy and although this also resulted in a few changes in the ranking of clones, the correlation between the ranks obtained using the complete data and those obtained for each simulation remained high. In this study, for hardness (measured using Pilodyn), the maximum estimated genetic gain was obtained using only two ramets per clone.

2.4 Within Tree Variation of *Eucalyptus* Wood

Homogeneity of wood properties is an aim for many users. Due the mechanics of tree growth all wood presents variation both in the longitudinal and radial direction of the stem. The central material, formed near the pith, is termed "juvenile" wood, while the wood formed in subsequent periods is called "normal" or "mature" wood. The pattern of variation in the log is the result of both extension and the properties of each tissue. Zobel and Van Buijtenen (1989) recall that greater uniformity in the wood will avoid inefficiencies for example, a structure must be designed for the weakest boards that will comprise it. Since strength properties vary considerably from board to board, inefficient utilisation can result since most boards are actually stronger than needed to meet the desired standard (Zobel and Van Buijtenen, 1989).

Juvenile wood has been defined as secondary xylem produced by cambial regions that are influenced by the activity in the apical meristem (Rendle, 1960). Thus it is the first wood laid down by the cambium near the centre of the tree (Zobel and Van Buijtenen, (1989). Its origin is controlled by auxin production in the tree crown (Larson, 1962) and results from close proximity to the foliage (Larson, 1969). Pearson *et al.* (1980) stated that the growth ring from the pith (i.e. the age of the cambium) is crucial, rather than the rate of growth. The age of the tree is not usually considered to be of importance in determining the properties of juvenile wood, since the characteristics of juvenile and mature tissues are generally related to the number of rings separating the cambium from the tree centre, or the closeness of the crown, regardless at what height in the tree (Zobel and Van Buijtenen, 1989). It is very important to separate absolute tree age from the juvenile wood concept - many persons retain the impression that young trees produce juvenile wood (a correct assumption) but conversely feel that older trees produce only mature wood (an incorrect assumption).

This material presents characteristics which differ from the mature or normal wood, formed in further years. According to Zobel and Van Buijtenen (1989) this type of wood is of more importance in conifers, particularly pines, and less important in hardwoods. In areas of fast growth reforested with *Eucalyptus* however, juvenile wood is of considerable importance as it constitutes a large proportion of the stem and is a serious source of variation. The variation in the basic wood properties of young *Eucalyptus grandis* can be adequately described by studying wood basic density, fibre lengths and vessel properties such as size, frequency and fractional volume (Malan, 1991). All these properties vary significantly among families, suggesting some genetic influence (Malan, 1991). In addition he did not find any significant phenotypic correlation between growth rate and wood properties. On the other hand, significant negative genetic correlations of rate of growth with wood basic density and fibre length were found, although the estimates obtained were considerably less than previously calculated.

In both hardwoods and softwoods juvenile wood cells are shorter than those of mature wood (Haygreen and Bowyer, 1982). Mature cells of softwoods may be three to four times the length of juvenile wood cells, whilst the mature fibres of hardwoods are commonly double the length of those found near the pith (Dadswell, 1958). Besides differences in cell length, cell structures also differ. There are relatively few latewood cells in the juvenile zone, and a high proportion of cells have thin wall layers (Haygreen and Bowyer, 1982): the result is low basic density and a corresponding low strength compared to adult wood. Gerard *et al.* (1995) reported that for various *Eucalyptus* hybrids the density, longitudinal modulus of elasticity and longitudinal residual maturation strain showed a transition between wood from a juvenile phase to an adult phase. Also, an increase in *Eucalyptus* wood density by about 30 % between 21 and 142 months was reported by Gerard *et al.* (1995). Moreover they relate that this phenomenon, of morphogenetic origin, depends on local conditions of growth and the age of the tree. In one clone, for example, they observed a very slight influence of age on the longitudinal residual maturation strain levels during the early years, corresponding to a period of healthy growth. In *Eucalyptus grandis* density increases rapidly with increasing distance from the pith, especially in the zone of juvenile wood (Taylor, 1973; Malan, 1988).

According to Ohbayashi and Shiokura (1989), working on radial variation of anatomical characteristics and specific gravity of *E. saligna* wood, fibre length, vessel element length, pore diameter and specific gravity increased from the pith towards the bark direction. Only pore density was greater near the pith than near the bark. In the juvenile wood region, the fibre length showed the most significant growth rate, increasing from 0.5 mm near the pith to up to 1.8 mm near the bark.

2.5 The Effects of Genotype, Environment and Genotype × Environment Interaction on Wood Properties

That environmental factors alter the phenotype can be easily observed, when, for example, two identical clonal trees are planted in two different environments. The resulting two trees will be very different in several characteristics, in spite of the fact that they have the same genetic make-up. Otherwise, two different genetic individuals could eventually produce an identical phenotype in the same environment. In reality, the phenotype is the result of the mutual action of the genotype and the environment: phenotype = genotype + environment.

Several studies have been conducted to show variation of wood properties due the effect of the environment (such as climate, soil characteristic, topography and others). Studies by Malan (1988b) revealed significant genetic variations with regard to wood density, spirality, proportional volume of the various tissue types, vessel frequency, fibre length and growth stresses.

Large between-tree variations in wood properties are known to exist between trees of *Eucalyptus grandis*, even among trees growing within one uniform site (Malan, 1988). However these variations appear not to be reliably correlated with changes in specific factors of the environment, such as temperature, altitude, latitude, rainfall and soil properties (Wilkes, 1988; Taylor, 1973a; Bhat *et al.*, 1990). Studies by Taylor (1973b) and Bhat *et al.* (1990) revealed very little differences in the wood properties of *E. grandis* between plots within geographical areas and between geographical areas. These studies suggest that a considerable proportion of the variation must be due to genetic effects.

Within-trees gradients also differ between trees (Malan, 1988). Little is known about the effect of environment on within tree variation in density, although such an effect has been reported for *E. grandis* by De Villiers (1968), as cited by Malan (1991).

Scientists agree that spiral grain is both genetically programmed and can be induced under special environmental conditions (Skatter and Kucera, 1997).

Between-tree differences in fibre lengths, though small, were found to be statistically significant, whilst differences in fibre diameter were small and non-significant (Taylor, 1973b). Bhat *et al.* (1990) observe no significant difference in fibre length between trees. As fibre-wall thickness is closely related to wood density, variation in wall thickness from tree to tree and within individual trees is similar to the patterns of variation in density (Malan, 1991).

The relatively narrow range of variation in microfibril orientation in the S_2 wall layer in angiosperms and in the normal wood of gymnosperms, makes it clear that broad genetic influences are involved (Boyd, 1985). On the other hand, detailed studies of many hundreds of tissues, from a substantial number of trees, show that all the significant variation of microfibril orientation in the S_2 are closely related to strains which were imposed on the fibres at the time of their differentiation (Boyd, 1985). Indeed, the correlation between growth strain and microfibril orientation have been demonstrated to be highly significant at the 99 per cent level of probability (Boyd, 1980). The microfibril angle in the S_2 could be somewhat different between fibres, as a consequence of differing genetic influences and differing environmental strains imposed on the individuals during differentiation (Boyd, 1985).

In contrast to spiral grain which has been the subject of a considerable amount of genetic assessment and is under moderate to strong genetic control (Zobel and Jett, 1995), microfibril angle, which is of much concern to solid wood users, has not been well studied. It has been shown that microfibril angle is highly correlated with tracheid length and wall thickness, making it probable that it is under moderate genetic control (Zobel and Van Buijtenen, 1989). The small number of studies relating microfibril angle with wood properties may reflect the complexity of the experimental methods required. However, significant variation of microfibril angle in the S_2 was observed by Donaldson and Burton (1995), both among clones and within and between trees for each of the 11 *Pinus radiata* clones studied.

However, there is another factor that contributes to the performance of the phenotype, which is the genotype × environment interaction (G×E) [The genotype x environment interaction is a change in the performance ranking of given genotypes when grown in different environments (Zobel and Jett, 1995)]. Consequently, Phenotype = Genotype + Environment + (Genotype × Environment). The G×E presents a difficulty for the geneticists, since the genetic improvement of trees must be carried out in the conditions where the genotype will be grown.

According to Zobel and Jett (1995), wood quality depends to some extent on genotype × environment interaction, but the question is whether the effect of the interaction is large enough to have any practical significance. Also, the correct characterisation of both the site and the assessed wood property may define the level of the interaction: it is possible that an apparently small variation in the environment may produce a meaningful response in the wood quality. Again, the difficulty will be to identify what environmental factor interacts with the genotype to produce a particular wood property in the tree.

Most of the studies on the effects of environment, genotype and their interaction on wood properties are limited to density (or specific gravity), since this is easily determined and supposedly well correlated to other wood properties.

Following a study of the interaction it is possible to identify clones which present higher adaptability (i.e. superior quality in all sites) and clones with better performance in specific sites. The genotype is considered to be unstable if the stability-variance for that genotype is statistically significant (Zobel and Jett, 1995).

Such a procedure, associated with assessment of the forestry productivity, permits high gains in the industrial production process to be obtained.

Genotype-environment interactions are of particular importance in clonal forestry, where they can be utilised to great advantage (Zobel and Jett, 1995). The effect of environment on growth stress induced splitting, wood density, fibre length, shrinkage and heartwood content was studied using 31 five-year-old eucalypt clones, mostly *E. grandis* and *E. grandis*-based hybrids, grown in replicated trials at 26 sites (Malan and Verryn, 1996). The regression coefficients that they presented indicated that genotype-environment interaction does exist for some clones and is applicable to all the wood properties considered. Also, Demuner and Bertolucci (1993) working with nine *Eucalyptus* clones planted in three sites, found that the interactions of clones × sites were predominantly complex for: *i)* four wood characteristics: basic density, lignin, pentosan content and extractive content obtained with ethanol and toluene; *ii)* six pulp characteristics: pentosans, viscosity, coarseness, tension index, nominal density and roughness, *iii)* two cooking characteristics: refined yield and gain in production. A summary of the results found by Demuner and Bertolucci (1993) are presented in the Table 2.2.

However, despite the significance of either clone or site, the interaction site × clone were not significant for characteristics such as fibre diameter, fibre cell wall, vessel diameter, pulp fibre length and pulp strength, among others (Demuner and Bertolucci, 1993). An "unexpected situation" considered by Zobel and Jett (1995) was the highly significant interaction between wood strength and site found by Waugh (1972) for poplar clones grown in Australia.

There is no consensus among tree breeders (or agricultural crop breeders) on the best way of detecting genotype × environment interactions or the way they should be handled in breeding programmes. The number of methods available for detecting genotype × environment interactions can be a deterrent, since breeders have too many options to consider (Romagosa and Fox, 1993), and the methods may give contradictory results. Crop breeders continue to debate the merits of breeding for general and specific adaptation and of selection in optimum and stress environments (Romagosa and Fox, 1993). Tree breeders are facing similar questions as they complete the first generation of tree improvement programmes, in which selection has usually been for general adaptation over a range of sites (Matheson ana Cotterill, 1990).

A number of authors have pointed out the need to assess the practical importance of genotype × environment interactions before drawing up tree breeding strategies (Pswarayi *et al.*, 1997; Matheson and Cotterill, 1990). This is obviously desirable, but there is little evidence that the techniques available for estimating the effects of interactions on breeding programmes (see Matheson and Raymond, 1984) are used routinely.

Pswarayi *et al.* (1997) found that, of the five methods used to analyse data on wood density of *Pinus elliotti*, only one (analysis of variance) detected statistically significant family × site interactions. They concluded that interactions were of little practical importance. MacDonald *et al.* (1997) reached a similar conclusion when they found that, although family × site interactions for pilodyn pin penetration in *Eucalyptus globulus* ssp. *globulus* were significant, they only accounted for 3% of the total variance.

For the same set of environments, family × environment interactions are expected to be less pronounced than clone × environment interactions because the mixture of genotypes within families provides a measure of genetic buffering. The loss of potential genetic gain resulting from clone × site interactions in basic density (Matheson and Raymond, 1984) may be as high as 20%.

2.6 *Eucalyptus* Breeding (Clonal Reforestation)

When plants are propagated by asexual means the non-additive gene effects are transmitted in full because the particular gene combinations of individuals remain intact and unchanged (Harris, 1989). Coppice growth sprouting from a common rootstock provides ready-made clonal groups for many species, and might be expected to reproduce the original plant closely, since all aspects of the environment, apart from mutual shading, are guaranteed to be as uniform as possible (Harris, 1989).

Table 2.2 Summary of the analysis of variance for wood properties of nine *Eucalyptus* clones cultivated in three sites (Demuner and Bertolucci, 1993). [* - P ≤ 0.05; **- P≤ 0.01; ns - non-significant].

Material	Characteristic	Site	Block Per Site	Clone	Clone x Site
Wood	Basic Density	ns	ns	**	*
	Lignin	ns	ns	**	*
	Pentosan	ns	ns	**	**
	Extractive Et/Tol	**	ns	**	**
	Extractive DCM	ns	ns	**	ns
	Fibre Diameter	ns	ns	**	ns
	Fibre Wall Thick.	**	ns	**	ns
	Vessel Diameter	ns	ns	**	ns
	Pentosan	ns	ns	**	**
	Extractive DCM	ns	ns	**	**
Pulp	Viscosity	*	ns	**	**
	Fibre Length	**	ns	ns	ns
	Coarseness	**	ns	**	*
	No of Fibre/Gram	**	ns	ns	ns
	Tension Index	ns	ns	**	*
	Nominal Density	ns	ns	**	*
	Air Strength	ns	ns	**	ns
	Shear Index	ns	ns	**	ns
	Roughness	ns	ns	**	**
Cooking Process	Alkaline Load	**	ns	**	ns
	Refined Yield	ns	ns	*	*
	Production Gain	**	ns	**	*

Reforestation with clones has increased significantly in the last two decades in response to the development of operational cloning systems (usually rooted cuttings) and to enhanced awareness of the benefits of such systems (Foster and Bertolucci, 1992).

Some of the most important benefits of clonal reforestation include (Foster and Bertolucci, 1992):

i) faster availability of genetically improved planting stock for reforestation compared with a traditional seed orchard/seedling based tree improvement program (Matheson and Lindgren, 1985);

ii) greater levels of genetic gain per generation are available compared to a seed orchard/seedling based tree improvement program (Chaperon, 1991);

iii) greater uniformity of the resultant stands and forest products (Campinhos and Claudio-da-Silva, 1990; Zobel *et al.*, 1983);

iv) greatly reduced dependence on seeds for planting stock production. Hence problems of seed production, viability, storage and germination for many tropical species become less of an impediment to large scale reforestation.

Although clonal material contains the total genotype of the ortet, this does not automatically ensure uniformity in all ramets, even when allowance is made for classical environmental effects on the ramets (Harris, 1989).

2.7 Modelling Wood Mechanical Properties

Most of the mechanical properties of wood have been demonstrated to be positively correlated to density (or specific gravity). The correlation is somewhat weaker for the parameters of elasticity, such as modulus of elasticity, than for the parameters of strength, such as modulus of rupture. Markwadt and Wilson (1935) presented the following general relationships: $MOE = 2.36 \cdot \rho$ (for green wood) or $MOE = 2.80 \cdot \rho$ (for wood at 12 % MC), where MOE = modulus of elasticity (10^6 psi), ρ = specific gravity.

According to Verkasalo (1992), several attempts have been made to model modulus of elasticity for wood fibres, cells and cell walls. A model has presented to predict the effect of variation in moisture content on the longitudinal value of Young's modulus (E) and on longitudinal shrinkage of wood: the effects of variation in moisture content on the stiffness and swelling characteristics of lignin, cellulose and hemicellulose were defined mathematically (Cave, 1978a). He suggested that the bound fraction of absorbed water is responsible for a variation in swelling stress and stiffness in lignin and hemicellulose. Estimates of stiffness of each constituent were similar to experimental values for longitudinal E and shrinkage of wood. In addition, stiffness characteristics of *in situ* constituents were compatible with experimental data for extracted lignin and hemicellulose and for native cellulose. In a later work (Cave, 1978b) showed that the structure and properties of cellulose, hemicellulose, lignin and water can be used to predict the longitudinal shrinkage and Young's modulus of earlywood of *Pinus radiata* at varying moisture contents. Koponen *et al.* (1987) and Koponen (1988), both cited by Verkasalo (1992), linked the different predictors for the strength of clear wood. At first, they developed a general model for estimating elastic and shrinkage properties of the softwood cell wall. Finally, the model was enlarged for defect-free softwood, where the structure of tracheid walls, cross-sectional shape of the tracheids, quantity of rays, density and moisture content were the contributing predictors.

Table 2.3 Regression equations for the prediction of mechanical properties of Malaysian timbers by density under green and air dry conditions (Ong,1988).

Condition	Equation	Number of Observation	R^2
Air-dry	MOR = -17 + 153D	109	0.88
Green	MOR = -15 + 148BD	155	0.84
Air-dry	MOE = - 1240 + 21510D	109	0.79
Green	MOE = - 559 + 22892BD	155	0.77
Air-dry	C = -5.4 + 75.7D	117	0.87
Green	C = - 10.6 + 83BD	176	0.83
Air-dry	H = - 5408 + 15621D	117	0.88
Green	H = - 4475 + 16208BD	176	0.90

MOR = modulus of rupture in bending, $N.mm^{-2}$; MOE = modulus of elasticity, $N.mm^{-2}$; C = compression strength parallel to the grain, $N.mm^{-2}$; D = wood density based on weight and volume at 15 % moisture content, $g.cm^{-3}$; BD = basic density based on oven-dried weight and green volume, $g.cm^{-3}$.

The estimation of a certain mechanical property using another mechanical property as predictor (or any other wood property) by analysis of regression has advantages if the predictors are easily determined and/or well correlated with the response variable. Furthermore, by the analysis of regression it is possible to estimate the relative contribution of each parameter, especially if is carried out using a multiple regression. The most usual parameter in the estimation of mechanical properties of wood is the specific gravity or density. Sometimes it is associated with other predictors such as moisture content, through a multiple linear regression. In this sense, multiple linear regressions showed that moisture content and basic density account for up to 89 % of the variation in the data for stress at limit of proportionality, stress and strain at failure and modulus of elasticity for *E. pilularis* wood (Alexiou, 1994).

Table 2.4 Correlations coefficients between some properties in the air-dry condition (Ong, 1988).

	D	MOR	MOE	C
MOR	0.939			
MOE	0.890	0.931		
C	0.933	0.985	0.940	
H	0.938	0.899	0.782	0.894

The mechanical properties of a wide range of Malaysian timbers can be efficiently estimated by a linear model using density as the independent variable (predictor) (Ong,1988). Some of the equations fitted to predict mechanical properties of both dry and green wood samples are summarised in the Table 2.3.

The phenotypic correlation between different mechanical properties also produced high correlation coefficients, as shown in the Table 2.4.

Modulus of rupture has been highly correlated with modulus of elasticity in *E. camaldulensis* using simple linear regression analysis (El-Osta *et al.*,1979). When they introduced density into the regression equation the correlation coefficients did not improve, and using density alone for predicting MOR was found to be unreliable. According to Divos and Tanaka (1997), the multi parameter regression model was first introduced into strength prediction by Ross and Pellerin (1988). The estimation of bending and tensile strengths of *Pinus* and *Picea* woods were remarkably improved when the regression model was changed from a single parameter regression to a two parameter regression (Divos and Tanaka,1997). In their study the best estimator for modulus of rupture was modulus of elasticity.

Simple linear regression analyses have also been used to estimate the modulus of elasticity in bending of Scots pine wood (Verkasalo, 1992). In his study, in addition to density he also applied different anatomical parameters as predictors. The best predictors for modulus of elasticity were fibre density index and several parameters determined in the tangential direction, such as a coefficient of cell flexibility and Runkel's ratio. Specific gravity and growth ring width were also good estimators. In contrast, double cell wall thickness and latewood percentage appeared to be inefficient predictors. Moreover, the small range of cell wall thickness found, practically made the conclusions on its effect impossible. His results indicated that the absolute tracheid dimensions do not predict modulus of elasticity well, but the parameters that relate them to each other are quite useful. Stepwise regression analysis was not attempted due to the known multicolinearity between most of the parameters (Verkasalo, 1992). Some of the results found are presented in Table 2.5.

There is no published report which attempts to explain the manner of incorporation of wood anatomical parameters in the models in terms of their contribution to the mechanical properties of *Eucalyptus* wood. Also, the simple correlation among those parameters is rarely considered in the literature.

2.8 Broad-Sense Heritability

The most commonly used quantitative measure of inheritance is the ratio called heritability. Heritability is defined as the fraction of the phenotypic variation in a trait that is due to genetic differences as opposed to environmental effects on individuals (Ayala and Kiger, 1980). In essence it expresses the relative importance of genetics and the environment in determining a specific character (Harris, 1989).

Table 2.5 Simple linear regression analyses to correlate the longitudinal modulus of elasticity (MOE) (Gpa), to characteristics of the wood structure (Verkasalo, 1992).

Characteristics of wood structure	R^2	S_x	Constant	x-coefficient
Specific gravity	0.904	1396	- 3651	41
Radial tracheid diameter, µm	0.770	2165	37.75	- 769
Radial lumen diameter, µm	0.898	1441	30.65	- 1058
Radial double cell wall thickness, µm	0.185	4077	32.94	- 1214
Fibre density index	0.954	969	4715	4694

Heritability, in the broad-sense, considers total genetic variability in relation to the phenotypic variability (Harris, 1989). Thus, if phenotypic variance (V_p) is seen as the sum of genotypic variance (V_G) and variance caused by the environment (V_E) then:

$$\text{Broad-sense heritability } h^2 = \frac{V_G}{V_P} = \frac{V_G}{V_G + V_E}$$

Broad sense heritabilities are typically estimated using vegetatively propagated groups, or clones.

2.9 Summary of the Literature Review and Objectives of the Thesis

Because of its rapid rate of growth, the adaptability of the genera, the possibility of genetic improvement, and its numerous possibilities of utilisation, *Eucalyptus* is the main genus of tree cultivated in Brazil. Recently, the properties of the trees began to be reproduced with high homogeneity due to the technique of clonal propagation. However, some variations in properties will always occur due to the genotype, environment and genotype-environment interaction.

In Brazil the utilisation of *Eucalyptus* has mainly been directed towards pulp and charcoal production, but although new alternatives have been investigated, its use for solid purposes is still not common partly because there is no consistent information relating to the mechanical properties.

To satisfy the growing industrial and domestic demands, there is continuing effort to increase the growth rate. In order to reduce the harvesting age, silvicultural and management techniques, where tree breeding plays an important role, have been adopted. There is thus a great need for information on the basic wood properties of young trees, in particular concerning mechanical properties, especially if consideration is placed mainly on their variation. Information at this level is important for the more efficient planning of activities aimed at improving the quality of wood produced in the future.

Thus, it is of importance to carry out studies involving different genetic material collected from the different sites where they are cultivated. It is also important to know the magnitude of the mechanical properties and their correlation with other wood characteristics, such as anatomy, for example. The review has demonstrated that these factors are of great influence on the mechanical properties.

The main objectives of this thesis are to determine the variations of the mechanical properties of 26 clones of *Eucalyptus* wood cultivated in four different sites, and to correlate these properties with their anatomical characteristics. It is also intended to predict different mechanical properties using density and anatomical characteristics.

The specific objectives of this thesis are:

1) to determine the clone-site interaction of basic density;

2) to determine patterns of within-tree, inter-clonal, between-sites variation and clone-site interaction associated with nominal density, mechanical properties, grain angle, fibre dimensions and microfibril angle;

3) to estimate the broad-sense heritabilities for these characteristics;

4) to assess the predictability of the microfibril angle using fibre dimensions as predictors;

5) to assess the predictability of the nominal density using fibre dimensions as predictors;

6) to assess the predictability of the mechanical properties (modulus of rupture, modulus of elasticity and compression strength parallel to grain) using nominal density, fibre dimensions, grain angle and microfibril angle as predictors.

3 MATERIAL AND METHODS

A summary of the methodology adopted is given diagramatically as Figure 3.5.

3.1 The Genetic Material, Growth Conditions, and Sampling Methods

The wood samples used in this study were collected from eight-year-old clones of *Eucalyptus grandis* × *Eucalyptus urophylla* (natural hybrids) experimentally established by Aracruz Celulose S.A., in Brazil. The experimental stands were originally planted on four sites (Table 3.1), using the experimental design of randomised blocks, spaced 3.0 x 3.0 m, with 26 treatments (clones) and three replicates. The original experiment presented 21 plants per block (three lines of seven trees, resulting in five useful trees when the bordered (edge) trees have been excluded). For the present study the effect of the block was not considered, since early studies assessing the relationship between forest yield and soil characteristics made use of some trees. Table 3.2 summarises the parameters studied in each site per clone. The genetic material utilised was not originally selected for wood quality, which allowed the utilisation of a randomised statistical model. Despite the good homogeneity of the experimental stand, in terms of the dimensions of the trees, the sampled trees were considered representative only of the dominant and co-dominant trees.

From each tree the 3.10 m long basal log was collected after the circumference at breast height and total height had been measured (Table 3.3).

After felling the 124 logs, after being marked by both clone and site, and having their ends sealed were shipped into a container to the University of Wales, Bangor, where they arrived with a high level of moisture (in excess of 100 % on dry weight basis).

Table 3.1 Characteristics of four experimental sites in Brazil planted with *Eucalyptus* clones.

CHARACTERISTIC	SITE			
	Southern Bahia -SBA (State of Bahia)	São Mateus 1 -SM1 (State of Espírito Santo)	São Mateus 2 - SM2 (State of Espírito Santo)	Aracruz - ARA (State of Espírito Santo)
Latitude	17°50' S	18°40' S	18°40' S	19°48' S
Longitude	39°50' W	39°45' W	39°45' W	40°17' W
Altitude	5-100 m	5-60 m	5-60 m	4-50 m
Topography	Flat	Flat	Flat	Flat
Climate	Af	Aw	Aw	Aw
Average temperature	25 °C	24 °C	24 °C	24 °C
Annual relative humidity	82 %	82 %	82 %	83 %
Annual rainfall	1374 mm	1282 mm	1282 mm	1290 mm
Soils	Utisols, kaolinitic, acidic, very low natural fertility			

The difference between the two sites at São Mateus (São Mateus 1 and São Mateus 2) are defined by details of soil type, and especially by textural differences which imply a greater or lesser availability of water to the plants.

Table 3.2 Summary of the parameters determinated, where: basic density (BD); nominal density (ND); modulus of elasticity in static bending (MOE), modulus of rupture in static bending (MOR), work to the limit of proportionality (R), Janka hardness (JH), compression-strength-parallel-to-grain (CP); grain angle (GA); fibre length (FL), fibre diameter (FD); fibre wall thickness (WT); lumen width (LD); microfibril angle (MF). (* no-sampled clone for that characteristic).

SITE	SOUTHERN BAHIA																									
CLONE	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26
BD																										
ND																										
MOR																										
MOE																										
R																										
CP																										
JH																										
GA																										
MF											*	*	*	*	*	*	*		*	*	*	*	*	*	*	*
FL											*	*	*	*	*	*	*		*	*	*	*	*	*	*	*
FD											*	*	*	*	*	*	*		*	*	*	*	*	*	*	*
WT											*	*	*	*	*	*	*		*	*	*	*	*	*	*	*
LD											*	*	*	*	*	*	*		*	*	*	*	*	*	*	*

SITE	SAO MATEUS 1																									
CLONE	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26
BD																										
ND																										
MOR																										
MOE																										
R																										
CP																										
JH																										
GA																										
MF											*	*	*	*	*	*	*		*	*	*	*	*	*	*	*
FL											*	*	*	*	*	*	*		*	*	*	*	*	*	*	*
FD											*	*	*	*	*	*	*		*	*	*	*	*	*	*	*
WT											*	*	*	*	*	*	*		*	*	*	*	*	*	*	*
LD											*	*	*	*	*	*	*		*	*	*	*	*	*	*	*

SITE	SAO MATEUS 2																									
CLONE	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26
BD																										
ND																										
MOR																										
MOE																										
R																										
CP																										
JH																										
GA																										
MF											*	*	*	*	*	*	*		*	*	*	*	*	*	*	*
FL											*	*	*	*	*	*	*		*	*	*	*	*	*	*	*
FD											*	*	*	*	*	*	*		*	*	*	*	*	*	*	*
WT											*	*	*	*	*	*	*		*	*	*	*	*	*	*	*
LD											*	*	*	*	*	*	*		*	*	*	*	*	*	*	*

SITE	ARACRUZ																									
CLONE	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26
BD																										
ND																										
MOR																										
MOE																										
R																										
CP																										
JH																										
GA																										
MF											*	*	*	*	*	*	*		*	*	*	*	*	*	*	*
FL											*	*	*	*	*	*	*		*	*	*	*	*	*	*	*
FD											*	*	*	*	*	*	*		*	*	*	*	*	*	*	*
WT											*	*	*	*	*	*	*		*	*	*	*	*	*	*	*
LD											*	*	*	*	*	*	*		*	*	*	*	*	*	*	*

3.2 Determination of Basic Density

A 2.5 cm thick disc was removed from the top and base of each log and cut into quarters for basic density determination using the immersion method (oven dry

Table 3.3 Total height (m) and diameter overbarked at breast height (DBH, cm).

Site	Total Height		DBH	
	MEAN (m)	CV (%)	MEAN (cm)	CV (%)
Southern Bahia	32.2	12.4	24.2	17.8
São Mateus 1	27.1	13.2	19.1	13.8
São Mateus 2	29.0	10.8	19.7	15.3
Aracruz	29.9	11.6	21.4	13.9

mass/green volume) (Vital, 1984). The basic density of each disc was considered to be the average value of the density of two opposite quarters of each disc (Lima *et al.*, 1992), and the mean basic density of each log was taken as the average of the values obtained for the two discs cut from it. The remaining portion of the log was used for the determination of mechanical properties and for anatomical studies.

Two groups of trees were assessed. Group I consisted of three trees representing each of five clones (clones 3, 5, 7, 8 and 20) planted on two sites (Southern Bahia and Aracruz) (i.e. 30 trees in total). Group II consisted of one tree representing each of twenty-six clones (clones 1, 2, 3, ..., 26) planted on four sites (Southern Bahia, São Mateus 1, São Mateus 2 and Aracruz (i.e. 104 trees in total).

3.3 Specimen Preparation for Nominal Density Determination, Mechanical Tests, Grain Angle, Fibre Morphology and Microfibril Angle

Following the taking of measurements relating to taper and circularity, the logs were broken down into six-centimetre thick planks using a mobile band-sawmill. To avoid possibilities of collapse (Bariska, 1992) these planks were then piled in air conditions to receive a pre-drying treatment in accordance with recommendation by Vermaas (1995). The three metre long planks were then cut down into three shorter planks of about one metre long. Only the one-metre long pieces from the base and from the top of the log were considered in this study. The Figure 3.1 shows the sampled positions in the log.

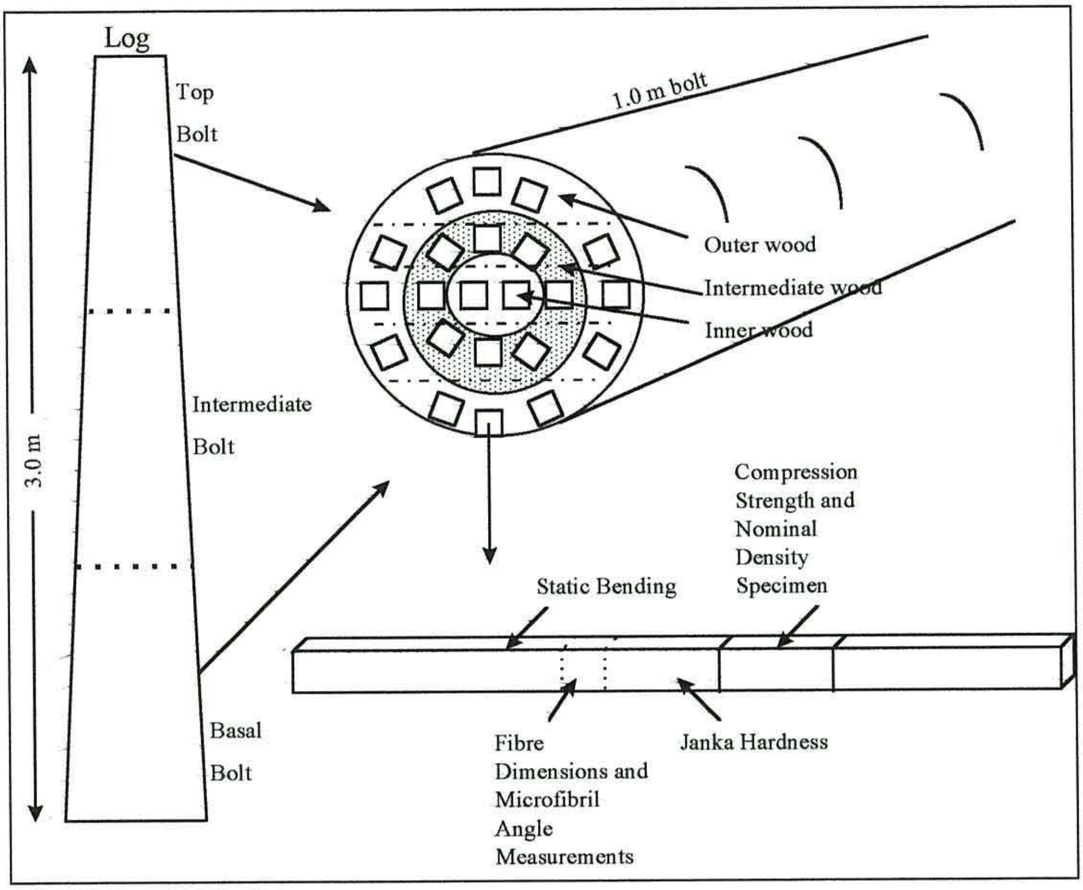


Figure 3.1 Sampled positions in each log.

Subsequently they were kiln-dried following the modified schedule presented in the Table 3.4. The modification of the schedule was necessary due the thickness of the pieces (about 6 cm). When the average moisture content of the batch reached approximately 12 %. the drying was terminated. The complete drying time varied from 20 to 30 days depending on the initial moisture content. Four batches were necessary to dry all planks used in the experiments.

Following drying and marking the 23 mm × 23 mm sticks were subsequently reduced to 20 × 20 mm in the plane. During this operation care was taken to ensure representation of the whole extension of the logs, which was divided in three regions: inner, intermediate and outer.

The inner region characterised the inner heartwood around the pith, representing about 10 % of the sectional area of the log. The intermediate region characterised the subsequent heartwood following the inner heartwood and represented about 40 % of the sectional area of the log, and the outer region, characterised by the outer heartwood and sapwood, representing about 50 % of the sectional area of the log (Figure 3.1).

Table 3.4 Modified drying schedule for 60 mm thick planks (Pratt, 1986).

Moisture content (%)	Dry bulb temperature (°C)	Wet bulb temperature (°C)
green	40	38.5
40	40	37.5
30	45	41.5
25	50	45.0
20	55	47.5
15	60	49.0

3.3.1 Nominal Density and Mechanical Tests

The mechanical tests carried out in this study were: static bending by central loading method, compression strength parallel to grain and Janka hardness tests, in concordance with B.S. 373 (1957). From the bending test the modulus of rupture, modulus of elasticity, and resilience (work-to-the-limit-of-proportionality) were determined. The testing conditions are summarised in the Table 3.5.

The samples were tested only in the seasoned condition. Before the preparation of the specimens for testing in the seasoned condition, the material were brought practically to constant weight by storage under controlled temperature (20 ± 3°C) and humidity conditions (65 ± 2 %). The same stick was utilised to provide a complete set of specimens (Figure 3.1). The nominal density was determined using the same specimen utilised for compression-parallel-to-grain, and also to supply the material for moisture content determination.

Table 3.5 Summary of the conditions of testing (B.S. 373, 1957).

Test	Specimen Size mm	Loading rate	Property
Static Bending	300 x 20 x 20	6.5 mm/min	Modulus of rupture Modulus of rupture Resilience
Compression strength // to grain	60 x 20 x 20	0.6 mm/min	Compression strength parallel to grain
Janka Hardness	60 x 20 x 20	6.5 mm/min	Hardness- resistance to indentation
Nominal Density	60 x 20 x 20		Oven dry weight/volume at moisture content when testing.

3.3.2 Grain Angle

Grain angles were determined using a scriber on both the opposite tangential faces of the static bending specimen before carrying out these tests. The scriber comprises a steel bar that is freely pivoted in a wooden handle at one end and which has a steel gramophone needle protruding from the other (Harris, 1989). When it is drawn approximately along the grain the true grain direction is indicated by a scratch mark. The deviation of the grain over a length of 100 mm along the longitudinal axis of the specimen is converted to degrees by the calculation of the arc tangent (Figure 3.2). The value of the grain angle applied in the analyses was the arithmetic average between the values obtained for both opposite tangential faces of the specimen.

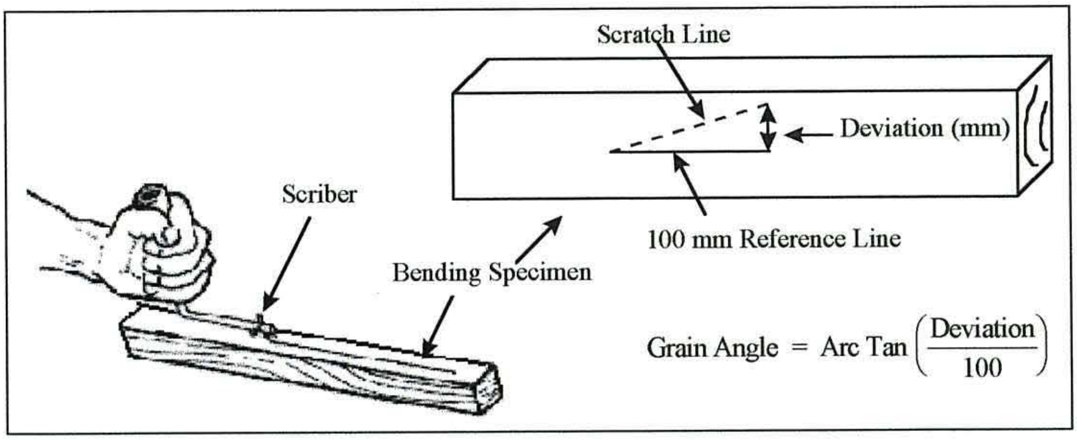


Figure 3.2 Grain angle determination

3.3.3 Fibre Dimensions

For the fibre dimension determination, only the basal bolts from eleven clones were used. In this case, one bending specimen from each radial position (inner, intermediate and outer) was selected.

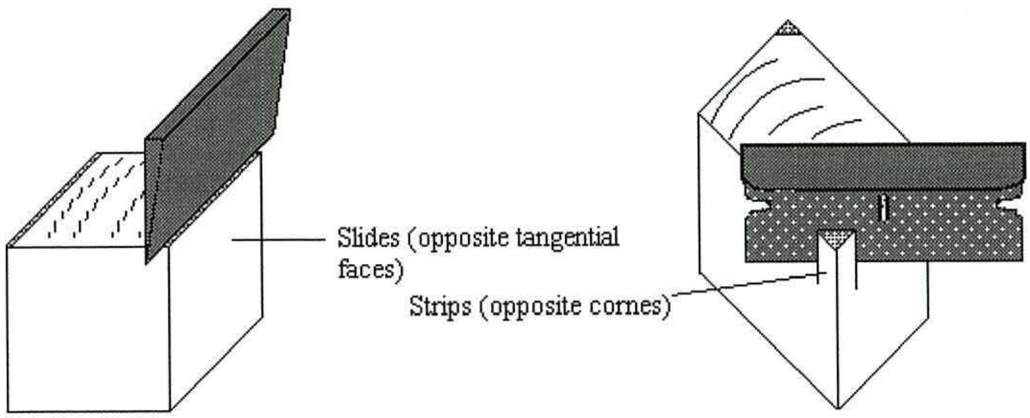


Figure 3.3 Sampling for determination of microfibril angle and fibre dimensions.

Fibre length (FL), fibre diameter (FD), and lumen diameter (LD) were measured to characterise the fibre dimensions. The fibre wall thickness (WT) was calculated by the relation WT = (FD - LD)/2. All the measurements were performed on macerated material that had been prepared using two small strips removed from blocks removed from the bending specimen after being tested. The position of the blocks and also the position in the block which supplied the strips are shown in the Figure 3.3.

To prepare the maceration, the strips were placed in a small test tube with an adequate amount of maceration solution (a mixture of 50 parts of glacial acetic acid and 50 parts of 30 % hydrogen peroxide). The test tube was heated in a water bath at 90-95 °C until the sections were bleached white and easily separate into individual fibres when shaken gently. The time required was usually less than 60 minutes. The maceration solution was next removed avoiding losing fibres. This was done by settling the fibres to the bottom of the test tube. Next, most of the solution was removed by careful use of a bulb pipette without disturbing the material. The test tube was then filled with distilled water to dilute the remaining maceration solution. Two of these water exchanges reduced the maceration chemicals to an acceptable level.

To mount the fibres, the test tube was agitated to produce an even distribution of the fibres in the water. The end of a wide-mouth bulb pipette, was put into the suspension and one bubble were squeezed out. The bulb of the pipette was then release quickly to draw a random sample of fibres into the tube. The pipette was held vertically and moved to a position over the slide. The amount of water remaining was small enough so that the fibres should not move out from under the cover glass when it was applied but large enough so that numerous bubbles would not be trapped among the fibres.

The fibre dimensions of this water mount were measured immediately using a digital length-measuring set. The fibre dimension was considered to be the arithmetic average calculated from the 50 values. 6600 fibres were measured (50 measurements × three radial position × one longitudinal position × 11 clones × four sites)

3.3.4 Microfibril Angle in the Fibre Wall S_2 Layer

The microfibril angle in the S_2 layer of the fibre walls was determined using the technique of polarised-light microscopy. As the polarised light technique requires that only a single cell-wall thickness is in the path of the light, recommendations made by Preston (1974) were here adopted. However, it must be considered that when various layers of the single cell-wall are superimposed in the light path, the observed extinction directions represent averages for all these layers together and thus are not accurately informative about any one layer. Nevertheless, they usually approximate closely to the direction given by the S_2 alone (Preston,1974), due its large relative volume. Accordingly, a simplified method was used to produce microscope slides of half-fibres (fibres with a single cell-wall) using the same principle used by Leney (1981). In this case, fibres were cut in half longitudinally by maceration of 10 µm thick microtomed wood tangential sections. In many cases, instead of single-walled fibres, holed-fibres were produced (this did not cause a serious problem for the measurements). The macerated material, prepared as described in the item 3.5. was mounted on a slide and observed under polarised light following instructions given by Preston (1974).

The measurement of the microfibril angle was performed at three radial positions (inner, intermediate and outer) for one longitudinal position of the log (base) of 11 clones cultivated on four sites. Thus, 6600 microfibril angles were measured(50 microfibril angles × three radial position × one longitudinal position × 11 clones × four sites). The microfibril angle was determined using the same blocks used for fibre dimension determination as presented in section 3.5. The microfibril angle was considered to be the arithmetic average calculated from 50 measurements.

3.4 Data Analysis

All statistical analyses were conducted using the MINITAB statistical package, Release 11.11, Minitab Inc. Minitab for Windows, 1996) and SPSS (Release 7.5.2, Statistical Package for Social Science, 1997).

3.4.1 Basic Density

Data from two groups of sample trees were analysed. Group I consisted of three trees representing each of five clones planted on two sites (i.e. 30 trees in total). Group II consisted of one tree representing each of 26 clones planted on all four sites (i.e. 104 trees in total).

Analysis of variance was carried out to determine the effects of clone, site and clone × site interactions on basic density (Group I data only). All effects were assumed to be random, since clones were not selected for wood properties, sites were a random sample of the environments available for growing *Eucalyptus* clones in Brazil and a random effects model is appropriate when deriving estimates of variance components for the calculation of heritability (Stonecypher, 1992). The expected mean squares for the analysis of Group I and Group II data are shown in Table 3.6.

Using Group II data, clones were ranked in order of decreasing basic density at each of the four sites. Ranking between sites was determined by calculating Spearman's rank correlation coefficient (Snedecor and Cochran, 1980) for all pairs of sites.

Variance components derived from the analysis of variance were used to estimate the broad sense heritability of basic density (h^2_{BS}).

$$h^2_{BS} = \frac{\delta^2_C}{\delta^2_P},$$

where δ^2_P is the phenotypic variance, calculated as

$\delta^2_P = \delta^2_C + \delta^2_{SC} + \delta^2_{T(C)}$ (Group I data), or

$\delta^2_P = \delta^2_C + \delta^2_{SC}$ (Group II data).

The method of Finlay and Wilkinson (1963) was used to examine the response of the 26 clones to the different environments at the four test sites. For each clone, the linear regression was computed between the basic density of the clone at each site (dependent variable) and the mean density of all clones at each site (independent variable). The mean performance of all genotypes growing in a particular environment is used as an environmental index (Finlay and Wilkinson,

Table 3.6 Expected mean squares for analysis of variance, showing variance components due to sites (δ^2_S), clones (δ^2_C), site × clone interactions (δ^2_{SC}) and trees within clones ($\delta^2_{T(C)}$).

(a) Expected mean squares for the analysis of variance of Group I data.

Source of variation	df	Expected mean squares
Site	1	$\delta^2_{T(C)} + 3\delta^2_{SC} + 15\delta^2_S$
Clone	4	$\delta^2_{T(C)} + 3\delta^2_{SC} + 6\delta^2_C$
Site × clone	4	$\delta^2_{T(C)} + 3\delta^2_{SC}$
Trees (within clone)	20	$\delta^2_{T(C)}$

(b) Expected mean squares for the analysis of variance of Group II data.

Source of variation	df	Expected mean squares
Site	3	$\delta^2_{SC} + 26\delta^2_S$
Clone	25	$\delta^2_{SC} + 4\delta^2_C$
Site × clone	75	δ^2_{SC}

1963), and gives a numerical indication of the average effect of the environment on the property being measured. The interpretation of the results of regression analysis is as follows:

i) if a clone has a regression coefficient of the order of 1 (average stability over all environments), its response to the environment is similar to that of the average clone;

ii) if a clone has a regression coefficient of more than 1 (below average stability), it is more sensitive to changes in the environment than the average clone;

iii) if a clone has a regression coefficient of less than 1 (above average stability), it is less affected by changes in the environment than the average clone. The procedure recommended by Freese (1984) for group regression analysis was used to determine whether any of the 26 linear regression coefficients were significantly different from 1. Coefficients of determination (R^2) were calculated for all regressions.

3.4.2 Nominal Density, Mechanical Properties, Grain Angle, Fibre Dimensions and Microfibril Angle

Firstly, the arithmetic average for each test or measurement was determined for each radial position (inner, intermediate and outer). To know the mean value for the radial positions of sampling in the bolts (mean per bolt) for nominal density, mechanical properties, grain angle, fibre dimensions and microfibril angle in each bolt the weighted average was determined using the formula:

$$W_a = (I_v \times 0.1) + (\times 0.4) + (O_v \times 0.5),$$

where W_a is weighted average for certain property, I_v is the inner value for the same property, M_v is the middle value for the same property and O_v is the outer value for the same property. The factors 0.1, 0.4 and 0.5 reflect the proportion of the sectional areas from where the specimens were collected.

For the properties studied at two longitudinal positions, the average property per clone was the arithmetic average between the basal and top bolts.

Analyses of variance were performed for the properties and characteristics following the same design applied for Group II of the basic density (section 3.7.1). The method of Finlay and Wilkinson (1963) was used to examine the response of the clones to the different environments at the four test sites. This method was also applied for the Group II data of the basic density (section 3.7.1).

Variance components derived from the analysis of variance were used to estimate the broad sense heritability of each property and characteristic (h^2_{BS}).

3.4.3 Correlations and Analyses of Regression

To assess the degree of linear correlation between variables coefficients of correlation (r) were determined, firstly between the microfibril angle and the fibre dimensions, secondly between the nominal density and the fibre dimensions, and thirdly between each mechanical property and nominal density, fibre dimensions, grain angle and microfibril angle.

Analyses of regression were executed to assess the dependence of microfibril angle (dependent variable) from each fibre dimensions (independent variables). The equations were selected from among eleven standard models (one linear and ten curvilinear) established in the SPSS (Statistical Package for Social Science program, Release 7.5.2). The selection of the models was based firstly on the coefficient of determination. Sequentially, other aspects were considered to support the selection: the significance of the regression, the significance of the predictors, the analysis of the residuals, the clearness of the model and the appropriateness of the model to the relationship studied.

The dependence of the nominal density on fibre dimensions and the dependence of some mechanical properties on nominal density, fibre dimensions, grain angle and microfibril angle were also estimated using simple linear regression for all data together and using the eleven standard models (one linear and ten curvilinear) established in the SPSS for analyses performed for individual site.

The multiple linear regression was tested to predict the nominal density using fibre length, fibre diameter, lumen diameter and fibre wall thickness as predictors. Finally, some mechanical properties (compression strength, modulus of rupture and modulus of elasticity) were also predicted using seven variables as predictors (nominal density, fibre length, fibre diameter, lumen diameter, fibre wall thickness, grain angle and microfibril angle). Independent variables which presented co-linearity (high correlation) with others coefficient were eliminated from participation in the model.

3.5 Summary of the Methodology

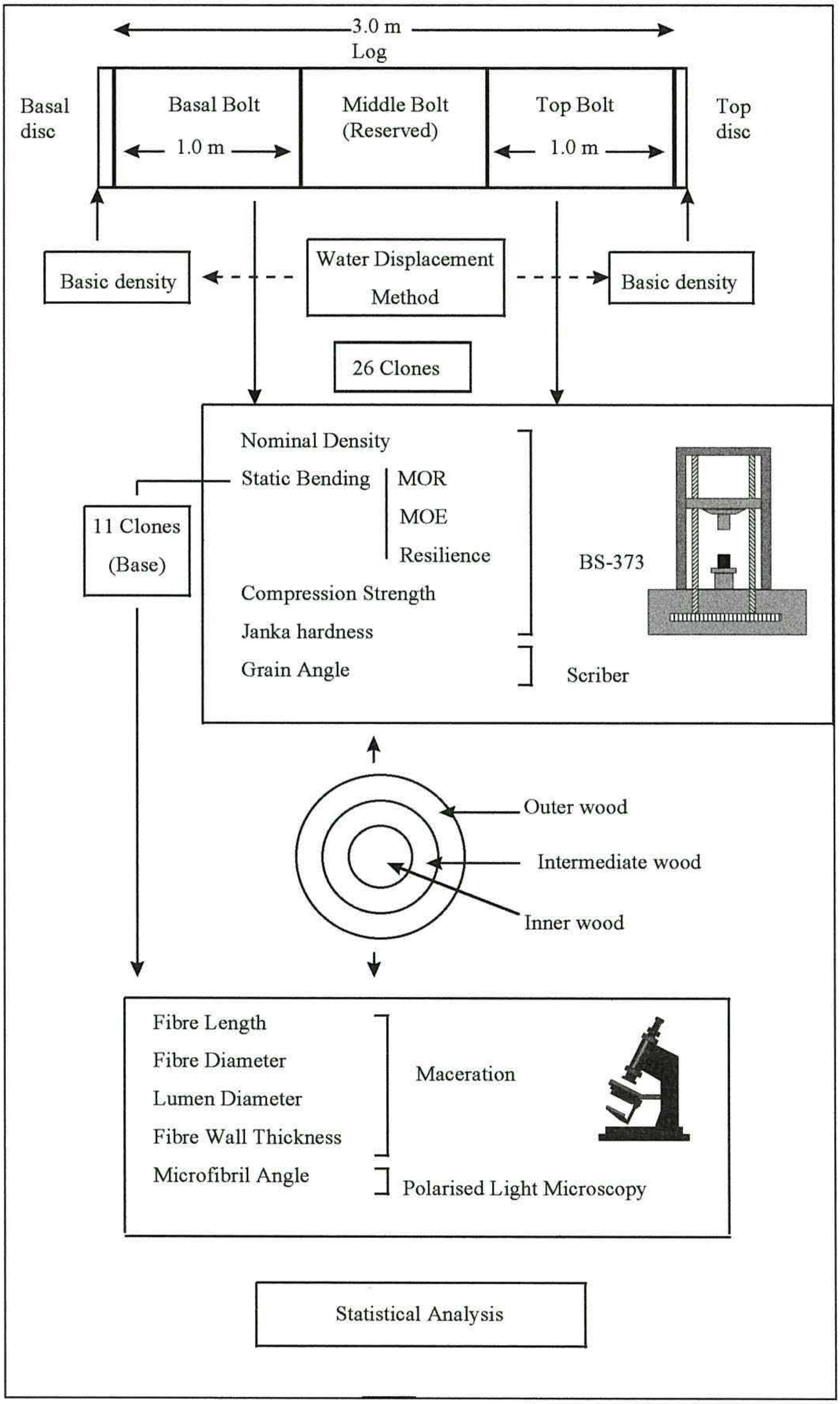


Figure 3.4 Summary of the methodology.

4 GENOTYPE-ENVIRONMENT INTERACTIONS ON WOOD BASIC DENSITY

The mass of oven-dried wood substance present in a given green volume of wood (basic density) is often used as an indicator of wood quality, since both values are reproducible and basic density correlates well with wood properties such as strength (Alexiou, 1994), dimensional stability (Chafe, 1990) and permeability (Kollmann and Cote, 1968). Thus, basic density is normally the first wood property to be assessed in a tree improvement programme. Raymond (1995), reviewing the genetic control of wood and fibre properties in *Eucalyptus*, reported that amongst the physical properties of wood, basic density is notable for the relatively large number of estimates of heritability.

Wood properties are affected not only by genetic factors and the sites where trees are grown, but also by interactions between genotype and environment (Zobel and Jett, 1995). For example, Malan and Verryn (1996) showed the existence of a clone × site interaction for several wood properties, density amongst them, in *Eucalyptus* clones grown over a wide range of sites in South Africa. Following a study of interactions it may be possible to identify genotypes with high general adaptability (for example, genotypes which produce wood with high basic density on a range of sites) and others which perform better on particular sites.

The objective of this part of the study was to examine genotype × environment interactions in wood basic density of 26 clones grown on four sites in Brazil. Interactions were examined using analysis of variance, rank correlations and regression analysis (Finlay and Wilkinson, 1963).

4.1 Basic Density: Five Clones Planted on Two Sites

Table 4.1 shows that mean basic density was higher on the site at Aracruz than at Southern Bahia in all five sampled clones. The same table shows that within clone variation in basic density had associated with it very low coefficients of variation.

Lima (1995) reported that within clone variation of basic density in *Eucalyptus saligna* decreased with increasing age, falling to less than 2.0 % by the age of 42 months. Given this low variation, the ideal sample size, according to the formula given by Freese (1984), is equal to one tree per clone for the most variable case (clone 3, Southern Bahia). The small number of sample trees required for the estimation of basic density of clonal material represents a great advantage in terms of the time and costs of experimentation. However, it is likely that this small sample size will only be acceptable when clones are grown on very uniform sites. It is also important to recognise that patterns of within tree variation may be such that a number of samples will be needed from each tree.

Table 4.1 Mean values and within-clone coefficients of variation (CV) for wood basic density of five *Eucalyptus* clones at two sites (Southern Bahia and Aracruz) in Brazil.

	Southern Bahia		Aracruz	
Clone	Mean ($g.cm^{-3}$)	CV (%)	Mean ($g.cm^{-3}$)	CV (%)
3	0.420	1.94	0.460	1.52
5	0.503	1.06	0.545	0.28
7	0.466	1.52	0.482	1.69
8	0.536	1.03	0.560	1.24
20	0.457	1.10	0.488	0.41

Analysis of variance (Table 4.2) showed that there were significant differences between sites and between clones. Of more interest was the significance of the site × clone interaction. Similar results were obtained by Malan and Verryn (1996) in five-year-old clones of *Eucalyptus* raised in South Africa and by Demuner and Bertolucci (1993), who found significant clone × site interactions in eleven out of 22 wood properties, including basic density, of five-year-old *Eucalyptus* clones growing in Brazil.

The implications of genotype × environment interactions for plant breeding and the methods used for detecting them have been discussed by a number of authors including Matheson and Cotterill (1990) and Ramagosa and Fox (1993). Pswarayi *et al.* (1997) have recently discussed five methods of evaluating the importance of genotype × environment interactions in tree species, using *Pinus elliottii* as an example.

Table 4.2 Results of analysis of variance of wood basic density of *Eucalyptus* clones (three trees of each of five clones on two sites). ** P≤ 0.01.

Source	DF	SS	MS	F	P
Clone	4	0.0452781	0.0113195	66.20	**
Site	1	0.0069312	0.0069312	40.53	**
Site × Clone	4	0.0006841	0.0001710	4.66	**
Trees (within clone)	20	0.0007334	0.0000367		
Total	29	0.0536268			

In their review, Zobel and Jett (1995) stated that, although few well-designed studies of genotype × environment interactions for wood properties have been made, essentially all have found relatively small interactions unless the differences between the environments are very large. Work done since the publication of Zobel and Jett's book generally supports this assertion, at least at the family level. Thus MacDonald *et al.* (1997) found "relatively low genotype × environment interactions" for pilodyn pin penetration (an indirect measure of wood density) in open pollinated families of *Eucalyptus globulus* ssp. *globulus* growing on five sites in Tasmania. Similarly, Wei and Borralho (1997) felt that genotype × environment interactions for basic density of open pollinated families of *Eucalyptus urophylla* growing on four sites in China were "unimportant".

4.2 Basic Density: Twenty-six Clones Planted on Four Sites

Figure 4.1 shows the basic density of the 26 clones at the four sites. The lowest mean basic density (i.e. the lowest site index) was 0.479 $g.cm^{-3}$ at Southern Bahia and the highest was 0.523 $g.cm^{-3}$ at São Mateus 2. Coefficients of variation of basic density were low at all sites, ranging from 6.4 to 8.8%.

Analysis of variance showed that there were significant differences in basic density between sites and between clones (Table 4.3).

Table 4.3 Results of analysis of variance of wood basic density of *Eucalyptus* clones (one tree of each of 26 clones on four sites). ** $P \leq 0.01$.

Source	DF	SS	MS	F	P
Clone	25	0.1160390	0.0046416	8.03	**
Site	3	0.0301055	0.0100352	17.36	**
Error	75	0.0433540	0.0005781		
Total	103	0.1894985			

Table 4.4 shows the values of Spearman's rank correlation coefficients for all pairs of sites. All correlations were significant ($P \leq 0.01$), suggesting that the ranking of clones is fairly consistent across sites and that it may be possible to identify clones which produce wood of high or low basic density on all sites. Inspection of Figure 4.1 shows that clones 4, 8 and 9 fall into the former category and clones 3 and 24 into the latter.

Table 4.5 shows the average basic density of the 26 clones over the four sites, the coefficients of linear regression of clone means against site means, and the associated coefficients of determination. Regression coefficients varied from -0.002 to 1.989, and coefficients of determination from zero to 93.4%.

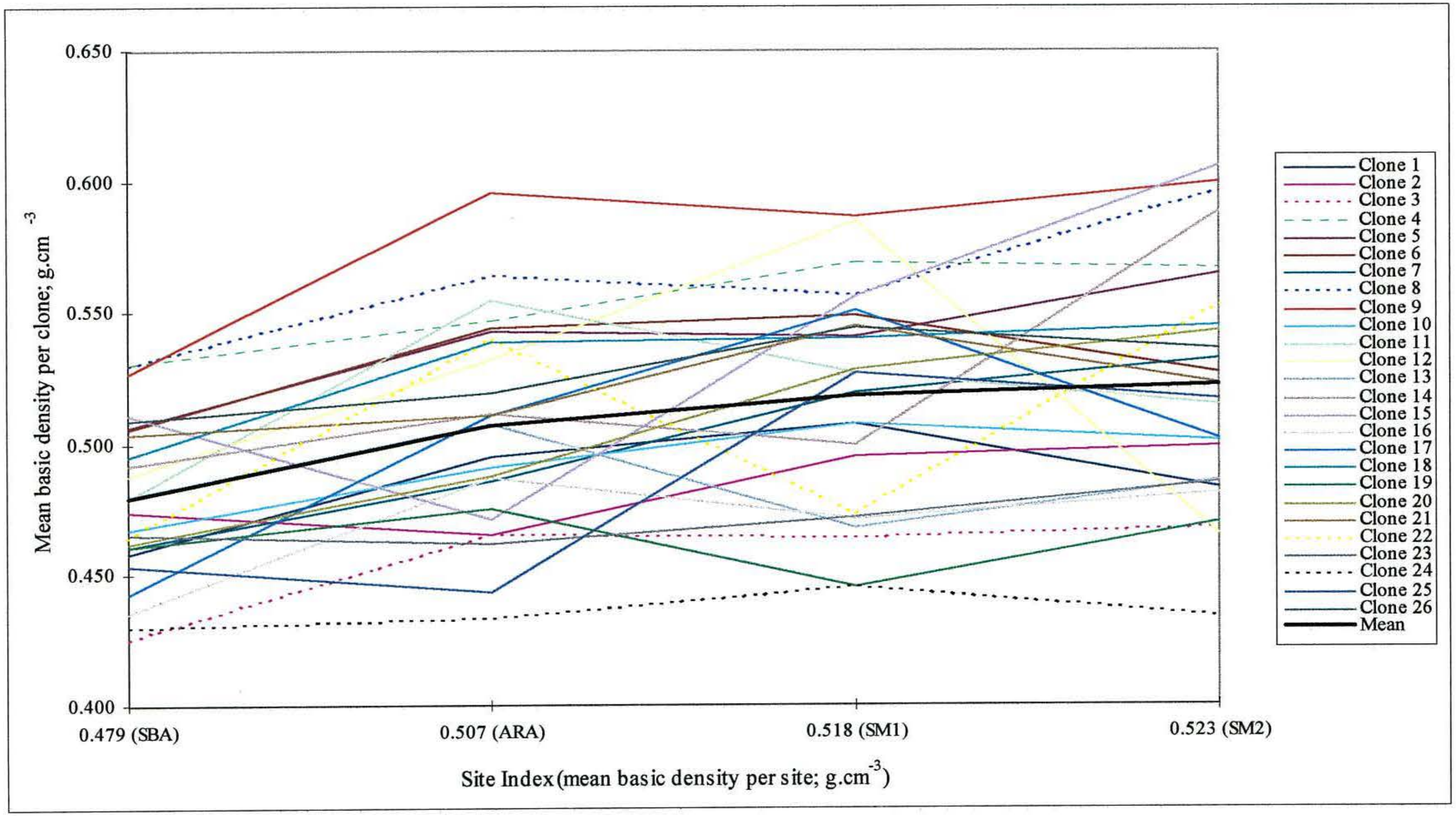


Figure 4.1 Wood basic density of 26 *Eucalyptus* clones at four sites. (ARA - Aracruz; SBA - Southern Bahia; SM1 - São Mateus 1; SM2 - São Mateus 2).

Table 4.4 Spearman's rank correlation coefficients between sites; 26 *Eucalyptus* clones ranked in decreasing order of wood basic density at each site. ARA - Aracruz; SBA - Southern Bahia; SM1 - São Mateus 1; SM2 - São Mateus 2. ** P ≤ 0.01.

	SM1	SM2	ARA
SBA	0.712 **	0.727 **	0.690 **
SM1		0.601 **	0.650 **
SM2			0.560 **

Malan and Verryn (1996) suggested that genotypes can be classified as having average stability (regression coefficients between 0.8 and 1.2), below average stability (regression coefficients greater than 1.2) or above average stability (regression coefficients less than 0.8). In this case eight clones (numbers 1, 3, 4, 5, 10, 11, 16 and 18) showed average stability, nine clones (numbers 7, 8, 9, 14, 15, 17, 20, 22 and 25) below average stability and nine clones (numbers 2, 6, 12, 13, 19, 21, 23, 24 and 26) above average stability.

Despite the wide range of regression coefficients, only one (β = 0.202, clone 24) was significantly different from 1, and only five coefficients of determination were greater than 90% (Table 4.5). This suggests that for most clones the predictable component of the observed genotype × environment interactions (estimated by the regression coefficient) is much smaller than the unpredictable component (estimated by the deviations from the regression). It appears that, for this group of clones on these four sites, it is generally not possible to predict the basic density of wood produced at one site from its value at another site.

4.3 Estimates of Heritability

In spite of the significant clone × site interaction, estimates of broad sense heritability of basic density were high: $h^2 = 0.96$ for five clones grown on two sites (Table 4.2) and $h^2 = 0.64$ for 26 clones grown on four sites (Table 4.3). In

Table 4.5 Mean basic density of 26 *Eucalyptus* clones over four sites, coefficients of linear regression (β) of clone basic density on site mean basic density, coefficients of determination (R^2) and the results of group regression analysis (F is significant if β is significantly different from 1).

Clone	Mean basic density ($g.cm^{-3}$)	β	R^2 (%)	F
1	0.486	0.843	60.7	ns
2	0.483	0.552	43.9	ns
3	0.456	0.989	90.8	ns
4	0.553	0.890	92.4	ns
5	0.539	1.173	89.5	ns
6	0.532	0.719	53.0	ns
7	0.500	1.571	91.2	ns
8	0.562	1.207	74.2	ns
9	0.577	1.618	87.1	ns
10	0.492	0.879	93.1	ns
11	0.519	0.986	37.9	ns
12	0.518	0.628	5.4	ns
13	0.485	-0.026	0.1	ns
14	0.523	1.440	40.3	ns
15	0.536	1.757	35.3	ns
16	0.469	1.004	71.9	ns
17	0.502	1.911	69.7	ns
18	0.530	1.145	93.4	ns
19	0.463	-0.002	≤ 0.1	ns
20	0.505	1.779	89.4	ns
21	0.521	0.665	53.0	ns
22	0.508	1.350	34.0	ns
23	0.471	0.347	44.6	ns
24	0.436	0.202	36.7	*
25	0.485	1.611	54.0	ns
26	0.527	0.720	80.9	ns

a literature survey, Raymond (1995) concluded that the basic density of *Eucalyptus* wood was under reasonably strong genetic control: individual tree heritability ranged from 0.05 to 0.84 (mean 0.57) in 16 estimates presented in 13 publications, while family heritability ranged from 0.45 to 0.91 (mean 0.65) in 13 estimates presented in 10 papers (Raymond, 1995).

There are fewer published estimates of broad sense heritabilities of basic density, but those which exist are comparable with the results of the present study. Thus the heritability of basic density estimated from nine clones of *Eucalyptus* growing on one site in Brazil was 0.90 (Bertolucci *et al.*, 1992) and heritability estimated from data for the nine clones on three sites was 0.92 (Demuner and Bertolucci, 1993). There were strong genetic correlations between basic density and cooking and pulp characteristics (Bertolucci *et al.*, 1992).

4.4 Conclusions

Wood basic density determined in samples taken from eight-year-old trees of 26 *Eucalyptus* clones growing in tests at four sites in Brazil has permitted the following conclusions:

i) Within-clone variation in basic density was low.

ii) The broad sense heritability of basic density was 0.96 when estimated from five clones growing on two sites and 0.64 when estimated from 26 clones on four sites.

iii) Analysis of variance showed that there were significant differences in basic density between clones and sites, and that the clone × site interaction was also significant.

iv) There were marked differences in stability between clones (linear regression coefficients 0.03 to 1.93).

v) Interactions were unpredictable (coefficients of determination zero to 93%), and in most cases it was not possible to predict the basic density of wood produced at one site from its value at another site. However, interactions accounted for less than 4% of the total variance in basic density, rank correlations between sites were all significant, and it was possible to identify clones which produced wood of consistently high or low basic density on the four test sites.

5 VARIATION OF NOMINAL DENSITY AND MECHANICAL PROPERTIES

The primary purpose of this chapter is to present results and discuss the intra-tree, interclonal and environmental variations associated with the nominal density, modulus of rupture, modulus of elasticity, resilience, compression strength parallel to the grain and Janka hardness. Also, aspects of broad sense heritability of these properties will be discussed.

5.1 Radial Variation of the Properties

5.1.1 Nominal Density: Radial Variation

In contrast to wood basic density, it is unusual to find references to studies of variation of the wood nominal density, especially if the considered wood is *Eucalyptus*. However, the two forms of wood density representation are interrelated, as follows:

$$BD = \frac{ODW}{GV}$$

$$\text{and} \quad ND = \frac{ODW}{V_{12}},$$

$$\text{so} \quad BD \times GV = ND \times V_{12};$$

$$\text{then} \quad ND = BD \times \frac{GV}{V_{12}},$$

where BD is basic density, ODW is oven-dry weight, GV is green volume, ND is nominal density and V_{12} is the volume at 12 % moisture content. $\frac{GV}{V_{12}}$ is a constant factor determined by the volumetric shrinkage that occurs from the green condition (above the fibre saturation point) to the equilibrium moisture content condition (12 % m.c. at 20 °C and 65 % RH). Similar inter-relationships exist for other forms of representation of density, such as specific gravity, for example. Normally, the problem is the understanding of the correct definition of the term density, since some authors fail to define its terms.

Table 5.1 Radial variation (inner-wood, intermediate-wood and outer-wood) of the nominal density, modulus of rupture, modulus of elasticity, resilience, compression strength parallel to the grain, and Janka hardness in the base and top of the log of 26 *Eucalyptus* clones for four sites in Brazil (SBA - Southern Bahia; SM1 - São Mateus 1; SM2 - São Mateus 2; ARA - Aracruz).

Property	Site	Base			Top		
		Inner	Inter	Outer	Inner	Inter	Outer
Nominal Density (g.cm^{-3})	SBA	0.457	0.486	0.540	0.442	0.478	0.532
	SM1	0.480	0.528	0.615	0.474	0.494	0.565
	SM2	0.498	0.540	0.598	0.485	0.514	0.562
	ARA	0.486	0.534	0.600	0.482	0.507	0.560
	Mean	0.480	0.522	0.588	0.471	0.498	0.554
Modulus of Rupture (MPa)	SBA	63.17	78.23	96.08	60.62	75.27	94.49
	SM1	68.47	85.60	104.60	72.70	84.45	103.65
	SM2	67.40	81.99	99.14	67.93	84.84	105.92
	ARA	67.54	81.46	101.14	66.54	83.19	104.68
	Mean	66.65	81.82	100.24	66.95	81.94	102.19
Modulus of Elasticity (MPa)	SBA	7536	8667	10090	8075	9480	10851
	SM1	7573	8789	10622	8578	9591	11178
	SM2	7860	9178	10361	8461	10176	11749
	ARA	7671	8976	10437	8236	9520	11597
	Mean	7660	8903	10378	8338	9692	11344
Resilience (kJ.m^{-3})	SBA	8.99	10.96	14.91	7.82	9.60	13.44
	SM1	11.20	13.27	16.25	10.18	11.34	14.27
	SM2	9.32	12.03	15.48	9.62	10.64	14.86
	ARA	11.42	12.71	17.31	9.89	12.34	16.12
	Mean	10.23	12.24	15.99	9.38	10.98	14.67
Compression Strength Parallel to Grain (MPa)	SBA	40.86	47.76	56.57	41.46	49.13	56.93
	SM1	42.79	49.78	61.40	46.61	51.23	61.49
	SM2	43.27	51.06	59.19	47.11	52.50	61.52
	ARA	41.01	49.13	59.71	44.55	50.90	59.29
	Mean	41.98	49.43	59.22	44.93	50.94	59.81
Janka Hardness (N)	SBA	3499	3673	4876	3029	3393	4541
	SM1	3937	4201	6116	3546	3637	5169
	SM2	3713	4248	5576	3564	3871	4958
	ARA	3829	4203	5649	3546	3617	5060
	Mean	3744	4082	5554	3421	3629	4932

The nominal density was found to increase from the inner most position in the log to the outer region both for the basal and top regions in the log (Table 5.1 and Figure 5.1). This behaviour was observed in all the sites studied and is summarised by the mean values. The increment rates of the mean values of the basal nominal

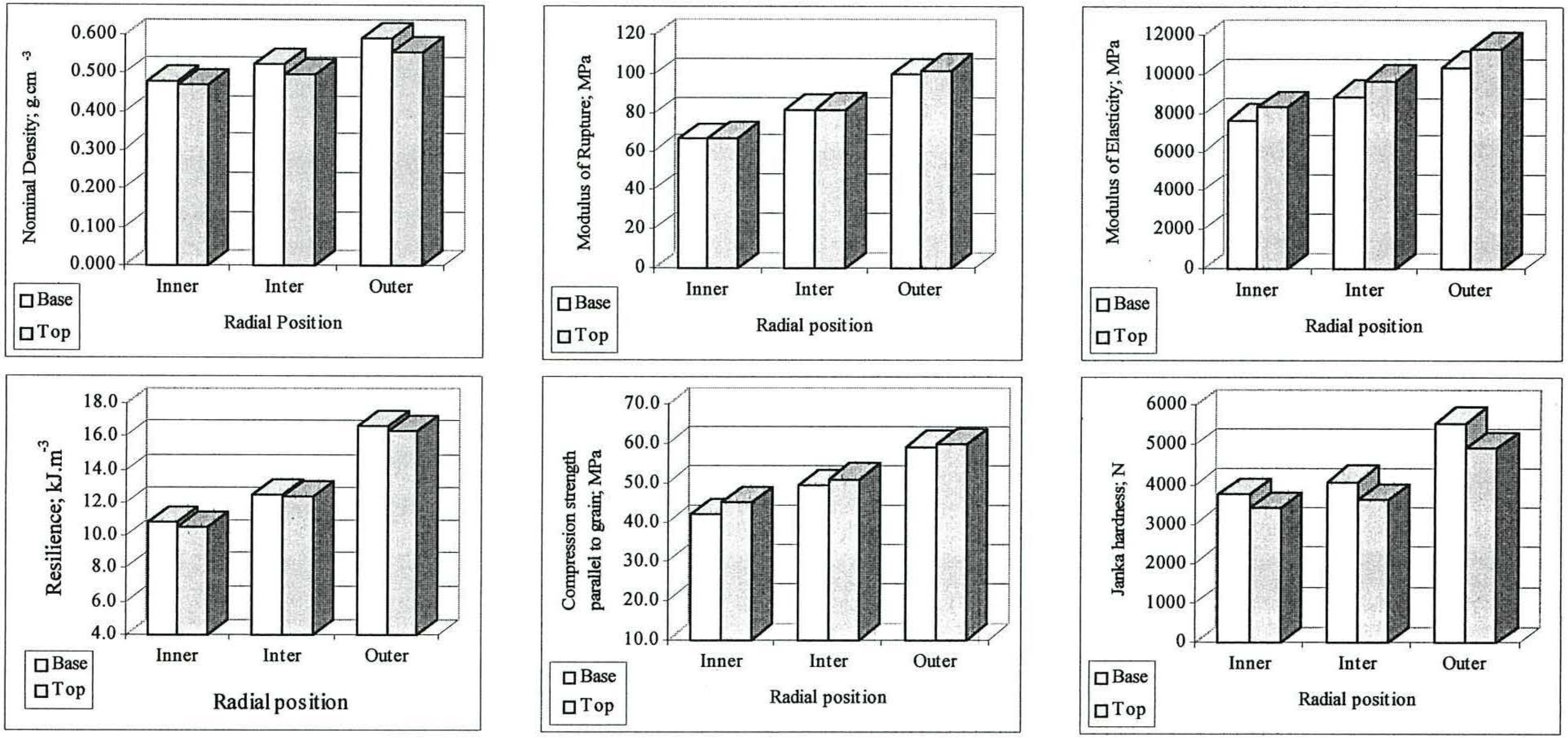


Figure 5.1 Radial variation in the base and in the top of the logs for nominal density, modulus of rupture, modulus of elasticity, resilience, compression strength parallel to the grain and Janka hardness.

density (Table 5.1) showed that this property increased 22.5 % from inner-wood to outer-wood. For the upper bolt, the nominal density also increased outwards, but at slightly smaller rates than those observed for the lower position. The occurrence of radial differences in nominal density was verified by the analysis of variance when all data are analysed together (Table 5.2) or when the data are analysed for each site and individual bolt (Table 5.3). These values can also be observed in Appendices 1.1 and 1.2.

Table 5.2 Summary of one-way analysis of variance of wood properties (nominal density, modulus of rupture, modulus of elasticity, resilience, compression strength parallel to the grain and Janka hardness) of *Eucalyptus* clones per radial and longitudinal positions. (ns- no significant; * P≤ 0.05; ** P≤ 0.01).

Property	Radial position	Longitudinal position
	d.f. (position) = 2 d.f. (error) = 621 df (total) = 623	d.f.(position) = 1 d.f. (error) = 206 df (total) = 207
Nominal density	**	**
Modulus of rupture	**	ns
Modulus of elasticity	**	**
Resilience	**	*
Compression strength // to grain	**	ns
Janka hardness	**	**

Radial patterns in density variations within cross sections of mature tree stems can be classified into three general types on the basis of the shapes of curves of the mean density from the pith outward to the bark (Panshin and De Zeeuw, 1980):

i) increases from the pith to the bark (most common pattern);

ii) decreases outward from the pith, then increases toward the bark;

iii) mean density higher at the pith than at the bark.

Table 5.3 Summary of the analysis of variance between radial positions in each site and each longitudinal position in the log for different properties [d.f. (radial positions) = 2, d.f. (error) = 75, d.f. (total) = 77]. (**-significant at 0.01 level, ***- significant at 0.001 level).

Property	Southern Bahia		São Mateus 1		São Mateus 2		Aracruz	
	Base	Top	Base	Top	Base	Top	Base	Top
ND	***	***	***	***	***	***	***	***
MOR	***	***	***	***	***	***	***	***
MOE	***	***	***	***	***	***	***	***
R	***	***	**	**	***	***	***	***
CP	***	***	***	***	***	***	***	***
JH	***	***	***	***	***	***	***	***

A study by Tomazello-Filho (1987) showed that basic density increased from the pith towards the bark in *E. pellita* and *E. acmenioides*, in contrast to *E. globulus*, for which density decreased after 50% of the sample radius. The normal result of this occurrence is the formation of high density in the proximity of the sapwood and neighbouring region of the heartwood and the formation of lighter wood in the central region of the stem. This is particularly true for fast grown hardwood, such as *Eucalyptus*, which is cut prematurely, before a significant amount of extractives have been deposited into the heartwood, which would result in some increase in its density. This phenomenon has been demonstrated by various authors studying wood basic density of fast grown *Eucalyptus* planted in Brazil (Foelkel *et al.*, 1983; Carpim and Barrichelo, 1983; Tomazello Filho, 1985).

The relationship between fibre dimensions and density deserve a special consideration in this work (Chapter 9).

5.1.2 Modulus of Rupture: Radial Variation

Table 5.1 and Figure 5.1 show that the modulus of rupture increases in the radial direction (from pith to bark) both in the basal and top bolts for all four sites studied. This is summarised by the mean values. The rates of increase of the mean values of the basal modulii of rupture showed an increased 50.4 % from inner-wood to outer-wood. In the upper position, the modulus of rupture also increased outward but at slightly higher rates than those observed in the lower position. Note that these increments are more than twice as high as those shown by nominal density. Modulus of rupture presented higher variation in the radial direction than nominal density. Possibly this is caused by more influential factors acting on this mechanical property than on density. Factors supposed to be unimportant for density (such as grain angle, microfibril angle and macroscopically imperceptible defects, among others), can be influential for modulus of rupture, either increasing or decreasing this property. During the production of the sticks for specimen preparation it was observed that the outer wood was less prone to defects such as knots and cracks. Material containing these defects was rejected. The existence of radial differences in modulii of rupture for all four sites was verified by the analysis of variance when all data are analysed together (Table 5.2) or when they are analysed for each site and individual bolt (Table 5.3).

Studies on conifer timbers show some similarities with the findings of the present research. For example, modulus of rupture for mature wood of Norway spruce (near the bark) was 47 % higher than that of the inner wood (Kliger *et al.*,1998). The results found in this work also find some support in a study of the radial variation of static bending of *Eucalyptus* hybrid [*E. tereticornis*] carried out by Shukla *et al.* (1988). According to them modulus of rupture increased from pith to periphery in three zones of the heartwood but decreased in the sapwood region. They added that although the sapwood strength was less than that of the outer heartwood there was no difference in average strength between sapwood and heartwood. In this work, the modulus of rupture (as represented by the mean value) also increases in the radial direction. For a particular clone or bolt it is possible, although unusual, to find other patterns of variation. For instance, in clone 6 the basal bolt modulus of rupture was higher in the intermediate position (Appendices 1.3, 1.4).

5.1.3 Modulus of Elasticity: Radial Variation

Similarly to the nominal density and the modulus of rupture, Table 5.1 shows that for all four sites studied the modulus of elasticity increases in the radial direction (from inner wood to outer wood) both in the basal and in the top bolt of the log. The increment rates of the mean values of the basal modulii of elasticity showed that this property increased 35.5 % from inner-wood to outer-wood. In the upper bolt the modulus of elasticity increased outward at a very similar rate to that observed for the lower bolt. These rates are higher than those observed for nominal density, but lower than those found for modulus of rupture. *Eucalyptus* wood commands a low price in the market due to the poor quality of its inner wood: in certain clones the outer wood is 80 % stiffer than the inner wood. The production of a stiffer inner wood would improve the overall wood quality, as a result of the greater homogeneity of inner and outer wood. This would be possible if the radial pattern of variation of modulus of elasticity were under genetic control. The existence of radial differences in modulus of elasticity were confirmed by the analysis of variance when all data are analysed together (Table 5.2) or when data are analysed for each site and specific bolt (Table 5.3). Modulus of elasticity presented a higher variation in the radial direction than did nominal density. Possibly this is caused by more factors altering this mechanical property than the density. However, in the same direction modulus of elasticity varied less than modulus of rupture (50 %). The results suggest that modulus of elasticity is less defective (or morphologically) dependent than is modulus of rupture: it seems that factors which cause ruptures in the tissues can be more influential on modulus of rupture than on modulus of elasticity, so increasing the heterogeneity of this property in the radial direction. Figure 5.1 shows that in both the basal and in the upper position modulus of elasticity increases in a similar pattern.

The results found in this work find some support in a study of the radial variation of static bending of *Eucalyptus* hybrid [*E. tereticornis*] carried out by Shukla *et al.* (1988) where strength properties increased from pith to periphery in three zones of the heartwood but decreased in the sapwood region. They added that although the sapwood strength was less than that of the outer heartwood there was no difference in average strength between sapwood and heartwood. Also in studies on conifer timbers it is possible to find some similarities with the results found in this research. For example, modulus of elasticity from mature Norway spruce (near the bark) was 30 % higher than that of the inner wood (Kliger *et al.*,1998).

It is important to mention that the variation reported here is the result of the formation of wood in young trees (eight year-old), with a high proportion of juvenile wood. It will not pass through a process of transformation in heartwood for a long time, which could increase its density. Other patterns of variation have been reported for mature wood: Della Lucia *et al.* (1983), for example, detected modulus of elasticity, amongst other properties, to be higher in the inner wood (dark red heartwood) than in the sapwood of 40 year-old *E. saligna* planted in Brazil.

In the face of the growth of trade and utilisation of *Eucalyptus* sawn wood in Brazil and to meet standard specifications the tendency is that the demand of machine stress graded timber will increase in the next years. The basic information necessary to utilise wood in a machine stress rating (MSR) is knowledge of its modulus of elasticity.

5.1.4 Resilience: Radial Variation

As with the other properties discussed, Table 5.1 shows that the resilience increases in the radial direction (from inner wood to outer wood) both in the basal and in the top bolt of the log for all four sites studied. This is summarised by the mean values. The increment rates calculated for the mean values of the basal resilience showed that this property increased 56.3 % from inner-wood to outer-wood. In the upper position, the resilience increased outwards at a similar rate to that observed in the lower position. The radial differences in resilience verified by the analysis of variance (Table 5.2) when all data are analysed together or when they are analysed for each site and particular bolt (Table 5.3). Resilience presented a similar variation in the radial direction to modulus of rupture but was more variable than modulus of elasticity. The results suggest that resilience is more defective (or morphologically) dependent than modulus of elasticity, in spite of the fact that both properties refer to the same elastic limit. Figure 5.1 shows that both in the base and in the top positions resilience increases in a similar pattern.

For a particular clone it is common to find resilience higher in the inner position than in the intermediate. However, the external sampling position generally produced wood with higher resilience. This can be noted in the Appendices 1.7 and 1.8.

5.1.5. Compression strength parallel to the grain: Radial Variation

In a manner similar to the other properties discussed, Table 5.1 shows that the compression strength of the material (parallel to grain) increases in the radial direction (from pith to bark) both in the basal and in the top bolt of the log for all four sites studied. This is summarised by the mean values. The increment rates calculated using the mean values of the basal compression strength parallel to the grain showed that this property increased 41.1 % from inner-wood to outer-wood. In the upper bolt, the compression strength parallel to the grain was more homogeneous, increasing outwards at a smaller rate (33.1 % from centre to outer) than that observed in the lower position.

The existence of radial differences in compression strength parallel to the grain for all data analysed together was verified by the analysis of variance (Table 5.2) where it can be noted that the F value was significant at $P \leq 0.01$. Also, when the data were analysed for each site and individual bolts the difference between radial regions was statistically significant (Table 5.3). Compared with other properties, compression strength parallel to the grain presented a higher variation in the radial direction than did nominal density, but smaller than the modulus of rupture and the modulus of elasticity. Possibly this is caused by more factors than density influencing compression strength. Since bending properties are the result of multiple stresses acting simultaneously (compression, tension and shear) any factor that affects each of these stresses may be a source of variation in the final result.

Figure 5.1 shows that both in the base and in the top position compression strength parallel to the grain increases outward in a similar pattern.

The results found in this work are partially corroborated by results found by Shukla *et al.* (1988) studying wood of *Eucalyptus* hybrid [*E. tereticornis*]. According to them, compression strength parallel to the grain increased from pith to periphery in three zones of the heartwood but decreased in the sapwood region. For mature wood, however, the pattern of variation can be different. Della Lucia *et al.* (1983), for example, detected higher resistance to compression parallel to the grain in the inner wood than in the sapwood of 40 year-old *Eucalytus saligna* planted in Brazil.

For a particular clone or bolt compression strength parallel to the grain showed a very consistent behaviour the radial direction. Only in a few cases was compression strength parallel to the grain higher in the intermediate zone than in the centre. These can be observed in the Appendices 1.9 and 1.10.

5.1.6 Janka Hardness: Radial Variation

Table 5.1 shows that the Janka hardness increases in the radial direction (from pith to bark) both in the basal and in the top bolts of the logs for all the four sites studied. This is summarised by the mean values. The increment rates calculated using the mean values of the basal Janka hardness showed that this property increased 48.3 % from inner-wood to outer-wood. In the upper position, the Janka hardness increased outward at a smaller rate (44.2 % from centre to outer) than that observed in the lowest position. The occurrence of radial differences in the values of Janka hardness for all data together was verified by the analysis of variance (Table 5.2) and when the data were analysed for each site and individual bolt (Table 5.3). Shukla *et al.* (1988) working with *Eucalyptus* hybrids also found an increasing tendency in surface hardness from pith to periphery, however the results of outermost heartwood of sectors failed to show continuity due to sudden fall in value. Janka hardness presented a higher variation in the radial direction than did nominal density, modulus of elasticity and compression strength parallel to the grain but smaller than modulus of rupture and resilience. Likely causes associated with the pattern of variation in Janka hardness can be similar to those associated with crushing strength. According to Kollmann and Côté (1968) the Janka hardness test is nothing other than a modified impression test influenced by effects such as friction, shearing and cleavage. Figure 5.1 shows that both in the lowest and in the upper bolts, Janka hardness increases from the inner region outward in a similar pattern. At the level of a particular clone or bolt it is unusual although possible to find other patterns of variation (Appendices 1.11 and 1.12).

5.2 Base-top Variation of the Properties

5.2.1 Nominal Density: Longitudinal Variation

Table 5.4 shows the results of analysis of variance for nominal density and mechanical properties performed to test the difference between basal and top bolts at different sites.

Table 5.4 Summary of analysis of variance for nominal density, modulus of rupture, modulus of elasticity, resilience, compression strength and Janka hardness between basal and top bolts at different sites [d.f. (position) = 1; d.f. (error) = 50; d.f. (total) = 51). (ns- no significant; * $P \leq 0.05$; ** $P \leq 0.01$)].

Property	Site			
	SBA	SM1	SM2	ARA
Nominal density	ns	**	*	*
Modulus of rupture	ns	ns	ns	ns
Modulus of elasticity	ns	ns	ns	ns
Resilience	ns	ns	ns	ns
Compression	ns	ns	ns	ns
Janka hardness	ns	**	*	*

Table 5.1 shows that the mean nominal density is higher at the base of the log (lower bolt) than at the top (upper bolt). However, this difference is small, varying

from 1.8 % (Southern Bahia) to 7.6 % (São Mateus 1) (Table 5.5). According to the analysis of variance presented in Table 5.2 there is a significant difference ($P \leq 0.01$) between the density of the basal and the top bolts of the log, when the four sites are analysed together. Also, analyses performed for each site separately (Table 5.4) reveal differences for nominal density between axial positions at São Mateus 1 ($p \leq 0.01$), São Mateus 2 ($p \leq 0.05$) and at Aracruz ($p \leq 0.05$), but not at Southern Bahia.

A high value of the density in the basal position does not imply that this tendency will be maintained in positions higher than 3.0 m, since several patterns of axial variation in density have been found in the literature, depending on species, age and radial position of sampling.

In hardwoods, variation of density with height follows one of three general patterns (Panshin and De Zeeuw, 1980):

i) it may decrease upwards;

ii) it may decrease in the lower stem and increase in the upper stem;

iii) it may increase from the ground upward.

Moreover, other patterns can be seen for specific wood or conditions. Shimoyama (1991), for example, showed for *E. grandis*, *E. saligna* and *E. urophylla* that the axial pattern of variation of wood basic density depended on the species. In *E. grandis* basic density decreased from the base to the maximum height of the stem, whereas *E. saligna* basic density decreased from the base to 25 % of the total height and then increased up to 75 % of the height, reducing from this point upward. *E. urophylla* presented values of basic density both increasing and reducing along of the stem, but with a tendency to increase.

Despite the different longitudinal patterns displayed by the three species studied by Shimoyama (1991), it is possible to deduce from her results that basic density reduced from the base up to 25 % of the total height (± 5.0 m height) for all the three species. The reductions of density in this region of the stem were 7.6 %

(0.506 g.cm^{-3} - 0.471 g.cm^{-3}), 6.4 % (0.532 g.cm^{-3} - 0.500 g.cm^{-3}) and (0.533 g.cm^{-3} - 0.513 g.cm^{-3}) for *E. grandis*, *E. saligna* and *E. urophylla*, respectively. These findings indicate the same tendency observed in the present study, where a 3.0 m long log has been studied.

For species in which juvenile wood greatly differs from mature wood, a change in wood properties with height is automatic since the proportion of juvenile wood in the stem increases greatly from the base to the top (Zobel and van Buijtenen, 1989). As a result of this a decrease in density often occurs in many species, especially in softwoods (Malan, 1991). In *E. grandis*, density commonly increases with height above ground level although an initial decline may sometimes be present. The log utilised in the present work possibly represents the part of the stem where normally there is observed a reduction in the density.

5.2.2 Modulus of Rupture: Longitudinal Variation

The axial variation of the modulus of rupture can be examined in Table 5.1, Table 5.6 (for each site and clone) and Figure 5.1, where it can be noted that there is no predominant tendency of increase or reduction in the property. Only at the external region of the upper position did the material show a higher modulus of rupture (102.19 MPa) than at the lower position (100.24 MPa), but this represents no more than a 2 % difference. In both inner and intermediate positions there is practically no difference.

According to Table 5.2 there is no significant difference in the modulus of rupture between the axial positions for the four sites together. Analyses performed for each site separately (Table 5.3) also revealed no difference for modulus of rupture between axial positions. These results are different to those found for nominal density and suggest that other factors overpass the effect of density on this mechanical property. Possibly, the existence of imperceptible defects in the basal bolt does not permit stronger gains in modulus of rupture when compared with the top bolt. Modulus of rupture was the only trait studied by Shukla *et al.* (1989) for *E. grandis* to show significant differences between the height positions. However,

Table 5.5 Nominal density (g.cm^{-3}) of 26 *Eucalyptus* clones, mean density per site and within-site coefficient of variation (CV) for four sites in Brazil (SBA - Southern Bahia; SM1 - São Mateus 1; SM2 - São Mateus 2; ARA - Aracruz).

Clone	Southern Bahia			São Mateus 1			São Mateus 2			Aracruz		
	Base	Top	Mean	Base	Top	Mean	Base	Top	Mean	Base	Top	Mean
1	0.498	0.472	0.485	0.544	0.486	0.515	0.531	0.503	0.517	0.547	0.490	0.518
2	0.468	0.477	0.473	0.555	0.566	0.560	0.522	0.544	0.533	0.489	0.500	0.494
3	0.466	0.453	0.459	0.531	0.497	0.514	0.493	0.477	0.485	0.484	0.522	0.503
4	0.600	0.587	0.594	0.666	0.571	0.619	0.630	0.568	0.599	0.632	0.599	0.616
5	0.555	0.523	0.539	0.628	0.585	0.607	0.620	0.573	0.596	0.622	0.592	0.607
6	0.453	0.512	0.483	0.524	0.509	0.516	0.551	0.504	0.527	0.569	0.519	0.544
7	0.518	0.512	0.515	0.632	0.533	0.583	0.625	0.556	0.591	0.593	0.548	0.571
8	0.579	0.588	0.584	0.596	0.589	0.592	0.644	0.618	0.631	0.633	0.591	0.612
9	0.604	0.581	0.592	0.668	0.636	0.652	0.687	0.650	0.668	0.689	0.659	0.674
10	0.529	0.494	0.511	0.495	0.548	0.521	0.552	0.505	0.528	0.503	0.515	0.509
11	0.461	0.475	0.468	0.599	0.533	0.566	0.518	0.515	0.516	0.528	0.508	0.518
12	0.587	0.491	0.539	0.627	0.570	0.598	0.600	0.539	0.569	0.680	0.563	0.621
13	0.516	0.517	0.516	0.494	0.464	0.479	0.569	0.522	0.545	0.541	0.572	0.556
14	0.577	0.551	0.564	0.594	0.464	0.529	0.656	0.617	0.637	0.579	0.516	0.547
15	0.488	0.536	0.512	0.575	0.609	0.592	0.593	0.536	0.564	0.568	0.473	0.520
16	0.486	0.445	0.465	0.479	0.481	0.480	0.481	0.454	0.467	0.607	0.495	0.551
17	0.472	0.463	0.468	0.662	0.572	0.617	0.540	0.479	0.509	0.608	0.515	0.562
18	0.526	0.561	0.543	0.525	0.550	0.537	0.603	0.602	0.603	0.553	0.564	0.559
19	0.452	0.483	0.467	0.480	0.443	0.461	0.511	0.498	0.504	0.519	0.523	0.521
20	0.520	0.474	0.497	0.594	0.517	0.556	0.530	0.505	0.517	0.519	0.502	0.510
21	0.512	0.529	0.520	0.563	0.502	0.533	0.598	0.598	0.598	0.522	0.520	0.521
22	0.529	0.470	0.500	0.522	0.481	0.501	0.521	0.493	0.507	0.637	0.523	0.580
23	0.533	0.506	0.520	0.549	0.502	0.525	0.498	0.513	0.505	0.530	0.517	0.524
24	0.430	0.421	0.425	0.513	0.455	0.484	0.511	0.482	0.497	0.452	0.419	0.436
25	0.457	0.448	0.453	0.556	0.560	0.558	0.530	0.505	0.518	0.506	0.510	0.508
26	0.452	0.468	0.460	0.555	0.487	0.521	0.575	0.552	0.564	0.510	0.544	0.527
Mean	0.510	0.501	0.506	0.566	0.527	0.547	0.565	0.535	0.550	0.562	0.531	0.547
C.V.(%)	9.9	9.1	8.9	10.0	9.7	9.1	9.9	9.4	9.4	11.0	8.9	9.1

Table 5.6 Modulus of rupture (MOR) of 26 *Eucalyptus* clones, mean modulus of rupture per site and within-site coefficient of variation (CV) for four sites in Brazil (SBA - Southern Bahia; SM1 - São Mateus 1; SM2 - São Mateus 2; ARA - Aracruz).

Clone	Southern Bahia			São Mateus 1			São Mateus 2			Aracruz		
	Base	Top	Mean	Base	Top	Mean	Base	Top	Mean	Base	Top	Mean
1	94.00	80.13	87.07	93.22	87.78	90.50	97.95	95.69	96.82	81.46	100.34	90.90
2	91.05	96.79	93.92	108.35	110.98	109.67	88.83	101.85	95.34	97.94	91.37	94.66
3	76.59	80.81	78.70	93.52	75.85	84.69	80.24	88.92	84.58	78.15	87.55	82.85
4	116.30	103.39	109.85	112.43	116.95	114.69	104.95	121.46	113.21	113.76	108.72	111.24
5	82.91	80.73	81.82	99.93	92.09	96.01	79.04	95.41	87.23	103.56	107.59	105.58
6	85.34	92.77	89.06	95.87	97.88	96.88	99.27	93.77	96.52	95.06	91.50	93.28
7	87.38	77.59	82.49	112.33	106.97	109.65	104.62	105.32	104.97	101.38	102.07	101.73
8	116.06	119.84	117.95	111.71	111.31	111.51	105.52	116.23	110.88	113.07	114.70	113.89
9	98.69	90.93	94.81	102.54	113.16	107.85	116.36	122.22	119.29	112.63	123.54	118.09
10	89.43	87.40	88.42	74.61	89.89	82.25	81.62	91.05	86.34	77.02	85.33	81.18
11	55.69	77.14	66.42	85.49	91.50	88.50	68.92	93.73	81.33	93.03	81.75	87.39
12	97.98	80.72	89.35	122.88	110.66	116.77	99.74	96.25	98.00	102.82	101.57	102.20
13	74.34	73.58	73.96	80.58	77.68	79.13	85.69	82.61	84.15	70.65	97.80	84.23
14	92.14	76.82	84.48	89.13	69.97	79.55	81.17	85.57	83.37	74.77	70.62	72.70
15	85.83	75.21	80.52	88.24	89.84	89.04	75.00	83.54	79.27	76.57	53.21	64.89
16	80.67	73.11	76.89	78.80	83.82	81.31	87.68	92.19	89.94	95.13	95.20	95.17
17	81.62	76.93	79.28	93.54	99.60	96.57	88.47	70.63	79.55	82.73	84.74	83.74
18	96.92	98.75	97.84	85.79	101.12	93.46	104.71	88.33	96.52	91.47	100.23	95.85
19	75.92	84.51	80.22	82.44	79.50	80.97	84.90	91.12	88.01	87.53	108.25	97.89
20	105.36	100.09	102.73	84.10	97.68	90.89	85.22	94.55	89.89	101.10	97.90	99.50
21	96.28	89.04	92.66	87.65	80.36	84.01	80.86	111.04	95.95	85.18	85.77	85.48
22	76.29	77.76	77.03	79.51	92.32	85.92	93.60	84.98	89.29	93.69	90.88	92.29
23	78.26	90.47	84.37	101.81	89.54	95.68	74.38	94.60	84.49	96.91	91.68	94.30
24	61.02	59.08	60.05	80.52	71.81	76.17	73.25	60.31	66.78	67.94	67.86	67.90
25	68.16	50.24	59.20	98.35	96.89	97.62	87.90	82.25	85.08	66.86	88.03	77.45
26	62.71	74.93	68.82	84.65	79.55	82.10	86.87	92.36	89.62	77.24	70.77	74.01
Mean	85.65	83.41	84.53	93.38	92.87	93.13	89.11	93.69	91.40	89.91	92.27	91.09
C.V.(%)	17.79	16.82	16.29	13.46	14.44	12.95	13.39	14.83	12.55	15.46	16.76	14.96

Table 5.7 Modulus of elasticity (MOE) of 26 *Eucalyptus* clones, mean modulus of elasticity per site and within-site coefficient of variation (CV) for four sites in Brazil (SBA - Southern Bahia; SM1 - São Mateus 1; SM2 - São Mateus 2; ARA - Aracruz).

Clone	Southern Bahia			São Mateus 1			São Mateus 2			Aracruz		
	Base	Top	Mean	Base	Top	Mean	Base	Top	Mean	Base	Top	Mean
1	9061	9459	9260	9502	9559	9531	10424	10327	10376	8347	11139	9743
2	10538	10360	10449	10736	11802	11269	9945	11079	10512	10190	10105	10148
3	8131	9067	8599	9335	8437	8886	8774	9510	9142	7948	9082	8515
4	10772	10324	10548	10670	11856	11263	10093	11980	11037	10660	11437	11049
5	9491	10810	10151	10760	11186	10973	9395	11650	10523	10713	11935	11324
6	8447	9936	9192	9559	9465	9512	10234	10516	10375	10151	9934	10043
7	9722	10356	10039	10271	11394	10833	10654	11304	10979	10774	11093	10934
8	12461	12656	12559	11752	12277	12015	11199	12787	11993	11864	12558	12211
9	10354	10672	10513	10372	11655	11014	11479	13705	12592	10233	12770	11502
10	9341	9936	9639	7577	9709	8643	8040	9414	8727	7931	9048	8490
11	6684	8997	7841	9106	9561	9334	7820	10184	9002	9204	8413	8809
12	10359	10160	10260	9938	11431	10685	10900	10756	10828	10633	11159	10896
13	8500	9516	9008	8812	8825	8819	9272	11368	10320	8010	10925	9468
14	9884	9449	9667	8824	8390	8607	8732	9879	9306	7732	8698	8215
15	8078	10362	9220	8259	10353	9306	8931	9944	9438	9557	6854	8206
16	8674	9165	8920	8297	9459	8878	9989	10431	10210	10266	10218	10242
17	9370	9906	9638	9663	11670	10667	9951	10179	10065	10487	10805	10646
18	11667	11819	11743	9080	11144	10112	10624	10690	10657	9879	11467	10673
19	7820	9504	8662	8608	8683	8646	9943	11108	10526	8127	10781	9454
20	10526	11978	11252	11286	11271	11279	9657	11386	10522	11712	11543	11628
21	10310	10889	10600	9785	10199	9992	8863	11992	10428	9729	10738	10234
22	8656	9592	9124	8531	10438	9485	9460	9800	9630	10830	11185	11008
23	9866	10607	10237	10196	9992	10094	9267	11172	10220	10778	10726	10752
24	7533	6935	7234	8784	7668	8226	6960	7804	7382	7106	7714	7410
25	7933	8430	8182	10116	11086	10601	10107	10370	10239	7813	10184	8999
26	6848	9765	8307	9368	9860	9614	9862	11231	10547	8292	10667	9480
Mean	9270	10025	9648	9584	10283	9934	9637	10791	10214	9576	10430	10003
C.V.(%)	15.26	11.42	12.53	10.50	12.27	10.50	10.85	10.79	9.96	14.20	13.53	12.30

Table 5.8 Resilience (kJ.m^{-3}) of 26 *Eucalyptus* clones, mean resilience per site and within-site coefficient of variation (CV) for four sites in Brazil (SBA - Southern Bahia; SM1 - São Mateus 1; SM2 - São Mateus 2; ARA - Aracruz).

Clone	Southern Bahia			São Mateus 1			São Mateus 2			Aracruz		
	Base	Top	Mean	Base	Top	Mean	Base	Top	Mean	Base	Top	Mean
1	9.81	8.80	9.30	15.49	9.35	12.42	8.72	11.49	10.10	10.60	13.15	11.87
2	18.94	21.20	20.07	21.20	14.68	17.94	16.01	14.58	15.30	21.16	20.02	20.59
3	11.87	11.99	11.93	12.02	11.01	11.51	8.56	12.26	10.41	12.31	12.76	12.54
4	21.49	15.56	18.53	13.52	18.15	15.83	17.45	16.81	17.13	19.19	14.46	16.83
5	9.46	9.98	9.72	17.49	11.64	14.56	11.02	10.28	10.65	22.34	22.29	22.32
6	11.87	14.05	12.96	14.21	11.81	13.01	11.15	12.63	11.89	12.97	11.15	12.06
7	9.61	13.15	11.38	28.31	13.44	20.87	19.01	12.75	15.88	21.60	20.22	20.91
8	15.83	17.39	16.61	21.28	19.95	20.61	15.91	20.31	18.11	22.65	13.75	18.20
9	13.52	10.06	11.79	18.42	18.52	18.47	15.44	16.63	16.04	25.88	26.40	26.14
10	12.92	9.70	11.31	10.94	14.91	12.92	12.07	10.43	11.25	9.04	13.01	11.02
11	8.20	10.74	9.47	13.41	13.41	13.41	11.55	10.91	11.23	21.95	21.61	21.78
12	14.28	12.64	13.46	16.04	20.44	18.24	14.72	12.07	13.39	11.23	12.45	11.84
13	9.46	7.68	8.57	9.47	6.62	8.04	14.52	11.48	13.00	9.51	14.10	11.81
14	14.54	12.55	13.54	10.23	5.96	8.10	10.99	10.44	10.72	8.41	8.17	8.29
15	10.67	7.42	9.04	10.84	12.24	11.54	9.63	14.02	11.83	7.37	5.28	6.33
16	15.01	11.00	13.01	10.05	10.35	10.20	8.52	9.15	8.84	13.48	14.40	13.94
17	9.01	7.84	8.43	21.47	23.67	22.57	13.10	8.31	10.70	14.11	9.95	12.03
18	15.51	15.54	15.53	11.15	11.29	11.22	23.37	22.09	22.73	12.69	16.34	14.51
19	9.44	9.83	9.64	10.41	7.89	9.15	13.47	10.79	12.13	16.54	17.61	17.08
20	12.80	11.75	12.28	11.65	11.71	11.68	11.87	10.30	11.09	14.76	11.51	13.14
21	18.96	15.83	17.40	14.46	8.77	11.61	8.92	22.30	15.61	12.73	11.25	11.99
22	12.43	8.06	10.25	12.00	9.40	10.70	15.98	8.60	12.29	13.04	9.78	11.41
23	10.64	7.24	8.94	13.17	9.84	11.51	8.65	8.54	8.59	18.63	12.52	15.58
24	14.08	11.95	13.02	11.63	8.41	10.02	18.10	13.64	15.87	15.38	13.74	14.56
25	11.87	5.29	8.58	20.60	15.64	18.12	18.43	9.20	13.81	9.38	9.32	9.35
26	8.96	7.68	8.32	8.96	10.82	9.89	13.45	8.87	11.16	10.05	8.32	9.19
Mean	12.74	11.34	12.04	14.55	12.69	13.62	13.49	12.65	13.07	14.89	13.98	14.43
C.V.(%)	26.96	32.43	27.52	32.98	35.30	30.42	28.58	31.70	24.74	35.02	35.11	33.43

Table 5.9 Compression strength parallel to the grain of 26 *Eucalyptus* clones, mean compression strength parallel to the grain per site and within-site coefficient of variation (CV) over four sites in Brazil (SBA - Southern Bahia; SM1 - São Mateus 1; SM2 - São Mateus 2; ARA - Aracruz).

Clone	Southern Bahia			São Mateus 1			São Mateus 2			Aracruz		
	Base	Top	Mean	Base	Top	Mean	Base	Top	Mean	Base	Top	Mean
1	51.38	48.39	49.88	53.92	52.25	53.08	58.07	54.50	56.28	53.91	55.62	54.76
2	54.14	56.17	55.15	62.71	66.20	64.45	58.72	65.27	62.00	54.20	56.54	55.37
3	47.78	51.73	49.75	54.96	55.45	55.20	47.14	53.11	50.12	54.63	55.11	54.87
4	62.79	62.73	62.76	64.01	62.71	63.36	64.93	64.86	64.90	56.64	63.12	59.88
5	52.03	53.54	52.78	60.19	59.99	60.09	56.67	56.77	56.72	56.13	60.82	58.47
6	47.17	53.98	50.58	54.20	56.36	55.28	53.69	56.87	55.28	55.08	49.03	52.05
7	51.39	53.17	52.28	63.83	58.15	60.99	64.12	59.16	61.64	53.95	56.59	55.27
8	61.07	62.24	61.65	65.75	59.11	62.43	59.30	65.61	62.46	66.11	62.74	64.43
9	58.59	55.92	57.25	57.48	62.12	59.80	64.34	66.34	65.34	62.82	64.03	63.42
10	50.21	49.11	49.66	48.95	56.37	52.66	48.13	52.24	50.18	42.18	51.96	47.07
11	42.55	51.50	47.03	52.80	54.75	53.77	48.75	54.37	51.56	51.03	48.22	49.63
12	60.65	53.13	56.89	65.64	58.48	62.06	56.16	54.95	55.55	67.12	58.40	62.76
13	49.34	47.04	48.19	43.90	43.78	43.84	48.70	49.82	49.26	48.24	59.12	53.68
14	50.21	48.24	49.22	52.23	43.98	48.10	54.30	56.40	55.35	45.64	46.00	45.82
15	46.25	55.89	51.07	49.62	61.71	55.67	54.92	57.97	56.44	51.46	40.15	45.81
16	48.05	45.48	46.77	45.68	51.48	48.58	47.87	51.59	49.73	53.85	53.69	53.77
17	49.22	50.46	49.84	59.73	62.13	60.93	51.56	52.58	52.07	56.49	50.56	53.53
18	58.49	63.45	60.97	47.54	62.54	55.04	65.08	66.11	65.60	55.42	62.54	58.98
19	48.97	53.24	51.11	50.67	50.78	50.73	54.71	57.93	56.32	51.57	60.12	55.84
20	60.72	54.52	57.62	57.30	58.38	57.84	54.21	58.60	56.40	57.27	54.96	56.11
21	56.03	60.01	58.02	56.53	56.26	56.39	55.32	63.11	59.21	53.60	55.80	54.70
22	52.50	46.63	49.57	46.48	54.59	50.53	50.24	51.87	51.05	57.41	54.71	56.06
23	51.43	54.61	53.02	52.46	53.73	53.10	46.98	52.90	49.94	55.30	54.38	54.84
24	40.30	35.55	37.93	46.62	40.68	43.65	41.13	41.89	41.51	37.92	39.64	38.78
25	44.94	44.08	44.51	60.50	62.00	61.25	50.88	48.82	49.85	44.92	51.04	47.98
26	42.17	47.99	45.08	53.49	49.44	51.47	57.14	54.54	55.84	50.85	51.07	50.96
Mean	51.48	52.26	51.87	54.89	55.90	55.40	54.35	56.47	55.41	53.60	54.46	54.03
C.V.(%)	11.93	11.91	11.15	11.84	11.43	10.45	11.40	10.71	10.64	12.11	11.80	10.82

for *E. tereticornis* and *E. camaldulensis* the difference in this property at different heights was not significant (Shukla *et al.*,1989). Also for conifer wood (Norway spruce) there was no significant difference in modulus of rupture when comparing the respective values for the lower and upper butt logs (Kliger *et al.*, 1998).

5.2.3 Modulus of Elasticity: Longitudinal Variation

In contrast to modulus of rupture which has not exhibited a common trend of increase or reduction with axial position in the stem, modulus of elasticity was higher at the top than in the base of the log. This can be noted for the three radial positions, i.e., modulus of elasticity was higher in the upper than in the lower position in the centre (8.9 %), intermediate (8.5%) and external position (9.3 %). The axial variation of the modulus of elasticity can be observed in Table 5.1, Table 5.7 and Figure 5.1. More interesting however is the difference of axial behaviour between modulus of elasticity and nominal density, because the latter reduced from the lower to the upper bolt. It is possible that the consequent reduction in the modulus of elasticity that should be expected due its high positive correlation with density was countered by the gain induced by other factors, anatomical or chemical. It is possible that the same factors that induced reduction in one property (modulus of rupture) cause gain in the other (modulus of elasticity). There is also another alternative: despite wood from the bottom be denser, it is more defective than wood from the top bolt. In this case, the relative reduction in density from base to top is offset by other factors making it stiffer. The relationship between anatomical characteristics and modulus of elasticity will be considered in Chapter 9.

According to Table 5.2 there is a significant difference in the modulus of elasticity between the axial position in the log of *Eucalyptus* for the four sites together. However, analyses performed for each site separately (Table 5.4) have not revealed differences for modulus of elasticity between axial positions, in any of the sites studied. Modulus of elasticity was the only mechanical property to show significant differences at different heights in a study carried out by Shukla *et al.* (1989) in *E.*

tereticornis and *E. camaldulensis*. In contrast, in *E. grandis* these authors have not found any significant difference for this property at various heights in the stem.

5.2.4 Resilience: Longitudinal Variation

Contrary to the performance shown by modulus of elasticity, which exhibited higher values in the upper position than in the base of the log, resilience was higher in the basal bolt. For each radial position, resilience was higher in the base than in the top bolt. The mean axial variation of the resilience can be observed in Table 5.1 and Figure 5.1, while Table 5.8 shows the behaviour at the different sites. The rates of increase of resilience are different in the four sites studied, varying from 6.5 % (Aracruz) to 14.7 % (São Mateus 1). The same axial behaviour displayed by resilience (increase from the base upwards) can also be seen for nominal density, but at smaller rates. It seems that the factors which act on modulus of elasticity, increasing its value, act in a different manner longitudinally for resilience.

Table 5.2 shows that there are significant differences in the resilience between the axial positions in the log of *Eucalyptus* for the data of all the four sites together. However, analyses of variance performed for each site separately (Table 5.4) have not revealed significant differences for resilience between axial positions for any of the four sites.

5.2.5 Compression strength parallel to the grain: Longitudinal Variation

According to Table 5.1 the mean compression strength parallel to the grain was higher in the upper than in the basal bolt of the log. However, the difference between bolts was extremely small. Compression strength parallel to the grain was higher in the upper than in the basal position for each radial position. Modulus of rupture also displayed a very similar behaviour.

The axial variation of the compression strength parallel to the grain on each site can be observed in Table 5.9. The maximum difference between top and basal position (observed on the mean) occurred at São Mateus 2 (3.9 %). However, several clones planted on a particular site have shown higher resistance to compression in the basal portion than in the top position. According to Table 5.2 there is no significant difference in the compression strength parallel to the grain between the axial positions in the log of *Eucalyptus* for the data of the four sites. Also, analyses performed for each site separately (Table 5.4) do not reveal differences for compression strength parallel to the grain between axial positions, for any of the studied sites. Similarly, for *E. tereticornis* and *E. camaldulensis* the difference in compression strength at various heights was not significant (Shukla *et al.*, 1989).

Of more interest however is the different behaviour of the compression strength parallel to the grain and the nominal density, since the latter reduced upwards. The same explanation used in the discussion of the modulus of rupture can be used here: it is possible that the expected reduction in compression strength associated with reducing density was countered by the influence of other factors, anatomical or chemical. The relationship between anatomical characteristics and compression strength parallel to the grain will be a matter of discussion in Chapter 9.

5.2.6 Janka Hardness: Longitudinal Variation

Table 5.1 shows that for the same radial position, Janka hardness is less in the upper than in the lower position of the 3.0 m long log. This is valid for the central, intermediate and external positions: the inner wood was 9.4 % harder in the base than in the top, the intermediate wood was 12.5 % harder in the base, and the outer wood 12.6 % harder in the base. This behaviour is the opposite to that displayed by compression strength parallel to the grain and the modulus of rupture, where the stronger wood was found in the top. However it was similar to that presented by nominal density. It is important to consider that Janka hardness is said to be positively correlated to crushing strength (Kollmann and Côté, 1968).

Table 5.2 shows that there are differences between the values for the different axial positions ($p \leq 0.01$) when all four sites are analysed together.

Analyses made for each site separately (Table 5.4) showed that there are significant differences between longitudinal position for São Mateus 1 ($p \leq 0.01$), São Mateus 2 ($p \leq 0.05$) and Aracruz ($p \leq 0.05$). However, at Southern Bahia, there was no significant difference for Janka hardness between the base and the top of the log. It is interesting to note that for all the mechanical properties that have been discussed, none of them presented significant difference between axial position, when analysed per site. However, the performance observed for Janka hardness matches very well with that displayed to nominal density, both in terms of site and level of probability. It is important to mention that "no-difference" equates to more homogeneous timber - a good quality characteristic for commercial purposes.

5.3 Variation of the Properties between Clones and Sites

5.3.1 Nominal Density: Variation between Clones and Sites

The overall mean nominal density, for all clones and sites has been found in this work to be 0.519 $g.cm^{-3}$. The nominal density was higher at São Mateus 2 (0.550 $g.cm^{-3}$) and smaller at Southern Bahia (0.506 $g.cm^{-3}$). The coefficient of variation of nominal density varies from 8.9 % (Southern Bahia) to 9.4 % (São Mateus 2). This small range indicates that the variation is similar in the four sites studied. According to the analysis of variance (Table 5.11) there were significant differences in the nominal density between clones, and between sites ($p \leq 0.01$), both for wood from the basal and upper bolts. The significant differences between sites and clones were also observed for wood from inner, intermediate and outer regions of the bolts.

In spite of the fact that density is a good index of wood quality (due its high correlation with other properties), this *per se* it does not represent a good parameter for utilisation, since it does not indicate directly values of mechanical properties, fibre dimensions, calorific value, chemical composition, or the existence of defects, for example. Thus, the selection of trees to produce timber based only

Table 5.11 Summary of balanced analysis of variance of nominal density and mechanical properties of *Eucalyptus* between clones and between sites in each radial position at the basal and top bolts. [g.l. (clone) = 25, g.l. (site = 3), g.l. (error) = 75, g.l. (total) = 103]. [(ns- no significant at P = 0.05; * P≤ 0.05; ** P≤ 0.01; *** P≤ 0.001). Results of anova in Appendices 3.1-3.6.

Property	Bolt	Inner		Intermediate		Outer		Average	
		Clone	Site	Clone	Site	Clone	Site	Clone	Site
Nominal density	Base	***	***	***	***	***	***	***	***
	Top	***	***	***	**	***	**	***	***
Modulus of rupture	Base	***	ns	***	ns	***	ns	***	*
	Top	***	***	***	**	***	**	***	***
Modulus of elasticity	Base	**	ns	***	ns	***	ns	***	ns
	Top	***	ns	***	*	***	**	***	**
Resilience	Base	**	*	*	ns	**	ns	**	ns
	Top	***	*	***	ns	*	ns	**	ns
Compression strength	Base	***	ns	***	*	***	*	***	*
	Top	***	***	***	*	***	***	***	***
Janka hardness	Base	***	ns	***	**	***	***	***	***
	Top	***	***	***	**	***	*	***	**

on density is a risky procedure, especially if the end-use is not a direct result of mass (as is the case of charcoal or pulp). Furthermore, the radial variation of density suggests that special attention must be taken for the commercial application of this wood, since different material is formed in different parts of the log.

5.3.2 Modulus of Rupture: Variation between Clones and Sites

The overall mean modulus of rupture for all clones and sites found in this work was 90.0 MPa. The mean modulus of rupture varies from 84.53 MPa at Southern of Bahia to 93.13 at São Mateus 1 (Table 5.6). The coefficient of variation, varied between 12.6 % at São Mateus 1 and 16.0 % at Southern Bahia. According to Bendtsen and Ethington (1975) the inter-specific coefficient of variation (based on 23 North American hardwoods) determined for modulus of rupture was 16 %. The stronger and weaker clones (in terms of modulus of rupture) are also shown in Table 5.6. The differences between these values can be as high as 99 % when clones 8 and 25 (Southern Bahia) are considered or as small as 53 % between clones 12 and 24 at São Mateus 1.

Table 5.11 shows that there are significant differences ($p \leq 0.01$) between clones and between sites for modulus of rupture both for wood from the basal and upper bolts. The significant differences between clones were observed for wood from the inner, intermediate and outer regions of the bolts. However, only wood of the upper bolt showed significant differences between sites for modulus of rupture in the inner, intermediate and outer wood. Also in *Pinus taeda* wood site showed a significant effect on modulus of rupture (and also on modulus of elasticity) of both juvenile and mature wood (McAlister and Clark, 1991).

5.3.3 Modulus of Elasticity: Variation between Clones and Sites

The overall mean of modulus of elasticity for all clones and sites found in this work was 9950 MPa. The mean modulus of elasticity between clones varies from 9648 MPa at Southern of Bahia to 10214 MPa at São Mateus 2 (Table 5.7). The coefficient of variation ranged from 10 % at São Mateus 2 and 12.5 % at Southern

Bahia. This is smaller than the inter-specific of variation (CV = 22 %) (based on 23 North American hardwoods) determined for modulus of elasticity by Bendtsen and Ethington (1975). The stronger and weaker clones, in terms of modulus of elasticity, are also shown in Table 5.7. The differences between these values can be as high as 74 % when clones 8 and 24 (Southern Bahia) are considered or as small as 46 % between the same clones at the São Mateus 1. Clone 8 was the stiffer at all sites, except at São Mateus 2 (clone 9). In contrast, clone 24 was the most flexible at all sites studied. Table 5.11 shows that there are significant differences in elastic behaviour between clones ($p \leq 0.01$) for wood from the basal and upper bolts. However, except for inner wood, significant differences between sites only were observed for wood from the upper position. In *Pinus taeda* wood, site showed a significant effect on modulus of elasticity for both juvenile and mature wood (McAlister and Clark, 1991).

Differences in elasticity have important practical implications. If an equal load is applied to two beams with equal dimensions and unequal elasticity is found, the beam with a greater elasticity (clone 24 for example) will be able to bend more without a permanent deformation, than clone 8 for example. Applied to lumber drying, the board with the higher strength will be able to resist higher drying stresses without checking. Similar considerations might predict the relation between modulus of elasticity and the effects caused by growth stresses. Among others, Boyd (1980) and Chafe (1990) discuss the relationship between growth stress and modulus of elasticity in *Eucalyptus* wood. Boyd (1980) showed that of 11 *Eucalyptus* trees representing normal growth, only four showed a statistically significant direct relationship between growth strain and modulus of elasticity. However, of six stems that had been re-oriented, five exhibited strong direct relationships. Also Chafe (1990), studying the relationships among growth strain, density and strength properties in nominally straight *E. regnans* and *E. nitens*, concluded that in no instance was growth strain significantly correlated with modulus of elasticity. Conversely, when modulus of elasticity was plotted against growth stress he observed (*E. regnans*) that modulus of elasticity increased in accordance with a quadratic equation fitted for all data, tending to constancy at high stress levels of modulus of elasticity or declining. This effect was accentuated if modulus of elasticity was corrected for density (MOE/σ). He indicated that such observations were consistent with the presence of tension wood since strength for this tissue have been reported to be lower than that for normal wood, especially when corrected for density, which tends to be higher than normal (Lassen, 1959).

For Brazilian *Eucalyptus* high levels of growth stresses are undoubtedly the most serious growth phenomenon affecting wood quality, product yield and product dimensions. A reduction in stress levels in tree stems would certainly be by far the most important improvement that can be made regarding many *Eucalyptus* species, as the impact on the wood processing industry would be impressive (Malan, 1995).

5.3.4 Resilience: Variation between Clones and Sites

The overall mean resilience for all clones and sites has been found in this work to be 13.39 $kJ.m^{-3}$. The mean resilience varies between clones from 12.04 $kJ.m^{-3}$ at Southern Bahia to 14.44 $kJ.m^{-3}$ at Aracruz (Table 5.8). The coefficient of variation varied between 24.7 % at São Mateus 2 and 33.4 % at Aracruz. It is interesting to appreciate that this property presented a distinctly higher inter-clonal coefficient of variation than did other properties discussed up to here. The largest and smallest value of the resilience for the clones are also shown in Table 5.8. Particularly interesting is the ratio between these values (maximum/minimum) since it can be can be as high as 4.1 at Aracruz (clone 9/clone 15) or relatively low as 2.4 times (clone 2/clone 26) at Southern Bahia. It is suspected that a particular factor (or factors) affects this property in a special way, increasing or reducing its value. To have an experimental indication of this role, it is necessary to establish some level of correlation between resilience and other basic properties of wood. Table 5.11 shows that for resilience there are significant differences between clones for all radial positions but not between sites. Only for the inner wood were significant differences ($P \leq 0.05$) observed between sites.

Table 5.8 shows that clones 2 and 4 at Southern Bahia, clones 2 and 17 at São Mateus 1, clone 18 and 8 at São Mateus 2, and clones 9 and 2 at Aracruz, may represent some cases of clones and sites where the amount of recoverable energy is high. Put in a slightly different way, a timber from clone 2, for example, which presents high resilience, demands a higher amount of energy to be permanently deformed (or broken), even though the maximum load supported might be equal to that of another, less resilient clone. Matttheck and Kubler (1995) present an interesting discussion of the elastic performance of living trees under the action of wind forces. This is of importance to trees for selection in genetic programs. They remark that spiral grain may perform a special role in optimising this elastic property in trees.

5.3.5 Compression strength parallel to the grain: Variation between Clones and Sites

The overall mean compression strength parallel to the grain, for all clones and sites found in this work was 54.2 MPa. The mean compression strength parallel to the grain observed varies between sites from 51.8 MPa at Southern of Bahia to 55.4 at São Mateus 2 (Table 5.9). The coefficient of variation varied between 10.6 % at São Mateus 1 and 11.8 % at Aracruz. These rates are smaller that the inter-specific variation (CV = 18 %) (based on 23 North American hardwoods) determined for compression strength parallel to the grain by Bendtsen and Ethington (1975). The stronger and weaker clones in terms of compression strength parallel to the grain are also shown in Table 5.9. The differences between these values can be as high as 66 %, when clones 4 and 24 (Southern Bahia) are considered, or as small as 48 % between clones 2 and 24 at São Mateus 1. Clone 24 was the weaker on all four sites. According to the analysis of variance (Table 5.11) there were significant differences in the compression strength parallel to the grain between clones, and between sites, both for wood from the basal and upper bolts. In general, the significant differences between sites and clones were also observed for wood from inner, intermediate and outer regions of the bolts.

5.3.6 Janka Hardness: Variation between Clones and Sites

The overall mean Janka hardness, for all clones and sites, found in this work was 4522 N. The mean Janka hardness varied between sites from 4094 N at Southern of Bahia to 4610 N at Aracruz (Appendix 1.15). The coefficient of variation varied from 15.3 % at Southern Bahia to 18.7 % at São Mateus 1. These variations are higher than that presented by either nominal density or compression strength parallel to the grain, but alike to that presented by the modulus of rupture. This was similar to the inter-specific variation (CV = 20 %) (based on 23 North American hardwoods) determined for hardness by Bendtsen and Ethington (1975). Through Appendix 1.15 it can be noted that São Mateus 2 produced the hardest wood, while Southern Bahia produced the softest. It can also be noted that clone 9 at Southern Bahia, São Mateus 2 and Aracruz produced the hardest wood, but that on the same sites clone 24 produced the softest. At São Mateus 1, clone 17 and 25 were the hardest and softest, respectively. The ratio between the hardest and softest wood displayed in Appendix 1.15 changes from 1.90 times at São Mateus 2 to 2.30 at Aracruz. According to the analysis of variance (Table 5.11) there were significant differences in the Janka hardness between clones and between sites, both for wood from the basal and upper bolts. In general, the significant differences between sites and clones were also observed for wood from inner, intermediate and outer regions of the bolts.

5.4 Site-Clone Interaction (Stability)

The performance of a clone or a group of clones cannot be extrapolated to other environments if there is a change in the performance ranking of a set of clones when grown in other environments. An examination of Table 5.12 and Table 5.13 shows the coefficients of linear regression of clone means against site means and the classification (Malan and Verryn, 1996) of the stability for each clone. The different slopes of the linear regressions suggest that the clone × site interactions for all the properties are complex. Table 5.14 shows the associated coefficients of determination (R^2) of the regression of the clone means, using the site means as the independent variable. Figures 5.2 and 5.3 provide examples of the regression lines between sites for modulus of elasticity and for compression strength parallel to the grain. Figures 5.4 and 5.5 illustrate the interaction between clones in the four sites, using modulus of elasticity and compression strength parallel to the grain as examples.

Table 5.12 Classification of the clone stability based on the coefficient of regression of the clone means, using the site means as independent variable [average stability (regression coefficients between 0.8 and 1.2), below average stability (regression coefficients greater than 1.2) or above average stability (regression coefficients less than 0.8)]. (*- regression coefficient significantly different from 1.0 at 0.05 level; **- regression coefficient significantly different from 1.0 at 0.01 level).

Clone	Nominal Density		Modulus of Rupture		Modulus of Elasticity	
	Class.	β	Class.	β	Class.	β
1	above	0.751**	above	0.652	below	1.930
2	below	1.336	average	1.200	above	- 0.070
3	average	0.952	above	0.722	average	0.820
4	above	0.383	above	0.491	average	0.882
5	below	1.508	below	1.780	average	0.902
6	average	1.086	average	0.906	below	2.152
7	below	1.601*	below	3.150**	below	1.729**
8	above	0.699	above	-0.79**	above	- 0.97*
9	below	1.730	below	2.290	below	3.624*
10	above	0.217*	above	-0.690*	above	-1.747
11	below	1.509	below	2.590*	below	2.042
12	below	1.290	below	2.57	average	1.081
13	above	0.294	average	0.950	below	2.282
14	above	0.315	above	-0.681	above	-0.952
15	average	1.118	above	0.190	above	0.014
16	above	0.741	average	1.180	below	2.512
17	below	2.123	below	1.370	average	0.917
18	above	0.636	above	-0.41**	above	-1.941
19	above	0.691	above	0.740	below	3.263
20	above	0.703	below	-1.340*	above	-1.057
21	average	0.834*	above	-0.697	above	- 0.338
22	above	0.645	below	1.410	below	1.393
23	above	0.077	average	1.070	above	0.154
24	average	1.180	below	1.570	above	0.200
25	below	1.755	below	4.050*	below	3.348
26	below	1.893	below	1.750	below	3.865

Table 5.13 Classification of the clone stability based on the coefficient of regression of the clone means, using the site means as independent variable [average stability (regression coefficients between 0.8 and 1.2), below average stability (regression coefficients greater than 1.2) or above average stability (regression coefficients less than 0.8)]. (*- regression coefficient significantly different from 1.0 at 0.05 level; **- regression coefficient significantly different from 1.0 at 0.01 level).

Clone	Resilience		Compression Strength		Janka Hardness	
	Class.	β	Class.	β	Class.	β
1	below	1.251	below	1.308	average	1.040
2	above	0.315	below	2.318	below	1.773
3	above	0.296	above	0.756	below	1.603
4	above	- 0.834*	above	0.439	below	1.781
5	below	5.213	below	1.529	below	1.348
6	above	- 0.255*	below	1.329	above	0.375
7	below	4.302*	below	2.553*	below	1.991
8	average	0.926	above	0.186	below	1.542
9	below	5.833**	below	1.439	below	2.212
10	above	0.071	average	0.953	above	0.779
11	below	4.945	below	1.580	below	1.385
12	above	-0.085	above	0.457	below	1.876
13	average	0.838	above	-0.553	above	-0.560*
14	above	-2.369**	above	0.777	above	-0.395
15	above	-0.957	below	1.515	average	0.847
16	above	0.354	above	0.579	above	0.767
17	below	2.737	below	1.854	below	3.224
18	above	-1.384	above	-0.150	below	1.253
19	below	2.571	above	0.625	above	-0.235*
20	above	0.347	above	- 0.121*	above	-0.220
21	above	- 2.54*	above	- 0.011	above	- 0.316
22	above	0.338	above	0.252	above	0.101
23	below	2.810	above	- 0.461	above	0.448
24	above	0.044	below	1.323	below	1.574
25	below	1.933	below	3.116	average	0.797
26	above	0.288	below	2.380	average	1.028

Table 5.14 Coefficients of determination (R^2; %) of the regression of the clone means, using the site means as independent variable (*- regression coefficient significantly different from 1.0 at 0.05 level; **- regression coefficient significantly different from 1.0 at 0.01 level).

Clone	ND	MOR	MOE	R	CP	JH
1	99.0**	37.0	90.0*	73.6	65.4	72.4
2	52.7	36.2	0.1	1.7	69.8	51.0
3	69.4	94.7*	45.0	11.0	18.9	42.4
4	42.2	75.4	46.5	56.6	12.6	88.9*
5	94.7*	41.7	16.9	83.5	68.2	39.4
6	78.4	89.8*	90.3*	19.2	90.9*	28.0
7	96.6*	99.4**	83.5	89.1*	91.5*	93.4*
8	48.8	86.7	75.4	31.5	7.1	94.5*
9	94.0*	58.1	91.0*	94.6*	45.4	82.5
10	27.0	58.0	62.0	0.7	43.2	89.1*
11	44.8	92.3*	55.4	83.2	88.6*	56.1
12	57.7	71.9	78.4	0.1	4.6	65.1
13	3.0	53.7	63.6	12.1	5.4	32.1
14	2.0	23.0	11.4	87.1	10.5	3.1
15	39.5	0.5	0.0	14.1	27.5	13.5
16	14.2	29.1	58.7	2.2	11.0	8.5
17	47.6	41.1	18.6	19.2	42.9	55.9
18	20.3	70.3	44.2	8.2	0.3	31.0
19	24.9	12.2	74.0	50.7	12.6	18.7
20	34.2	63.9	28.3	15.8	5.7	5.2
21	22.7	21.1	9.1	82.2	0.0	11.5
22	11.8	64.7	15.6	14.5	2.2	0.2
23	3.2	43.1	1.5	76.8	14.8	36.1
24	49.9	80.6	1.1	0.0	73.8	57.2
25	59.7	90.4*	49.1	4.6	53.2	20.7
26	85.7	52.3	96.8*	5.8	83.4	53.8

ND- nominal density, MOR- modulus of rupture, MOE- modulus of elasticity, R- resilience, CP- compression strength parallel to the grain, JH- Janka hardness.

For nominal density, regression coefficients varied from 0.077 to 2.123 (Table 5.12), and coefficients of determination from 2 % to 99 % (Table 5.14). In this case five clones showed average stability, nine clones below average stability and twelve clones above average stability. Despite the wide range of regression coefficients, only those for clones 1, 7, 10 and 23 were significantly different from 1. Only four coefficients of determination were significant (Table 5.14). It appears that it is only possible to predict the nominal density of wood produced at one site from its value at another site in four clones.

If the slope of the regression of the clone averages per site against average nominal density per site is close to 1 it signifies that this clone behaves similarly to the "mean clone". If the coefficient of regression is higher than 1 the clone has below average stability. It is supposed that the clone is sensitive to environmental changes. Conversely, clones with a coefficient of regression smaller than 1 have above average stability and are not responsive to changes in the environmental. Based on this classification is possible to select genetic material depending on site conditions and technological requirements.

For modulus of rupture in static bending five clones have average stability, ten clones have above average stability and eleven clones have below average stability (Table 5.12). In seven clones the slopes of the regression lines were statistically different from 1 (Table 5.12), but only in five clones was the coefficient of determination significant (Table 5.14). It appears that it is only possible to predict the modulus of rupture of wood produced at one site from its value at another site in five clones.

For modulus of elasticity in static bending it can be said that six clones showed average stability, eleven clones below average stability and nine clones above average stability (Table 5.12). Examples of the slope lines are given in Figure 5.2 for six clones.

Three clones had regression coefficients which were significantly different from 1 (Table 5.12), and four coefficients of determination were significant (Table 5.14).

In Table 5.13 it can be noted that for resilience only clones 8 and 13 showed average stability, nine clones had below average stability and fifteen clones had above average stability. Six clones had regression coefficients which were significantly different from 1 and only two coefficient of determination was significant (Table 5.14). For compression strength parallel to the grain, Table 5.13 shows that only clone 1 showed average stability, twelve clones had below average stability and thirteen clones had above average stability. Examples are given for six clones in Figure 5.4. Despite the wide range of regression coefficients (Table 5.13), only those for clones 7 and 20 were significantly different from 1, and only three coefficients of determination were significant (Table 5.14).

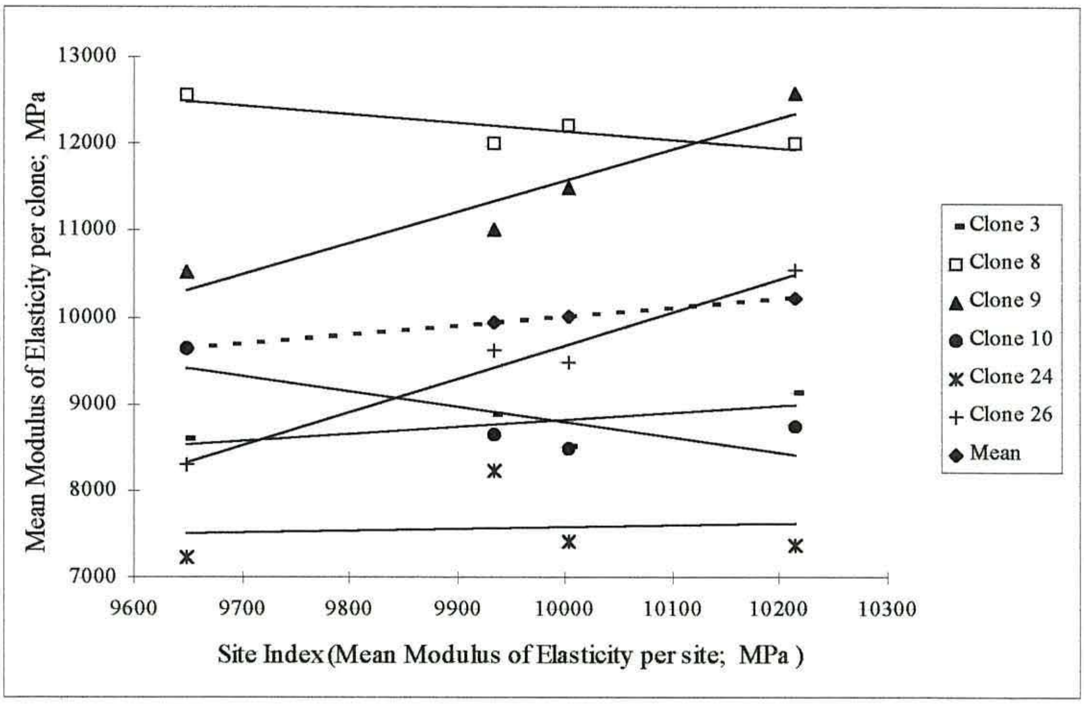


Figure 5.2 Regression lines showing the relationship between individual clone modulus of elasticity and the population mean of 26 clones (Site Index).

Table 5.13 shows that for Janka hardness three clones showed average stability, twelve clones had below average stability and eleven clones had above average stability. Despite the wide range of regression coefficients given in Table 5.13, only clones 13 and 19 were significantly different from 1 and only four coefficients of determination were significant (Table 5.14).

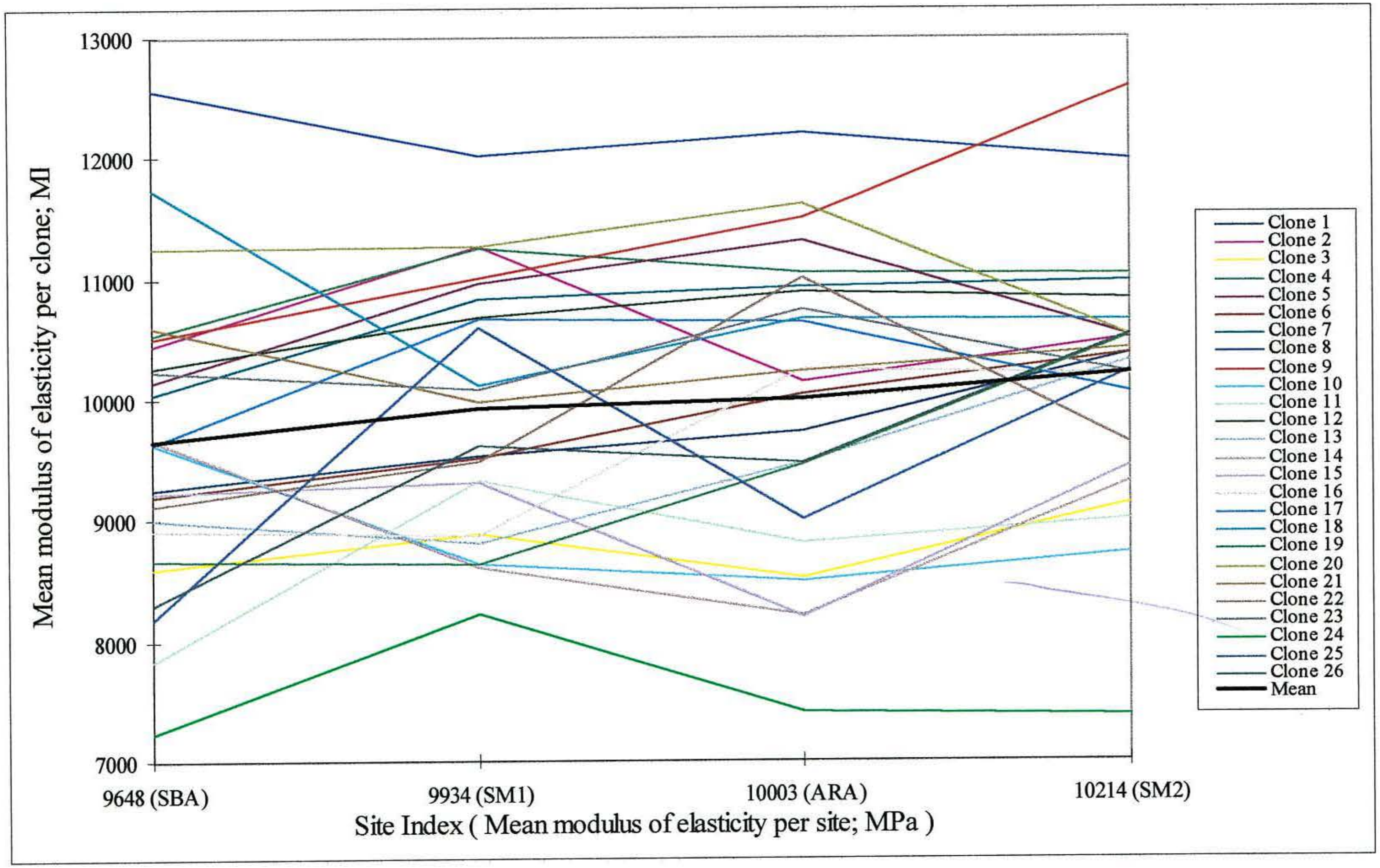


Figure 5.3 Modulus of elasticity of 26 clones at four sites. (SBA- Southern Bahia; ARA- Aracruz; SM1- São Mateus 1; SM2- São Mateus 2).

The comparison between clones (Table 5.12 and Table 5.13) reveals that only clones 7, 9, 11 and 14 can be classified in the same way for all properties, and only clone 7 had a linear regression coefficient significantly different (below) from 1 for all seven properties. The comparison between properties indicates that the range of coefficients of regression (β) is smaller for nominal density and for basic density (Chapter 4) than for the mechanical properties. Many of the regression lines for mechanical properties are steeper than found for density, and this suggests that the environment has more influence for mechanical properties than for density.

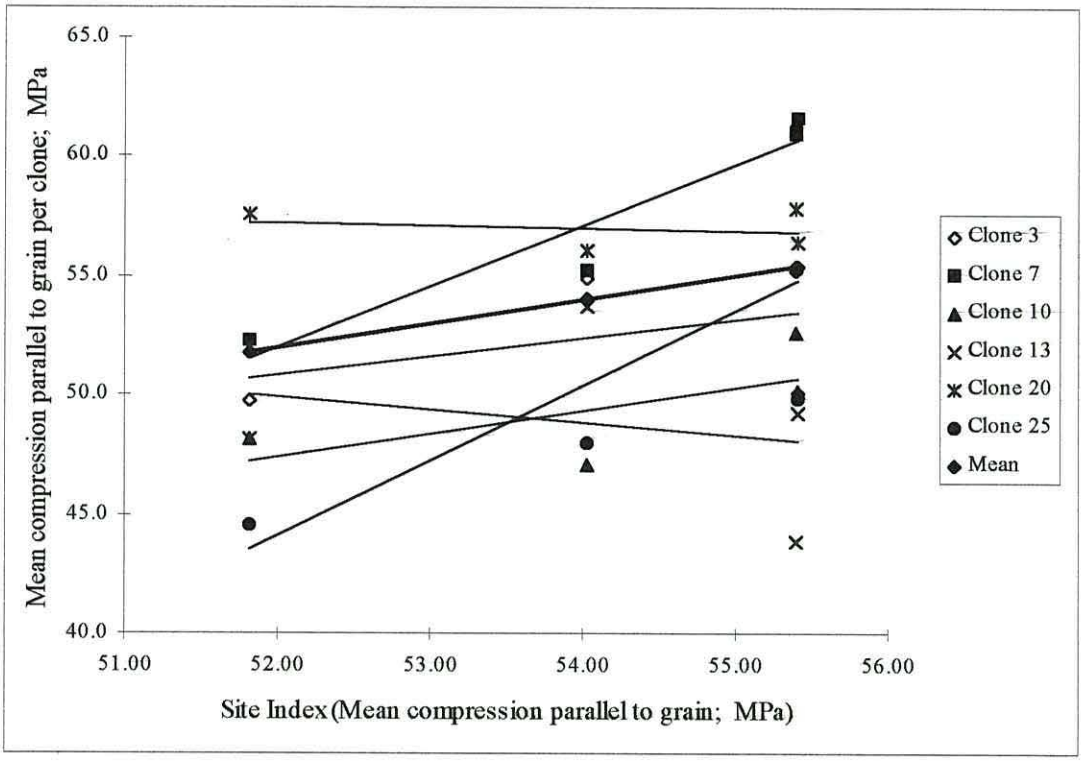


Figure 5.4 Regression lines showing the relationship between individual clone compression parallel to the grain and the population mean of 26 clones (Site Index).

5.5 Estimates of Heritability

In spite of the clone × site interaction, estimates of broad sense heritability based on the analysis of variance summarised in Table 5.4 for nominal density and

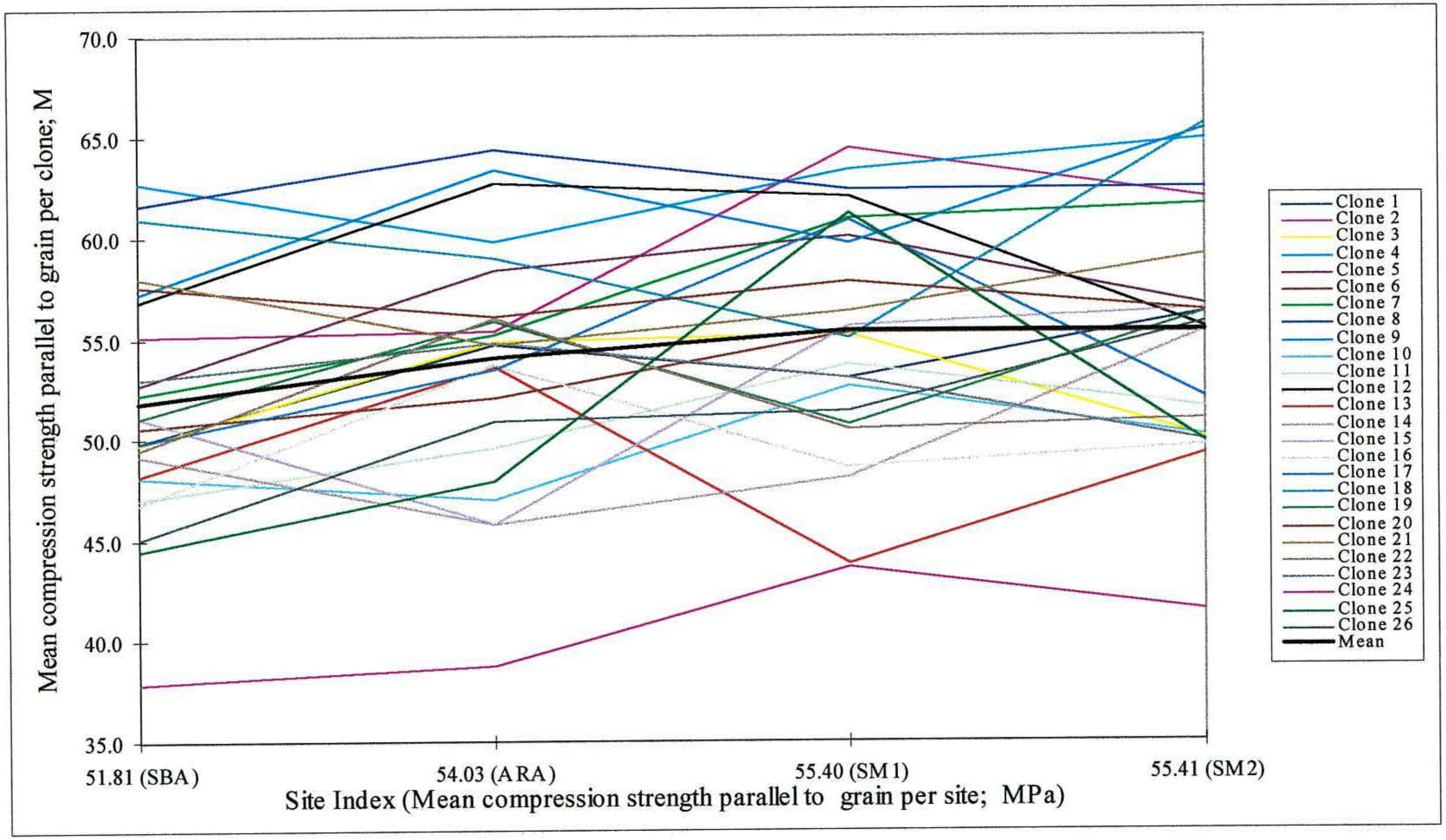


Figure 5.5 Compression strength parallel to the grain of 26 clones at four sites. (SBA- Southern Bahia; ARA- Aracruz; SM1- São Mateus 1; SM2- São Mateus 2).

mechanical properties were generally high, with h^2 varying from 0.254 (resilience) to 0.618 (nominal density) (Table 5.15). This suggests that nominal density and mechanical properties are under strong genetic control. Unfortunately there are very few of similar studies in the literature which permit comparison with these findings. Nonetheless, Fujisawa *et al.* (1992) studying dynamic moduli of elasticity in *Cryptomeria japonica* clones found that the broad sense heritability ranged from 0.58 to 0.86. These values are similar to that found for basic density (h^2 = 0.64, Chapter 4). Only resilience showed moderately weak heritability, which suggests that contrary to the other properties it is not under strong genetic control.

Table 5.15 Estimation of broad sense heritability calculated for inner, intermediate and outer positions, and for average between radial positions for nominal density and mechanical properties for 26 *Eucalyptus* clones planted in four sites.

Property	Bolt	Inner	Inter	Outer	Average
Nominal density	Base	0.526	0.561	0.608	0.630
	Top	0.651	0.493	0.574	0.607
Modulus of rupture	Base	0.438	0.479	0.491	0.567
	Top	0.511	0.553	0.462	0.589
Modulus of elasticity	Base	0.391	0.506	0.493	0.556
	Top	0.413	0.469	0.625	0.659
Resilience	Base	0.261	0.179	0.219	0.256
	Top	0.306	0.274	0.174	0.253
Compression strength	Base	0.484	0.553	0.475	0.579
	Top	0.472	0.520	0.618	0.626
Janka hardness	Base	0.357	0.472	0.419	0.535
	Top	0.463	0.510	0.296	0.455

It is worth noting that, with one or two exceptions, the heritabilities of the different properties are very similar (Table 5.15). Nominal density and all mechanical properties, except resilience, at any radial position of sampling, gave moderately high values of h^2, indicating strong genetic control. The central position of the log produces poorer wood quality, which was shown for all properties. Bearing in mind the strong genetic control exerted over these properties, it is recommended that the genetic selection of trees to produce solid wood be directed towards improving the properties of the central juvenile wood. This has advantages for the breeder, since selection can be done when the trees are quite young.

5.6 Conclusions

Determination of wood nominal density and mechanical properties (modulus of rupture, modulus of elasticity and resilience in static bending, compression strength parallel to the grain and Janka hardness) in samples taken from eight-year-old trees of 26 *Eucalyptus* clones growing in tests at four sites in Brazil has permitted the following conclusions:

i) nominal density and all mechanical properties increased from inner to outer parts of the log both in the basal and upper bolts. The variation from the inner wood to the outer wood amounted to about 22 % for nominal density, with higher values for mechanical properties, which suggests the influence of other factors beyond density in determining mechanical properties;
ii) nominal density, resilience and Janka hardness were higher at the base than in the top bolt. Conversely, modulus of elasticity and compression strength parallel to the grain were higher in the upper bolt. For modulus of rupture the difference between longitudinal positions is practically nil. These opposite results suggest that different characteristics in wood affect different properties in a different way. However, modulus of rupture and compression strength parallel to the grain showed no statistical significant difference between longitudinal positions.
iii) except for resilience, the results of the estimation of the heritability suggest that nominal density and mechanical properties are under strong genetic control with h^2 varying from 0.495 (Janka hardness) to 0.618 (nominal density);
iv) analysis of variance showed that there were significant differences in nominal density and all mechanical properties between clones and between sites. In general, the differences between sites for nominal density and mechanical properties

presented higher levels of significance for wood from the upper bolt than for wood from the base. It seems that defects offset the effect of the site on wood from the base.

v) there were marked differences in stability between clones for nominal density and all mechanical properties;

vi) interactions were unpredictable and in most cases it was not possible to predict the properties of wood produced at one site from their value at another site.

6 VARIATION OF GRAIN ANGLE

The primary purpose of this chapter is to present results and discuss intra-tree, interclonal and environmental variations in grain angle. Also, broad sense heritability will be presented.

Harris (1989), describing the pattern of grain angle, stated that intricate patterns of interlocked and wavy grain are much more frequently encountered in the stems of hardwoods than softwoods: spiral grain has more of the aspect of an "aberration" in hardwoods whereas in softwoods it might be considered as "normal", and indeed inevitable, developmental pattern. In the face of this behaviour, Zobel and Van Buijteneen (1989) state that spiral grain appears to be the most troublesome defect affecting sawn timber. These authors argue that spiral and interlocked grain occurs everywhere, but seems to be accentuated under tropical conditions, as is evident in numerous *Eucalyptus* species. Bootle (1983) listed 34 *Eucalyptus* species as being frequently interlocked, whilst others were occasionally interlocked.

Although it is customary to measure angles in degrees, and indeed this is the unit most frequently used to quantify spiral grain in wood, in this study the values will be expressed as a deviation of the grain, in millimetres, corresponding to a 100 mm straight line running parallel to the axis of the sample. The system utilised here may be converted to degrees or directly to percentage: a grain angle equal to 4.0 mm, for example, also will mean 4 % deviation or:

$$\text{Grain Angle} = \text{Arc}\tan\left(\frac{4}{100}\right) = 2.3^{\circ}.$$

It should be noted that the scriber used to determine the grain angle proved to be a very adequate instrument. The angle used in this chapter is the average between two measurements made on the opposite tangential faces using the bending test specimens.

6.1 Radial Variation of Grain Angle

Table 6.1 and Figure 6.1 show that the mean grain angle is higher in the outer region than in the inner, both at the base and the top of the log. Nonetheless, the pith to bark variation of angle is not one of gradual (linear) increase at all heights, since in the base, grain angle presents its maximum in the intermediate position, and in the top the inner position presents a minimum value of grain angle. More interesting to note (Figure 6.2) is that the radial variation behaves in a distinct form depending on the site of origin: at Southern Bahia and São Mateus 2, in the base, the grain angle is maximum in the intermediate region of the log, while in the upper position the grain angle is at a minimum in the intermediate region. In contrast, at São Mateus 1 and at Aracruz the angle increases from the inner to the outer areas, both at the base and in the upper position of the log. Harris (1989) confirms that change of grain angle across a stem seldom proceeds absolutely smoothly: when plotted graphically (Figure 6.2), angles at successive radial positions do not necessarily produce a straight line or a smoothed curve.

Table 6.1 Radial variation (inner-wood, inter-wood and outer-wood) of the grain angle (mm) in the base and top of the log of 26 *Eucalyptus* clones over four sites in Brazil (SBA - Southern Bahia; SM1 - São Mateus 1; SM2 - São Mateus 2; ARA - Aracruz).

	Base			Top		
Site	Inner	Inter	Outer	Inner	Inter	Outer
SBA	3.9	4.2	3.7	3.5	2.8	3.8
SM1	2.7	3.1	3.2	2.2	2.4	2.9
SM2	2.6	3.5	2.9	2.8	2.3	2.6
ARA	3.3	3.5	4.0	3.0	3.0	3.6
Mean	3.1	3.6	3.5	2.9	2.6	3.2

The difference between the maximum and minimum angles determined for the base is 16 % while at the top, 23 %. This suggests that the grain angles are more homogeneous in the base than the upper position of the log. The existence of radial differences in grain angle was confirmed by the analysis of variance shown in Table 6.2 (a) ($P \leq 0.01$) when all data were analysed together.

At the level of a particular clone or bolt the radial behaviour of grain angle is also rather variable, both in the base as in the top position. The different types of variation, as well their magnitude, are detailed in the Appendices 1.13 and 1.14.

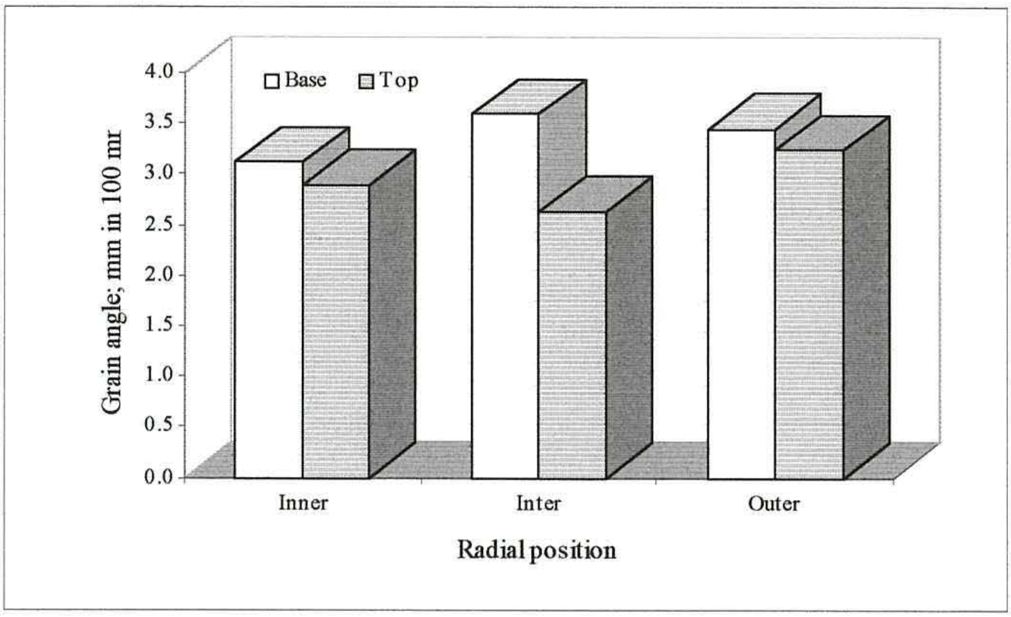
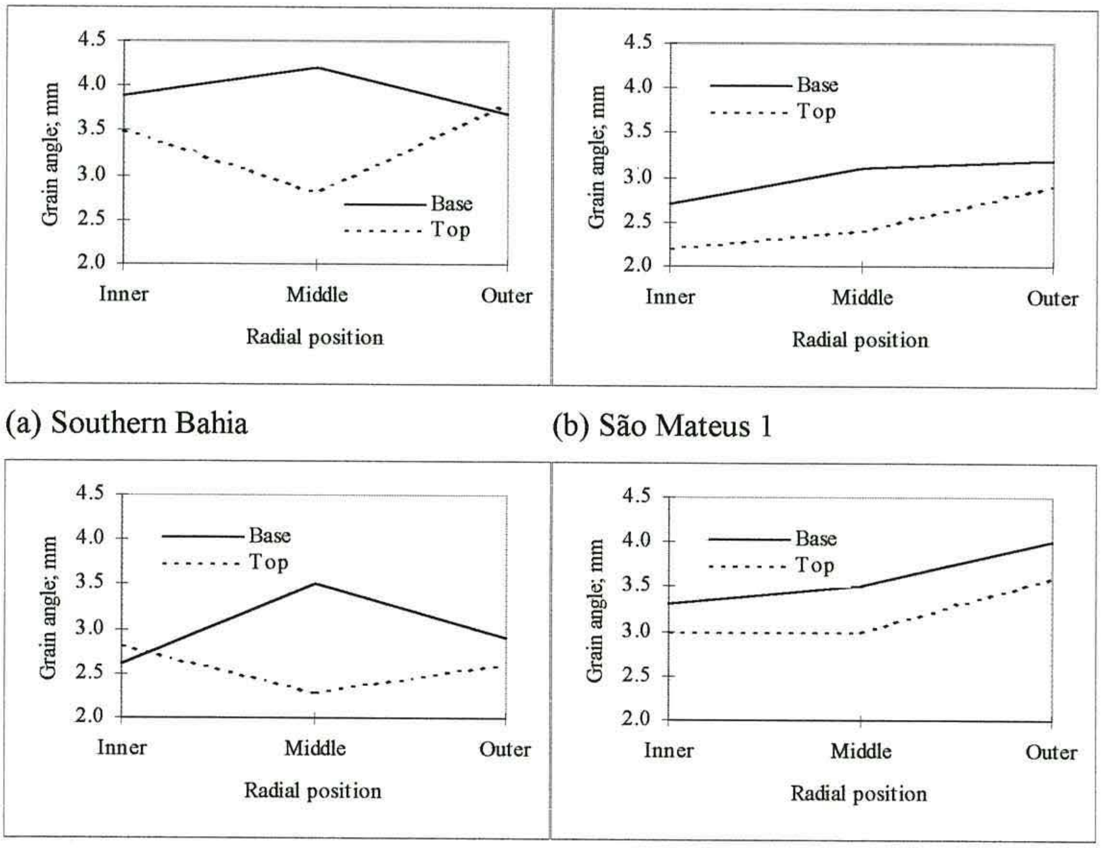


Figure 6.1 Radial variation of grain angle (note grain angle refers to deviation over 100 mm run).

Priestley (1945), cited by Harris (1989), tried to explain the radial behaviour of grain angle by suggesting that if the grain in the first year's growth followed an oblique course, then this was maintained through successive increments in the geometrical sense, so that grain angle increased simply as a consequence of the increasing girth of the stem (geometrical effect). However, Harris (1989) pointed out that such a geometrical increase is not of universal application to hardwoods. Nevertheless, the concept raises two very interesting and quite fundamental questions (Harris, 1989):

ii) The first concerns the application of geometry to the enlargement of woody stems which are, after all, produced by repeated, and in a sense independent, cell divisions. As the number of cells around a circumference increases to meet the requirements of growth in girth by anticlinal divisions in the cambium, what justification is there for assuming that successive cells produced by cambial initials will re-orientate geometrically to retain their relative positions? Priestley's measurements, demonstrating that the cotangents of the grain angle show a linear relation to girth in a stem of *Sambucus nigra*, certainly provide some support for the concept in this instance.

ii) The second question is really the corollary of the first, relating to species that are predominantly straight grained or in which grain is restored to the axial direction after temporarily becoming oblique. Since minor twists and grain deviations must inevitably occur in the life of every tree, what is the nature of the process which restores straight grain (e.g., after branch stub occlusion) in the face of the growth in circumference of the stem to exaggerate all such deviations?



(a) Southern Bahia (b) São Mateus 1

(c) São Mateus 2 (d) Aracruz

Figure 6.2 Radial variation of the grain angle in the base and top of the log in the four sites (ARA - Aracruz; SBA - Southern Bahia; SM1 - São Mateus 1; SM2 - São Mateus 2.). (grain angle: deviations over 100 mm run)

In the majority of hardwood species spirality does not increase in line with increasing stem diameter and is therefore under some other type of influence. It may be that inability to reduce oblique grain arising by chance in the leading shoot is the abnormal characteristic of species such as *Sambacus nigra*. If this is so it deserves closer investigation to discover in what respect this species lacks the normal control over grain direction. It is of interest that Okhura (1958) reported that *Sambacus sieboldiana* produces both left and right hand grain directions, apparently at random, though these did not exceed 2 degrees in the ten specimens he examined. For the present it need only be remarked that some trees appear to lack the ability to restore chance grain deviations to the axial or prevailing spiral direction (Harris, 1989).

Table 6.2 Results of analysis of variance of grain angle of *Eucalyptus* clones. NS- No significant; **- $P \leq 0.01$.

(a) Grain angle and radial position (one-way analysis of variance).

Source	DF	SS	MS	F	P
Radial	2	29.39	14.69	6.98	**
Error	621	1307.66	2.11		
Total	623	1337.05			

(b) Grain angle and axial position (one-way analysis of variance).

Source	DF	SS	MS	F	P
Longitudinal	1	14.58	14.58	11.85	**
Error	206	253.47	1.23		
Total	207	268.05			

6.2 Base-top Variation of Grain Angle

Table 6.1, Figure 6.1 and Figure 6.2 show that the mean between-site angle is higher at the base than the upper position of the log. Table 6.4 also shows that in each site grain angle was higher in the base than in the upper position. The difference reaches its highest value at São Mateus 2 (23 %) and its lowest at Aracruz (13 %). The coefficient of variation changed from 31 % at Aracruz to 22.1 % at Southern Bahia. Purnell (1988) working with eleven-year-old *Eucalyptus nitens* fast grown in South Africa found that grain angle decreased rapidly from 0 m to 4.8 m, where it remained constant with increasing height. It is possible to infer from his data that the grain angle reduced from 12° at the base to 5° at 3.0 m height in the stem. This represents a reduction of 2.4 times (140 %) over the section considered. This is a much larger difference than that observed for the mean of this study. However, similar or even higher rates have been found in the present study when a particular clone is considered: in Table 6.4, at Southern Bahia, clone 23, for example, shows a grain angle 4.8 times higher in the base than in the top of the log.

Table 6.3 Summary of analysis of variance for grain angle between basal and top bolts at different sites. (ns- no significant at P = 0.05; ** P≤ 0.01)

Site	Longitudinal Position d.f. (position = 1), d.f. (error) = 50, d.f. (total) = 51
Southern Bahia	n.s.
São Mateus 1	n.s.
São Mateus 2	**
Aracruz	n.s.

The difference in grain angle between longitudinal positions is significant ($p \leq 0.01$) when all data are analysed together using analysis of variation [Table 6.2 (b)]. Results of analysis of variation for grain angle between basal and higher bolts at specific sites resulted in a different response (Table 6.3) since there was found to be no significant difference between positions in three sites. Only at São Mateus 2 was the difference significant ($p \leq 0.01$). Despite differences in the magnitude of the angles, in *Eucalyptus dalrympleana*, Birot *et al.* (1980) showed that between 1.30 m (grain angle = 5.5°) and 4.0 m (grain angle = 2.7°) the angles were significantly

Table 6.4 Grain angle (mm) of 26 *Eucalyptus* clones, mean grain angle per site (mm) and within-site coefficient of variation (CV, %) over four sites in Brazil (SBA - Southern Bahia; SM1 - São Mateus 1; SM2 - São Mateus 2; ARA - Aracruz).

Clone	SITE											
	Southern Bahia			São Mateus 1			São Mateus 2			Aracruz		
	Base	Top	Mean	Base	Top	Mean	Base	Top	Mean	Base	Top	Mean
1	1.91	3.32	2.61	2.74	2.84	2.79	2.81	2.39	2.60	2.27	1.30	1.79
2	2.84	2.32	2.58	2.52	1.52	2.02	3.72	3.36	3.54	3.73	3.96	3.85
3	2.84	3.59	3.21	1.90	2.01	1.96	2.33	1.98	2.15	1.73	1.39	1.56
4	4.18	3.67	3.92	1.89	1.96	1.92	1.22	1.66	1.44	3.13	3.41	3.27
5	3.48	3.11	3.30	5.62	1.60	3.61	4.97	2.35	3.66	6.31	4.92	5.61
6	4.18	6.66	5.42	3.78	3.01	3.40	2.95	4.03	3.49	5.32	4.38	4.85
7	3.22	3.17	3.20	3.95	1.71	2.83	3.32	1.78	2.55	3.85	3.13	3.49
8	3.35	3.36	3.35	1.21	3.56	2.38	2.81	1.60	2.20	2.75	2.64	2.70
9	4.36	4.00	4.18	5.72	2.85	4.28	4.59	3.42	4.00	4.67	3.87	4.27
10	4.45	2.58	3.51	4.54	5.36	4.95	4.21	1.87	3.04	4.25	2.93	3.59
11	4.23	4.05	4.14	4.62	1.83	3.22	4.39	2.32	3.36	4.11	5.06	4.59
12	3.74	2.07	2.91	1.67	1.11	1.39	1.59	2.28	1.93	1.81	1.85	1.83
13	3.73	2.80	3.26	1.56	2.80	2.18	3.13	2.46	2.79	2.71	2.78	2.74
14	3.21	4.34	3.78	4.58	2.56	3.57	2.68	2.68	2.68	4.34	5.79	5.06
15	3.83	3.31	3.57	2.74	2.64	2.69	2.71	2.83	2.77	5.80	4.98	5.39
16	4.66	3.02	3.84	3.00	3.24	3.12	1.63	1.51	1.57	3.90	3.50	3.70
17	2.81	3.31	3.06	4.46	2.70	3.58	2.77	2.48	2.62	3.03	2.98	3.00
18	5.67	5.23	5.45	2.56	3.60	3.08	2.79	4.25	3.52	4.81	3.38	4.09
19	4.30	1.83	3.06	2.68	2.27	2.47	3.04	1.69	2.36	2.83	2.97	2.90
20	2.78	2.78	2.78	2.03	3.01	2.52	2.97	1.98	2.47	4.18	3.00	3.59
21	4.82	1.95	3.39	2.70	3.82	3.26	3.94	3.56	3.75	3.30	2.81	3.06
22	4.70	3.68	4.19	2.45	1.78	2.11	3.54	3.06	3.30	3.69	2.70	3.19
23	5.33	1.12	3.23	3.44	1.56	2.50	3.67	2.57	3.12	3.03	2.74	2.88
24	3.70	3.61	3.65	2.71	2.81	2.76	2.49	3.21	2.85	4.75	2.63	3.69
25	3.93	5.52	4.72	3.34	3.48	3.41	3.07	2.05	2.56	4.68	4.72	4.70
26	7.00	3.66	5.33	2.94	2.42	2.68	4.13	2.68	3.41	2.04	2.04	2.04
Mean	3.97	3.39	3.68	3.13	2.62	2.87	3.13	2.54	2.84	3.73	3.30	3.52
C.V.(%)	26.6	34.9	22.1	38.8	35.2	27.2	29.2	29.5	23.5	31.9	34.6	31.3

different at the 1 % level. They also stated that the deviation of the grain at any level in the stem could be used to estimate values at all levels.

The differences in the grain angle between basal and upper bolts, at the same radial position (Table 6.1), has not received much attention in the literature, but has particular relevance for defining those phenomena which should be included within the idea of spiral grain (Harris, 1989). It can be noted in the table that there is an indication of consistence in the changing of the angle with height within the same region. For instance, at Southern Bahia the grain angle reduces from 3.9 mm in the inner position of the base to 3.5 mm in the inner position of the top. If the considered site is São Mateus 1, for example, in the same radial position there is a reduction of the grain angle from 2.7 mm to 2.2 mm. It has to be considered that in this study the direction of the slope (whether left handed side - LH - or right hand side - RH) was not taken in account, however it is well known that the direction of the grain angle changes with radial and/or longitudinal position within the stem (Harris, 1989). Also, in spite of the fact that the radial sampling used in this study has been carefully carried out it must be noted that the locations of sampling do not refer precisely to the same growth rings.

6.3 Grain Angle Variation: between Site and Between Clone

The overall mean grain angle found in this study was equal to 3.23 mm in a 100 mm run (1.85°). Table 6.5 shows that (for the average angles of the radial positions) the differences (between sites and between clones) are significant. However only for the outer wood are the differences between clones and between sites statistically significant.

The small angles found in this study indicate a relatively straight grain for the material studied. Despite the indication that the spirality of the grain represents a advantageous adaptation for the tree, mainly to face predominant winds (Mattheck and Kubler, 1995), for solid wood utilisation as straight a grain as possible is desirable. Thus wood collected from São Mateus 1 or São Mateus 2 should tend to produce better quality timber than that from Aracruz or Southern Bahia (all other factors being constant). Champion (1929) and Dadswell and Nicholls (1959), both cited by Zobel and Van Buijtenen (1989), used the figure of 7° spirality as being the upper limit of acceptability for quality solid wood products. Applications which demand a straight grain to improve performance such as in structures or for surface finishing (planing) are not likely to be significantly affected by the level of grain angle deviation observed for *Eucalyptus* wood.

Table 6.5 Summary of the analysis of variance of grain angle of *Eucalyptus* between clones and between sites in each radial position at basal and top bolts. [g.l. (clone) = 25, g.l. (site = 3), g.l. (error) = 75, g.l. (total) = 103]. [(ns- no significant at P = 0.05; ** P≤ 0.01; *** P≤ 0.001). Results of anova in Appendices 4.1 and 4.2.

Position	Clone	Site
	Basal bolt	
Inner	ns	ns
Intermediate	**	ns
Outer	**	**
Average	***	**
	Top bolt	
Inner	ns	**
Intermediate	ns	ns
Outer	**	**
Average	**	***

An examination of Table 6.6 shows the mean grain angle of the 26 clones over the four sites and the coefficients of linear regression of clone mean angle against site mean angles, and the associated coefficients of determination. Regression coefficients varied from - 0.544 (clone 10) to 2.615 (clone 4), and coefficients of determination from 0.4 to 98.9 % . Following the assessment used by Malan and

Table 6.6 Mean grain angle of 26 *Eucalyptus* clones over four sites, coefficients of regression (β) of clone grain angle on site mean grain angle, coefficient of determination (R^2) and the results of group regression analysis (F is significant if β is significantly different from 1). * $P \leq 0.05$; ** $P \leq 0.01$; ns - not significant at P= 0.05.

Clone	Mean (mm in 100 mm)	β	R^2	F
1	2.45	- 0.528	26.5%	ns
2	3.00	0.351	3.3%	ns
3	2.22	0.660	16.6%	ns
4	2.64	2.615	97.3%	**
5	4.05	0.748	9.5%	ns
6	4.29	2.293	98.9%	ns
7	3.02	0.825	75.8%	ns
8	2.66	1.060	83.1%	ns
9	4.18	0.106	12.7%	*
10	3.77	-0.544	8.3%	ns
11	3.83	1.342	80.8%	ns
12	2.02	1.069	52.6%	ns
13	2.74	0.732	52.0%	ns
14	3.77	1.541	46.7%	ns
15	3.60	2.036	49.9%	ns
16	3.05	1.929	65.2%	ns
17	3.07	- 0.058	0.4%	ns
18	4.03	2.107	79.3%	ns
19	2.70	0.766	98.7%	*
20	2.84	0.792	44.2%	ns
21	3.36	- 0.334	25.0%	*
22	3.20	1.401	51.2%	ns
23	2.93	0.354	22.7%	ns
24	3.24	1.126	95.7%	ns
25	3.85	2.287	89.0%	ns
26	3.36	1.283	15.4%	ns

Verryn (1996), four clones (numbers 7, 8, 12 and 24) showed average stability, ten clones (numbers 4, 6, 11, 14, 15, 16, 18, 22, 25 and 26) below average stability and twelve clones (numbers 1, 2, 3, 5, 9, 10, 13, 17, 19, 20, 21 and 23) above average stability. The different slopes of the linear regression lines (examples are given in Figure 6.3) suggest that the clone × site interactions are complex.

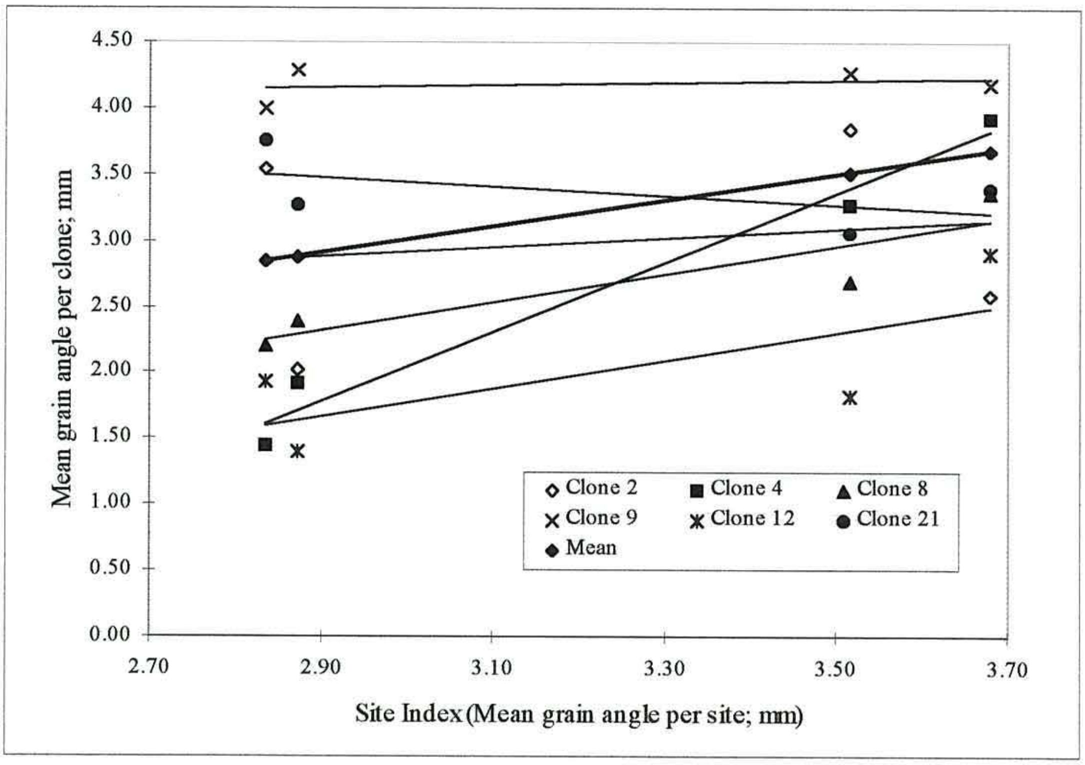


Figure 6.3 Regression lines showing the relationship of individual clone grain angle and the population mean of 26 clones (Site Index).

Despite the wide range of regression coefficients (Table 6.6), only clones 4, 9, 19 and 21 were significantly different from 1, and only four coefficients of determination were greater than 90 %. This suggests that for most clones the predictable component of the observed genotype × environment interactions (estimated by the regression coefficient) is much smaller than the unpredictable component (estimated by the deviations from the regression, which could not be tested for significance because of a lack of replication). It appears that for this group of clones on these four sites, only for four clones is it possible to predict the grain angle of wood produced at one site from its value at another site. Harris (1989) states that the general unpredictability of environmental effects on spiral grain points to the need for a better understanding of its physiological and genetic origins, as well as the anatomical process that lead to its development.

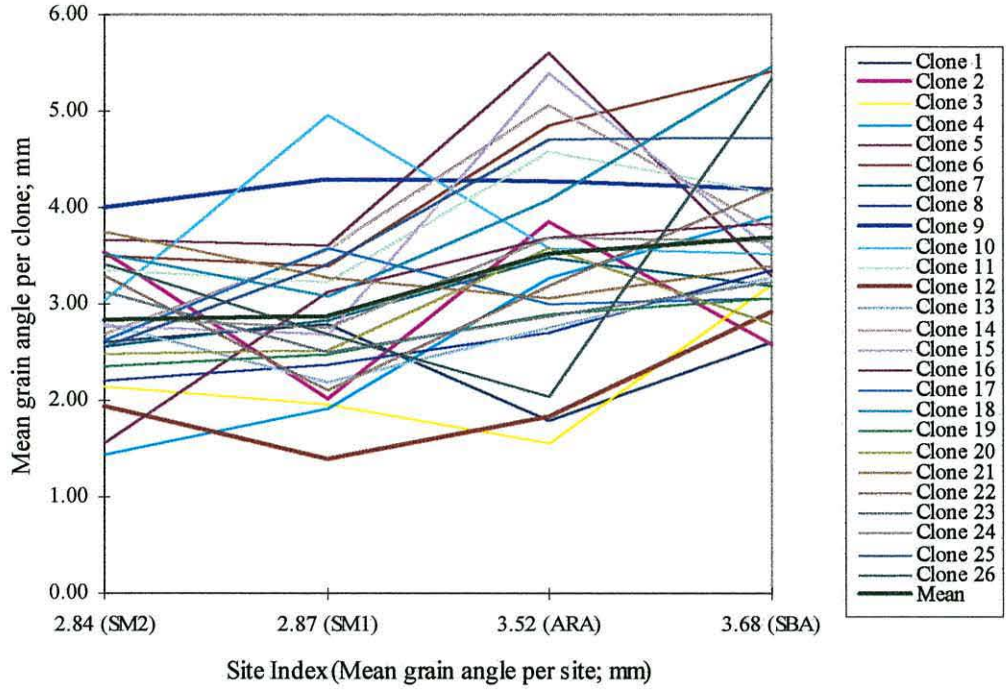


Figure 6.4 Grain angle of 26 *Eucalyptus* clones over four sites. ARA - Aracruz; SBA - Southern Bahia; SM1 - São Mateus 1; SM2 - São Mateus 2.

6.4 Estimates of Heritability

Table 6.7 Broad sense heritability of grain angle estimated for the inner, intermediate, outer regions and for the average between radial positions in the basal and top bolts.

Bolt	Radial Positions			Average
	Inner	Inter	Outer	
Base	0.022	0.131	0.297	0.294
Top	0.061	0.001	0.263	0.211
Average				0.363

Estimates of broad sense heritability of grain angle based in analyses of variance summarised in Table 6.5 were comparatively low if compared to other reported estimates: h^2 = 0.363 (Table 6.7). Table 6.7 shows weaker heritabilities for the inner grain angle than for the outer. This indicates that the grain angle of inner wood, formed in the first years of growth of the trees is more under environmental control than the grain angle of wood later formed. Vité (1967) considers that grain patterns are genetically fixed and are specific to related genera or closely related species. If this is correct, it is also correct to assume that the occasionally found absence of pattern or an "erratic pattern" is characteristic of the *Eucalyptus* genera, or at least for the clones and sites employed in this study. In *Eucalyptus dalrympleana*, Birot *et al.* (1980) showed that the heritability of the grain angle seems weak to moderate, since a significant but low genetic effect had been found. According to Harris (1989) it seems probable that the propensity for spiral grain is determined by heredity, although its expression may be dependent, at least in part, on the environment.

6.5 Conclusions

Grain angle determined for static bending samples taken from eight-year-old trees of 26 *Eucalyptus* clones growing in tests at four sites in Brazil has permitted the following conclusions:

i) In general the grain angle found in this study was small, varying between 2.84 mm in 100 mm (1.6°) (at São Mateus 2) and 3.68 mm in 100 mm (2.1°) (at Southern Bahia).

ii) Grain angle was higher in the outer than in the inner-wood, both in the base and in the top of the 3.0 m log. In the base the grain angle was at a maximum in the intermediate-wood, while in the top the intermediate position presented the minimum angle. Variation from the inner wood to the outer wood amounted to about 16 % in the base and 23 % in the top of the log.

iii) There was significant difference in the grain angle between axial positions when all data were analysed together. For the sites, however, only São Mateus 2 showed a significant statistical difference between longitudinal positions.

iv) The broad sense heritability of grain angle was 0.37 when estimated from 26 clones on four sites.

v) Analysis of variance showed that there were significant differences in grain angle between clones and sites.

v) There were marked differences in stability between clones (linear regression coefficients from - 0.544 to 2.615).

vi) Interactions were unpredictable (coefficients of determination zero to 99 %), and in most cases it was not possible to predict the grain angle of wood produced at one site from its value at another site. However, it was possible to identify clones which produced wood of consistently high or low grain angle on the four test sites.

7 VARIATION OF FIBRE MORPHOLOGY

The main objective of this chapter is to present results and discuss intra-tree, interclonal and environmental variations associated with the fibre of *Eucalyptus* wood, considering variations in fibre length, diameter, lumen diameter and wall thickness. Also, broad sense heritability of these characteristics will be presented. In this chapter, only eleven clones planted over four sites will be considered.

In contrast to the nominal density and mechanical properties discussed previously, here the longitudinal variation of fibre dimensions will be disregarded since only the basal portion of the log was studied. Each of the wood samples used in the fibre morphological characterisation was collected from one same block removed from one bending test specimen taken from each radial position. For *E. grandis*, Taylor (1973 a, b) has shown that height in tree has little effect on fibre length.

7.1 Fibre Morphology: Radial Variation

7.1.1 Fibre Length: Radial Variation

The fibre length increased in the radial direction (from inner wood to outer wood) for all sites studied. An examination of Table 7.1 and Figure 7.1 shows that the mean fibre length increased by 19.1 % from inner to outer wood. In spite of the small number of radial sampling positions, the smaller rate observed from the intermediate to the outer position suggests that a tendency to stabilisation of fibre length is taking place, as reported by Tomazello-Filho (1985), for instance. Also Shimoyama (1991) studying seven-year-old *Eucalyptus* wood, showed that fibre length increased from the intermediate[1] region of the log to the outer[2] region. In *E. grandis* this increase was 14 % (from 0.93 mm to 1.06 mm), in *E. saligna* it was 11.5 % (from 0.96 mm to 1.07 mm) and in *E. urophylla* the fibre length increased 13.1 % (from 0.99 mm to 1.12 mm). These results are close to the results found in this research. According to Chalk (1983), it has been almost universally found,

[1] Somewhere in the interval between 10-45 % of the extension of the ray.
[2] Somewhere in the interval between 55-90 % of the extension of the ray.

except in storeyed woods, that the length of fibre cells at any one level in the stem increases outwards from the pith, at first very rapidly, but usually slowing down considerably after 8-15 rings.

Table 7.1 Radial variation (inner-wood, intermediate-wood and outer-wood) of the fibre length (mm), fibre diameter (μm), lumen diameter (μm) and fibre wall thickness (μm) of 11 *Eucalyptus* clones over four sites in Brazil (SBA - Southern Bahia; SM1 - São Mateus 1; SM2 - São Mateus 2; ARA - Aracruz).

Characteristic	Site	Radial Position			Mean
		Inner	Intermediate	Outer	
Fibre length (mm)	SBA	0.980	1.089	1.214	1.141
	SM1	0.965	1.048	1.111	1.071
	SM2	0.915	1.018	1.105	1.051
	ARA	0.933	1.040	1.084	1.051
	Mean	0.948	1.049	1.129	1.079
Fibre Diameter (μm)	SBA	19.28	19.57	20.82	20.17
	SM1	18.88	19.00	18.33	18.65
	SM2	16.68	18.18	18.07	17.97
	ARA	17.70	18.30	17.66	17.92
	Mean	18.14	18.76	18.72	18.68
Lumen Diameter (μm)	SBA	12.2	12.0	12.4	12.2
	SM1	12.4	12.1	10.6	11.4
	SM2	9.8	10.5	10.2	10.3
	ARA	11.1	11.2	10.0	10.6
	Mean	11.4	11.5	10.8	11.1
Wall Thickness (μm)	SBA	3.5	3.8	4.2	4.0
	SM1	3.2	3.5	3.8	3.6
	SM2	3.4	3.8	3.9	3.9
	ARA	3.3	3.5	3.9	3.7
	Mean	3.4	3.7	4.0	3.8

Table 7.2 demonstrates that there is a significant statistical difference in the fibre length between radial positions ($P \leq 0.01$) when the data of the four sites are analysed together. Also, when analysed separately, each of the four sites show significant statistical differences in the fibre length between radial positions ($P \leq 0.01$) (Appendix 5.1). For a particular clone and site (Appendix 2.1), however, the radial variation in the fibre length can exhibit a different tendency from that of the mean: clone 10 at São Mateus 1, for instance, presented the minimum fibre length in the intermediate wood. In a literature survey Wilkes (1988) found that in *Eucalyptus* over the first 10-20 years of growth (period of juvenile wood production) about 50 % of the increase in the fibre length from pith to bark can be observed.

Table 7.2 Summary of one-way analysis of variance of fibre dimensions (fibre length, fibre diameter, lumen diameter and fibre wall thickness) of eleven *Eucalyptus* clones between radial position. (ns- not significant at $P = 0.05$; * $P \leq 0.05$; ** $P \leq 0.01$).

Characteristic	Radial Position d.f. (position) = 2; d.f. (error) = 129; d.f. (total) = 131
Fibre Length	**
Fibre Diameter	ns
Lumen Diameter	ns
Fibre Wall Thickness	**

7.1.2 Fibre Diameter: Radial Variation

Table 7.1 shows that the mean fibre diameter increases from the inner wood to the intermediate wood but decreases slightly from the intermediate wood to the outer wood. However, as is evident in Figure 7.1, more precisely behaviour of the mean fibre diameter depends on the site considered, since each site presents its own distinct pattern of variation. A closer examination of Table 7.1 permits the

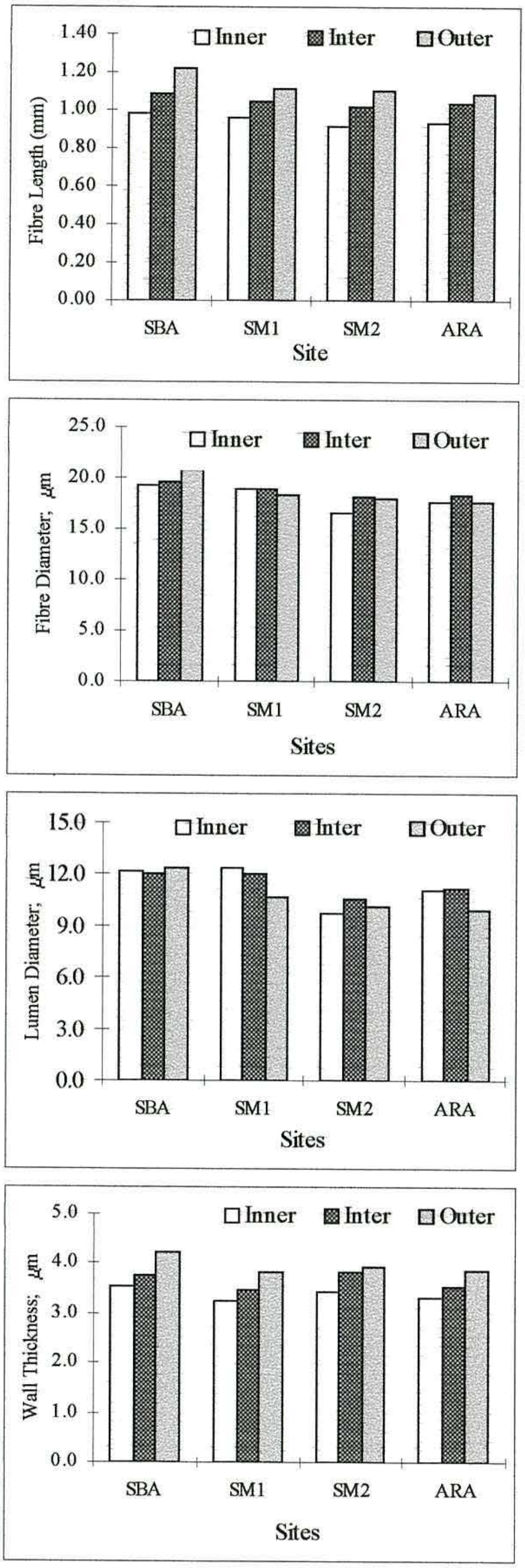


Figure 7.1 Radial variation of the fibre length, fibre diameter, lumen diameter and fibre wall thickness.

inference that the mean fibre diameter observed in the intermediate position (18.76 μm) is only 3.4 % higher than that of the inner position (18.14 μm) and practically the same as that observed in the outer position (18.72 μm). Indeed, Table 7.2 demonstrates that there is no significant difference in the fibre diameter between the radial positions provided that all data are analysed together. In contrast, for *Eucalyptus grandis*, Malan and Gerisher (1987) and Bhat *et al.* (1990) pointed out that, as with fibre length and fibre wall thickness, fibre diameter increases rapidly with increasing distance from the pith levelling off after about 8 to 15 years. Also, according to Chalk (1983) there is a general tendency for diameter to increase from pith outwards. It is apparent that this is not the behaviour observed in this study for the mean fibre diameter.

When the data for fibre diameter were analysed separately per site (Appendix 5.2), only at São Mateus 2 was a significant difference ($P \leq 0.05$) found between the three radial positions. For a particular clone and site, however, as can be examined in the Appendix 2.2, the radial variation can exhibit a more specific behaviour: the fibre diameter of clone 10 at Southern Bahia, for example, increased from the inner to the outer position. Shimoyama (1991) studying seven-year-old *Eucalyptus* wood, showed that fibre diameter increased from the intermediate region of the log to the outer region. According to her results, only in *E. grandis* was a reduction of the dimensions of about 2 % observed (from 19.8 μm to 19.4 μm). Even so, in *E. saligna* there was a growth of only 1 % (from 18.5 μm to 18.7 μm) and in *E. urophylla* the fibre diameter increased 3 % (from 19.5 μm to 20.1 μm). The values found by Shimoyama are close to the results of this research, and similarly they do no show statistically significant difference between the internal and external positions. In contrast, in a literature survey Wilkes (1988) concluded that for *Eucalyptus* over the first 10-20 years of growth (period of juvenile wood production) about 10 % of radial increase is observed in the fibre diameter. In seven-year-old *E. globulus* and *E. nitens* cultivated at Tasmania, fibre diameter showed little difference within ring and also between rings (pith-bark direction) for a given height in the stem (Hudson *et al.*, 1998).

The majority of rain forest trees do not show annual growth rings such as are found in temperate zone trees, but there is a relatively high proportion of species showing clear demarcation of radial growth activity, as is the case for *Eucalyptus* wood. However, because tropical climates are often regarded as non-seasonal, there is much uncertainty as to the factors controlling growth periodicity under tropical conditions (Alvin, 1964). In tropical areas subjected to seasonal drought, a clear association between growth periodicity and rainfall has often been established, but in regions with fairly uniform rainfall distribution the situation seems rather confusing (Alvin, 1964).

7.1.3 Lumen Diameter: Radial Variation

The mean fibre lumen diameter increased in the radial direction from the inner wood to the intermediate wood but decreased from the intermediate to the outer wood (Table 7.1). However, as for fibre diameter, it is evident from Figure 7.1 that a more precise behaviour of the mean lumen diameter depends on the site considered, since each site presents its own distinct pattern of variation, which suggests some environmental effect. In none of the sites, however, was it possible to find a consistent increase of the lumen diameter from the inner wood outwards. Nevertheless, a closer examination of Table 7.1 permits the inference that the mean fibre lumen diameter observed in the intermediate position (11.5 μm) is only 0.9 % higher than that of the inner position (11.4 μm) and 6.5 % higher than that observed in the outer position (10.8 μm). Indeed, Table 7.2 shows that there is no significant difference in the fibre lumen diameter between the radial positions provided that all data are analysed together. Brasil and Ferreira (1979), studying wood fibre characteristics of three-year-old *E. grandis* at breast height, found that lumen diameter did not vary significantly at three positions across the stem (from pith to bark).

For fibre lumen diameter when the data were analysed per site (Appendix 5.3), in none of the sites was a significant difference between the three radial positions found. For a particular clone and site however, the radial variation can exhibit a more specific behaviour (Appendix 2.3): the fibre lumen diameter of clones 3, 5, 8 and 18 at Aracruz, for example, decreased from the inner to the outer position. Shimoyama (1991) studying seven-year-old *Eucalyptus* wood, showed the variation of the fibre lumen diameter from the intermediate region of the log to the outer region. According to the results of this author, in *E. grandis* the lumen diameter decreased by approximately 9.4 % (from 11.6 μm to 10.6 μm), in contrast to the behaviour reported in the present work. However, the lumen diameter showed similar values in these two positions in *E. saligna* (lumen diameter = 10.1 μm) and in *E. urophylla*, where the lumen diameter was equal to 10.6 μm, both in the intermediate and in the external positions. The values found by Shimoyama (1991) are close to the results described here for *Eucalyptus* clones. Results with more consistent conformation have been reported in the literature. For instance, in 3-year-old *E. grandis* lumen diameter was shown not to vary significantly from pith to bark (Brasil and Ferreira, 1979) contrasting with the behaviour reported for the same species at five years of age (Bamber and Humphreys, 1963), when the lumen diameter reduced from pith to bark. However, Carpin *et al.* (1985) found that lumen diameter increased from pith to the bark both in *E. grandis* and *E. saligna*. The absence of consistency in the variation of the lumen diameter from the inner to the outer region suggests that for the clones and sites reported here there was no indication of influence of cambial age.

7.1.4 Fibre Wall Thickness: Radial Variation

The mean fibre wall thickness increased in the radial direction at all sites studied. An examination of Table 7.1 and Figure 7.1 shows that the mean wall thickness increased 17.6 % from inner to outer wood. These figures are somewhat similar to those presented for fibre length. According to Malan (1991) the wall thickness of fibres increase rapidly with age as a result of the combined effects of an increase in fibre diameter and a decrease in lumen size. According to Chalk (1983) there is some evidence that the wall thickness of fibre increases from the pith outwards but it may decrease slightly close to the periphery. However, as shown in Section 7.1.2 and 7.1.3 for fibre diameter and lumen diameter respectively, this behaviour was not generally observed in the different sites studied here. As observed for fibre length, the lower rate of increase observed in the external region (from the intermediate to the outer position) suggests that a tendency to stabilisation of the wall thickness is occurring. In the same way Shimoyama (1991) studying seven-year-old *Eucalyptus* wood, showed that wall thickness increased from the intermediate region of the log to the outer region. In *E. grandis* this increase was 7.6 % (from 4.08 μm to 4.39 μm), in *E. saligna* it was 8 % (from 4.12 μm to 4.45 μm) and in *E. urophylla* the wall thickness increased 4.2 % (from 4.54 μm to 4.73 μm). Table 7.2 demonstrates that there is a significant statistical difference in the wall thickness between radial positions ($P \leq 0.01$) when the data of the four sites are analysed together. Also, when separately analysed, in each of the four sites significant statistical difference in the wall thickness between radial positions were observed ($P \leq 0.01$) (Appendix 5.4). It seems that wall thickness is similar to fibre length, in terms of the significance of the differences between radial positions. In a particular clone and site, however, the radial variation in the wall thickness can present different behaviour from that displayed by the mean: clone 2 at Aracruz, for instance presented the highest thickness in the intermediate position (Appendix 2.4).

7.2 Fibre Morphology Variation: between Sites and between Clones

Table 7.3 shows the matrix of simple correlations between all fibre characteristics for each site. The correlations between fibre wall thickness and lumen diameter were all significant and all negative. Conversely, the correlation between wall thickness and fibre diameter showed no significance for any site, which suggests independence of these dimensions. This indicates that the diameter of the fibre may increase and not be accompanied by thickening of the fibre wall. However, lumen diameter was significantly correlated with fibre diameter, except for Southern Bahia despite its moderate coefficient of correlation (0.556). In these correlations an increase of the fibre diameter corresponds to an increase of the lumen diameter. The correlations between fibre length and the other fibre dimensions are rather variable depending of the site and characteristic considered.

Table 7.3 Correlation coefficients between fibre dimensions in different sites.

Site		Fibre length	Fibre diameter	Lumen diameter
Southern Bahia	FD	0.039		
	LD	-0.815**	0.556	
	WT	0.731*	0.254	-0.663*
São Mateus 1	FD	-0.058		
	LD	0.030	0.898***	
	WT	-0.126	-0.174	-0.739*
São Mateus 2	FD	0.013		
	LD	-0.655*	0.697*	
	WT	0.675*	-0.404	-0.860**
Aracruz	FD	0.566		
	LD	0.361	0.893***	
	WT	0.094	-0.363	-0.743**

7.2.1 Variation of Fibre Length: between Sites and between Clones

The overall mean fibre length, between clones and sites found in this study was 1.079 mm (Table 7.1 and Table 7.5). This value is inside of the range of fibre lengths for *Eucalyptus* wood of 0.75 mm to 1.30 mm as described by Barrichelo and Brito (1976). The mean fibre length (Table 7.5) was greatest at Southern Bahia (1.141 mm) and smallest at both São Mateus 2 and Aracruz (1.051 mm). Table 7.4 shows that the differences between sites are statistically significant.

The variation of the fibre length around the mean, represented by the coefficient of variation (Table 7.5), alternated between 5.9 % (Aracruz) and 6.8 % (Southern Bahia). This suggests that the within site variation is somewhat homogeneous for all sites studied. Clone 3 exhibited the highest fibre length (mean between sites = 1.184 mm) while clone 10 exhibited the shortest (1.017 mm). The difference between the shortest and longest fibres was highest at São Mateus 1 (28 % between clone 3 and clone 9) and least at Aracruz (16.8 % between clone 5 and clone 6). Table 7.4 shows that there are significant differences ($p \leq 0.01$) between clones and between sites for fibre length. This result is partially corroborated by the results shown by Demuner and Bertolucci (1993). They found that fibre length of nine five-year-old *Eucalyptus* clones cultivated in three sites in Brazil presented significant differences between sites but not between clones. Otherwise, Malan and Verryn (1996) verified for *E. grandis* that differences in fibre length between 26 sites and between 37 clones were highly significant. Clones of juvenile *E. camaldulensis* grown under controlled environmental conditions in two phytotron glasshouses showed marked differences in the fibre length between clones and between temperatures (significance at 0.1 % level), however the interaction clone × temperature produced no significant difference (Rudman, 1970).

Young fibre cells are much shorter than when they are fully mature. A daughter cell of the cambium that is destined to become a fibre is at first equal in length to one that will develop into a vessel element or a strand of axial parenchyma (Chalk, 1983). It initially has bluntly ends, and before secondary thickening of the cell wall takes place narrow extension occurs at both ends of the growing fibre cell and it appear to push its way between the cells above and below it (Chalk, 1983). The process by which this extension in length is achieved is known as intrusive growth.

It was shown by Chattaway (1936), cited by Chalk (1983), that mean fibre length may be 1.1 - 9.5 times the mean length of the cambial initials as indicated by the length of the vessel elements. Of considerable practical interest is the discovery that the amount of intrusive growth may be increased by tree vigour (Chalk, 1983).

The growth rate of the tree also affects the increase in length of the cambial initial cells. Fast growth retards the rate of length increase of cambial initials during the early years of activity of the cambium and delays the time of production of cells of maximum length (Panshin and De Zeeuw, 1970). It can be presumed that in fast grown trees (as is the case of the some *Eucalyptus* grown in tropical conditions and in particular of the trees applied in this study), the high growth rate causes some reduction in the overall fibre length observed during the entire life of the tree. If this is correct, the average length will be shorter than that which should be expected for trees growing in a more restrictive environmental condition.

Table 7.4 Balanced analysis of variance of fibre dimensions (fibre length, fibre diameter, lumen diameter and fibre wall thickness) of eleven *Eucalyptus* clones per clone and site. (ns- no significant; ** P≤ 0.01).

Property	Source	DF	SS	MS	F	P
Fibre Length	Clone	10	0.118532	0.011853	4.49	**
	Site	3	0.059538	0.019846	7.52	**
	Error	30	0.079214	0.002640		
	Total	43	0.257284			
Fibre Diameter	Clone	10	48.3516	4.8352	5.46	**
	Site	3	36.1506	12.0502	13.61	**
	Error	30	26.5628	0.8854		
	Total	43	111.0649			
Lumen Diameter	Clone	10	80.962	8.096	5.30	**
	Site	3	25.492	8.497	5.56	**
	Error	30	45.858	1.529		
	Total	43	152.312			
Wall Thickness	Clone	10	6.1491	0.6149	2.91	**
	Site	3	0.8389	0.2796	1.32	ns
	Error	30	6.3436	0.2115		
	Total	43	13.3316			

Within the growth layer the xylem mother cells, which are initially nearly identical in length to the cambial initials from which they were derived, divide rapidly during the production of early wood and produce cells which are shorter than the cambial initials (juvenile pattern) (Panshin and De Zeeuw, 1970). The reduction in length is proportional to the rate of growth, i.e., slower growth will tend to result in longer cells. It is possible to suppose that in fast grown trees (as *Eucalyptus* grown in Brazil) there is a shortening effect of the high growth rate, but this is overshadowed by the maturation of the tree.

Table 7.5 Wood fibre length (mm) of 11 *Eucalyptus* clones, mean fibre length per site (mm), maximum, minimum and within-site coefficient of variation (CV, %) for four sites in Brazil (SBA - Southern Bahia; SM1 - São Mateus 1; SM2 - São Mateus 2; ARA - Aracruz).

	SITE				
CLONE	SBA	SM1	SM2	ARA	MEAN
1	1.039	1.094	1.062	0.988	1.046
2	1.088	1.004	1.087	1.004	1.046
3	1.270	1.211	1.147	1.107	1.184
4	1.140	1.060	1.056	1.000	1.064
5	1.176	1.087	1.049	0.988	1.075
6	1.133	1.092	1.061	1.154	1.110
7	1.061	1.109	1.111	1.074	1.088
8	1.267	1.135	1.099	1.152	1.163
9	1.184	0.945	1.036	1.041	1.052
10	1.082	1.017	0.921	1.046	1.017
18	1.109	1.027	0.934	1.013	1.021
Mean (mm)	1.141	1.071	1.051	1.051	1.079
C.V. (%)	6.8	6.7	6.6	5.9	5.1
Min. (mm)	1.039	0.945	0.921	0.988	1.017
Max. (mm)	1.270	1.211	1.147	1.154	1.184

7.2.2 Variation of Fibre Diameter: between Sites and between Clones

The overall mean fibre diameter found in this work was 18.68 µm (Table 7.1 and Table 7.6), and can be classified as medium diameter fibre, using Panshin and De Zeeuw's (1970) classification. This value is within the published range of fibre diameters exhibited by *Eucalyptus* wood, where they vary from 12 µm to 20 µm (Barrichelo and Brito, 1976). The mean fibre diameter was highest at Southern Bahia (20.17 µm) and smallest at Aracruz (17.92 µm) (Table 7.6, Figure 7.2). As the mean fibre diameter at São Mateus 2 is very close (17.97 µm) to the latter, it can be inferred that there is a correspondence between the values of fibre length reported in the Section 7.1.1 and fibre diameter, in terms of maximum and minimum. This suggests that the same factors that affect the fibre length development could be also associated with the fibre diameter.

Table 7.6 Fibre diameter (μm) of 11 *Eucalyptus* clones, mean fibre diameter per site (μm), maximum, minimum and within-site coefficient of variation (CV, %) for four sites in Brazil (SBA - Southern Bahia; SM1 - São Mateus 1; SM2 - São Mateus 2; ARA - Aracruz).

	SITE				
CLONE	SBA	SM1	SM2	ARA	MEAN
1	22.84	18.98	17.92	17.23	19.24
2	20.15	18.56	17.63	17.69	18.51
3	22.18	22.91	19.08	20.41	21.14
4	21.10	17.08	19.92	19.00	19.28
5	18.56	17.70	16.71	15.72	17.17
6	19.99	19.74	19.04	19.78	19.64
7	18.60	17.52	17.24	17.61	17.75
8	19.53	17.52	17.01	17.66	17.93
9	20.32	17.62	16.99	17.71	18.16
10	20.05	19.07	18.30	17.05	18.62
18	18.52	18.50	17.87	17.28	18.04
Mean (μm)	20.17	18.65	17.97	17.92	18.68
C.V. (%)	7.1	8.7	5.7	7.4	5.9
Min. (μm)	18.52	17.08	16.71	15.72	17.17
Max. (μm)	22.84	22.91	19.92	20.41	21.14

The variation between clones in each site (Table 7.6), represented by the coefficient of variation, varied between 5.7 % (São Mateus 2) and 8.7 % (São Mateus 1). This suggests similar behaviour of the clones in the different sites. The mean (between three sites and nine clones) coefficient of variation of the fibre diameter of *Eucalyptus* clones found by Demuner and Bertolucci (1993) was 6.4 %. Clone 3 exhibited the widest variation of mean fibre diameters between sites (22.91 μm) while clone 5 exhibited the narrowest (17.17 μm). The difference between the widest and narrowest fibres was greatest at São Mateus 1 (34 % between clone 3 and clone 4) and smallest at São Mateus 2 (19.2 % between clone 4 and clone 5). Table 7.4 shows that for fibre diameter there are significant differences ($p \leq 0.01$) between clones and between sites. This finding is partially corroborated by the results shown by Demuner and Bertolucci (1993). They found that fibre diameter of nine five-year-old *Eucalyptus* wood clones cultivated in three sites in Brazil presented significant differences between clones, but not between sites.

7.2.3 Variation of Lumen Diameter: between Sites and between Clones

The overall mean fibre lumen diameter found in this work was 11.1 μm (Table 7.1 and Table 7.7). This value is slightly higher than the maximum in the range of fibre lumen diameters exhibited by *Eucalyptus* wood presented by Barrichelo and Brito (1976) (from 6.0 to 10.0 μm), but very close to those found by Shimoyama (1991) for *Eucalyptus grandis* (11.1 μm), *E. saligna* (10.1 μm) and *E. urophylla* (10.6 μm). The mean fibre lumen diameter was greatest at Southern Bahia (12.2 μm) and smallest at São Mateus 2 (10.3 μm) (Table 7.7, Figure 7.2). As the mean fibre diameter at Aracruz is similar (10.6 μm) to the latter, is possible to infer that there is a correspondence between the values of fibre length and fibre diameter reported in the previous sections and the lumen diameter, in terms of the performance of the mean dimensions in the different sites (Figure 7.2). This suggest that, in terms of the means between clones, the sites influence similarly all three characteristics.

The variation of the lumen diameter between clones for each site (Table 7.7), represented by the coefficient of variation, varied between 13.9 % (São Mateus 2) and 17.4 % (Aracruz). This suggests that the former produced wood having slightly more homogeneous lumen diameters than the other sites. Clone 3 exhibited

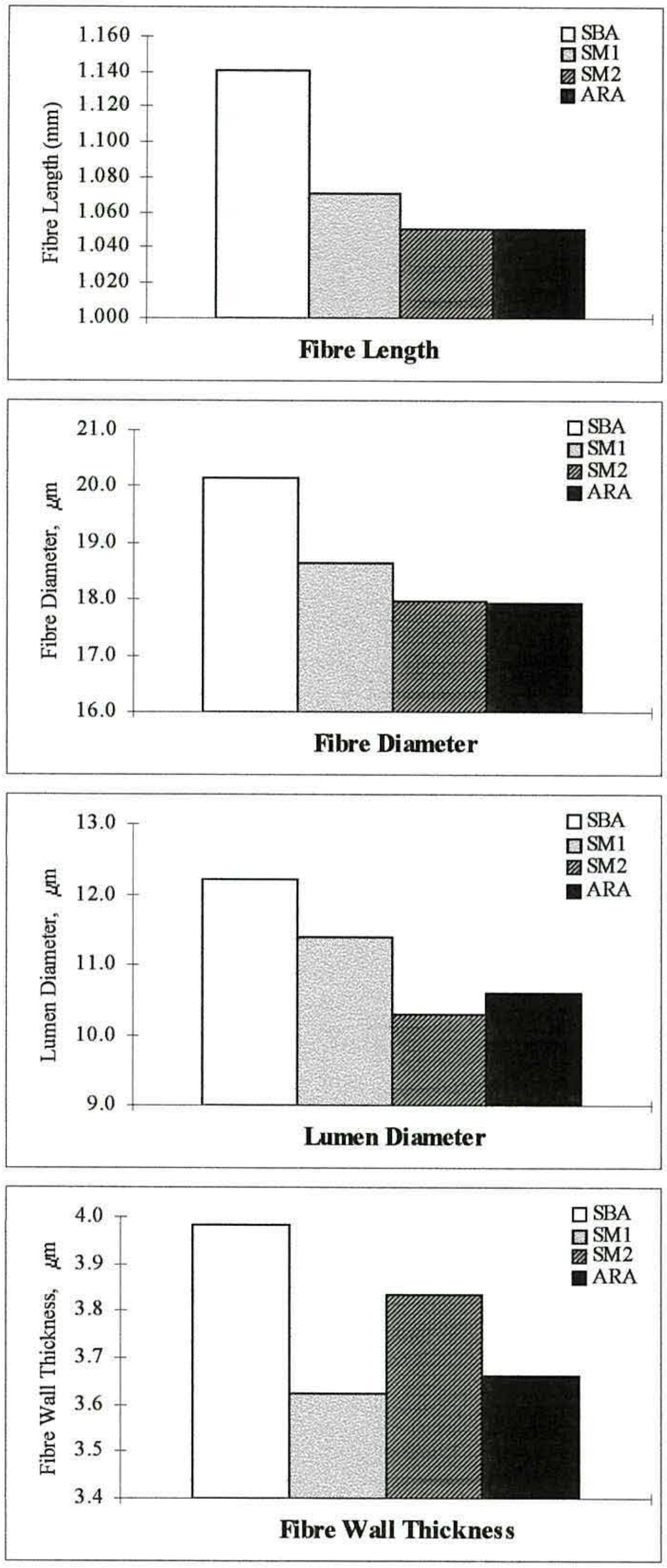


Figure 7.2 Comparison of the behaviour of the anatomical characteristic of the fibres in each of the four sites (SBA - Southern Bahia; SM1 - São Mateus 1; SM2 - São Mateus 2; ARA - Aracruz).

the widest variation in mean lumen diameter between sites (13.7 μm) while clone 9 exhibited the narrowest (9.1 μm). The difference between the widest and narrowest fibres was highest at Aracruz (89 % between clone 3 and clone 9) and smallest at São Mateus 2 (51 % between clone 3 and clone 9). Table 7.4 shows that there are significant differences ($p \leq 0.01$) between clones and between sites for lumen diameter.

Table 7.7 Fibre lumen diameter (μm) of 11 *Eucalyptus* clones, mean lumen diameter per site (μm) and within-site coefficient of variation (CV, %) for four sites in Brazil (SBA - Southern Bahia; SM1 - São Mateus 1; SM2 - São Mateus 2; ARA - Aracruz).

	SITE				
CLONE	SBA	SM1	SM2	ARA	MEAN
1	15.8	11.8	10.3	10.2	12.0
2	14.4	12.6	9.6	12.2	12.2
3	13.0	15.9	12.2	13.8	13.7
4	11.4	10.4	10.7	11.5	11.0
5	11.5	10.4	10.1	7.3	9.8
6	12.3	12.1	11.6	12.7	12.2
7	12.1	11.0	8.1	10.7	10.5
8	9.7	9.4	9.0	9.2	9.3
9	9.8	9.1	8.1	9.2	9.1
10	13.4	12.6	11.7	9.6	11.8
18	11.1	9.9	11.5	10.0	10.6
Mean (μm)	12.2	11.4	10.3	10.6	11.1
C.V. (%)	15.0	17.1	13.9	17.4	12.8
Min. (μm)	9.7	9.1	8.1	7.3	9.1
Max. (μm)	15.8	15.9	12.2	13.8	13.7

7.2.4 Variation of Fibre Wall Thickness: between Sites and between Clones

The overall mean wall thickness found in this work was 3.8 μm (Table 7.1 and Table 7.8). This value is inside of the assumed range of 2.5 μm to 6.0 μm for fibre lengths exhibited by *Eucalyptus* wood (Barrichelo and Brito, 1976). The mean wall thickness (Table 7.8, Figure 7.2) was greatest at Southern Bahia (4.0 μm) and smallest at São Mateus 1 (3.6 μm). The mean (of three sites and nine clones) wall thickness of five-year-old *Eucalyptus* clones found by Demuner and Bertolucci (1993) was 1.91 μm.

Table 7.8 Fibre wall thickness (μm) of 11 *Eucalyptus* clones, mean fibre wall thickness per site (μm) and within-site coefficient of variation (CV, %) for four sites in Brazil (SBA - Southern Bahia; SM1 - São Mateus 1; SM2 - São Mateus 2; ARA - Aracruz).

	SITE				
CLONE	SBA	SM1	SM2	ARA	MEAN
1	3.5	3.6	3.8	3.5	3.6
2	2.9	3.0	4.0	2.8	3.2
3	4.6	3.5	3.4	3.3	3.7
4	4.8	3.3	4.6	3.7	4.1
5	3.6	3.6	3.3	4.2	3.7
6	3.9	3.8	3.7	3.5	3.7
7	3.3	3.3	4.6	3.5	3.6
8	4.9	4.0	4.0	4.2	4.3
9	5.2	4.3	4.4	4.3	4.6
10	3.3	3.2	3.3	3.7	3.4
18	3.7	4.3	3.2	3.7	3.7
Mean (μm)	4.0	3.6	3.9	3.7	3.8
C.V. (%)	19.9	11.8	13.3	12.1	10.5
Min.(μm)	2.9	3.0	3.2	2.8	3.2
Max. (μm)	5.2	4.3	4.6	4.3	4.6

The variation between clones in each site, represented by the coefficient of variation, changed between 12.1 % (Aracruz) and 19.9 % (Southern Bahia) (Table 7.8). This suggests that the Aracruz site produced more homogeneous wood than the other sites. The mean variation (C.V. = 10.5 %) for wall thickness was similar to that observed for lumen diameter (C.V. = 12.8 %) but higher than that for both fibre diameter (C.V. = 5.9 % in Section 7.2) and fibre length (C.V. = 5.1 % in Section 7.1). The mean coefficient of variation (of three sites and nine clones) of the wall thickness of *Eucalyptus* clones found by Demuner and Bertolucci (1993) was 12.1 %. Clone 9 exhibited the greatest mean wall thickness between sites (4.6 μm) while clone 2 exhibited the smallest (3.2 μm). The difference between the thickest and thinnest fibres was highest at Southern Bahia (79 % between clone 2 and clone 9) and smallest at São Mateus 1 (43 % between clone 9 or 18 and clone 2). Table 7.4 shows that there are significant differences ($p \leq 0.01$) between clones for wall thickness, however between sites no significant difference was observed. Possibly, the higher fibre wall thickness observed for wood from São Mateus 2 contributed to this statistical result, as can be noted in Figure 7.2. Demuner and Bertolucci (1993) found that the wall thickness of nine clones of five-year-old *Eucalyptus* wood cultivated in three sites in Brazil showed significant difference between sites and between clones.

7.3 Site-Clone Interaction (Stability)

7.3.1. Stability of Fibre Length

Table 7.9 shows a classification of the clonal stability for fibre dimensions (fibre length, fibre diameter, lumen diameter and fibre wall thickness) based on the slope of the regression line (regression coefficient = β). This coefficient was obtained from the relationship between the fibre dimension of the clone (dependent variable) and the site means (independent variable). In addition, Table 7.9 presents the significance of the difference between the slope of the regression of the clone *versus* site means and the slope of the regression of the means *versus* mean (regression coefficient = 1.0). The classification of the stability was used by Malan and Verryn (1996) [as for basic density (Chapter 4) and nominal density and mechanical properties (Chapter 5)].

Table 7.9 Classification of the clone stability based on the coefficient of regression (β) of the clone means, using the site means as independent variable [average stability (regression coefficients between 0.8 and 1.2), below average stability (regression coefficients greater than 1.2), above average stability (regression coefficients less than 0.8)]. (*- regression coefficient significantly different from 1.0 at 0.05 level; **- regression coefficient significantly different from 1.0 at 0.01 level).

Clone	Fibre Length		Fibre Diameter		Lumen Diameter		Wall Thickness	
	Class.	β	Class.	β	Class.	β	Class.	β
1	above	0.065	below	2.37**	below	2.915*	above	0.100
2	above	0.542	average	1.117	below	2.112	average	1.000
3	below	1.517	average	1.064	above	0.474	below	2.300
4	below	1.235	above	0.768	above	0.114	below	3.90**
5	below	1.704	average	1.055	above	1.398	above	-0.900
6	above	0.312	above	0.254*	above	0.143	above	0.400
7	above	- 0.38*	above	0.527*	below	1.706	average	1.100
8	below	1.602	average	0.985	above	0.35**	below	1.600
9	below	1.789	below	1.334	above	0.697	below	1.900
10	average	1.078	average	1.071	below	1.453	above	- 0.20
18	below	1.473	above	0.424	above	-0.038	above	-1.700

Table 7.10 presents the coefficients of determination (R^2) of the regression of the property of the clone in each site *versus* the property mean for that site. Also the significance of the regression is shown.

For fibre length, four clones (1, 2, 6, and 7) have above average stability: these clones do not seem to be much affected by changes in the environment. Conversely, six clones (3, 4, 5, 8, 9 and 18) presented below average stability and are more sensitive to changes in the environment. For these clones an improvement in the site quality results in longer fibres. Only clone 10 has average stability and behaves similarly to the mean clone. The different slopes of the linear regression lines (examples are given in Figure 7.3) suggest that the clone × site interactions are complex. Studies carried out by Demuner and Bertolucci (1993) using nine clones of *Eucalyptus* on three sites and by Malan and Verryn (1996) using 37 clones of *E. grandis* on 26 sites have not found significant clone × site interaction for wood fibre length.

Table 7.10 Coefficients of determination (R^2; %) of the regression of the clone means, using the site means as independent variable (*- regression coefficient significantly different from 1.0 at 0.05 level; **- regression coefficient significantly different from 1.0 at 0.01 level).

Clone	Fibre Length	Fibre Diameter	Lumen Diameter	Wall Thickness
1	0.7	98.9**	90.2*	1.7
2	22.4	99.6**	83.0	10.8
3	82.5	41.6	6.5	48.1
4	81.6	22.5	3.3	98.8**
5	86.0	81.2	44.6	18.9
6	10.3	41.5	7.1	18.3
7	42.3	87.1	74.0	10.4
8	89.2*	87.9*	98.1**	46.8
9	59.9	90.1*	71.4	63.3
10	44.6	78.7	57.4	2.7
18	77.1	56.6	0.2	47.6

Despite the wide range of regression coefficients (Table 7.9), only clone 7 showed a value significantly different from 1 ($P \leq 0.05$). Four coefficients of determination were greater than 80 %, but only the regression for clone 8 was significant. This suggests that for most clones the predictable component of the observed genotype × environment interactions (estimated by the regression coefficient) is much smaller than the unpredictable component (estimated by the deviations from the regression, which could not be tested for significance because of the lack of replication). It appears that for the eleven clones on these four sites only clone 7 presented a significant slope different from the mean slope.

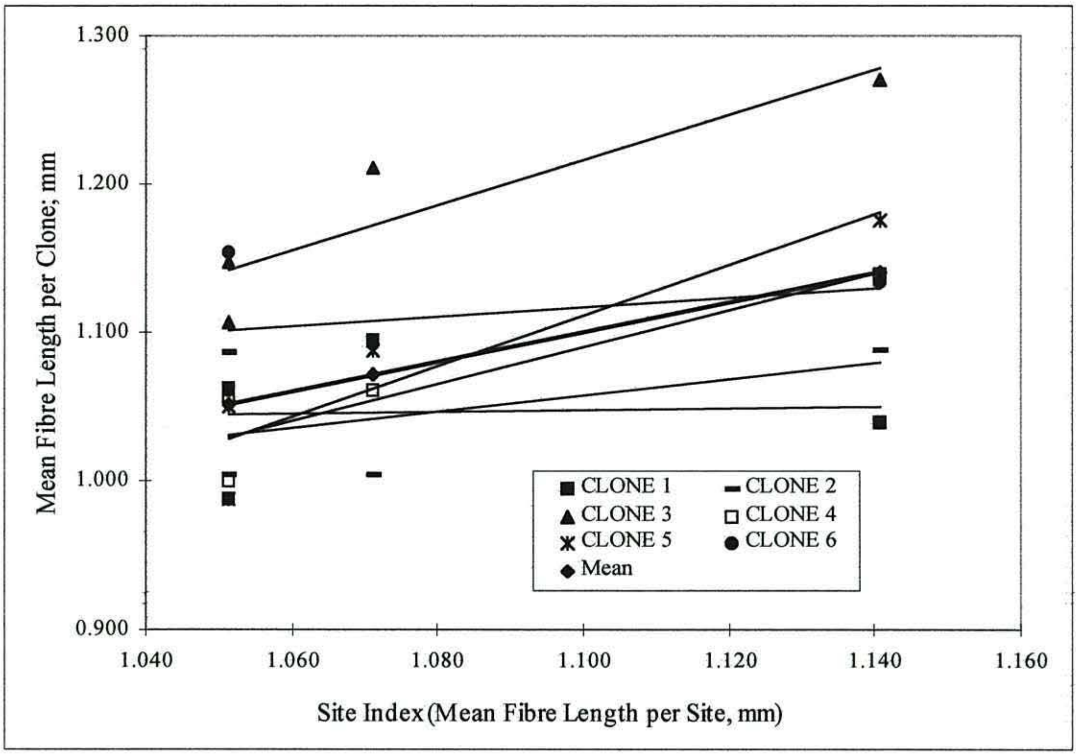


Figure 7.3 Regression lines showing the relationship between individual clone fibre length and the population mean of 26 clones (Site Index).

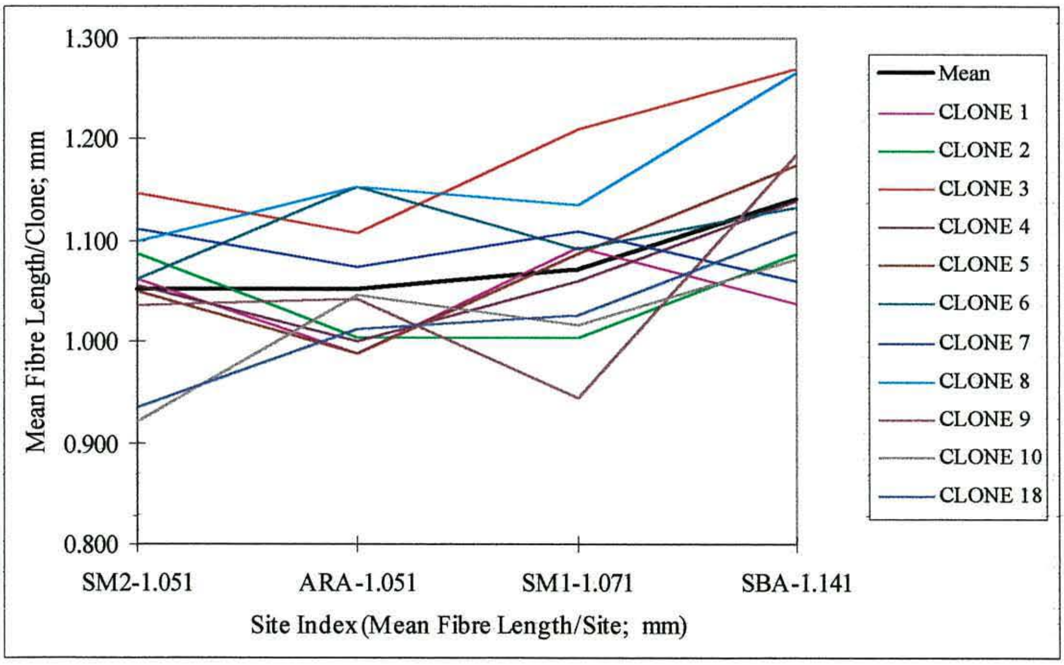


Figure 7.4 Fibre length of 11 *Eucalyptus* clones at four sites. ARA - Aracruz; SBA - Southern Bahia; SM1 - São Mateus 1; SM2 - São Mateus 2.

7.3.2 Stability of Fibre Diameter

Table 7.9 shows that five clones (2, 3, 5, 8 and 10) have average fibre diameter stability, clones 1 and 9 have below average stability and four clones (4, 6, 7 and 18) have above average stability. It seems that for this characteristic, the clones tends to behave more similarly to the mean clone. Three clones (1, 6 and 7) presented significant difference in their slopes compared with the slope of the mean (Table 7.9) and four clones (1, 2, 8 and 9) presented significant regressions which suggest that for these clones the fibre diameter in one site can be predicted using the fibre diameter of a wood clone collected at another site. The different slopes of the regression (examples are given in Figure 7.5) associated with the crossing lines shown in Figure 7.6 suggest that the clone × site interactions are complex. Studies carried out by Demuner and Bertolucci (1993) using nine clones of *Eucalyptus* and three sites or by Malan and Verryn (1996) using 37 clones of *E. grandis* and 26 sites have not found significant interaction clone × site for wood fibre diameter.

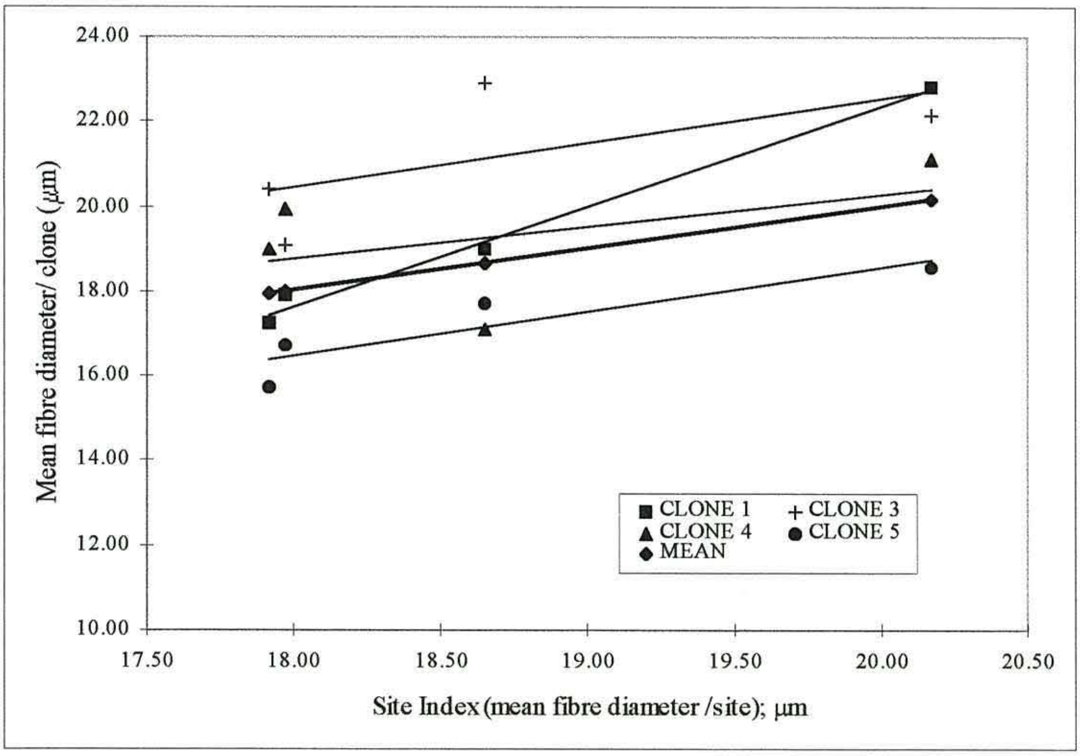


Figure 7.5 Regression lines showing the relationship of individual clone fibre diameter and the population mean of 11 clones (Site Index).

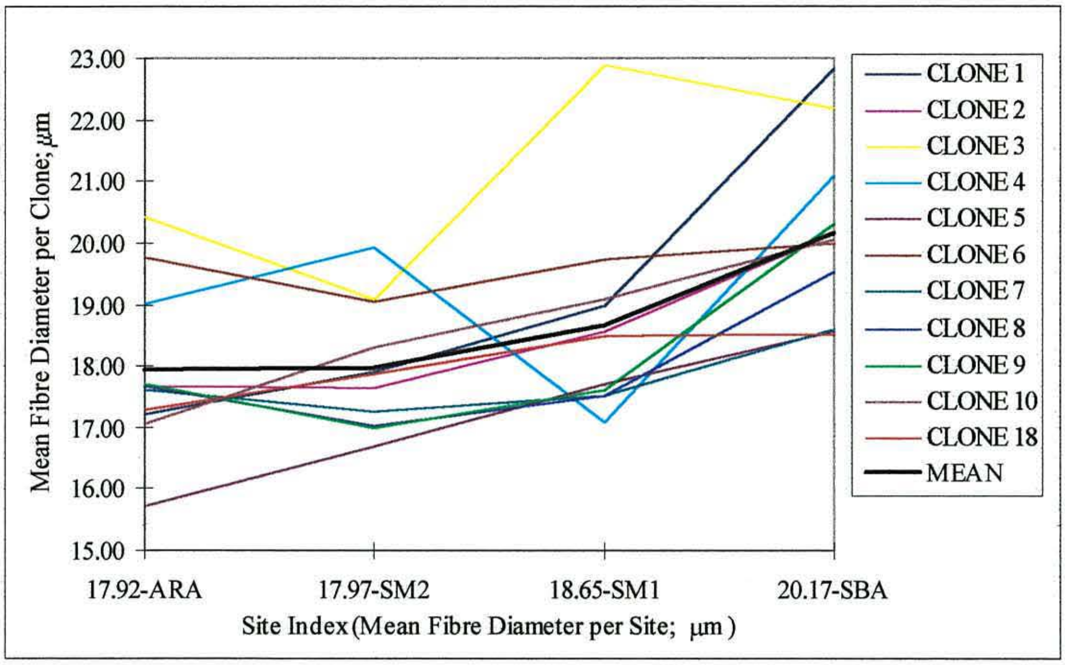


Figure 7.6 Fibre diameter of 11 *Eucalyptus* clones at four sites. ARA - Aracruz; SBA - Southern Bahia; SM1 - São Mateus 1; SM2 - São Mateus 2.

When these results are compared to those presented for fibre length it is possible to infer that there are greater possibilities of predicting fibre diameter in one site using data collected in other, than fibre length. Also, the significance of the difference between the slope of the linear regression of the mean (slope = 1) and the slope of the regression of a particular clone indicates that for fibre diameter more clones have behaviour distinctly different to the mean than do fibre length. This suggests a higher complexity of the clone × site interaction than that observed for fibre length.

7.3.3 Stability of Lumen Diameter

Table 7.9 shows the coefficients of linear regression of clone means against site means. The associated coefficients of determination are shown in Table 7.10. No clone showed average stability, five clones (numbers 1, 2, 5, 7, and 10) had below average stability and six clones (numbers 3, 4, 6, 8, 9, and 18) had above average stability. The different slopes of the linear regression lines (Figure 7.7 and 7.8) suggest that the clone × site interactions are complex. Despite the wide range of regression coefficients (Table 7.9), only clones 1 and 8 showed values significantly different from 1, and only the regression for clone 1 and 8 presented significant regressions.

The results presented in this section when compared with those presented for fibre diameter permit the inference that there are less possibilities of predicting lumen diameter in one site from the data collected in other, than for fibre diameter. Also, the significance of the difference between the slope of the linear regression of the mean (slope = 1) and the slope of the regression of a particular clone, indicates that for lumen diameter, a smaller number of clones than those revealed by the fibre diameter behave differently to the mean. This indicates less complexity of the clone × site interaction for lumen diameter than observed for fibre diameter.

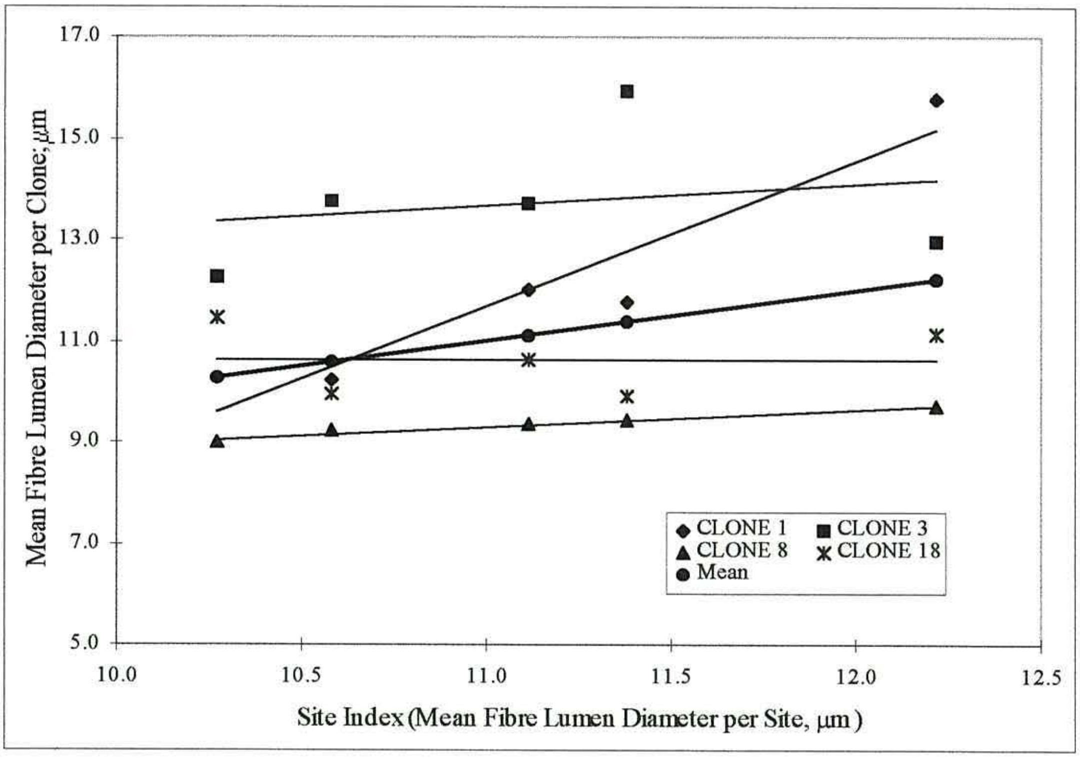


Figure 7.7 Regression lines showing the relationship of individual clone fibre lumen diameter and the population mean of 26 clones (Site Index).

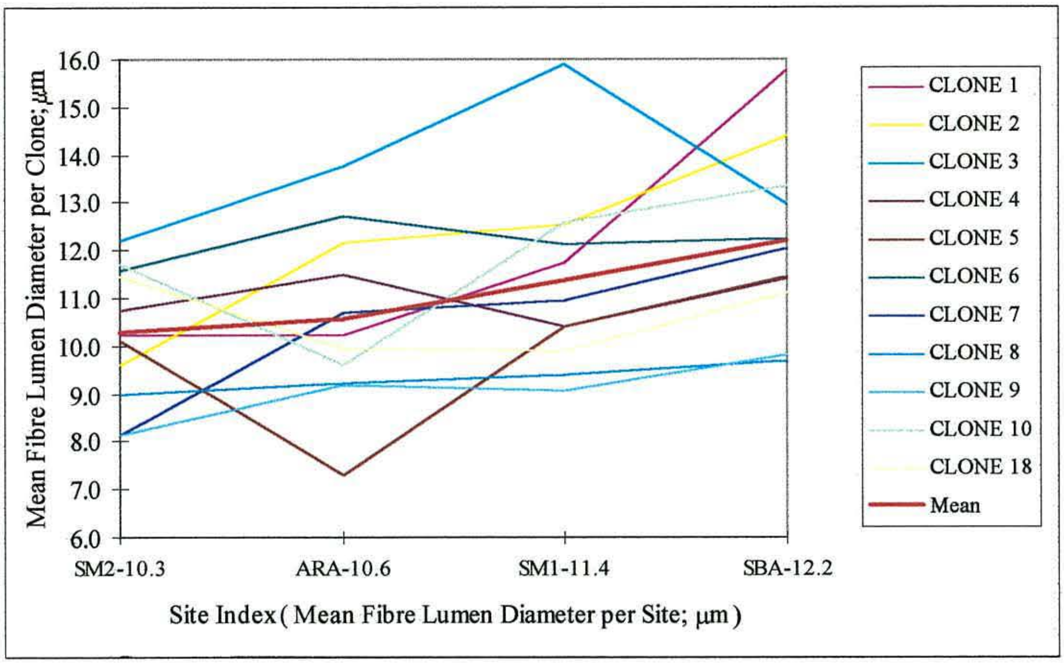


Figure 7.8 Lumen diameter of 11 *Eucalyptus* clones and mean at four sites. ARA - Aracruz; SBA - Southern Bahia; SM1 - São Mateus 1; SM2 - São Mateus 2.

7.3.4 Stability of Fibre Wall Thickness

Table 7.9 shows the coefficients of linear regression of clone means against site means of the 11 clones over the four sites. The associated coefficients of determination are presented in Table 7.10. Clones number 2 and number 7 showed average stability, four clones (numbers 3, 4, 8 and 9) had below average stability and five clones (numbers 1, 5, 6, 10 and 18) had above average stability. The different slopes of the linear regression lines (Figures 7.9 and 7.10) suggest that the clone × site interactions are complex.

Despite the wide range of regression coefficients (Table7.8), only clone 4 produced a value significantly different from 1 and presented a coefficient of determination greater than 80 %.

The results presented for this property when compared with those presented for fibre diameter permit the inference that there are less possibilities of prediction of wall thickness in one site from data collected in other, than for fibre diameter.

Also, the significance of the difference between the slope of the linear regression of the mean (slope = 1) and the slope of the regression of a particular clone, indicates

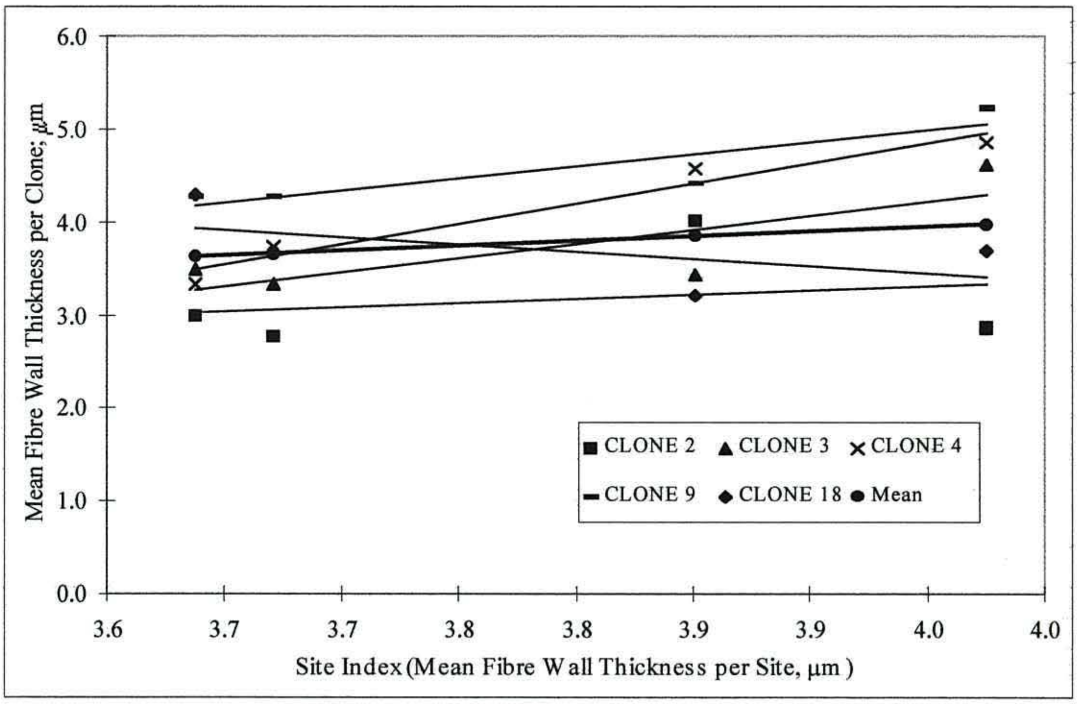


Figure 7.9 Regression lines showing the relationship of individual clone fibre wall thickness and the population mean of 26 clones (Site Index).

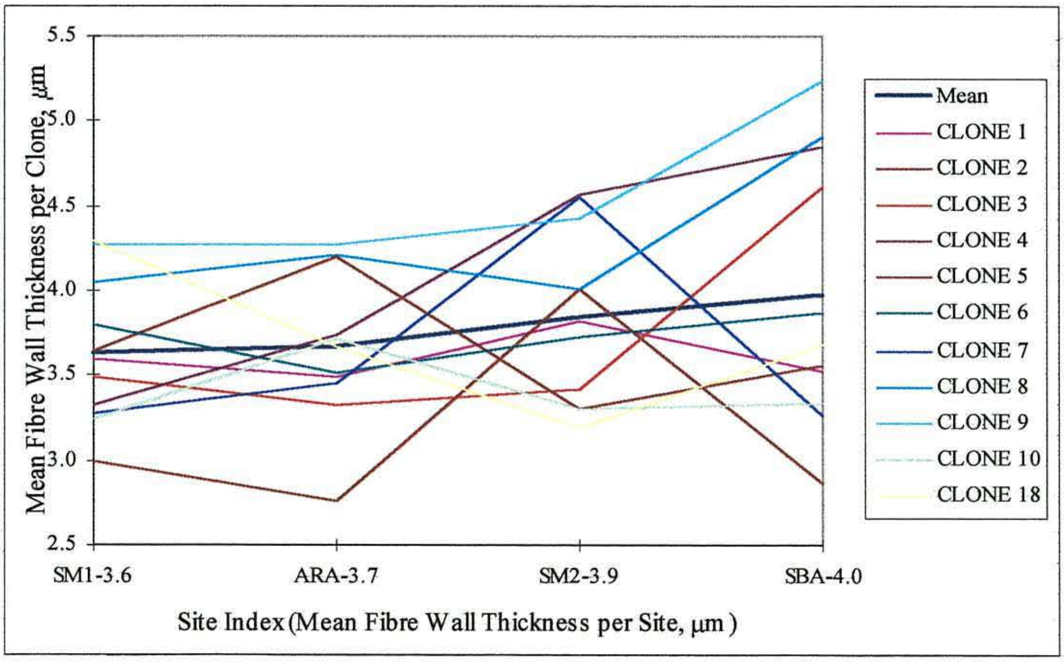


Figure 7.10 Wall thickness of 11 *Eucalyptus* clones and mean at four sites. ARA - Aracruz; SBA - Southern Bahia; SM1 - São Mateus 1; SM2 - São Mateus 2.

that for fibre wall thickness a smaller number of clones than those revealed by the fibre diameter behave differently to the mean.

7.4 Estimates of Heritability of Fibre Morphology

Broad sense heritability of fibre length for 11 clones grown on four sites were comparatively low (h^2 = 0.466) (Table 7.11) if compared to estimates for either density or mechanical properties (Chapter 5), where the heritabilities were higher than 0.5. It is important to mention however that the number of clones tested for fibre length was smaller than those previously presented. Except for wood density, the inheritance of fibre length has been the most studied wood property in hardwoods because it is often considered to be the limiting factor in their use (Zobel and Jett, 1995). A smaller heritability value suggests that in the studied conditions the dependency of the characteristic lies less on genetic factors than on environmental factors.

Table 7.11 Estimation of broad sense heritability for fibre dimensions calculated for inner, intermediate and outer positions for 11 *Eucalyptus* clones planted in four sites.

Property	Inner	Intermediate	Outer	Average
Fibre Length	0.127	0.335	0.284	0.466
Fibre Diameter	0.104	0.336	0.390	0.527
Lumen Diameter	0.228	0.220	0.554	0.518
Fibre Wall Thickness	0.216	0.188	0.360	0.323

In a literature survey, Raymond (1995) reported that the fibre length of *Eucalyptus* wood was under reasonably strong genetic control. Individual tree heritability ranged from 0.12 to 0.59 (mean 0.39), while family heritability ranged from 0.38 to 0.62 (mean 0.49) (Raymond, 1995). Based on these figures she concluded that this trait appears to be highly heritable.

There are fewer published estimates of broad sense heritabilities of fibre length in *Eucalyptus*, but those which exist are higher than the results of the present study. Thus the heritability of fibre length estimated from nine clones of *Eucalyptus* growing on one site in Brazil was 0.59 (Bertolucci *et al.*, 1992), and heritability estimated from data for nine *Eucalyptus* clones on three sites was 0.85 (Demuner and Bertolucci, 1993).

Estimates of broad sense heritability of fibre diameter for 11 clones grown on four sites were comparatively higher (h^2 = 0.527) than that reported for fibre length. Except for wood fibre length, the inheritance of other fibre dimensions of *Eucalyptus* wood has not been commonly studied. According to Zobel and Jett (1995) fibre diameter is rarely included in a tree breeding program because of its influence on the more easily measured specific gravity. Nevertheless, certain reported cases permit comparisons. Otegbeye and Kellison (1980), for instance, studying wood of 35 month-old *E. viminalis* grown in the southern United States, found family heritability equal to 0.82, which can be considered high despite the standard error being also high (0.42). Also, there are fewer published estimates of broad sense heritabilities of fibre diameter, but those which do exist are higher than the results of the present study. Thus the heritability of fibre diameter estimated from nine five-year-old clones of *Eucalyptus* growing on one site in Brazil was 0.76 (Bertolucci *et al.*, 1992), and heritability estimated from data for nine five-year-old *Eucalyptus* clones on three sites was 0.81 (Demuner and Bertolucci, 1993).

Estimates of broad sense heritability of lumen diameter for 11 clones grown on four sites were comparatively low (h^2 = 0.518) compared to estimates for either basic density (Chapter 4) or mechanical properties (Chapters 5) but were higher than that reported for fibre length and very similar to that reported for fibre diameter. An exception to the comparative lack of studies on the heritability in lumen diameter is the work of Otegbeye and Kellison (1980), who, studying wood of 35 month-old *E. viminalis* grown in the southern United States, found family heritability equal to 0.71.

Estimates of broad sense heritability of wall thickness for 11 clones grown on four sites were comparatively low ($h^2 = 0.323$) when compared to estimates for either the density or mechanical properties, and also lower than that reported for fibre length, fibre diameter and lumen diameter. Otegbeye and Kellison (1980), studying wood of 35 month-old *E. viminalis* grown in the southern United States found family heritability equal to 0.94, which is high despite the high standard error of 0.38. Also, there are fewer published estimates of broad sense heritabilities of wall thickness, but those which do exist are higher than the results of the present study. Thus the heritability of wall thickness estimated from nine clones of *Eucalyptus* growing on one site in Brazil was 0.85 (Bertolucci *et al.*, 1992) and heritability estimated from data for nine *Eucalyptus* clones on three sites was 0.80 (Demuner and Bertolucci, 1993).

The heritabilities for each fibre characteristic estimated for the inner, intermediate and outer positions are also presented in Table 7.11. It seems that there is a tendency of increasing heritability from inner to outer wood. This is clearer when the averages between characteristics are examined. These results suggest that genetic control of fibre dimensions are stronger for more mature wood than for juvenile wood. It is possible to infer from the heritabilities that the fibre dimensions of young trees are more susceptible to environmental factors. Contrary to nominal density and mechanical properties (Chapter 5), whose heritabilities were estimated for 26 clones, for these eleven clones the central position (or young trees) does not represent a recommended position to select clone for fibre dimension improvement.

7.5 Conclusions Regarding Variation of Fibre Morphology

Fibre dimensions determined in samples taken from eight-year-old trees of 11 *Eucalyptus* clones growing in tests at four sites in Brazil has permitted the following conclusions:

i) Fibre length and fibre wall thickness were higher in the outer than in the inner-wood in the four sites studied. The mean variation in these dimensions from the inner wood to the outer wood amounted to about 19 % in the former and 18 % in the latter. The difference in dimensions between the radial positions sampled was statistically significant ($p \leq 0.01$);

ii) Fibre diameter and lumen diameter showed no clear pattern of variation between radial position of sampling. Generally, there was no significant difference in the fibre diameters and lumen diameters between radial positions either when all data were analysed together or when analysed separately, per site. Only at São Mateus 2 was a significant difference in fibre diameter between the three radial positions found.

iii) Analysis of variance showed that there were significant differences in fibre length, fibre diameter and lumen diameter between clones and between sites. However, fibre wall thickness showed significant difference between clones, but not between sites.

iv) The broad sense heritability varied from 0.323 (fibre wall thickness) to 0.527 (fibre diameter), indicating that fibre dimensions are under moderate genetic control. It seems that there is a tendency of increasing the heritability from inner to outer wood. These results suggest that genetic control of fibre dimension are stronger for more mature wood than for juvenile wood.

v) There were marked differences in stability between clones for all fibre dimensions studied.

vi) Interactions were unpredictable and in most cases it was not possible to predict the fibre dimension found at one site from its value at another site. However, it was possible to identify clones which produced fibres of consistently larger or smaller dimension on the four test sites.

8 MICROFIBRIL ANGLE - VARIATIONS AND RELATIONSHIPS WITH FIBRE MORPHOLOGY

The microfibril angle referred to in this study is the average angle within the cell wall, observed using polarised light. The light passes through the complete cell wall comprising primary and secondary wall with its S_1, S_2 and S_3 layers, each having different predominant microfibril angles. As the S_2 layer comprises the largest proportion in the wall, the measured angle is close to that in this layer. In this work, bearing in mind that the microfibril angle changes along the length of the fibre, it was always measured at the mid point of the fibre. In conifers a larger microfibril angle is observed in radial walls where microfibrils form whorls around the bordered pits which are in greater numbers on radial walls than tangential walls (Meylan, 1967). Stuart and Evans (1995), however, point out that for *Eucalyptus* it is unlikely that pit apertures in fibre-tracheids would have a noticeable influence on microfibril angle, since fibre-tracheids in this wood have smaller and far fewer pits with only marginally more on radial walls than on tangential walls. Even so, the method used here favoured the measurement in the tangential face of the fibre, it being supposed that there are some variations in the angle between the radial and tangential walls.

Techniques for measuring microfibril angle such as X-ray diffraction, in spite of being quick and accurate, do not provide information on the between-fibre variability of microfibril angle and hence may give the impression that a sample with a microfibril angle of "x°" contains more or less uniform fibres (Donaldson, 1998). One advantage of the polarised light as a technique for measuring microfibril angle is that it gives information on between-fibre variability which provides a different perspective for treating wood as a composite of the properties of its individual fibres (Donaldson, 1998). The adopted method for determining microfibril angle using polarised light according to the method developed by Leney (1981) proved to be very adequate for the *Eucalyptus* fibres in this study, despite being time consuming. The main objective of this chapter is to discuss the variation of the microfibril angle in the S_2 layer of the libriform fibres of eleven clones planted in four sites. In addition, the mutual dependence of this characteristic with dimensions of the fibres was studied.

8.1 Microfibril Angle - Variation Across Stem Radius

Table 8.1 Radial variation (inner-wood, intermediate-wood and outer-wood) of microfibril angle (degree) of 11 *Eucalyptus* clones over four sites.

Site	Radial position			Mean
	Inner	Intermediate	Outer	
Southern Bahia	8.6	7.3	7.3	7.4
São Mateus 1	9.8	9.8	9.4	9.6
São Mateus 2	8.9	8.5	7.6	8.1
Aracruz	11.2	9.8	9.8	10.0
Mean	9.6	8.9	8.5	8.8

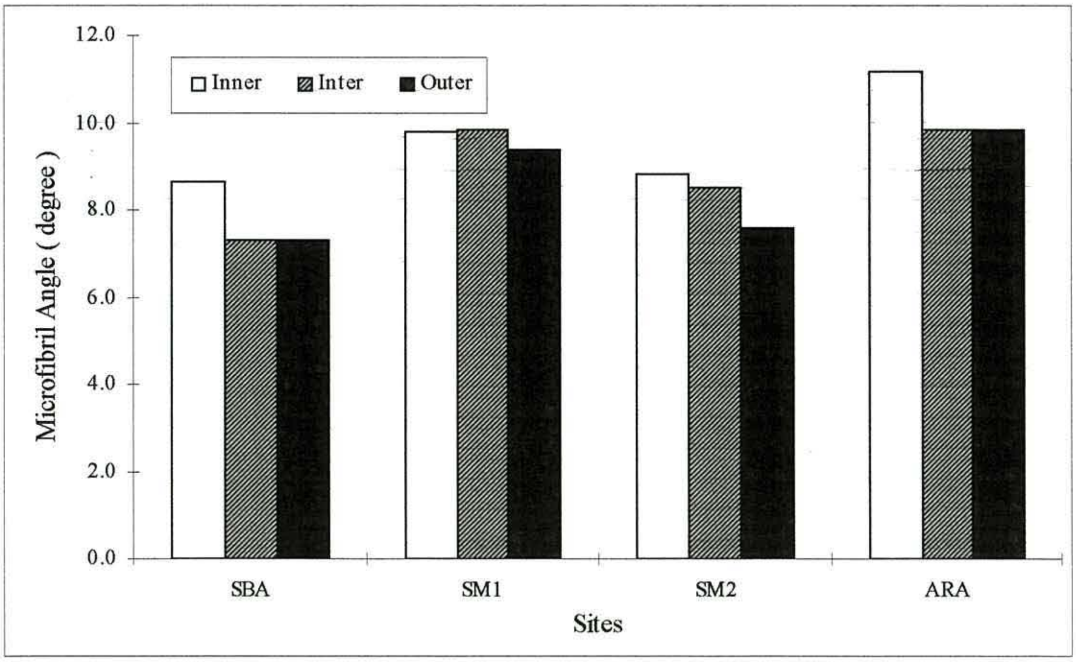


Figure 8.1 Radial variation of wood microfibril angle (degree) over different sites (SBA- Southern Bahia, SM1- São Mateus 1; SM2- São Mateus 2, ARA- Aracruz).

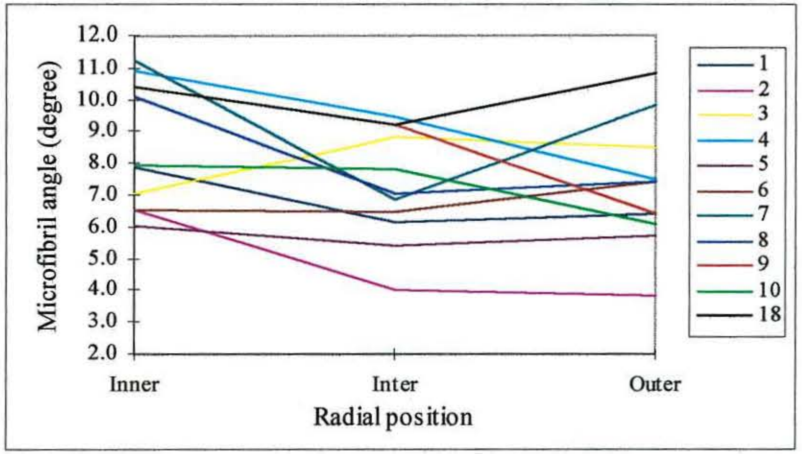
Table 8.2 Results of analysis of variance of wood microfibril angle of *Eucalyptus* clones. * - $P \leq 0.05$; **- $P \leq 0.01$; ns - non-significant at $P = 0.05$.

(a) Microfibril angle and radial position (one-way analysis of variance).

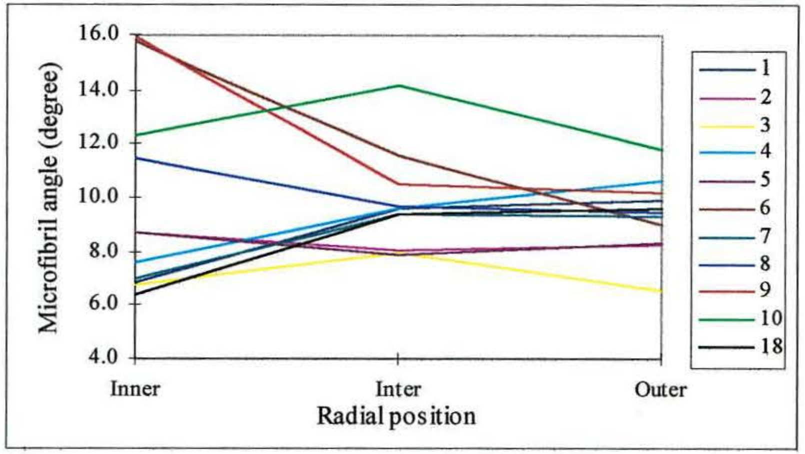
Source	DF	SS	MS	F	P
Radial	2	26.83	13.41	2.34	ns
Error	129	738.87	5.73		
Total	131	765.70			

(b) Microfibril angle, clone and site (Balanced Designs).

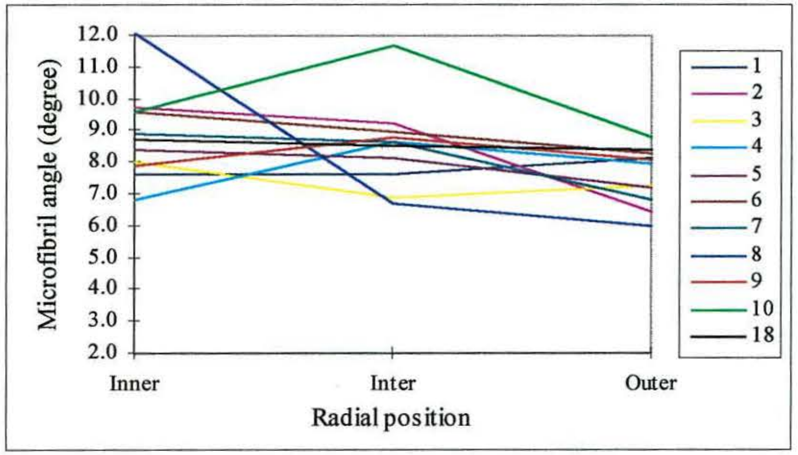
Position	Source	DF	SS	MS	F	P
	Clone	10	50.052	5.005	2.66	*
Average	Site	3	47.384	15.795	8.39	**
	Error	30	56.491	1.883		
	Total	43	153.927			
	Clone	10	118.534	11.853	1.60	ns
Inner	Site	3	43.089	14.363	1.94	ns
	Error	30	221.837	7.395		
	Total	43	383.461			
	Clone	10	81.157	8.116	3.26	**
Intermediate	Site	3	47.644	15.881	6.39	**
	Error	30	74.575	2.486		
	Total	43	203.376			
	Clone	10	36.487	3.649	1.76	ns
Outer	Site	3	53.493	17.831	8.62	**
	Error	30	62.053	2.068		
	Total	43	152.033			



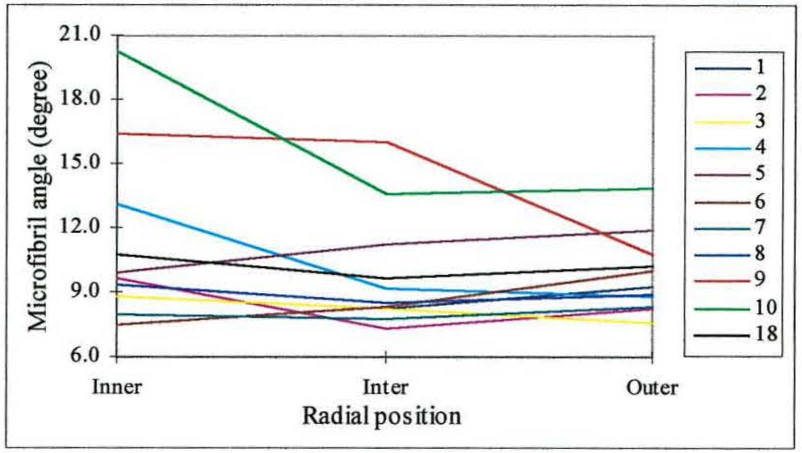
a) Southern Bahia



b) São Mateus 1



c) São Mateus 2



d) Aracruz

Figure 8.2 Radial variation of the microfibril angle per clone at different sites.

Table 8.1 indicates a decline in the mean measured microfibril angle from inner wood (9.6°) to intermediate wood (8.9°) and from intermediate wood to outer wood (8.5°). These represent an overall reduction of about 13 % from the inner position to the outer. However, there was no clear overall pattern of variation for all the four sites (Table 8.1 and Figure 8.1). Even so, the steepest angle was observed in the outer region of the log and the shallowest in the inner. This small variation was not sufficient to represent statistically significant differences between radial positions, as demonstrated by the analysis of variance in Table 8.2 (a) when all data were analysed together. Various authors, mainly working with conifers, but also with angiosperms, confirm that the helical angle of the microfibril indeed reduces from pith to bark or with the progress of the cambial age (Preston, 1934; Bendtsen *et al.*, 1981; Donaldson, 1992, 1993; Cave and Walker, 1994; Donaldson and Burdon, 1995; Li *et al.*, 1997). Saranpää *et al* (1998) showed that in Norway spruce (*Picea abies*) wood microfibril angle decreases from pith to bark according to a curvilinear, possibly exponential model. For *Eucalyptus*, in a study of the radial behaviour of the microfibril angle Stuart and Evans (1995), working with *E. nitens*, found that the angle decreased from pith to bark. In their work, the approximate reduction (from the cambial age of 11 years to 18 years) was from 22° to 17° for tangential latewood, from 29° to 19° for tangential earlywood and from 27° to 23° for radial earlywood. These rates are higher than those found in the present work and given in Table 8.1.

When the data of the present research were analysed by individual site, analysis of variance again showed no significant differences between radial positions (Table 8.3), even though differences between angles observed in microfibril from inner and outer wood were higher than those observed in the means. For a particular clone and site, however, the radial variation in the microfibril angle can exhibit a different tendency from that observed for the average between sites, as can be examined in Figure 8.2 and Appendix 2.5.

The systematic tendency of reducing microfibril angle in the pith to bark direction observed by various authors contrasts with the slight reduction shown in this work both for the mean (Table 8.1) and for individual clones (Figure 8.2). This is an aspect which deserves some consideration. Normally these findings have been reported for conifers (a few for broadleaves) slow grown in temperate regions with large numbers of growth rings present in a commercial sized log (Preston, 1934; Bendtsen *et al.*, 1981; Donaldson, 1992, 1993; Cave and Walker, 1994; Donaldson and Burdon, 1995). However, if a more detailed examination is done over some of these results it is possible to note that from one cambial age to the subsequent the microfibril angle stabilises or increases, and this is contrary to the general established tendency. Preston (1934) for example, relates that the average helical angle decreases across wood from one annual ring to the next (the helix steepens), though irregularly. In addition, Bendtsen *et al.* (1981) (for *Populus*) or Donaldson (1992) (for *Pinus radiata*) show variation between cambial ages varies at different heights in the stem and between different trees (genetic material). Thus, for fast grown eight-year-old *Eucalyptus* clone wood (which presents a large amount of juvenile wood and small number of growth layers), it is possible to suppose that the radial behaviour of the microfibril angle represents the "irregularity" as stated by Preston (1934) referring to the microfibril angle of slow grown woods. The above therefore suggests that the radial behaviour of the microfibril angle in a commercially sized log will depend not only on the nature of the genetic material, but also on the growth conditions. A more detailed study, between and within growth layers, is necessary so that the actual pattern of microfibril angle in this type of wood can be accurately described.

The tendency of the occurrence of higher microfibril angles in the central region of the log has some significant implications for tree improvement. Normally the central region of the log is the most critical zone, where juvenile wood is most troublesome. Thus, an alternative strategy for tree improvement might be to concentrate effort to reduce microfibril angle in this region. Since the innerwood is the first formed in the tree, is possible that such selection could be made early. Clearly, the results presented here specifically refer to only one longitudinal position and cannot characterise the whole tree. However, there are indications that for *Populus* (Bendtsen *et al.*, 1981), *Pinus radiata* (Donaldson, 1992) and for loblolly pine (Megraw *et al.*, 1998) microfibril angle is also highest in the base of the stem. A successful improvement program must, of course, initially assess the heritability of such characteristic.

Table 8.3 Analysis of variance of the microfibril angle between radial positions in each site. (n.s. not significant at P = 0.05)

Site	Radial Position
	d.f. (position = 2; d.f. (error = 30; d.f. (total) = 32
Southern Bahia	ns
São Mateus 1	ns
São Mateus 2	ns
Aracruz	ns

8.2 Variation of Microfibril Angle between Site and Between Clone

The overall mean microfibril angle found in this study was 8.8° (Table 8.1 and Table 8.4). The mean angle varied from 7.4° (at Southern Bahia) to 10° (at Aracruz) (Table 8.4) which are therefore within the range of angles reported by Boyd (1980) for wood of angiosperms, i.e., from 5° to 20°. Contrary to other anatomical characteristics discussed in previous chapters, the microfibril angle showed very different coefficients of variation between clones for each site, varying from 10.4 % to 22.2 % (Table 8.4), indicating a higher potential for improvement of characteristic. The maximum mean microfibril angle found was for clone 10 (11.1°) and the minimum for clone 2 (7.1°) (Table 8.4). Table 8.2 (b) shows that there are significant differences in microfibril angle between clones ($p \leq 0.05$) and between sites ($p \leq 0.01$). This indicates that microfibril angle must be selected in a particular circumstance to achieve a maximum gain in a genetic improvement of the wood. Variations in the microfibril angle were also shown to be significant between clones of *Populus* grown in China (Li *et al.*, 1997). In clones of radiata pine, Donaldson (1998) found that there was a large between-tracheid variation in microfibril angle. This variation was weakly influenced by genotype but not by cambial age. Trees within clones showed no significant variation.

Table 8.4 Wood microfibril angle (degree) of 11 *Eucalyptus* clones, mean microfibril angle per site (°), maximum, minimum and within-site coefficient of variation (CV, %) for four sites in Brazil (SBA - Southern Bahia; SM1 - São Mateus 1; SM2 - São Mateus 2; ARA - Aracruz).

CLONE	SITE				MEAN
	SBA	SM1	SM2	ARA	
1	6.5	9.5	7.9	8.8	8.2
2	4.2	8.3	7.9	8.0	7.1
3	8.5	7.1	7.2	8.0	7.7
4	8.6	10.0	8.1	9.4	9.0
5	5.6	8.2	7.7	11.5	8.3
6	7.0	10.7	8.7	9.1	8.9
7	8.8	9.1	7.8	8.1	8.5
8	7.6	9.8	6.9	8.8	8.3
9	7.9	10.9	8.3	13.4	10.2
10	7.0	12.8	10.0	14.4	11.1
18	10.2	9.2	8.5	10.0	9.5
Mean	7.4	9.6	8.1	10.0	8.8
C.V.	22.2	16.0	10.4	22.2	12.9
Min.	4.2	7.1	6.9	8.0	7.1
Max.	10.2	12.8	10.0	14.4	11.1

Table 8.5 shows the average microfibril angle of the 11 clones over the four sites, the coefficients of linear regression of clone means against site means and the associated coefficients of determination. Regression coefficients varied from -0.197 (clone 3) to 2.612 (clone 10), and coefficient of determination from 0.1 % (Clones 7 and 18) to 97.2 % (Clone 18). Adopting the assessment method used by

Malan and Verryn (1996), three clones (1, 6 and 8) showed average stability, four clones (2, 5, 9 and 10) below average stability and four clones (3, 4, 7 and 18) above average stability. The different slopes of the linear regression lines suggest that the clone × site interactions are complex (Figure 8.3 a, b).

Table 8.5 Mean wood microfibril angle (degree) of 11 *Eucalyptus* clones over four sites, coefficients of regression (β) of clone microfibril angle on site mean microfibril angle (degree), coefficients of determination (R^2) and the results of group regression analysis (F is significant if β is significantly different from 1) * P ≤ 0.05; ns - no significant.

Clone	Mean	β	R^2 (%)	F
1	8.2	0.960	83.0	ns
2	7.1	1.224	60.0	ns
3	7.7	-0.197	13.1	*
4	9.0	0.546	63.5	ns
5	8.3	1.757	78.1	ns
6	8.9	0.989	63.9	ns
7	8.5	0.014	0.1	ns
8	8.3	0.830	63.0	ns
9	10.2	1.975	90.1	ns
10	11.1	2.612	97.2	*
18	9.5	0.017	0.1	ns

Despite the wide range of regression coefficients, only clones 3 and 10 produced values different from 1 (P ≤ 0.05), and only three coefficients of determination were greater than 80 %. This suggests that for most clones the predictable component of the observed genotype × environment interactions (estimated by the regression coefficient) is much smaller than the unpredictable component (estimated by the deviations from the regression, which could not be tested for significance because of the lack of replication). It appears that for these eleven clones on these four sites, only for three clones is it possible to predict the microfibril angle found at one site from its value at another.

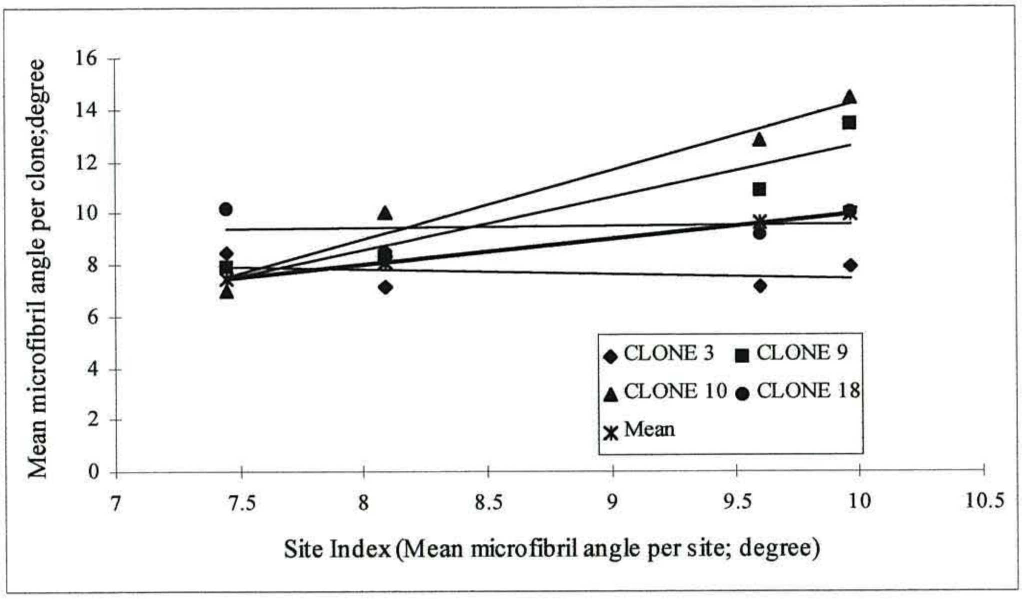


Figure 8.3 (a) Regression lines showing the relationship of individual clone microfibril angle and the population mean of 26 clones (Site Index).

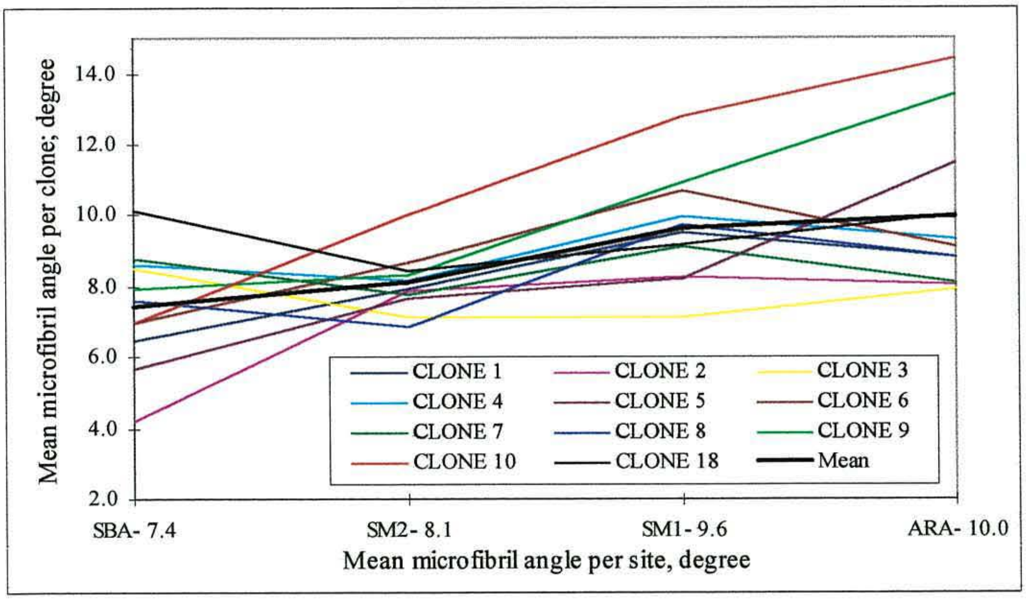


Figure 8.3 (b) Microfibril angle of 11 *Eucalyptus* clones at four sites. ARA - Aracruz; SBA - Southern Bahia; SM1 - São Mateus 1; SM2 - São Mateus 2.

8.3 Estimates of Heritability of the Microfibril Angle

Table 8.6 Estimates of heritabilities for each radial position of the basal bolt and for the average between positions based on analysis of variance (Table 8.2-b).

Position	Heritability
Inner	0.131
Intermediate	0.361
Outer	0.160
Average	0.293

The suggestion made by Zobel and Van Buijtenen (1989) that the microfibril angle is under moderate genetic control was not confirmed in this study. Estimates of broad sense heritability of microfibril angle for 11 clones grown on four sites [Table 8.2 (b)] were comparatively low (h^2 = 0.293) (Table 8.6) both for the average and for each radial position in the bolt if compared to estimates for other wood properties reported earlier in this study. Also, the heritabilities estimated for each radial position showed weak genetic control of the microfibril angle. This result also contrasts with that reported by Donaldson and Burdon (1995), where the clonal repeatability (an estimate of broad sense heritability) was equal to 0.7 for *Pinus radiata*. According to Donaldson and Burdon (1995) heritabilitiy can vary with site because of variations in the size of micro-environmental effects, and interactions between the genotypic effect and site. Heritability is therefore a site-specific as well as a population specific parameter. Despite its specificity, heritability is useful because when combined with variability it indicates the degree of response that can be expected by artificial selection for desirable traits (Donaldson and Burdon, 1995). In crops if heritability is high an improvement in wood quality may be readily achievable by selective breeding. The weak heritability found for microfibril angle (0.293) suggests that in the studied conditions the dependency of the characteristic is less on genetic than on environmental factors. Barnett *et al.* (1998) relate that microfibril angle is very sensitive to environmental stresses, such as wind, gravity and soil characteristics. According to them, this "plasticity", which seems to be largely independent of genetic control, may impose a serious limitation on what can be achieved by genetic transformation. If heritability is low then an environmental approach may sometimes be more successful. In practice, a combination of breeding and silviculture may yield the optimum improvement (Barnett, 1998).

Nakada *et al.* (1998) relate that for *Cryptomeria japonica* variation of microfibril angle between clone and between stands was significant, but clone × stands interaction was not significant. The variation in microfibril angle of *C. japonica* between stands was smaller than the variation between clones. The variation among stands was only statistically significant in the 5th ring but not in the 10th and 15th rings, and that F-values of a factor "stand" was much smaller than those of a factor "clone". These finding may have suggested that the environment could affect microfibril angle, but the effects of environment on microfibril angle were smaller than those of heritability. They concluded that microfibril angle was mainly controlled by genetic factors but could vary with the environmental factors.

Youming *et al.* (1998) relate that microfibril angle of *Pinus taeda* was genetically controlled at a medium level. The heritability of microfibril angle was from 0.934 to 0.788 and decreased as the tree aged, contrary to the environmental variance, which increased as the tree aged.

8.4 Relationship between Microfibril Angle and Fibre Morphology

In this discussion the microfibril angle and the fibre dimensions (length, diameter, lumen diameter and wall thickness) do not refer to same individual fibres but to averages of fifty measurements. However, it is important to note that both groups of variables were measured in material having approximately the same cambial age. This means that the influence of the cambial age in wood formation has been minimised for individual radial positions.

8.4.1 Correlation of Microfibril Angle with Fibre Morphology

Table 8.7 Correlation coefficients of microfibril angle with fibre morphology (fibre length, fibre diameter, lumen diameter and fibre wall thickness) for eleven clones at different sites. * - $P \leq 0.05$; **- $P \leq 0.01$; ns - non-significant at $P = 0.05$.

Site	Fibre length	Fibre diameter	Lumen diameter	Fibre wall thickness
Southern Bahia	0.17 (ns)	-0.13 (ns)	-0.48 (ns)	0.45 (ns)
São Mateus 1	-0.54 (ns)	-0.33 (ns)	-0.33 (ns)	0.13 (ns)
São Mateus 2	-0.82 (**)	0.25 (ns)	0.35 (ns)	-0.26 (ns)
Aracruz	-0.23 (ns)	-0.44 (ns)	-0.59 (*)	0.58 (*)
Mean between sites	-0.49 (ns)	-0.20 (ns)	-0.31 (ns)	0.29 (ns)

Table 8.7 shows the phenotypic correlation of the microfibril angle with fibre length, fibre diameter, lumen diameter and fibre wall thickness for each site and the mean between sites. According to the results (also shown in the Figure 8.4), only in a few cases were significant correlations between microfibril angle and the fibre dimensions found. The correlations of the microfibril angle against fibre length were predominantly negative, as were those for fibre diameter and lumen diameter. This indicates that in terms of these dimensions a large fibre corresponds to a small microfibril angle and *vice versa*. In sugi wood, researched by Hirakawa *et al.* (1998) microfibril angle was not affected by the growth rate and is not directly correlated with tracheid length, in spite of the fact that from pith to bark tracheid length increases and microfibril angle decreases. At Southern Bahia (Table 8.7) the correlation for fibre length, although weak, was positive, and at São Mateus 2 the correlations for fibre diameter and lumen diameter were also positive. In contrast, the correlations for fibre wall thickness with microfibril angle were predominantly positive, reflecting the opposite behaviour shown for the external and internal diameters of the fibres. In addition, for three sites, the correlations produced for wall thickness were of similar magnitudes to that exhibited for the lumen diameter, but with the opposite sign. This is due to the fact that the fibre wall thickness was

calculated from the difference between the fibre diameter and the lumen diameter. Most of the research carried out to assess the relationship between fibre dimensions and microfibril angle are directed towards conifers and normally use only tracheid length as a matched characteristic. Evidently this can result in inappropriate comparisons.

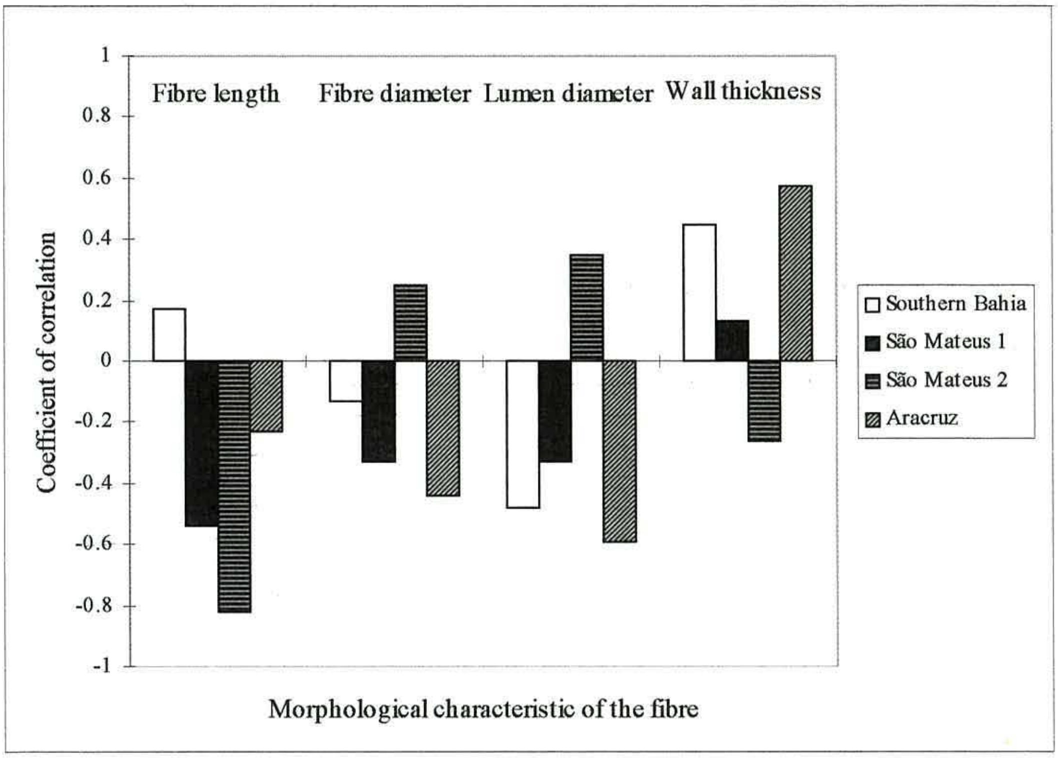


Figure 8.4 Coefficients of correlations of the microfibril angle with the fibre dimensions for eleven clones in four sites.

In general microfibril angle resulted in a higher correlation with fibre length than with the other dimensions (Table 8.7 and Figure 8.4). The highest coefficient of correlation of the microfibril angle with the fibre length was found at São Mateus 2. Except for the Aracruz site, most of the correlations were negative. In one described case, Jurbergs (1963) working with *Pinus elliottii*, found no significant correlation (-0.233) between microfibril angle and tracheid length. In contrast, the study carried out by Zhang and Zhong (1992) showed that the correlation between microfibril angle and fibre length of wood [five trees of *Quercus liaotungensis* (East-liaoning Oak)] was equal to -0.604, while the correlation of the microfibril angle with the fibre diameter was -0.869. Bendtsen *et al.* (1981) showed that while the microfibril angle decreased from pith to bark (*Populus*), fibre length increased in the same direction, however he did not correlate these characteristics. Indeed, the existence of parallelism in the patterns of two studied characteristic does not necessarily mean that the correlation between them has to be significant.

Table 8.8 Correlation coefficients of microfibril angle with fibre morphology (fibre length, fibre diameter, lumen diameter and fibre wall thickness) at the radial positions for eleven clones at different sites. * - $P \leq 0.05$; **- $P \leq 0.01$; ns - non-significant at $P = 0.05$.

Site	Radial position	Fibre length	Fibre diameter	Lumen diameter	Fibre wall thickness
	Inner	-0.24 (ns)	0.17 (ns)	-0.24 (ns)	0.42 (ns)
Southern Bahia	Inter	0.18 (ns)	0.19 (ns)	-0.27 (ns)	0.57 (ns)
	Outer	0.03 (ns)	-0.43 (ns)	-0.50 (ns)	0.19 (ns)
	Inner	-0.87 (***)	-0.32 (ns)	-0.41 (ns)	0.34 (ns)
São Mateus 1	Inter	-0.79 (**)	-0.26 (ns)	-0.19 (ns)	-0.17 (ns)
	Outer	-0.02 (ns)	-0.41 (ns)	-0.37 (ns)	0.13 (ns)
	Inner	-0.55 (ns)	-0.65 (*)	-0.57 (ns)	-0.43 (ns)
São Mateus 2	Inter	-0.81 (**)	-0.20 (ns)	0.04 (ns)	-0.27 (ns)
	Outer	-0.80 (**)	0.23 (ns)	0.30 (ns)	-0.22 (ns)
	Inner	-0.85 (**)	-0.28 (ns)	-0.36 (ns)	0.41 (ns)
Aracruz	Inter	-0.30 (ns)	-0.35 (ns)	-0.48 (ns)	0.65 (*)
	Outer	-0.08 (ns)	-0.35 (ns)	-0.44 (ns)	0.36 (ns)

Table 8.8 shows the phenotypic correlation of the microfibril angle with the fibre length, fibre diameter, lumen diameter and fibre wall thickness, calculated for specific radial positions, i.e., for the inner, intermediate and outer positions. The same lack of overall trends observed with the averages (Table 8.7) have been

found for individual positions. Even so, it was possible to identify significant correlations between some characteristics that had not been previously noted.

8.4.2 Modelling the Behaviour of Microfibril Angle with Fibre Morphology

Table 8.9 Linear regression to predict the microfibril angle of wood of the four sites together using fibre length (FL), fibre diameter (FD), lumen diameter (LD) and fibre wall thickness (WT) as predictors.

Predictor	Equation	R^2 (%)
Fibre length	MF = 16.6** - 7.38 FL **	17.5**
Fibre diameter	MF = 13.8** - 0.282 FD*	13.6 **
Lumen diameter	MF = 12.1** - 0.326 LD**	19 %**
Fibre wall thickness	MF = 7.42** + 0.357 WT	1.1 % (n. s.)

Table 8.9 shows that is possible to predict microfibril angle using fibre length, fibre diameter and lumen diameter as predictors when all the four sites are considered together. Despite the statistical significance of the equations, it can be noted in this table that the fibre dimensions are not very influential for microfibril angle, with the maximum coefficient of determination equal to 19 %, this being similar to that found for fibre length. Fibre wall thickness was not a significant predictor. The equations show that microfibril angle decreases with increase of fibre length, fibre diameter and lumen diameter.

Predictions of the microfibril angle of 11 clones in each site using fibre dimensions as predictors are given in Table 8.10, while the fitted lines are shown in Figures 8.5-8.8. The equations shown in this table have been selected from among eleven standard models (one linear and ten curvilinear) established in the SPSS (Statistical Package for Social Science) program, version 7.5. The selection of the models was firstly based on the coefficient of determination. Sequentially, other aspects were considered to support the selection: the significance of the regression, the analysis of the residuals, the clearness of the model and the appropriateness of the model to the studied relationship. The analyses were carried out using the data without transformation, since some transformations did not show significant results. As the table shows the quadratic model was favoured for three sites. However, at Aracruz the linear model was chosen for the regression with fibre length, while for the other characteristic the power model was preferred. Only in three cases was a significant result for the regression observed.

Table 8.10 Results of the analysis of regression to estimate the microfibril angle of 11 clones using the fibre morphology (fibre length-FL, fibre diameter-FD, lumen diameter-LD and fibre wall thickness-WT) as predictors for eleven clones at different sites. * - $P \leq 0.05$; **- $P \leq 0.01$; ns - non-significant.

Dimension	Site	Model	R^2	F	b0	b1	b2
FL		Power	0.040	ns	6.60	0.73	
FD	Southern	Quadratic	0.056	ns	80.48	-7.00	0.17
LD	Bahia	Quadratic	0.262	ns	0.94	1.47	-0.08
WT		Quadratic	0.364	ns	-19.82	12.81	-1.45
FL		Quadratic	0.315	ns	-27.30	80.03	-42.44
FD	São	Quadratic	0.302	ns	-72.78	8.61	-0.22
LD	Mateus 1	Quadratic	0.210	ns	-3.64	2.44	-0.11
WT		Quadratic	0.022	ns	18.86	-5.50	0.80
FL		Quadratic	0.664	**	18.47	-9.89	
FD	São	Quadratic	0.193	ns	-103.4	12.06	-0.33
LD	Mateus 2	Quadratic	0.127	ns	10.06	-0.62	0.04
WT		Quadratic	0.146	ns	28.71	-10.37	1.28
FL		Linear	0.05	ns	18.52	-8.14	
FD	Aracruz	Power	0.215	ns	418.06	-1.30	
LD		Power	0.381	*	51.94	-0.71	
WT		Power	0.361	*	2.72	0.99	

Considering that the results shown in Table 8.10 refer to the best models to express the relationships, it can be inferred that fibre length, external and internal diameters and wall thickness represent poor predictors of microfibril angle when the eleven clones are analysed together for each site. Even so, the contribution of each characteristic to microfibril angle variation is somewhat changeable: for fibre length it varies from 4 % to 66.4 %, for fibre diameter it varies from 5.6 % to 30.2 %, for lumen diameter it varies from 12.7 % to 38.1 %, and for fibre wall thickness it changes from 2.2 % to 36.1 %. These proportions suggest that another factor (or factors) not identified in this research are associated with the definition of the variation of the microfibril angle. Even so, the general tendency may be found for association with each predictor. Figures 8.5 - 8.8 illustrate the tendency of the relationships selected for each site.

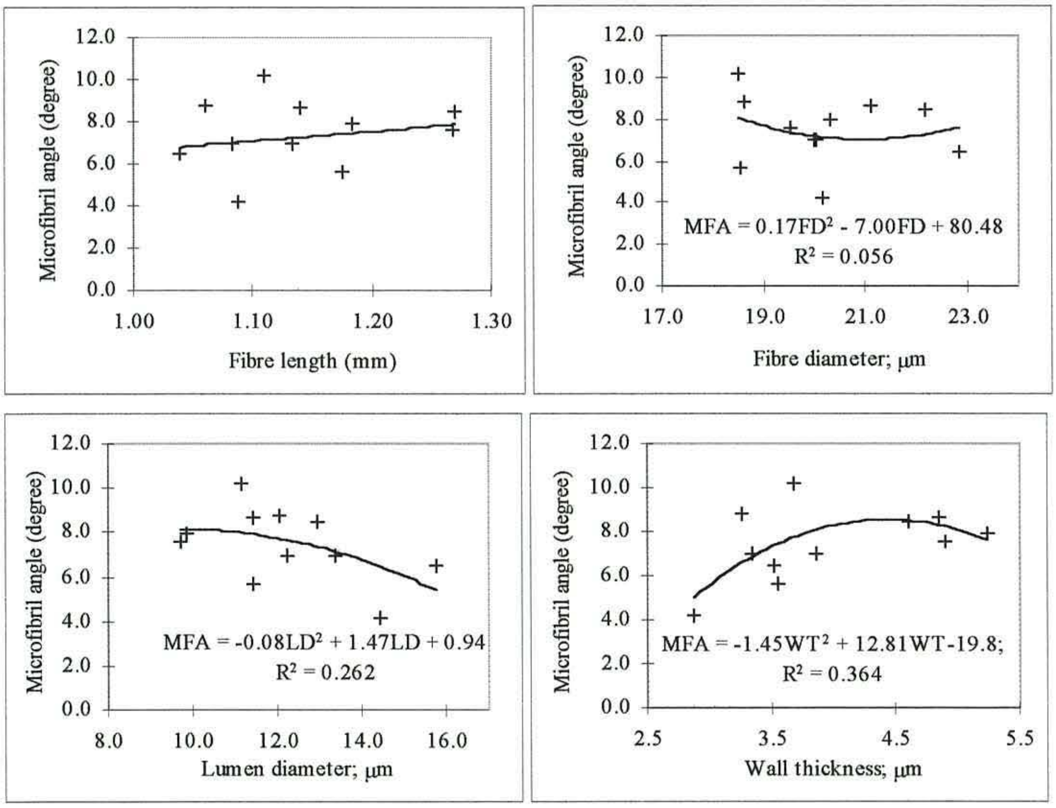


Figure 8.5 Estimation of the microfibril angle using analyses of regression, using the fibre dimension as the independent variable for eleven clones at Southern Bahia. (MFA- microfibril angle; FL- fibre length; FD- fibre diameter; LD- lumen diameter; WT- fibre wall thickness).

Table 8.11 Results of the analysis of regression to estimate the microfibril angle of 11 clones using the fibre morphology (fibre length, fibre diameter, lumen diameter and fibre wall thickness) at each radial position at Southern Bahia and São Mateus 1. * - P ≤ 0.05; **- P≤ 0.01; ns - non-significant.

Site	Size	Region	Model	R^2	F	b0	b1	b2
Southern Bahia	FL	Inner	Quadratic	0.064	ns	-4.29	29.46	-16.46
		Inter	Quadratic	0.039	ns	-16.14	38.78	-15.70
		Outer	Quadratic	0.200	ns	-186.83	322.7	-133.2
	FD	Inner	Quadratic	0.121	ns	-157.76	17.06	-0.44
		Inter	Quadratic	0.186	ns	-52.56	6.19	-0.16
		Outer	Quadratic	0.551	*	123.61	-10.9	0.26
	LD	Inner	Quadratic	0.246	ns	50.87	-6.60	0.25
		Inter	Quadratic	0.403	ns	-23.73	5.42	-0.23
		Outer	Quadratic	0.263	ns	7.23	0.45	-0.03
	WT	Inner	Quadratic	0.187	ns	9.93	-1.88	0.41
		Inter	Quadratic	0.594	*	-34.99	20.66	-2.41
		Outer	Quadratic	0.226	ns	-15.90	10.77	-1.20
São Mateus 1	FL	Inner	Quadratic	0.820	**	215.15	-386	178.9
		Inter	Quadratic	0.692	**	48.78	-66.1	27.29
		Outer	Quadratic	0.020	ns	-17.45	49.82	-22.93
	FD	Inner	Quadratic	0.193	ns	-111.87	13.19	-0.35
		Inter	Quadratic	0.086	ns	-15.97	2.84	-0.08
		Outer	Quadratic	0.278	ns	-12.84	2.64	-0.08
	LD	Inner	Quadratic	0.166	ns	22.43	-1.21	0.02
		Inter	Quadratic	0.184	ns	-18.70	4.64	-0.19
		Outer	Quadratic	0.216	ns	7.67	0.57	-0.04
	WT	Inner	Quadratic	0.119	ns	-11.91	7.56	-0.03
		Inter	Quadratic	0.058	ns	38.82	-15.3	1.99
		Outer	Quadratic	0.025	ns	11.53	-1.46	0.23

Table 8.12 Results of the analysis of regression to estimate the microfibril angle using the fibre morphology (fibre length, fibre diameter, lumen diameter and fibre wall thickness) for eleven clones at each radial position at São Mateus 2 and Aracruz. * - $P \leq 0.05$; **- $P \leq 0.01$; ns - non-significant.

Site	Size	Position	Model	R^2	F	b0	b1	b2
São Mateus 2	FL	Inner	Quadratic	0.295	ns	11.27	7.97	-11.56
		Inter	Quadratic	0.708	**	69.94	-106.2	44.85
		Outer	Quadratic	0.708	**	-9.52	39.56	-21.63
	FD	Inner	Power	0.476	*	117.93	-0.93	
		Inter	Quadratic	0.084	ns	103.11	-10.03	0.27
		Outer	Quadratic	0.059	ns	21.54	-1.75	0.05
	LD	Inner	Power	0.355	*	32.40	-0.58	
		Inter	Quadratic	0.385	ns	-74.37	16.51	-0.81
		Outer	Quadratic	0.194	ns	15.69	-1.82	0.10
	WT	Inner	Quadratic	0.269	ns	-5.81	9.63	-1.54
		Inter	Quadratic	0.062	ns	8.66	0.59	-0.16
		Outer	Quadratic	0.111	ns	20.83	-6.44	0.76
Aracruz	FL	Inner	Quadratic	0.934	**	273.61	-523.6	257.9
		Inter	Quadratic	0.099	ns	-31.17	88.48	-46.90
		Outer	Quadratic	0.046	ns	-116.90	235.0	-108.6
	FD	Inner	Quadratic	0.100	ns	-33.50	5.48	-0.17
		Inter	Quadratic	0.126	ns	45.24	-3.28	0.07
		Outer	Quadratic	0.129	ns	48.79	-3.87	0.09
	LD	Inner	Quadratic	0.131	ns	11.23	0.67	-0.06
		Inter	Quadratic	0.256	ns	30.35	-3.02	0.10
		Outer	Quadratic	0.199	ns	9.78	0.45	-0.04
	WT	Inner	Power	0.202	ns	0.88	2.10	
		Inter	Power	0.426	*	0.77	1.99	
		Outer	Power	0.164	ns	5.95	0.367	

When a particular region of the log was studied the analysis of regression carried out to estimate the microfibril angle using the fibre morphology as a predictor (Table 8.11 - 8.12) revealed a similar complexity to that found when the data were analysed using the average values between radial positions in the log (Table 8.10).

For clonal plantations, the behaviour of the microfibril angle for a specific clone is also important. Appendix 6 shows that microfibril angle can be predicted in each clone using fibre dimensions as predictors and each site as a replicate. However, as expected, there is no unanimity for all clones in terms of the chosen model, the best predictor, or the significance of the equation.

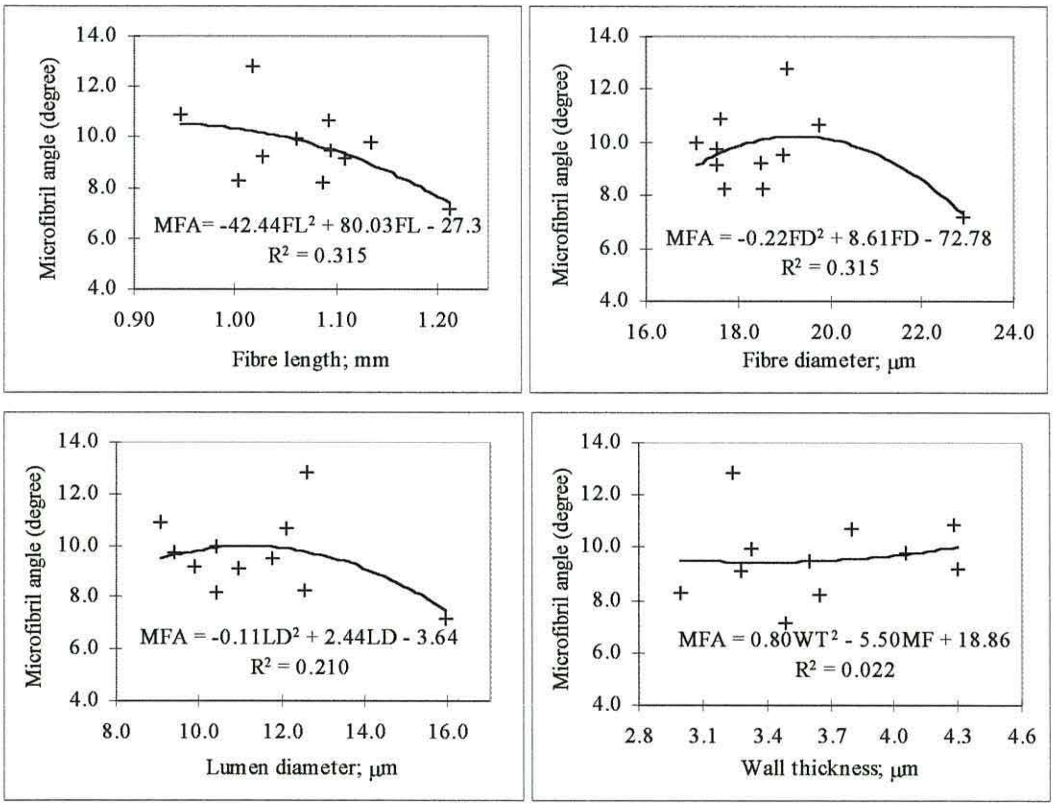


Figure 8.6 Estimation of the microfibril angle using analyses of regression, using the fibre dimension as the independent variable for eleven clones at São Mateus 1. (MFA- microfibril angle; FL- fibre length; FD- fibre diameter; LD- lumen diameter; WT- fibre wall thickness).

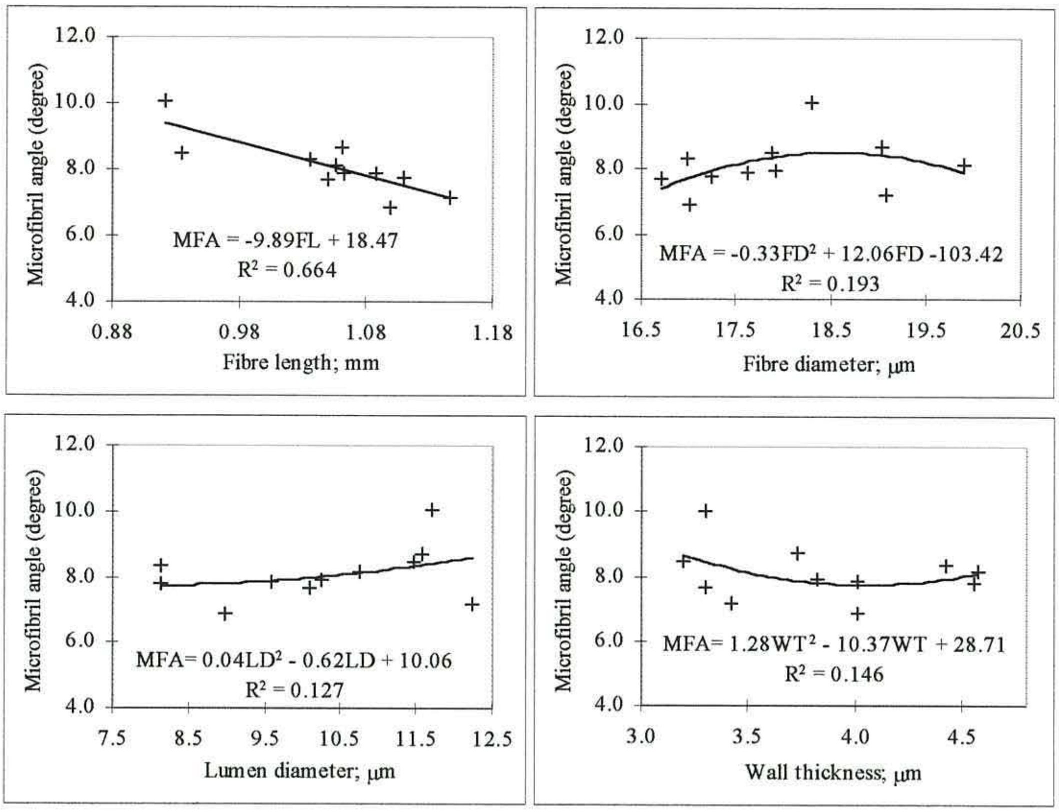


Figure 8.7 Estimation of the microfibril angle using analyses of regression, using the fibre dimension as the independent variable for eleven clones at São Mateus 2 (MFA- microfibril angle; FL- fibre length; FD- fibre diameter; LD- lumen diameter; WT- fibre wall thickness).

The considerable spread of the experimental points about the regression lines is not surprising in a biological study. According to Preston (1974) the microfibril angle indicated by the maximum extinction position (m.e.p.) under polarised light varies among the cell types. In cells which are broad and whose lengths may be measured in microns, the helices are flat; in tracheids which are narrower and whose lengths may be measured in milimetres, the helices are moderately steep; in fibres which are still narrower and whose lengths may be measured in centimetres, the helices are very steep (Preston, 1974). The possibility of a correlation between microfibril angle and cell dimensions was early directed to the chance that this might extend to variations among cells of the same type (Preston, 1934). The relationship of microfibril angle (θ) and tracheid length (L) was explained by Preston (1934) by a linear model. In general, as L increases, θ decreases and the relation between L and θ may be expressed as L = k cot θ, when L is expressed in μm and where k is a constant [c. 1500 μm for *Cedrus*, 880 μm for *Larix*, and 2200 μm for *Abies*]. In the present work the introduction of either the cotangent or tangent of microfibril angle instead of the direct angle as the predictor in the equations resulted only in a slight improvement of the regressions (not shown in this thesis).

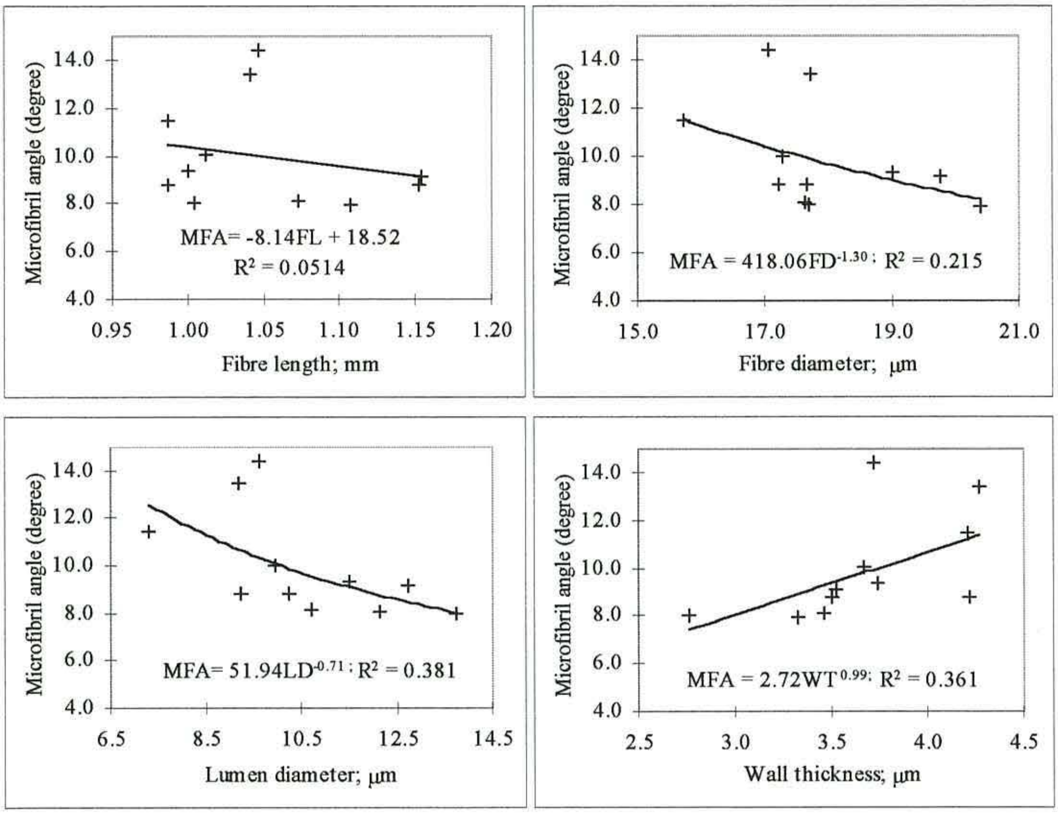


Figure 8.8 Estimation of the microfibril angle using analyses of regression, using the fibre dimension as the independent variable for eleven clones at Aracruz (MFA- microfibril angle; FL- fibre length; FD- fibre diameter; LD- lumen diameter; WT- fibre wall thickness).

The reasons for discrepancies between these results and the published data of other authors is not known. Nonetheless, a few tentative explanations may be offered in addition to the possibility of experimental error in measurement of microfibril angle, including variation in angle around and along individual fibres. In this work, the previously discussed variation of the microfibril angle from pith to bark, provides support in explaining the weak relationship between microfibril angle and fibre length. Since the microfibril angle does not appear to behave exactly as in woods more frequently presented in the literature, it may be expected that its relationship with fibre length also results in a different pattern. In addition, the pattern for fibre length presented in Chapter 7 showed a more standard behaviour, increasing from pith to bark in a consistent manner on all sites. This arises because in any one growing season these components are produced by longitudinal division of a fusiform initial in the cambium, which is itself steadily increasing in length (Preston, 1974). This lack of correspondence possibly contributed to a poorer fitting of the equations to the data. Also, it is important to consider that the data in this study covers only eight years growth, with a relatively small range of fibre lengths, mostly being juvenile wood - most previous work includes considerably more growth rings, with a larger range of fibre lengths.

Different rates of growth mediated by environmental factors between clones might also be another modifying factor. This possibility has been examined by Wardrop and Preston (1950) studying *Pseudotsuga* trees. They found that in tracheids which have elongated more rapidly the microfibrillar helix tends to remain flatter than in tracheids which have elongated more slowly. Growth rate is therefore a modifying factor, though not of course, necessarily a direct one (Preston, 1974). Despite this possible implication, this effect was not considered in the experimental design used in this study. Normally microfibril angle is higher in the region of juvenile wood (inner wood) with commensurate excessive longitudinal shrinkage and distortion of kiln-dried lumber (Megraw, 1985). The concern is that by improving the site condition in young plantations, the juvenile period might extended further than the standard. Research by Shupe *et al.* (1996) showed that a cultural treatment applied in young loblolly pine can lead to a significantly lower microfibril angle in the outerwood than corewood. Further evidence of the environmental effect on microfibril orientation was given by Megraw et *al.* (1998) describing the pattern of variation in microfibril angle as a function of ring position and height in the stem in loblolly pine wood. These authors were able to identify that a slight increase in microfibril angle was related to the thinning which took place four years prior to sampling: an increase in microfibril angle is frequently found following treatments resulting in a sudden increase in growth.

According to Boyd (1985), detailed studies of many hundreds of tissues from a substantial number of trees show that all the significant variations in microfibril orientation that occur in S_2 are closely related to strains imposed on the fibres at the time of their differentiation. Indeed, the correlation between growth strain and microfibril orientation was demonstrated to be highly significant at the 99 % level of probability (Boyd, 1980). For primary wall growth, the factors which define the direction of principal strain apparently determine microfibril angle (Boyd, 1985). Similar factors must influence microfibril orientation and wall architecture during secondary wall development, with lignification having an important additional effect: the entry of matrix material and lignin between the microfibrils leads to an increase in their average separation, and thus to thickness swelling of the cell wall (Boyd, 1985). According to Boyd, even though many investigators have recorded the orientations of microfibrils in different layers of the wall of wood fibres, apparently no substantial effort has been made to explain the basic causes of microfibrils forming at different characteristic orientations in each of the several wall layers. He says that the most supported theory on the regulation of orientation relates to microtubules[1] adjacent to the plasmalemma. According to Roberts *et al.* (1988) there has been general support for the concept that cortical microtubules regulate the orientation of the wall microfibril: it has been shown that there is frequent coincidence of direction of these microtubules in the protoplasm and the orientation of microfibrils formed simultaneously on the inner face of the wall (Boyd, 1985). However it has been pointed out by Preston (1974) that on many occasions contrary observations have been made, and in numerous other cases there was no evidence of the presence of microtubules during microfibril formation.

[1] Microtubules are straight, elongated, hollow structures composed of globular protein subunits. Their average diameter is 23-27 ηm. Microtubules occur in the peripheral cytoplasm close to cell walls still growing in area and thickness, in the mitotic and meiotic spindles, and in the phragmopalst that arises between the daughter nuclei at the telophase (Fahn, 1982).

The origins of variations in the microfibril angle in environmental factors have been considered by various authors. The idea that the microfibril angle is determined as a result of the effect of physical forces acting on the plasma membrane and changing its structure is an attractive one, and could account for alterations in the microfibril angle and the coincident alignment of microtubules (Barnett *et al.*, 1998). These authors argue that if microfibril angle is controlled by external factors (via microtubule orientation), it is possible that attempts to change it directly by genetic engineering may be doomed to failure. Controlling cell length would appear to offer one way by which small, useful changes could be induced, but the angles are known to be very sensitive to environment stresses (Barnett *et al.*, 1998). The relatively weak heritability found in this study for microfibril angle (h^2 = 0.29) seems to corroborate such considerations. According to Boyd (1985), apart from those serious anomalies, the theory fails to identify a basic factor responsible for "deciding on" a desirable, advantageous, or passively inevitable microfibril orientation. As an alternative to the microtubule theory, Preston considered that his concept of the involvement of "granule arrays" in the formation of microfibrils would be compatible with changes of orientation between lamellae in secondary walls (Boyd, 1985). According to Boyd (1985) that compatibility apparently is complete when considered in conjunction with his theory - that the strain pattern in the cell wall, as reflected in the plasmalemma, is the basic factor which determines or modulates microfibril orientation at formation.

8.5 Conclusions

Microfibril angle of the S_2 layer of the secondary wall of fibres determined in samples taken from eight-year-old trees of 11 *Eucalyptus* clones growing in tests at four sites in Brazil has permitted the following conclusions:

i) The overall mean microfibril angle measured for this wood was 8.8°. It reduced slightly across the stem, but this variation (which did not follow a linear pattern), was not statistically significant. However, the microfibril angle presented statistical differences between sites and between clones.

ii) The broad sense heritability of the microfibril angle was weak (h^2 = 0.293) when estimated from 11 clones on four sites.

iii) There were marked differences in stability between clones (linear regression coefficients from - 0.197 to 2.612).

iv) Interactions were unpredictable (coefficients of determination 0.1 % to 97.2 %) and in only two cases was it possible to predict the microfibril angle found at one site from its value at another. Also it was possible to identify clones which produced wood with steeper or wider microfibril angle on the four test sites.

v) Microfibril angle only occasionally significantly correlated with parameters of fibre dimensions. However, it was possible to identify that the strongest mean correlation was associated with fibre length.

vi) Analysis of regression showed that in particular cases the microfibril angle can be significantly predicted by the values of fibre length, fibre diameter, lumen diameter and fibre wall thickness using linear and non-linear models.

vii) Various theories attempt to explain the microfibril orientation, but it appears that environmental stresses have an important role in defining the microfibril angle of *Eucalyptus* wood. This is evidenced by the weaker genetic control (and consequent higher environmental influence) observed in wood formed near the pith, when the young tree is more susceptible to environmental stresses.

9 RELATIONSHIPS BETWEEN THE ANATOMICAL STRUCTURE AND DENSITY AND THE MECHANICAL PROPERTIES OF *Eucalyptus* WOOD

The object of this chapter is to provide a better understanding of the relationships between the mechanical properties of *Eucalyptus* and the nominal density. This chapter thus presents results and discusses: *1)* the dependence of the nominal density on fibre dimensions (length, fibre diameter, lumen diameter and fibre wall thickness) and *2)* the dependence of the mechanical properties (compression strength parallel to the grain, modulus of rupture in static bending, modulus of elasticity in static bending) on the nominal density, fibre dimensions, grain angle and microfibril angle.

The value of the property per clone was calculated as the weighted average for the three radial positions of the log. The association between variables was verified using simple, linear multiple and curvilinear (for individual site) analyses of regression. The statistical significance of the relationships when referred to in the text will be: * (significant at level of $p \leq 0.05$), ** (significant at level of $p \leq 0.01$), *** (significant at level of $p \leq 0.001$), ns (no significant).

9.1 Prediction of Nominal Density

Table 9.1 Mean, standard deviation and coefficient of variation of eleven clones of *Eucalyptus* on four sites.

Characteristic	Mean	Standard deviation	CV (%)
Nominal density (g.cm^{-3})	0.557	0.06	10.5
Modulus of rupture (MPa)	93.4	15.7	16.8
Modulus of elasticity (MPa)	9737	1476	15.2
Compression strength (MPa)	55.3	6.0	10.9
Fibre length (mm)	1.08	0.1	7.2
Fibre diameter (μm)	18.7	1.6	8.6
Lumen diameter (μm)	11.1	1.9	16.9
Fibre wall thickness (μm)	3.8	0.6	14.9
Grain angle (mm in 100 mm)	3.5	1.6	46.1
Microfibril angle (degree)	8.8	1.9	21.6

Table 9.1 presents the mean, standard deviation and coefficient of variation for all wood characteristics studied in this chapter of the eleven clones of *Eucalyptus* on four sites.

Table 9.2 Linear regression analysis to estimate the nominal density and mechanical properties of wood of 11 clones produced on four sites together, using nominal density and anatomical characteristics as predictors. [* - P ≤ 0.05; **- P≤ 0.01; ***- P≤ 0.001; ns - non-significant at P = 0.05].

Response	Predictor	R^2	F (sig)	b0	b1	S
Nominal Density	Fibre length	0.001	0.04 ns	0.570	- 0.0202	0.0496
	Fibre diameter	0.186	9.12 **	0.806	- 0.0136	0.0467
	Lumen diameter	0.386	23.93 ***	0.723	- 0.0158	0.0378
	Fibre wall thickness	0.498	32.72 ***	0.343	0.0535	0.0311
Compression Strength	Nominal density	0.502	40.27 ***	16.6	68.6	4.055
	Fibre length	0.020	0.84 ns	43.2	10.8	5.728
	Fibre diameter	0.059	2.55 ns	70.9	-0.855	5.614
	Lumen diameter	0.265	14.09 ***	72.0	- 1.49	4.763
	Fibre wall thickness	0.110	5.06 *	42.1	3.37	5.459
	Grain angle	0.003	0.13 ns	55.6	- 0.198	5.777
	Microfibril angle	0.004	0.15 ns	56.5	- 0.180	5.776
Modulus of Rupture	Nominal density	0.536	39.24 ***	- 4.6	177	9.079
	Fibre length	0.130	5.81 *	26.7	62.5	12.98
	Fibre diameter	0.012	0.48 ns	110	- 0.90	13.01
	Lumen diameter	0.129	5.64 *	119	- 2.42	12.37
	Fibre wall thickness	0.333	19.51 ***	38.9	14.3	11.79
	Grain angle	0.158	6.55 *	101	- 2.67	10.28
	Microfibril angle	0.006	0.20 ns	94.2	- 0.391	10.63
Modulus of Elasticity	Nominal density	0.340	19.10 ***	2854	12307	977
	Fibre length	0.179	8.53 **	2134	6970	1202
	Fibre diameter	0.068	2.70 ns	13277	- 186	1160
	Lumen diameter	0.266	13.44 ***	13528	- 323	1051
	Fibre wall thickness	0.218	10.58 **	6108	990	1110
	Grain angle	0.224	10.67 **	11020	- 364	1100
	Microfibril angle	0.190	8.43 **	11744	- 247	1035

Units: Nominal density, $g.cm^{-3}$; compression strength parallel to the grain, MPa; modulus of rupture, MPa; modulus of elasticity, MPa; fibre length, mm; fibre diameter, µm; fibre wall thickness, µm; grain angle, mm in 100mm; microfibril angle, degree). [b0 = constant; b1 = regression coefficient (slope); s = estimated standard deviation about the regression line.

Table 9.2 presents the results of the linear regression to estimate the nominal density using fibre dimensions as predictors. An examination of this table shows that the fibre wall thickness is the best predictor of nominal density, followed by lumen diameter and fibre diameter. Fibre length was not a good predictor of nominal density. This contrasts with the results found for *E. saligna* by Shymoyama (1991), who found a significant correlation between basic density and fibre length, but not between basic density and lumen diameter. This author also found significance in the correlation of the basic density with fibre diameter and fibre wall thickness (*E. saligna*). For *E. grandis* she found a significant correlation of the basic density with fibre diameter and lumen diameter, while for *E. urophylla* none of the fibre dimensions resulted in significant correlations with basic density.

The results presented here indicate that 50 % of the variation of nominal density may be significantly explained by fibre wall thickness, 40 % can be explained by lumen diameter and 19 % by fibre diameter. It is important to mention that fibre wall thickness has no significant correlation with fibre diameter, while lumen diameter is closely associated with fibre diameter. This means that clones with larger fibres also present larger lumen diameters, but fibre wall thickness remain approximately constant. Each of the fibre dimensions, as well nominal density (Chapter 5), is reasonably strongly controlled genetically (Chapter 7). Apart from this genetic control, they also can be altered by changing the growing conditions. In combination, they jointly determine what is defined as wood density, a most useful, important, and meaningful wood concept even though it is determined by a complex of characteristics (Zobel and Van Buijtenen, 1989). Of these, fibre wall thickness has been described as a key anatomical factor controlling density of wood. Wimmer (1992) showed that wood density of *Pinus sylvestris* is determined directly by wall thickness of latewood tracheids, followed by the tracheid length. Zhang and Zhong (1992) describe how the density of wood of *Quercus liaotungensis* is determined directly by the percentage of cell wall material.

With regard to the coefficient of regression (b1) shown in Table 9.2, Figure 9.1 illustrates that an increase of the fibre diameter and of lumen diameter results in a reduction of the nominal density, while an increase of the fibre wall thickness implies in an increase of the nominal density.

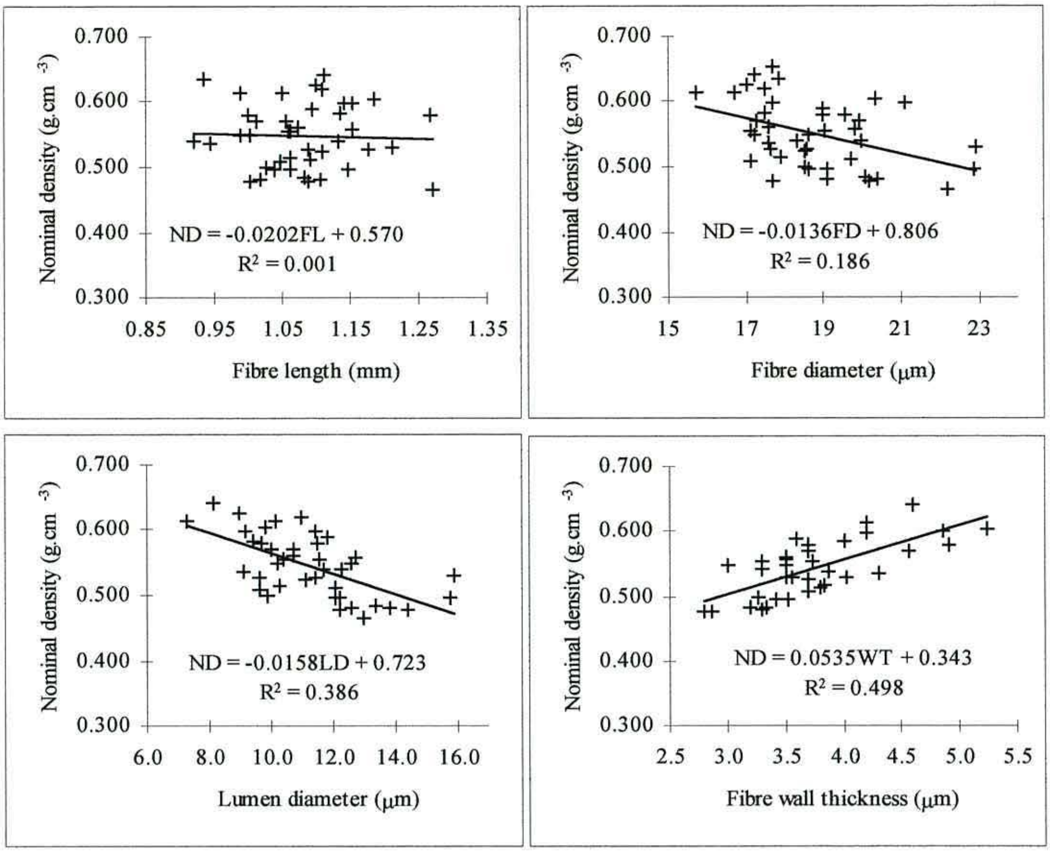


Figure 9.1 Fitted equations to represent the linear regression of the nominal density (ND, g.cm^{-3}) of 11 clones, using fibre length (FL, mm), fibre diameter (FD, μm), lumen diameter (LD, μm), fibre wall thickness (WT, μm) and microfibril angle (MF, mm) as predictors.

The prediction of the nominal density for each site is presented in Appendix 7.2. The response to the regression is rather variable, both in terms of the site and in terms of the independent variable. However, the prediction of the nominal density in each site is no less important since wood characteristics are strongly influenced by environmental factors, as has been demonstrated in previous chapters. For wood from Southern Bahia, only fibre diameter did not produce a significant estimation of nominal density. However, at São Mateus 1, nominal density has not shown significant dependence on any particular fibre dimension. At São Mateus 2 the nominal density is most dependent on fibre diameter and lumen diameter, while at Aracruz, lumen diameter and fibre wall thickness produced the best fitting.

A multiple linear regression using fibre length as an additional predictor to fibre wall thickness did not improve the significance of the regression. The relationship using the others parameters was not attempted due the co-linearity between the variables.

The dependence of the nominal density on fibre dimensions at the levels obtained for this wood indicates that mainly fibre wall thickness and lumen diameter are important factors in determining nominal density (50 % of the variation). It is important to consider that other anatomical characteristics, such as vessel diameter and parenchyma cell characteristics, as well their proportion in wood, are also important in the determination of wood density. In addition, there is the influence of the chemical composition which also contributes to the nominal density of wood.

It is expected that there is no general relationship between the microfibril angle and the density of wood from normal *Eucalyptus* trees. However, in wood from reorientated trees with induced reaction wood (tension) Boyd (1980) found a highly significant inverse relationship. This suggests that the occurrence of a close relationship between nominal density and microfibril angle could be caused by the same factors causing tension wood in the trees.

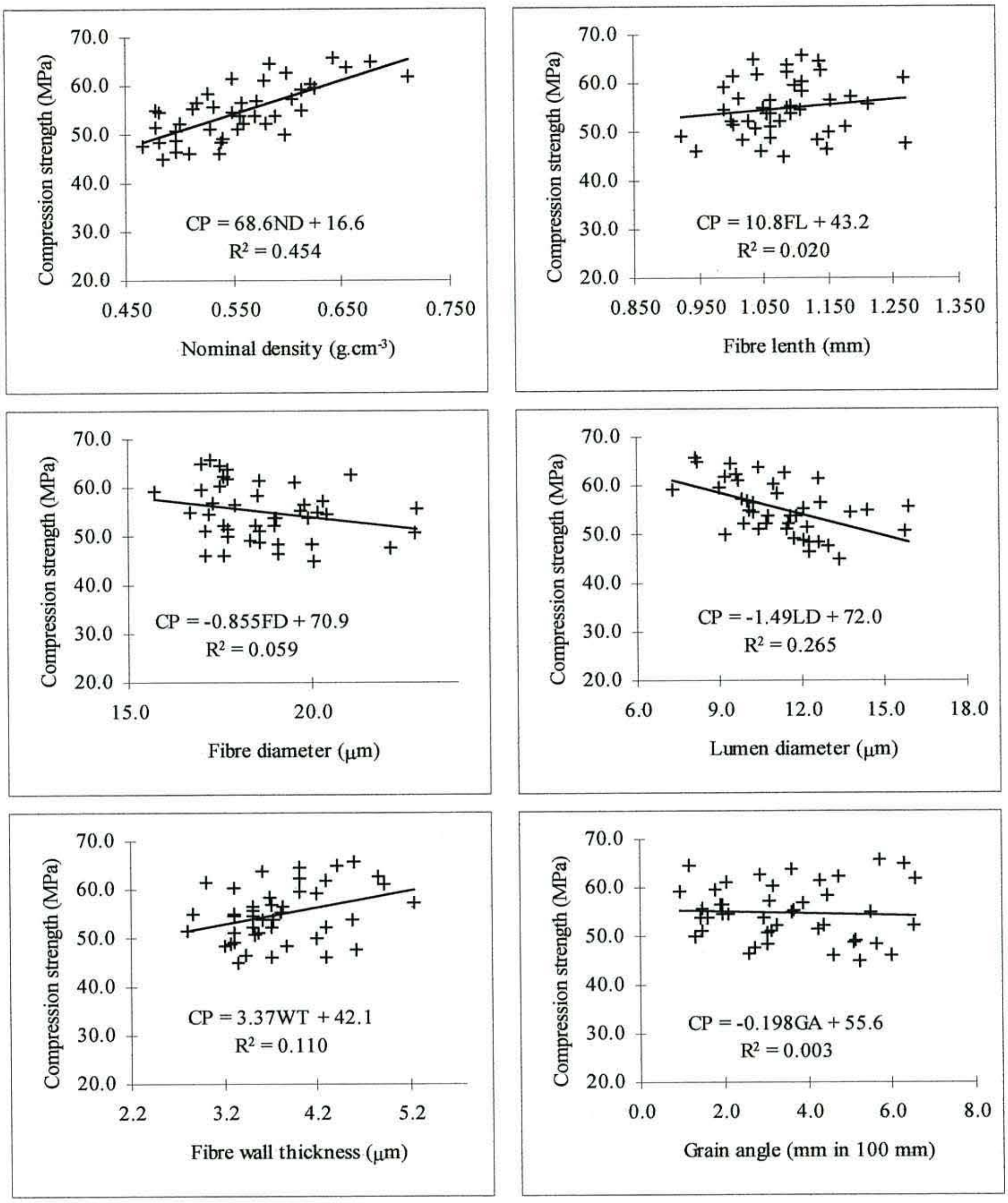
9.2 Prediction of the Compression Strength (Parallel to Grain)

Table 9.2 shows that the most influential factor acting on compression strength parallel to the grain is nominal density (R^2 = 50.2 %), followed by lumen diameter (R^2 = 26.5 %) and fibre wall thickness (R^2 = 11.0 %). Usually compression strength parallel to the grain is closely associated with density: for 117 Malaysian timbers, Ong (1988) found that CP = - 5.42 + 75.69 ND (R^2 = 0.87). Using nominal density as the predictor Zhang (1997) compared the ability of linear and curvilinear models ($CP = b0 \times ND^{b1}$) to predict compression strength parallel to the grain and found that for most species both models have a very comparable coefficient of determination (R^2). This author found that on average (eight hardwoods and eighth softwoods) nominal density was able to explain 45 % of the variation in compression strength parallel to the grain. It is worth noting that in the present study, for compression strength, contrary to the estimation of the nominal density, lumen diameter is more influential than fibre wall thickness. Apart from these two variaoles (and nominal density) no other variable presented a statistically significant influence on compression strength parallel to the grain. Thus, the variation of fibre length, fibre diameter, grain angle and microfibril angle have no influence on the compression strength parallel to the grain. According to Wimmer (1992), working with *Pinus sylvestris* from Austria, excluding the influence of density on the mechanical properties, the tangential diameter of latewood tracheids and microfibrillar angle had high percentages of determination. Also Bendtsen *et al.* (1981), studying the relationship between mechanical properties and thirteen anatomical and physical characteristics, found that for compression strength parallel to the grain, microfibril angle was the best single estimator, both for *Populus deltoides* ($R^2 = 0.68$) and *Populus* hybrid ($R^2 = 0.38$).

The coefficient of regression (b1) presented in Table 9.2 and Figure 9.2 shows that compression strength parallel to the grain increases (mainly) with increase of nominal density and fibre wall thickness, and reduces with increase of lumen diameter. Note that both lumen diameter and fibre wall thickness were the best predictors for nominal density. It seems that these two characteristics in their turn also affect compression strength parallel to the grain. The limited scope of the dependence (50 % for nominal density) also suggest that other factor (or factors) not examined in this study contribute (with density) to explain the total variation of compression strength parallel to the grain.

Table 9.3 Variation of the compression strength parallel to the grain corresponding to an increase of influencing characteristics.

Characteristic	Influence on modulus of rupture
Increase of 0.01 $g.cm^{-3}$ in nominal density	+0.7 MPa
Increase of 1 μm in lumen diameter	-1.5 MPa
Increase of 0.1 μm in fibre wall thickness	+0.3 MPa



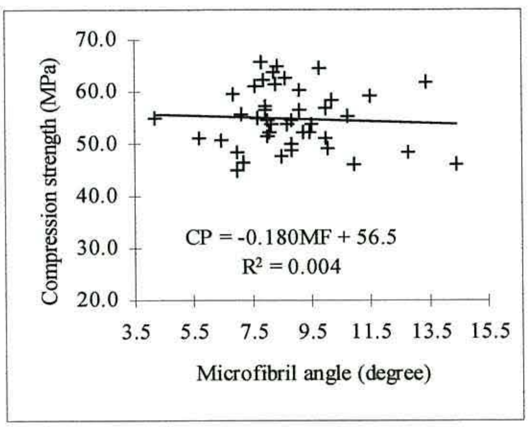


Figure 9.2 Fitted equations to represent the linear regression of the compression strength parallel to the grain (MPa) of 11 clones, using nominal density ($g.cm^{-3}$), fibre length (FL, mm), fibre diameter (FD, μm), lumen diameter (LD, μm), fibre wall thickness (WT, μm), grain angle (mm in 100 mm) and microfibril angle (degree) as predictors.

Table 9.3 shows examples of the variation of the compression strength parallel to the grain based on predicted values, associated with increases of the nominal density, lumen diameter and fibre wall thickness.

An estimation of compression strength parallel to the grain in each site can be examined in Appendix 7.4. Nominal density can be seen to be a significant predictor in all sites using a linear model: no other characteristic presented such unanimous results. Using an inverse model lumen diameter was a significant predictor for wood from Southern Bahia and using a linear model for São Mateus 2. Fibre length significantly influenced compression strength parallel to the grain at São Mateus 1. In addition, compression strength parallel to the grain was significantly estimated by microfibril angle ($R^2 = 0.742^{**}$) for wood from Aracruz.

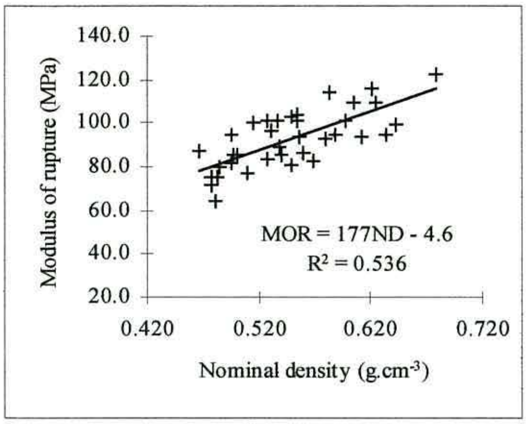
The multiple linear regression using fibre dimensions, microfibril angle, grain angle and nominal density as possible predictors showed that grain angle added about 12 % to the 50 % coefficient of determination of compression strength parallel to the grain already produced by nominal density. Thus, compression strength parallel to the grain can be more significantly predicted by the equation: $CP = 16.3^{**} + 74.5\ ND^{***} - 0.839\ GA^{*}$ [($F = 30.2^{***}$, $R^2 = 0.620$, $S = 3.48$ MPa)]. Kaya and Smith (1993) working with red pine using a stepwise regression, found that the best combination of two independent variables for predicting compression strength parallel to the grain was nominal density and tracheid length ($R^2 = 0.92$). However, they tested only nominal density, age and height as predictors. In a more complete investigation, Bendtsen *et al.* (1981) tested a multiple linear regression to predict compression strength parallel to the grain of cottonwood, adding 12 independent variables to microfibril angle. According to their results, the addition of nominal density significantly increased the R^2 from 0.68 to 0.90. Further, addition of fibre length significantly improved the relationship to 0.92. Finally, the inclusion of vessel diameter in the model added a further 1 %. In other genetic material (*Populus* hybrid), according to these authors, the observed lack of significant relationships between compression strength parallel to the grain and anatomical characteristics reflects the uniformity in the material, rather than an absence of inherent relationships commonly present in *Eucalyptus* wood, as studied here.

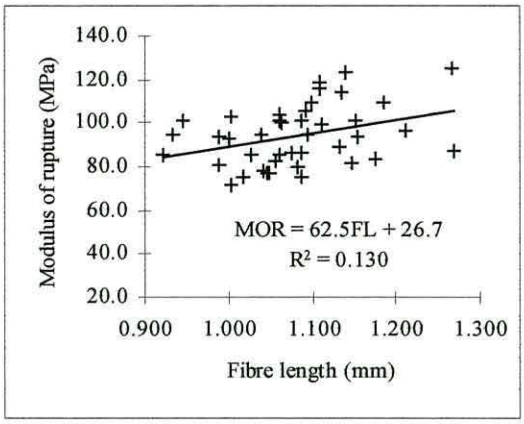
9.3 Prediction of Modulus of Rupture

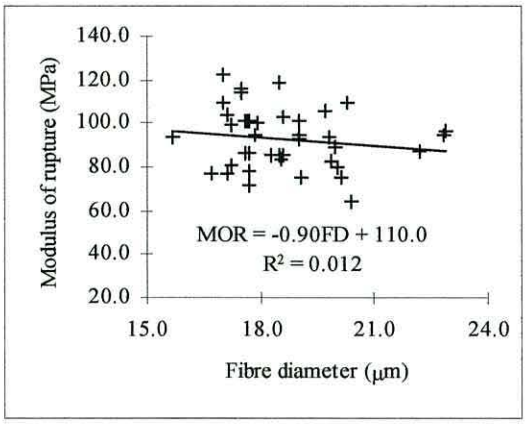
Table 9.2 presents the results of the analysis of regression to predict the behaviour of modulus of rupture. Again nominal density was found to be the best predictor, showing 53.6 % of the influence on modulus of rupture. Similarly, Zhang (1997) found that on average (eight hardwoods and eight softwoods) nominal density (specific gravity) could explain 50 % of the variation in modulus of rupture, using a linear model. This property can also be significantly predicted by fibre wall thickness (R^2 = 33 %), grain angle (R^2 = 16 %) and by fibre length and lumen diameter, both with 13 %. Fibre diameter and microfibril angle showed no significant influence on modulus of rupture. The latter contrast with results presented by Bendtsen *et al.* (1981), who, studying the relationships between mechanical properties and thirteen anatomical and physical characteristics, found that for modulus of rupture, microfibril angle was the best single estimator, both for *Populus deltoides* (R^2 = 0.81) and *Populus* hybrid (R^2 = 0.56). In Table 9.2 can be observed that, in contrast to nominal density and compression strength parallel to the grain (significantly correlated only with characteristics which signify addition of mass to the material), modulus of rupture was also significantly correlated with fibre length and grain angle. It appears that the higher complexity of modulus of rupture (which is simultaneously submitted to different stresses) requires the participation of a larger number of factors. It is supposed that longer fibres contribute to the tensile behaviour of wood, while shallower grain angle reduces the shear resistance.

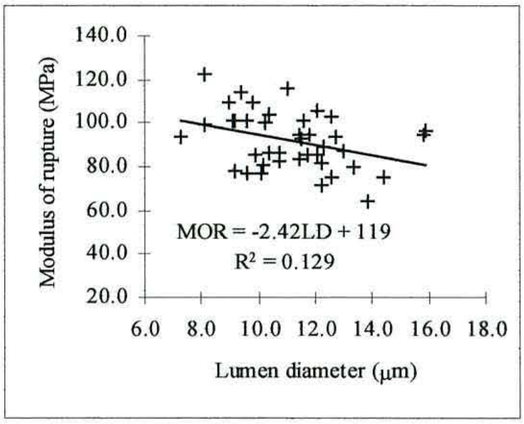
According to the coefficient of regression (b1) presented in Table 9.2 and Figure 9.3 it can be noted that modulus of rupture increases mainly with increase of nominal density, fibre diameter and fibre wall thickness, and reduces with increase of lumen diameter and grain angle.

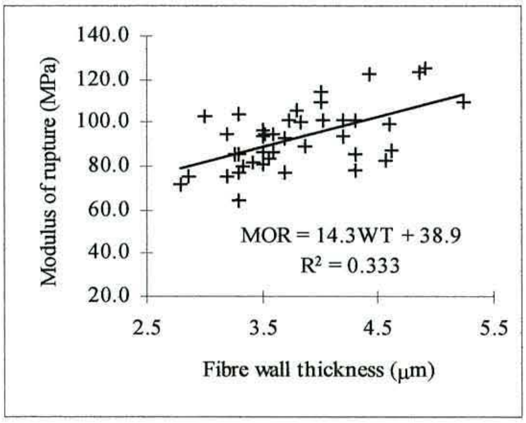
The effects of some random increases in the characteristics that significantly influence modulus of rupture are exemplified in Table 9.4. This table, as well Table 9.3 presented for compression strength parallel to the grain, has to be examined cautiously since it does not represent the potential of genetic-environmental

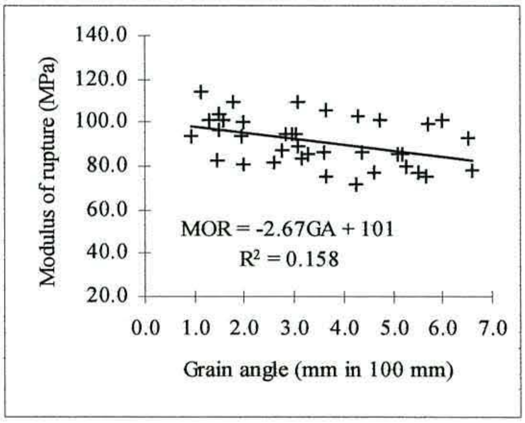












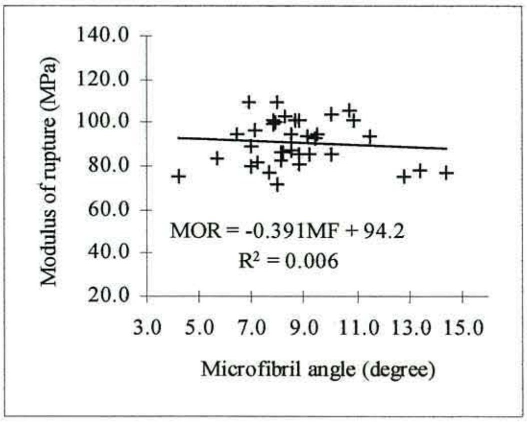


Figure 9.3 Fitted equations to represent the linear regression of the modulus of rupture (MPa) of 11 clones, using nominal density ($g.cm^{-3}$), fibre length (FL, mm), fibre diameter (FD, μm), lumen diameter (LD, μm), fibre wall thickness (WT, μm), grain angle (mm in 100 mm) and microfibril angle (degree) as predictors.

improvement of the property - the alteration of one may cause alterations in others. Nonetheless, it has a use since it shows that, depending on the rate of gain achieved for a particular characteristic, the result on the modulus of rupture can be beneficial, even if the dependence of the modulus of rupture from this characteristic is particularly weak. For example, grain angle which influences only 16 % of the definition of modulus of rupture, imposes relatively high influence on this mechanical property. For the range of variation of grain angles observed for this wood (approximately from 0.6° to 4°), it is possible to deduce from the equation (MOR = -2.67GA + 101) that an increase of 1° (1.75 mm deviation in 100 mm) in the grain angle results in a reduction of 4.7 MPa in the modulus of rupture. For a particular site (Appendix 7.6), however, the influence can be higher, as shown for Southern Bahia, or smaller, as shown for São Mateus 2 and Aracruz.

Table 9.4 Influences of random increases in nominal density and anatomical characteristics on the modulus of rupture.

Characteristic	Influence on modulus of rupture
Increase of 0.01 $g.cm^{-3}$ in nominal density	+1.8 MPa
Increase of 0.1 mm in fibre length	+6.2 MPa
Increase of 1 μm in lumen diameter	-2.4 MPa
Increase of 0.1 μm in fibre wall thickness	+1.4 MPa
Increase of 1° in grain angle	-4.7 MPa

The prediction of modulus of rupture for each site can be observed in Appendix 7.6. Besides nominal density, a significant predictor for all sites using a linear model, no other characteristic presented such unanimous results. However, specific cases can be presented. Modulus of rupture of wood from Southern Bahia was significantly correlated with lumen diameter (R^2 = 0.635**), fibre wall thickness (R^2 = 0.687**) and microfibril angle (R^2 = 0.359*). From São Mateus 2, the modulus of rupture was correlated with fibre diameter (R^2 = 0.591**), lumen diameter (R^2 = 0.428*) and fibre wall thickness (R^2 = 0.796**). Modulus of rupture of wood from Aracruz was also correlated with fibre wall thickness (R^2 = 0.565*).

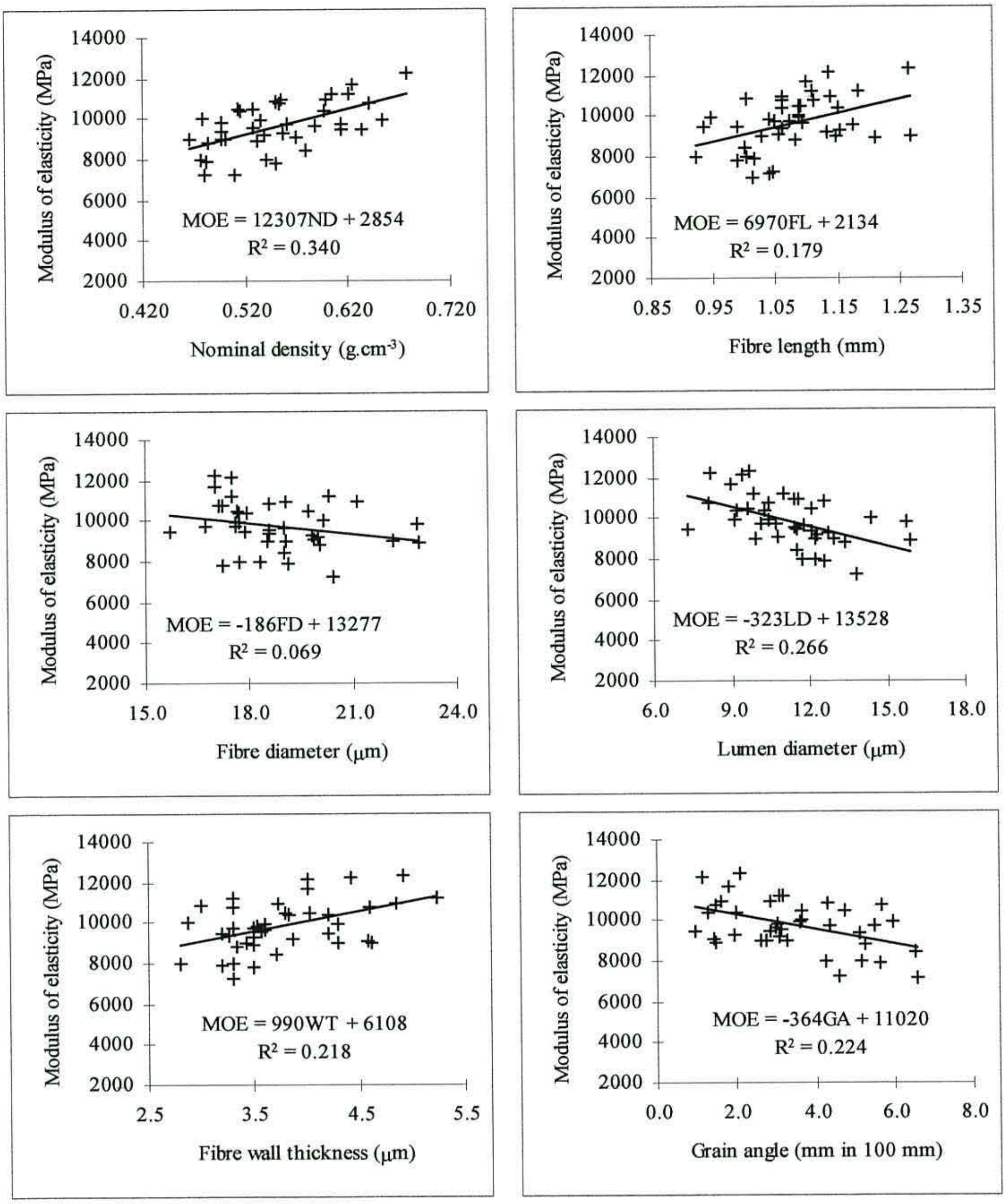
The multiple linear regression using nominal density, fibre dimensions, microfibril angle and grain angle as possible predictors showed that none of the variables tested in the model added significant value to the coefficient of determination already produced by nominal density (R^2 = 0.536). This result was rather different from some result reported in the literature (Bendtsen *et al.*, 1981; Downes *et al.*, 1993). According to results presented by Bendtsen *et al.* (1981), the addition of nominal density to the microfibril angle increased the already significant R^2 from 0.81 to 0.89. Further addition of fibre length significantly improved the relationship to 0.94. Finally, the inclusion of vessel lumen diameter in the model added 1 % more to the significance of the model.

9.4 Prediction of Modulus of Elasticity

Table 9.2 presents the results of the analysis of regression to predict the behaviour of modulus of elasticity. Again nominal density was the best predictor, producing 34.0 % of the influence on modulus of elasticity. Zhang (1997) comparing linear and curvilinear models ($CP = b0 \times ND^{b1}$) used to predict modulus of elasticity using nominal density as the predictor found that for most of the 16 softwood and hardwood species, the curvilinear had a slightly higher coefficient of determination compared to the linear equation. On average only 20 % of the variation in modulus of elasticity is accounted for by the linear equation, compared with 30 % by the curvilinear equation.

Also, modulus of elasticity (Table 9.2) can be significantly predicted by lumen diameter (R^2 = 27 %), grain angle (R^2 = 22 %), fibre wall thickness (R^2 = 22 %), microfibril angle (R^2 = 19 %) and by fibre length (R^2 =18 %). It is believed that fibres are the main cell types contributing to the strength and elasticity of wood. It has been suggested that this may be due to the relatively high slenderness ratio and the thicker wall (Bodig and Jayne, 1982). Fibre diameter was the only variable not to show a significant influence on modulus of elasticity. Usually, the correlations of the modulus of elasticity with the tracheids of conifers are stronger than those with the fibres. An example is the result of the relationships between tracheid characteristics and modulus of elasticity found for *Pinus sylvestris* by Verkasalo (1992), where the coefficient of determination of the modulus of elasticity with radial tracheid diameter was 0.770, with radial lumen diameter 0.894 and with double cell wall thickness 0.185. These results contrast with the relatively small values found for *Eucalyptus* wood in this study.

From the results presented for modulus of elasticity in Table 9.2 it is interesting to note firstly that the number of significant predictors is higher still than those obtained for modulus of rupture estimation in the same table. Secondly, (except perhaps for nominal density) the coefficients of determination for the different predictions are very similar. And thirdly, it is possible to verify that, based on the coefficient of determination, nominal density is less influential for modulus of elasticity than for compression strength parallel to the grain or for modulus of rupture. Somewhat similar to modulus of rupture, modulus of elasticity also depends not only on characteristics which signify addition of mass to the material. Similar results were obtained by Zhang (1997). On the other hand, fibre length, grain angle and microfibril angle are more influential for modulus of elasticity than for characteristics of resistance (compression strength parallel to the grain, modulus of rupture). Based on these results it is possible to infer that stiffness is dependent on several factors acting simultaneously, maybe due the complexity of its own definition. Probably the action of these factors is concomitant to determine the final behaviour of the modulus of elasticity, evidently associated with other characteristics of wood. According to Cave (1969), stiffness is dependent on density, microfibril angle and spiral angle, but Booker *et al.* (1998) consider that the relative importance of these factors is difficult to determine, as density, microfibril angle and spiral grain in trees are all highly correlated with distance from the pith, so that they are not independent. In a more complete investigation, Bendtsen *et al.* (1981), studying the relationship between modulus of elasticity and 13 anatomical and physical characteristics, found that for modulus of elasticity, microfibril angle was the best single estimator, both for *Populus deltoides* (R^2 = 0.81) and *Populus* hybrid (R^2 = 0.56). Booker *et al.* (1998) working with



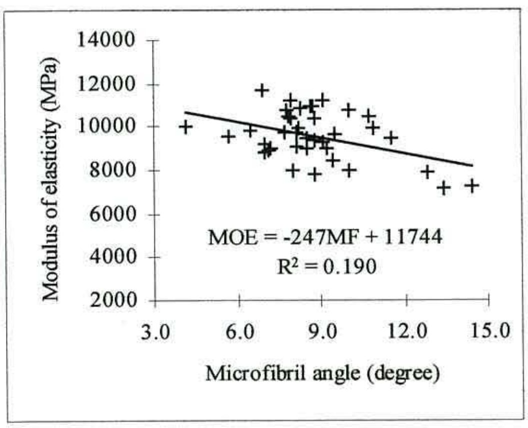


Figure 9.4 Fitted equations to represent the linear regression of the modulus of elasticity (MPa) of 11 clones, using nominal density (g.cm^{-3}), fibre length (FL, mm), fibre diameter (FD, μm), lumen diameter (LD, μm), fibre wall thickness (WT, μm), grain angle (mm in 100 mm) and microfibril angle (degree) as predictors.

radiata pine showed that stiffness presented high correlation with microfibril angle and density.

According to the coefficient of regression (b1) presented in Table 9.2 and Figure 9.4 it can be observed that modulus of elasticity increases with increase of nominal density, fibre length and fibre wall thickness. Conversely, it reduces with increase of fibre diameter, lumen diameter, grain angle and microfibril angle.

The effects of increases in the characteristics associated with modulus of elasticity are exemplified in Table 9.5. The caution noted in relation to the Table 9.4 (for modulus of rupture) must also be observed for this table. Nevertheless, it represents an attempt to establish practical effects of changes in the predictors. The effects act not individually and the alteration of one characteristic may causes alterations in others. Nonetheless, it has some use since it shows that depending on the rate of gain imposed on a particular characteristic, the result on the modulus of elasticity can be beneficial, even if the dependence of the modulus of elasticity from this characteristic is apparently weak.

Table 9.5 Influence of random increases of nominal density and anatomical characteristics on modulus of elasticity.

Characteristic	Influence on modulus of elasticity
Increase of 0.01 $g.cm^{-3}$ in nominal density	+123 MPa
Increase of 0.1 mm in fibre length	+697 MPa
Increase of 1 μm in lumen diameter	-186 MPa
Increase of 1 μm in fibre diameter	-323 MPa
Increase of 0.1 μm in fibre wall thickness	+99 MPa
Increase of 1° in grain angle	-364 MPa
Increase of 1° in microfibril angle	-247 MPa

The multiple linear regression using fibre dimensions, microfibril angle, grain angle and nominal density as possible predictors showed that microfibril angle adds about

9 % to the coefficient of determination of modulus of elasticity produced using nominal density (34 %). Thus, modulus of elasticity can be significantly predicted by the model: MOE = - 4497** + 12430 ND*** - 199 MF* (F = 13.77***, R^2 = 0.433; S = 918). The result shown by this equation, suggests that the significant predictions obtained with several predictors acting individually (Table 9.2) do not necessarily contribute to an improvement in the coefficient of determination when analysed together: it is possible that one characteristic offsets the effect of others. The addition of other variables however may not make a significant improvement in the equation. For example, the addition of fibre length increases the R^2 to 0.405, but this is not a statistically significant improvement in the regression. According to results presented by Bendtsen *et al.* (1981) to estimate modulus of elasticity, the addition of percentage of parenchyma to the microfibril angle increased the already significant R^2 from 0.63 to 0.77. Further addition of nominal density significantly improved the relationship to 0.81. No other variable was able to improve the predictability of the modulus of elasticity.

Booker *et al.* (1998) describe that the basic density and microfibril angle of radiata pine were strongly correlated with the specific modulus (modulus of elasticity per unit of mass). However, only the path coefficient[1] relating specific modulus and microfibril angle was significant at the 99 % level. Thus, path analysis has shown that the specific modulus is not significantly affected by density. Density is primarily governed by fibre wall thickness (which in this study is shown in Table 9.2). Also, Nakada *et al.* (1998) found that modulus of elasticity variation of sugi resulted from wood characteristics other than microfibril angle, such as wood density.

Tsehaye *et al.* (1998) report that comparisons between density and stiffness when selecting trees for structural timber indicates that stiffness is the better parameter for selecting superior trees within a natural population. They also reported that microfibril angle remains the key to interpreting stiffness of timber in radiata pine,

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[1] Path correlation coefficient measures the correlation between two random variables, while holding other random variables constant. For example, it is possible to correlate modulus of elasticity and microfibril angle removing the effect of density on modulus of elasticity.

but a genuine understanding of the contributions to stiffness of the various characteristics can best be established using realistic biophysical models.

9.4.1 Prediction of Modulus of Elasticity for each Site

Modulus of elasticity is also significantly correlated with several characteristics at the level of a particular site. The prediction of the modulus of elasticity for each site can be seen in Appendix 7.8. Besides nominal density, a significant predictor for all sites (using a linear model), no other characteristic presented such unanimous results. However, specific cases can be examined in Appendix 7.8. Modulus of elasticity of wood from Southern Bahia was significantly correlated also with fibre length (R^2 = 0.579*), lumen diameter (R^2 = 0.793**) and fibre wall thickness (R^2 = 0.687**). From São Mateus 1, significant results were found for grain angle (R^2 = 0.406*) and microfibril angle (R^2 = 0.524*). From São Mateus 2, the modulus of elasticity was correlated with fibre length (R^2 = 0.632**), lumen diameter (R^2 = 0.768***), fibre wall thickness (R^2 = 0.608**). Finally, for wood from Aracruz, modulus of elasticity was also significantly correlated with grain angle (R^2 = 0.571*). Due the significant effect of fibre length, grain angle and microfibril angle when the four sites were analysed together (Table 9.2), some consideration will be given regarding the effect of these characteristics on modulus of elasticity, when analysed for each individual site.

The dependence of modulus of elasticity on fibre length for each site is presented in Appendix 7.8. The linear model was selected to represent the relationships for all four groups of clones, despite the fact that only at Southern Bahia and São Mateus 2 were the equations statistically significant. According to the selected equations, it can be assumed that longer fibres optimise the stiffness of this wood.

The influence of grain angle on the modulus of elasticity for each site is also shown in Appendix 7.8. This relationship can be represented by the linear model (Southern Bahia and São Mateus 1) and by a quadratic model (São Mateus 2 and Aracruz). Only for wood from Aracruz and São Mateus 1 was the relationship statistically significant. According to the selected equations it can be noted that for wood from Southern Bahia and São Mateus 1, modulus of elasticity reduces with an increase of the spirality. However, for wood from São Mateus 2, the distribution of the data leads to an interpretation that modulus of elasticity reduces with an increase of the spiral angle up to about 3.5 mm in 100 mm, increasing with the grain angle afterward. When clone 9 is removed, a non-significant linear relationship is obtained [MOE = 10440 - 137 GA; $R^2 = 0.05$ (ns)].

The influence of microfibril angle on modulus of elasticity for individual sites is presented in Appendices 7.8 and 7.26. The best models selected to represent the relationships were the linear at Aracruz and the quadratic in the other sites. Only the relationship obtained for wood from São Mateus 1 showed statistical significance. At Southern Bahia, at low microfibril angles the modulus of elasticity is only slight reduced by microfibril angle up to a minimum, corresponding to approximately 6 °, afterwards it increases with increase of the microfibril angle. At São Mateus 1 the pattern of the curve is somewhat opposite to that shown for wood from Southern Bahia: in this case, following the quadratic model, the modulus of elasticity increases from small angles to reach a maximum around 9° corresponding to 10500 MPa. With higher angles, the modulus of elasticity starts to decrease. For wood from São Mateus 2 (Figure 9.11-g), microfibril angles smaller than 8 ° (corresponding to 10400 MPa in the modulus of elasticity) have no influence on the stiffness, afterward an increase in the angle results in reduction of the modulus of elasticity. For wood from Aracruz the microfibril angle influences linearly and negatively the modulus of elasticity.

In three of the studied groups of clones which present small microfibril angles (Southern Bahia, São Mateus 1 and São Mateus 2), it seems that microfibril angle influences negatively the modulus of elasticity only after a certain limit (6 - 9 °). After this limit a linear relationship might be obtained for these three sites. For wood from Aracruz the relationship is negatively linear, but the microfibril angles observed are higher (from 8 ° to 15 °). Also wood from Southern Bahia presents this "non-effect" pattern for small angles, however the gain in modulus of elasticity after this limit represents a certain pattern of variation, perhaps indicating an environmental stress. Butterfield and Pal (1998), studying three three-year-old radiata pine clones, found that in two of the clones, microfibril angle increased from centre outwards. They suggested that the seedlings were subjected to environmental stresses after their initial planting causing the microfibril angle to increase. They identified wind inducing compression wood as the most likely factor at the plantation site, even although further experimentation showed that compression wood can be considered a normal formation in seedlings of radiata pine even in the absence of wind.

The small microfibrillar angle observed in this *Eucalyptus* wood (discussed in Chapter 8), suggests that its influence on the modulus of elasticity is rather insignificant, mainly for small angles up to 6 - 9 °. This result contrasts with several results presented in the literature, most of them for conifers. However, the effect of microfibril angle in individual fibres suggests that once the wood quality is improved in terms of other characteristics (mainly related to its heterogeneity) the effect of microfibril angle will be more in evidence, and selection based on small microfibril angle will possibly result in improved wood quality. According to Boyd (1980) it has been shown that modulus of elasticity, and therefore the rigidity and tensile strength of fibres, vary rapidly and inversely with microfibril angle where the values of microfibril angle are small, as is generally the case with hardwoods. At appreciably larger values of microfibril angle, minor variations have relatively little effect on modulus of elasticity, and there is a marked increase in the influence of the matrix material (Mark and Gillis, 1973). However, it is important to define the exact meaning of "small angles" when referring to specific genetic material, as it has been shown in this study for different clones and sites.

9.5 Influence of Compression Damage on Mechanical Properties

The dependence of compressive strength on microfibril angle has been discussed by several authors seeking to explain failure initiation by cell wall deformation (slip planes[2]) (Dinwoodie, 1966,1967; Keith and Côté, 1968; Preston, 1974; Hoffmeyer, 1993). Slip planes in wood alter some physical and mechanical properties.

It has been suggested that slip planes can arise naturally due to stresses caused by the flexing of the stem as a result of wind (Trendelenburg, 1936; cited by Dinwoodie, 1966b) and that slip planes have been recorded to a limited extent in tension and shear failure (Dinwoodie, 1966). Slip planes are most usually found in abundance in timber compressed parallel to the grain (Dinwoodie, 1966).

The relationship between stress and slip plane formation can be seen at three different stages: an initial stage, when minute dislocations (slip planes) are formed in the structure of the cell wall (when the strain is about half the failing load); a second stage when the development of slip planes occurs in neighbouring cells to produce rows of dislocations throughout the timber (microscopic compression lines); and a third stage when increasing load results in severe crinkling of the cell wall (macroscopic compression failure) (Dinwoodie,1966).

Growth stresses contribute to a weakening of the inner wood of large hardwood trees due to the formation of large numbers of slip planes and minute compression failures (Jacobs, 1938). These result when high compressive forces, beyond the limit of elasticity of the timber, are applied (Robinson, 1920). The development of these deformations in low density tropical hardwoods was first observed by the Australians, who named the tissue "brittleheart" (Dinwoodie, 1966b). The amount of brittleheart occurring in *E. robusta* was recorded by Skolmen (1973) as ranging from 2.6 to 43.2 %, while the toughness of that region (which is also juvenile wood and low in density) was only 27 % of normal wood.

To have a preliminary notion concerning the possible natural occurrence of slip planes in the fibre wall of *Eucalyptus*, wood having been subjected to no (artificial) stresses were investigated. In this case, blocks sampled from two radial positions

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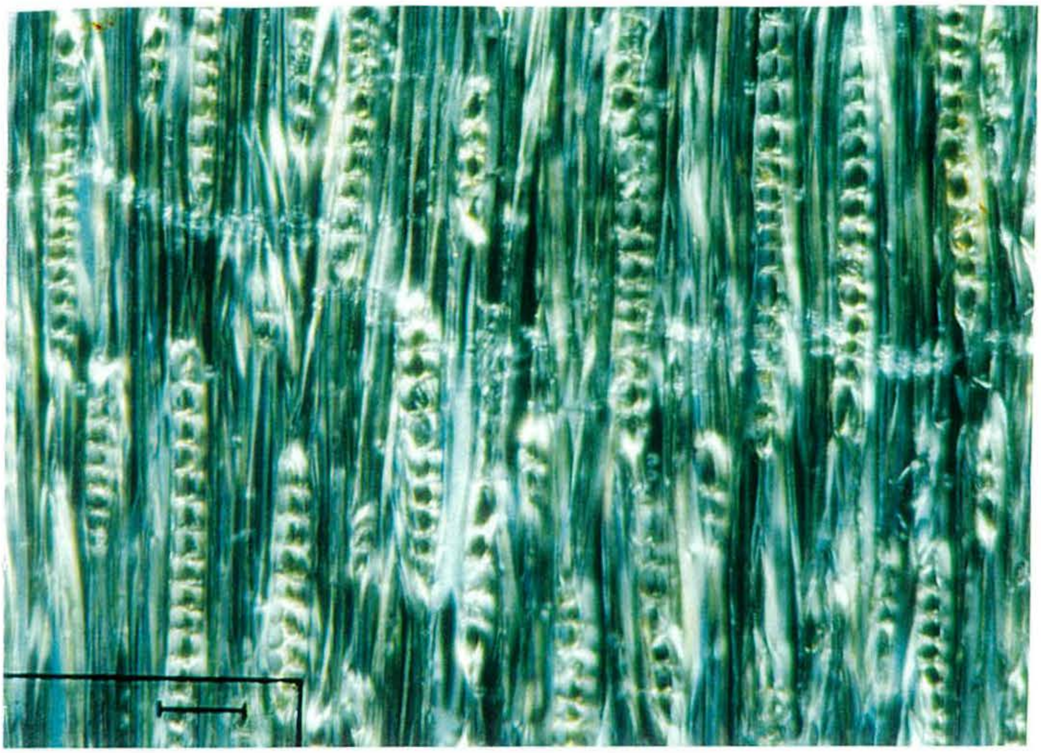
[2] Slip planes can be described as a zone of re-orientated microfibrils caused by a stability failure in the columns of S^2 microfibrils, whereby one part of the cell wall slips relative to another (Hoffmeyer, 1993)

were used, supposed to represent regions exposed to both longitudinal tensile and longitudinal compressive growth stresses. The blocks were sampled from one log collected from each of three clones (clones n. 17, 19 and 24) planted in Aracruz. The small blocks were fully saturated and microtomed to produce tangential longitudinal sections. To eliminate the possibility of inducing slip planes, sections were as thin as 10 μm, cut with a draw angle less than 5° and using a low cutting angle as prescribed by Dinwoodie (1966). Tangential longitudinal sections were then examined and slip planes observed using polarised light.

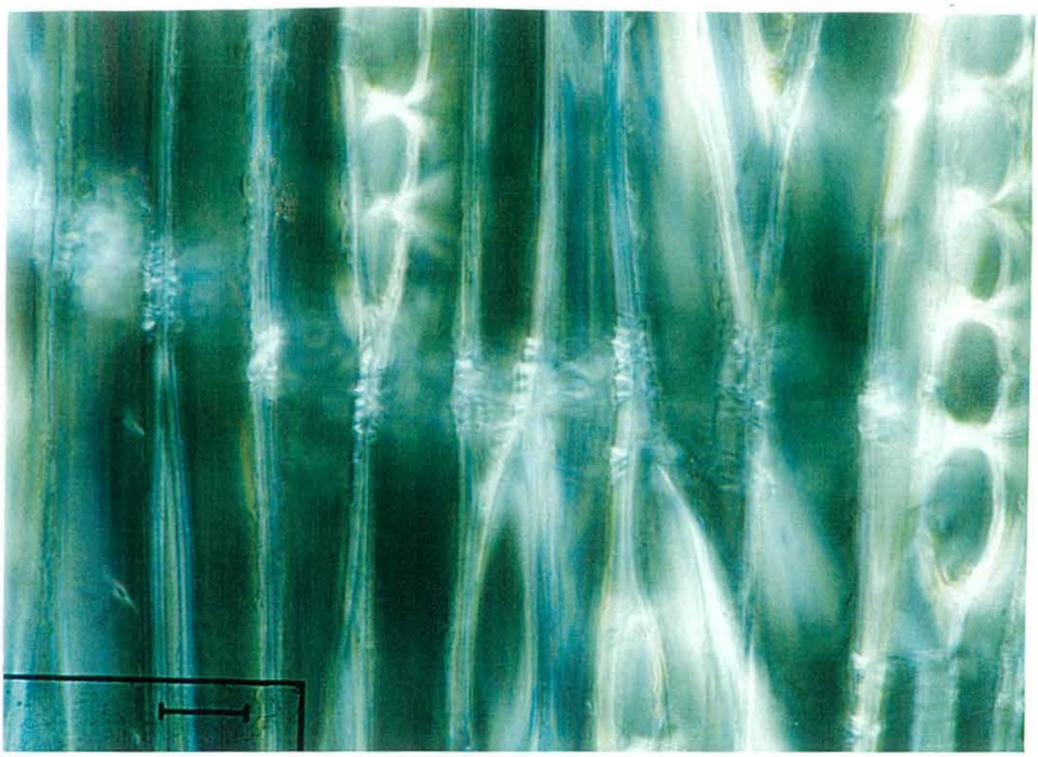
In two of the three clones (clones 19 and 24) slip planes were observed in the outer wood and in the three clones (17, 19 and 24) compression creases, possibly developed from the slip planes, were observed in the central blocks. Figure 9.5 illustrates the occurrence of compression creases in the inner wood and Figure 9.6 illustrates slip planes the outer wood of clone 24. In the inner wood compression crease lines characterised by high numbers of slip planes can be observed. This indicates an advanced stage of damage, possibly caused by compressive stresses associated with growth stress. In the outer wood slip planes can be observed in much smaller numbers than in the inner wood. In this case, the possible explanation is compressive stresses caused by wind forces as suggested by Henman (1991) or damage to the tree during felling or extraction (Dinwoodie, 1966). However, to have a more accurate idea about the extension, original causes, relationships and effects on the mechanical properties of these fibre wall deformations, a more controlled experiment would have to be conducted. In any case, it is important to mention that the existence of these deformations are a factor contributing to the reduction of the mechanical strength and stiffness of wood.

Specimens showing compression damage, mainly compression creases or macroscopic compression failures, may fail abruptly when submitted to bending stress (brashness[3]). Actually, when the failure type in the bending specimens were analysed, it was revealed that among all the mechanical tests executed, 12 % presented "brash" failure type (ASTM, 1981). These brash type failures were

[3] The term brashness is ascribed to timber which fails abruptly at lower than normal strength due to the rapid propagation of cracks (Koehler, 1933 cited by Dinwoodie, 1970).

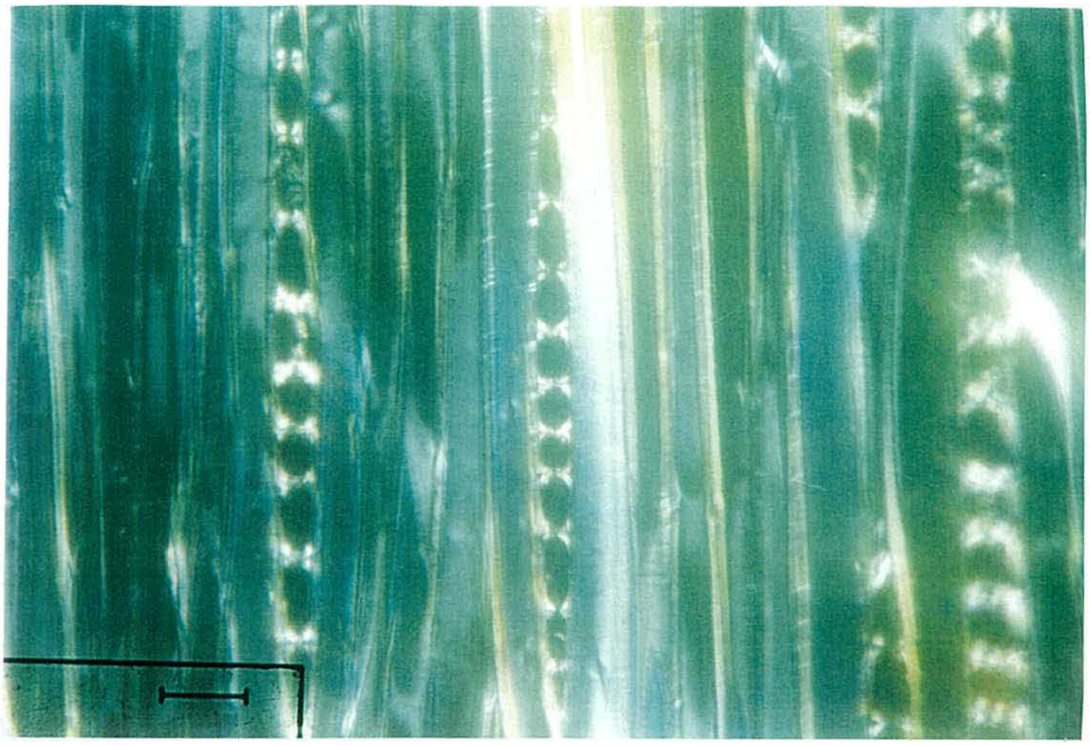


240 ×



960 ×

Figure 9.5 Slip planes and compression creases observed in the tangential face of inner wood of *Eucalyptus*.



480 ×

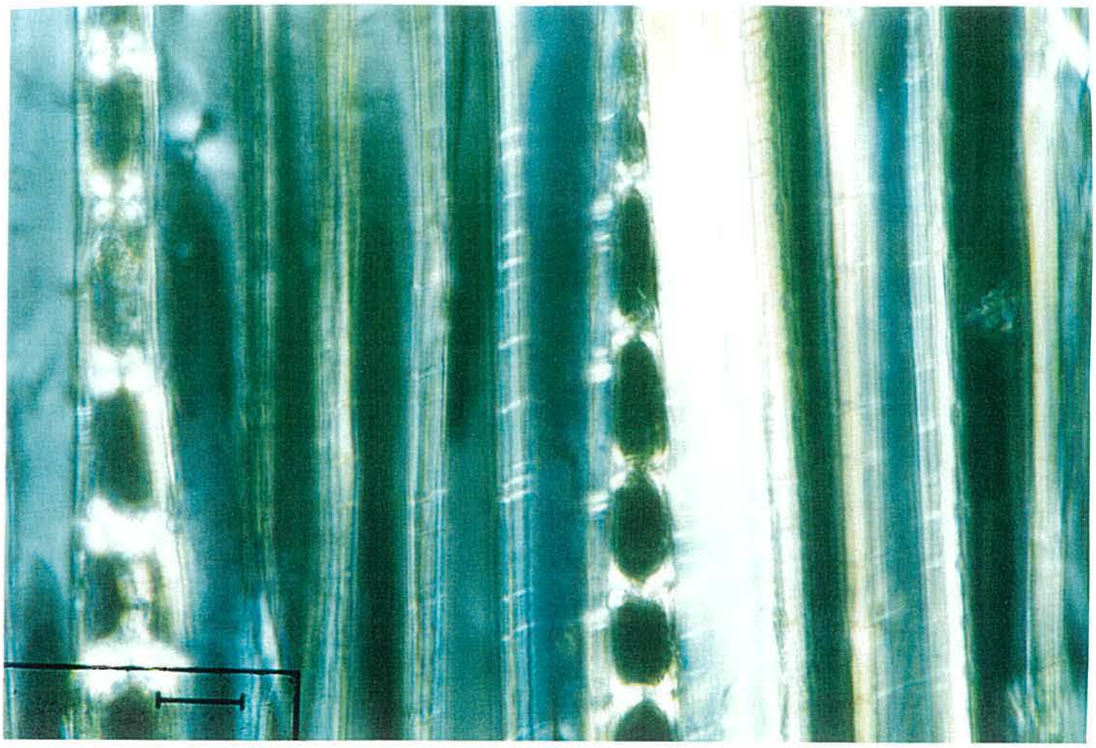


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Figure 9.6 Slip planes observed in the tangential face of outer wood of *Eucalyptus*.

highly concentrated in the central region of the log: 73 % of the brashness occurred in wood samples from the inner region of the log, both for the basal and top bolts. In terms of the distribution of brashness, it can be observed that wood from Southern Bahia and Aracruz presented more brashness than wood from the two other sites. This suggests that there is a environmental factor particularly important in determining this defect in *Eucalyptus* wood. Among the 26 clones, it was observed that clones 14, 15, 21 and 24 were particularly susceptible to brashness in wood from all the four sites. In this case, the previous supposition of the environmental factor affecting the damage of wood must be complemented by the assumption that certain genotypes are also prone to the action of compressive stresses causing brashness. The bending testing specimens correspondents to the clone 17, 19 and 24 (sampled in the inner region of logs) presented brashness failure.

9.5 Conclusions

From this study of the relationships of the fibre dimensions on nominal density, and of the relationships of the nominal density, fibre dimensions, grain angle and microfibril angle on mechanical properties of eleven eight-year-old *Eucalyptus* clones, it is possible to conclude that:

i) Nominal density can be significantly estimated by fibre wall thickness, lumen diameter and fibre diameter;

ii) Nominal density is the best predictor for compression strength parallel to the grain, modulus of rupture and modulus of elasticity. However, its influence is stronger for strength than for the elastic property;

iii) Compression strength parallel to the grain, as well as nominal density, can also be estimated by lumen diameter and fibre wall thickness;

iv) Modulus of rupture, in addition to nominal density, can also be significantly estimated by fibre length, lumen diameter, fibre wall thickness and grain angle;

v) Modulus of elasticity, in addition to nominal density, can also be significantly estimated by fibre length, lumen diameter, fibre wall thickness, grain angle and microfibril angle;

vi) The prediction of the modulus of rupture and the modulus of elasticity, when compared with the prediction of compression strength parallel to the grain, suggests that a higher diversity of anatomical structures are associated with the bending mode of stressing.

vii) Using a multiple linear regression it was possible to find that: grain angle adds 12 % in the determination of compression strength parallel to the grain by nominal density, and microfibril angle adds 9 % in the determination of the modulus of elasticity by nominal density.

viii) Particular sites present specific patterns of relationships, not all of them similar to those observed when the relationship was executed on the average between sites.

ix) Natural slip planes were observed in the outer wood and compression creases were observed in the inner wood. There were suggestions that the weakening of *Eucalyptus* wood in the inner wood was increased by the presence of natural damages in the fibre walls (compression creases). Brash type failure were concentrated in the inner wood, possibly associated with the presence of compression creases.

10 OVERALL CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE WORK

10.1 Relationships between Properties Studied

Nominal density, rather than fibre morphology, grain angle or microfibril angle was found to be the best predictor of mechanical properties, but its influence was stronger on strength properties than for stiffness. Possibly, stiffness is more sensitive than strength to the variability and defects of wood (it could be that microscopic cracks on the tension side allow greater flexibility but are not of a critical size to initiate failure). The occurrence of defects on the tension side of a bending specimen might reduce its strength and stiffness but would have little or no effect on the crushing strength. In addition, it may be suggested that other factors, such as short fibres observed in *Eucalyptus* wood for example, might reduce the expected influence of density on modulus of elasticity, despite the positive effect provided by the small microfibril angle associated with this material.

An increase of fibre wall thickness resulted in a reduction of the lumen diameter, the correlation being significant for all studied sites. This addition of cell wall material explains the close association between fibre wall thickness or lumen diameter and nominal density (50 % of this nominal density is determined by the fibre wall thickness and 40 % by the lumen diameter). Fibre diameter determines only 19 % of nominal density while fibre length was not significant for this characteristic. It can be assumed that the development of the fibre in diameter or length does not necessarily imply a gain of mass if this increase is not associated with wall thickening. However, it is possible that a reduction of the growth rate of the trees may extend the intrusive lengthening of the fibre (and subsequent increase of wall proportion) producing denser wood.

Lumen diameter and fibre wall thickness were also the most influential of the fibre dimensions in determining mechanical properties, although their influences were weaker on mechanical properties than on the nominal density. A larger number of factors affect mechanical properties than density. Indeed, fibre length which had not been shown to influence nominal density or compression strength parallel to the grain, did affect modulus of rupture and even more strongly modulus of elasticity. This may be due the higher ratio of slenderness in longer fibres, which is supposed to add elasticity to wood.

Grain angle was important in determining modulus of rupture (R^2 =16 %) and modulus of elasticity (R^2 = 22 %). Although statistically significant, the small influence of the grain angle on these mechanical properties is in accordance with the small range of observed grain angle.

Microfibril angle was only secondarily influential in determining stiffness (R^2 =19 %). This was contrary to several findings in the literature (mainly for conifer wood) where microfibril angle performs important role in the determination of stiffness. It is probable that the small range of microfibril angles observed in this wood contributes to this little influence. Also, the influence of other wood characteristics and defects concomitantly acting on the stiffness can not be disregard.

The estimation of the compression strength parallel to the grain was improved when grain angle was added to nominal density in a multiple linear regression. Combination of variables did not significantly improve the determination of modulus of rupture. In contrast, for modulus of elasticity, including microfibril angle added about 9 % to the 34 % already produced for the coefficient of determination using nominal density alone. In the case of the modulus of rupture, it can be suggested that the relatively steep angles observed for *Eucalyptus* wood did not contribute significantly to the mechanical failure (initiated by crack propagation in the tension side of the specimen or compression damages on the compressed side of the specimen).

Analyses performed for wood from each site showed that for both modulus of rupture and modulus of elasticity nominal density was usually the best predictor, and distinct relationships were produced, depending on the predictor and site. Normally, the analyses for individual sites are based on localised variability in the properties which not surprisingly can result in different findings. Of particular interest were the relationships between modulus of elasticity and microfibril angle for each site. In sites where wood showed higher microfibril angles the effect was best represented by a linear model, whilst in sites where wood showed smaller angles the relationship was best represented by a quadratic model. It was also found that microfibril angle was not influential on modulus of elasticity for angles smaller than 6° to 9°. In this case, the influence of the microfibril angle would have a similarity with the expected maximum influence produced by the microfibrils approximately parallel to the fibre axis.

10.2 Property Variation

Table 10.1 Radial (from inner wood to outer wood) and longitudinal (from base to top) variation in wood characteristics of *Eucalyptus* clones. The signs (+) and (-) signifies that there is an increase or reduction, respectively, for the property.

Characteristic	N	From inner to outer region	From basal to top position
Nominal density	26	+ 22.5	- 4.3 %
Modulus of rupture	26	+ 50.4	+1.0 %
Modulus of elasticity	26	+ 35.5	+ 9.0 %
Resilience	26	+ 56.3	- 1.9 %
Compression strength parallel to grain	26	+ 41.1	+ 3.3 %
Janka hardness	26	+ 48.3	- 11.7 %
Grain angle	26	+ 11.6	-17.2 %
Fibre length	11	+ 19.1	
Fibre diameter	11	+ 3.2	
Lumen diameter	11	- 5.6	
Fibre wall thickness	11	+ 17.6	
Microfibril angle	11	- 12.9	

Radial variation- Except for lumen diameter and microfibril angle, which decreased from inner to outer wood, all other anatomical, physical and mechanical properties increased in that direction. Small variations in the anatomical characteristics correspond to moderate variations in nominal density and higher variations in the mechanical properties. This suggests that other factors might be negatively affecting the mechanical properties in the centre of the log. Some indications of the existence of such factors are the occurrence of compression creases in the inner wood and the noted higher number of brash type failures for wood from this region during the bending test. In addition the presence of shorter fibres (for example) in the inner wood might have a weak influence on density but a pronounced effect on mechanical properties. Table 10.1 shows that mechanical properties vary more than nominal density or anatomical characteristics when the observation is made from inner to outer region of the log.

Base-top variation- Variations in the properties in the base-top direction were proportionally smaller than those observed from the pith to bark [except for grain angle (Table 10.1)]. It is a possible that the higher spirality observed in the base of the log has somewhat contributed to reducing the values of modulus of rupture and modulus of elasticity at that position. It was observed that, contrary to nominal density, the magnitudes of these properties were higher at the top than at the base of the log. However, it was not possible to associate the longitudinal pattern of variation with the fibre dimensions or microfibril angle, since these characteristic were not studied in the top bolt. Based on the relationships observed for wood from the basal bolt it may be expected that in the top bolt slightly longer and thicker fibres will be found.

Between tree variation- A little variation between trees was observed for basic density. This might suggest that only one tree per clone would also be sufficient to sample for other characteristics, due the high correlation between mechanical properties and density. However, this study demonstrated that although nominal density was the best predictor for mechanical properties, other factors are involved. Therefore estimation of the optimum number of samples for mechanical property determination deserves specific study.

Variation between clones and between sites- The differences between clones were statistically significant for all densities, mechanical properties and anatomical characteristics studied. The coefficient of variation between clones varied from 6.5 % to 17 % for most of the characteristics. However, grain angle and resilience showed higher values (26 % and 29 % respectively). With the exception of fibre wall thickness, differences between the four sites were statistically significant for all characteristics. For solid wood production the wide range of variation between clones and between sites means that it should be possible to select clones which will produce wood suitable for different end uses, but some clones may have to be directed towards different end use, perhaps the production of pulp or composites.

Clone × site interactions- The clone × site interaction was statistically significant for basic density when three trees were used as replicates of five clones grown at two sites. The different slopes of the linear regressions of the mean value of a characteristic of a particular clone against the mean value of that characteristic per site suggested that the clone × site interactions for all characteristics were complex. In addition, clone × site interactions were unpredictable, and in most cases it was not possible to predict the characteristic of the wood produced at one site from its value at another site. For all properties was it possible to identify clones which produced wood with consistently high or low values of a particular characteristic on the four test sites. In the set of *Eucalyptus* clones assessed in the present study, analysis of variance showed clone × site interactions in basic density to be statistically significant even for five clones on two sites. Regression analyses for various properties suggested that interactions were unpredictable, and there were marked differences in stability between clones. On the other hand, interactions accounted for less than 4% (adjusted R^2 statistic) of the variance in basic density of 26 clones on four sites, rank correlations between sites were all significant, and it was possible to identify clones which produced wood of consistently high or low values of density, mechanical and anatomical characteristic on the four test sites.

Wood density is positively correlated with many of the mechanical properties of solid wood. If tree breeders want to improve these properties, should they identify clones which give the highest wood density on a particular site type (i.e. select for specific adaptation)? Or should they select for general adaptation and identify clones which produce wood of above average (but not necessarily the highest) density on a range of sites?

These are difficult questions to answer, not least because the environmental factors which affect basic density are not well understood: practically environments cannot be well-defined and may not be repeatable - conditions considered essential if genotypes are to be matched to sites. Even if these conditions can be met, the costs of selecting and testing clones for specific adaptation can only be justified if they are outweighed by the commercial benefits of propagating and growing them. Ideally, decisions about selection strategies should be made only after the economic objectives of breeding programmes have been correctly defined and the relative importance of (e.g.) density in determining the mechanical properties of interest has been determined. Such decisions cannot be made by breeders alone - they should be taken in consultation with wood users.

10.3 Heritabilities

In spite of the evidence of clone × site interactions, the broad sense heritabilities calculated from average values of characteristics in the log were reasonably high, except for resilience, grain angle and microfibril angle. Thus, most of the anatomical, physical and mechanical characteristics are under reasonably strong genetic control. This means that the selection and breeding of these clones tends to reproduce such properties. Conversely, characteristics such as resilience, grain angle and microfibril angle are more likely to be affected by environmental conditions. In this case the improvement of wood must be obtained through the selection of the appropriate site to grow the trees. A summary of the values of heritabilities is presented in Table 10.2. The table shows two interesting aspects of the heritabilities. Firstly, for nominal density and mechanical properties there are practically no differences between inner, intermediate and outer wood heritabilities. Secondly, for grain angle and anatomical characteristics, it appears that heritability increases from the inner wood to the outer wood.

Table 10.2 Estimation of broad sense heritability of wood properties calculated for inner, intermediate and outer positions in the log and for log averages (N = number of clones).

Characteristic	N	Inner	Inter	Outer	Average
Basic Density	26				0.640
Nominal density	26	0.589	0.527	0.591	0.619
Modulus of rupture	26	0.475	0.516	0.477	0.578
Modulus of elasticity	26	0.402	0.488	0.559	0.608
Resilience	26	0.284	0.227	0.197	0.255
Compression strength	26	0.478	0.537	0.547	0.603
Janka hardness	26	0.410	0.491	0.358	0.495
Grain angle	26	0.042	0.07	0.280	0.252
Fibre length	11	0.127	0.335	0.284	0.466
Fibre diameter	11	0.104	0.336	0.390	0.527
Lumen diameter	11	0.228	0.220	0.554	0.518
Microfibril angle	11	0.216	0.188	0.360	0.323

For the characteristics which show small or unimportant differences in heritability between radial positions, it is worth noting that usually the central position of the log produces wood of poorer quality. Bearing in mind the strong genetic control exerted over these properties, it is recommended that the genetic selection of trees to produce solid wood be directed towards improving the properties of the juvenile wood at the centre of the stem. This has advantages for the breeder, since selection can be done when the trees are quite young. However, it is not advantageous to use this strategy for anatomical characteristics, since the heritabilities of anatomical characteristics in this part of the tree are low. It seems that, contrary to the nominal density and mechanical properties, anatomical characteristics were more influenced by the environment (when the trees were younger and producing wood which is later in the centre of the stem) than when trees were older (and producing outer wood).

10.4 Recommendation for Future Work

1. Further understanding of clonal variation in the solid wood properties of *Eucalyptus* requires more detailed studies. Possibly, the first level of detail must be the within-tree variation of the mechanical properties: higher numbers of cambial ages or growth layers might be studied and associated with the high growth rates observed in trees grown in experimental conditions. Only three radial and two longitudinal positions in the log as used in the present research are not sufficient to draw up a precise pattern of variation in the log. A study of the longitudinal variation in wood properties would contribute to the understanding of within-tree variation.

2. Other areas for further investigation are intra-clonal variation and genotype-environment interactions in mechanical properties. In this case it will be possible to know the significance of the variations of the mechanical properties of the clones cultivated in various sites. In this study it was only possible to test the statistical significance of such an interaction for basic density using only five clones and two sites: there was no information about the significance of interactions for mechanical properties, since for twenty-six clones, only one tree was studied. An investigation of this question must involve higher numbers of replicates and sites.

3. The phenotypic correlations obtained in this study should be complemented by a study of genetic correlations. This will show if the correlation between properties is mainly due to genetic linkages or the interaction of genotypes with their environments.

4. Despite the small angles measured, the effect of grain angle on modulus of rupture and modulus of elasticity has been shown to be significant (although of little influence). A more detailed study of the pattern of variation, which would include not only the angle but also its direction (left-handed or right-handed), in several growth layers, would provide more detailed information about the interlocked pattern in *Eucalyptus*.

5. This work demonstrated that 50 % of the variation in nominal density can be significantly determined by the fibre morphology. However only fibres were studied and it is known that other anatomical characteristics also affect nominal density. Thus, it would be interesting to investigate the contributions of vessels and rays in determining nominal density and mechanical properties.

6. This study demonstrated that microfibril angle performs a interesting role in determining certain mechanical properties, mainly related to the stiffness. However, the relationships were confined to only three radial positions within the log. Thus, a more detailed study of the within-tree variation, as suggested for other properties, should also be conducted for microfibril angle. In addition, more detailed measurements, which consider both inter and intra-fibre variation would be appropriate to provide a better understanding of these ultra-structural component of wood.

7. Although not included in this study, the dimensional instability of wood and its relationship with fibre morphology and microfibril angle is an important aspect for the utilisation of solid wood, and so deserves an appropriate investigation.

8. Evidence presented in this study indicates that cell wall deformations (slip planes) caused by compression stresses occur naturally in non-machined, naturally stressed *Eucalyptus* wood. It is well known that these deformations can be the initial cause of failure in wood. Thus, a specific study should investigate the origins of these slip planes and their characteristics in *Eucalyptus* wood, their distribution in the stem and their relationships with other microscopic and ultra-microscopic wood characteristics, mainly related to fibre morphology and microfibril angle.

9. An assessment of the mechanical behaviour of wood should be followed by in-grade testing of samples of given size and grade of full-sized structural timber. These tests would enable a practical evaluation of the quality of the final sawn timber product.

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APPENDIX 1 Magnitude of nominal density, mechanical properties and grain angle.

Appendix 1.1 Nominal density (g.cm-^{3}) of *Eucalyptus* wood of the basal bolt in each radial position and the weighted average in each of four sites.

Clone	Southern Bahia				São Mateus 1				São Mateus 2				Aracruz			
	Inner	Inter	Outer	Mean	Inner	Inter	Outer	Mean	Inner	Inter	Outer	Mean	Inner	Inter	Outer	Mean
1	0.454	0.503	0.503	0.498	0.458	0.514	0.586	0.544	0.467	0.500	0.569	0.531	0.450	0.537	0.574	0.547
2	0.394	0.451	0.497	0.468	0.450	0.503	0.618	0.555	0.453	0.515	0.542	0.522	0.390	0.443	0.545	0.489
3	0.488	0.453	0.471	0.466	0.460	0.493	0.576	0.531	0.500	0.466	0.513	0.493	0.423	0.447	0.526	0.484
4	0.541	0.558	0.645	0.600	0.546	0.607	0.738	0.666	0.535	0.618	0.658	0.630	0.579	0.595	0.673	0.632
5	0.513	0.520	0.592	0.555	0.535	0.586	0.681	0.628	0.535	0.610	0.644	0.620	0.568	0.607	0.645	0.622
6	0.487	0.473	0.431	0.453	0.494	0.508	0.542	0.524	0.503	0.546	0.565	0.551	0.544	0.543	0.595	0.569
7	0.475	0.496	0.544	0.518	0.555	0.609	0.666	0.632	0.537	0.578	0.681	0.625	0.612	0.593	0.589	0.593
8	0.503	0.533	0.631	0.579	0.502	0.533	0.666	0.596	0.565	0.636	0.667	0.644	0.557	0.602	0.673	0.633
9	0.543	0.563	0.648	0.604	0.531	0.595	0.754	0.668	0.589	0.634	0.748	0.687	0.554	0.627	0.766	0.689
10	0.491	0.482	0.575	0.529	0.459	0.469	0.523	0.495	0.512	0.547	0.563	0.552	0.521	0.486	0.513	0.503
11	0.419	0.456	0.473	0.461	0.472	0.612	0.614	0.599	0.473	0.481	0.556	0.518	0.475	0.522	0.544	0.528
12	0.464	0.589	0.610	0.587	0.518	0.593	0.676	0.627	0.545	0.590	0.618	0.600	0.541	0.666	0.718	0.680
13	0.504	0.493	0.536	0.516	0.453	0.474	0.519	0.494	0.512	0.529	0.613	0.569	0.491	0.509	0.576	0.541
14	0.417	0.574	0.612	0.577	0.431	0.548	0.664	0.594	0.516	0.608	0.723	0.656	0.441	0.579	0.606	0.579
15	0.422	0.471	0.515	0.488	0.494	0.593	0.577	0.575	0.537	0.600	0.598	0.593	0.388	0.596	0.581	0.568
16	0.437	0.461	0.515	0.486	0.443	0.450	0.510	0.479	0.439	0.466	0.502	0.481	0.495	0.550	0.675	0.607
17	0.428	0.429	0.515	0.472	0.642	0.607	0.709	0.662	0.516	0.512	0.567	0.540	0.521	0.584	0.645	0.608
18	0.448	0.513	0.551	0.526	0.456	0.502	0.557	0.525	0.478	0.536	0.682	0.603	0.454	0.515	0.603	0.553
19	0.390	0.418	0.491	0.452	0.379	0.416	0.551	0.480	0.478	0.493	0.531	0.511	0.474	0.477	0.561	0.519
20	0.487	0.495	0.546	0.520	0.464	0.535	0.667	0.594	0.498	0.513	0.549	0.530	0.423	0.473	0.574	0.519
21	0.419	0.488	0.549	0.512	0.477	0.491	0.638	0.563	0.423	0.598	0.632	0.598	0.424	0.451	0.599	0.522
22	0.495	0.497	0.561	0.529	0.457	0.490	0.561	0.522	0.465	0.456	0.584	0.521	0.557	0.630	0.658	0.637
23	0.441	0.457	0.613	0.533	0.398	0.425	0.678	0.549	0.435	0.467	0.535	0.498	0.415	0.475	0.597	0.530
24	0.401	0.411	0.451	0.430	0.449	0.499	0.536	0.513	0.471	0.512	0.519	0.511	0.417	0.444	0.465	0.452
25	0.393	0.429	0.493	0.457	0.525	0.531	0.583	0.556	0.470	0.509	0.559	0.530	0.469	0.460	0.551	0.506
26	0.422	0.419	0.484	0.452	0.428	0.539	0.594	0.555	0.485	0.531	0.628	0.575	0.463	0.474	0.549	0.510

Appendix 1.2 Nominal density (g.cm-³) of *Eucalyptus* wood of the top bolt in each radial position and the weighted average in each of four sites.

Clone	Southern Bahia				São Mateus 1				São Mateus 2				Aracruz			
	Inner	Inter	Outer	Mean	Inner	Inter	Outer	Mean	Inner	Inter	Outer	Mean	Inner	Inter	Outer	Mean
1	0.427	0.456	0.493	0.472	0.462	0.469	0.505	0.486	0.445	0.477	0.536	0.503	0.436	0.485	0.504	0.490
2	0.405	0.456	0.508	0.477	0.465	0.535	0.610	0.566	0.488	0.513	0.580	0.544	0.438	0.456	0.548	0.500
3	0.429	0.433	0.473	0.453	0.416	0.474	0.532	0.497	0.419	0.466	0.497	0.477	0.438	0.449	0.598	0.522
4	0.559	0.577	0.601	0.587	0.526	0.537	0.607	0.571	0.519	0.544	0.596	0.568	0.569	0.583	0.617	0.599
5	0.497	0.481	0.561	0.523	0.549	0.572	0.602	0.585	0.567	0.555	0.589	0.573	0.567	0.560	0.623	0.592
6	0.479	0.506	0.523	0.512	0.495	0.500	0.519	0.509	0.502	0.505	0.503	0.504	0.506	0.532	0.512	0.519
7	0.466	0.496	0.534	0.512	0.493	0.505	0.564	0.533	0.536	0.530	0.580	0.556	0.512	0.536	0.565	0.548
8	0.525	0.554	0.628	0.588	0.568	0.578	0.601	0.589	0.598	0.622	0.618	0.618	0.548	0.560	0.625	0.591
9	0.488	0.562	0.615	0.581	0.625	0.553	0.704	0.636	0.576	0.599	0.706	0.650	0.544	0.672	0.671	0.659
10	0.445	0.485	0.510	0.494	0.471	0.504	0.598	0.548	0.491	0.479	0.529	0.505	0.526	0.511	0.515	0.515
11	0.397	0.452	0.508	0.475	0.502	0.522	0.547	0.533	0.452	0.507	0.533	0.515	0.507	0.496	0.518	0.508
12	0.435	0.459	0.528	0.491	0.544	0.500	0.631	0.570	0.464	0.552	0.544	0.539	0.476	0.570	0.574	0.563
13	0.438	0.498	0.548	0.517	0.469	0.447	0.477	0.464	0.537	0.472	0.558	0.522	0.571	0.551	0.589	0.572
14	0.424	0.506	0.612	0.551	0.427	0.417	0.508	0.464	0.503	0.569	0.678	0.617	0.504	0.440	0.579	0.516
15	0.421	0.510	0.579	0.536	0.528	0.597	0.634	0.609	0.495	0.529	0.549	0.536	0.469	0.402	0.531	0.473
16	0.422	0.427	0.464	0.445	0.413	0.434	0.532	0.481	0.420	0.420	0.487	0.454	0.484	0.470	0.518	0.495
17	0.434	0.433	0.493	0.463	0.453	0.505	0.650	0.572	0.431	0.472	0.494	0.479	0.502	0.502	0.528	0.515
18	0.468	0.538	0.597	0.561	0.429	0.491	0.621	0.550	0.472	0.569	0.654	0.602	0.440	0.522	0.623	0.564
19	0.419	0.424	0.542	0.483	0.405	0.390	0.492	0.443	0.458	0.478	0.521	0.498	0.466	0.499	0.553	0.523
20	0.429	0.446	0.505	0.474	0.464	0.495	0.546	0.517	0.466	0.479	0.533	0.505	0.433	0.480	0.533	0.502
21	0.435	0.512	0.561	0.529	0.441	0.474	0.537	0.502	0.543	0.565	0.636	0.598	0.456	0.494	0.554	0.520
22	0.443	0.464	0.481	0.470	0.429	0.464	0.504	0.481	0.488	0.477	0.506	0.493	0.450	0.520	0.540	0.523
23	0.417	0.468	0.555	0.506	0.402	0.442	0.570	0.502	0.405	0.479	0.561	0.513	0.412	0.475	0.572	0.517
24	0.366	0.397	0.451	0.421	0.402	0.440	0.478	0.455	0.425	0.512	0.470	0.482	0.359	0.425	0.427	0.419
25	0.375	0.438	0.471	0.448	0.497	0.533	0.594	0.560	0.439	0.488	0.532	0.505	0.445	0.488	0.541	0.510
26	0.439	0.445	0.493	0.468	0.444	0.463	0.514	0.487	0.474	0.498	0.611	0.552	0.471	0.501	0.593	0.544

Appendix 1.3 Modulus of rupture (MPa) of *Eucalyptus* wood of the basal bolt in each radial position and the weighted average in each of four sites.

Clone	Southern Bahia				São Mateus 1				São Mateus 2				Aracruz			
	Inner	Inter	Outer	Mean	Inner	Inter	Outer	Mean	Inner	Inter	Outer	Mean	Inner	Inter	Outer	Mean
1	72.9	91.9	99.9	94.0	70.9	89.0	101.1	93.2	85.9	95.7	102.2	98.0	76.6	74.9	87.7	81.5
2	60.3	75.8	109.4	91.1	72.6	101.1	121.3	108.4	67.8	76.8	102.7	88.8	67.9	87.8	112.0	97.9
3	51.9	73.5	84.0	76.6	69.9	81.5	107.9	93.5	64.6	76.9	86.1	80.2	72.3	65.8	89.2	78.2
4	93.1	108.8	127.0	116.3	81.6	102.5	126.5	112.4	82.5	84.7	125.6	105.0	85.6	106.4	125.3	113.8
5	60.6	80.6	89.2	82.9	63.4	95.4	110.9	99.9	69.9	73.4	85.4	79.0	84.9	101.1	109.3	103.6
6	82.2	89.6	82.6	85.3	89.4	96.2	96.9	95.9	90.4	101.2	99.5	99.3	93.9	98.0	92.9	95.1
7	74.6	82.6	93.8	87.4	98.4	94.4	129.5	112.3	82.6	90.8	120.1	104.6	107.0	91.4	108.2	101.4
8	83.5	100.1	135.4	116.1	87.5	102.2	124.2	111.7	68.3	101.0	116.6	105.5	84.7	97.3	131.4	113.1
9	80.3	94.8	105.5	98.7	83.2	94.9	112.5	102.5	93.8	92.4	140.1	116.4	76.9	104.1	126.6	112.6
10	70.7	79.7	101.0	89.4	56.4	63.2	87.4	74.6	81.9	72.2	89.1	81.6	73.2	72.8	81.1	77.0
11	34.3	47.2	66.8	55.7	58.2	82.7	93.1	85.5	53.9	49.2	87.7	68.9	70.2	96.6	94.8	93.0
12	58.5	81.3	119.2	98.0	96.3	125.8	125.8	122.9	69.4	106.4	100.5	99.7	61.3	102.5	111.4	102.8
13	56.0	59.8	89.7	74.3	62.0	79.8	85.0	80.6	72.3	86.2	87.9	85.7	69.5	76.0	66.6	70.7
14	60.0	86.0	103.5	92.1	42.5	66.6	116.5	89.1	50.5	75.7	91.7	81.2	42.0	63.2	90.6	74.8
15	56.5	70.9	103.6	85.8	53.9	97.3	87.9	88.2	60.8	74.3	78.4	75.0	46.0	52.9	101.6	76.6
16	66.2	78.0	85.7	80.7	48.8	78.1	85.4	78.8	62.3	77.4	101.0	87.7	79.8	95.2	98.2	95.1
17	54.9	65.5	99.8	81.6	71.0	81.0	108.1	93.5	40.6	82.6	102.8	88.5	50.3	65.8	102.8	82.7
18	52.5	90.3	111.1	96.9	68.3	82.7	91.7	85.8	70.5	101.8	113.9	104.7	55.6	78.4	109.1	91.5
19	65.0	75.2	78.7	75.9	59.6	73.2	94.4	82.4	76.8	78.5	91.7	84.9	67.3	71.5	104.4	87.5
20	85.2	104.6	110.0	105.4	65.8	92.9	80.7	84.1	47.6	79.4	97.4	85.2	54.9	93.2	116.7	101.1
21	68.6	92.9	104.5	96.3	67.1	77.9	99.6	87.6	58.0	73.8	91.1	80.9	43.9	77.4	99.7	85.2
22	59.2	67.0	87.1	76.3	59.6	73.7	88.2	79.5	64.9	85.3	105.9	93.6	53.4	75.4	116.4	93.7
23	48.5	62.0	97.2	78.3	44.2	70.5	138.4	101.8	56.9	67.5	83.4	74.4	59.5	76.1	121.0	96.9
24	37.8	59.0	67.3	61.0	58.6	73.3	90.7	80.5	52.7	77.4	74.0	73.2	69.4	65.1	69.9	67.9
25	38.2	58.6	81.8	68.2	100.4	81.7	111.2	98.3	69.1	70.1	105.9	87.9	43.2	54.5	81.5	66.9
26	70.7	58.3	64.7	62.7	50.6	68.1	104.7	84.7	58.5	81.3	97.0	86.9	66.8	74.7	81.4	77.2

Appendix 1.4 Modulus of rupture (MPa) of *Eucalyptus* wood of the top bolt in each radial position and the weighted average in each of four sites.

Clone	Southern Bahia				São Mateus 1				São Mateus 2				Aracruz			
	Inner	Inter	Outer	Mean	Inner	Inter	Outer	Mean	Inner	Inter	Outer	Mean	Inner	Inter	Outer	Mean
1	56.3	73.8	90.0	80.1	80.1	86.3	90.5	87.8	87.4	82.6	107.8	95.7	73.0	98.5	107.3	100.3
2	70.6	91.1	106.6	96.8	81.1	109.2	118.4	111.0	57.9	91.9	118.6	101.9	48.2	89.8	101.3	91.4
3	57.6	71.9	92.5	80.8	83.5	81.6	69.7	75.8	63.0	84.6	97.6	88.9	68.9	72.5	103.4	87.5
4	73.1	95.9	115.4	103.4	99.5	110.1	125.9	116.9	73.6	125.8	127.6	121.5	63.1	99.6	125.2	108.7
5	60.1	80.5	85.1	80.7	68.3	84.6	102.8	92.1	77.8	92.5	101.3	95.4	62.0	106.1	117.9	107.6
6	68.5	92.6	97.7	92.8	97.0	95.6	99.9	97.9	78.3	102.1	90.2	93.8	68.9	95.4	92.9	91.5
7	75.4	85.0	72.1	77.6	82.8	96.2	120.5	107.0	88.8	93.0	118.5	105.3	77.2	94.6	113.0	102.1
8	99.3	103.6	136.9	119.8	86.8	97.7	127.1	111.3	90.6	112.7	124.2	116.2	78.8	102.8	131.5	114.7
9	66.5	80.7	104.0	90.9	112.3	99.2	124.5	113.2	87.6	91.9	153.4	122.2	82.5	117.8	136.4	123.5
10	71.8	80.3	96.2	87.4	83.2	77.2	101.4	89.9	83.0	84.1	98.2	91.0	78.2	83.5	88.2	85.3
11	49.9	68.6	89.4	77.1	49.1	89.7	101.4	91.5	52.3	75.5	116.6	93.7	63.0	71.2	93.9	81.8
12	62.4	71.8	91.5	80.7	91.1	91.0	130.3	110.7	63.9	98.6	100.9	96.2	69.4	84.1	122.0	101.6
13	49.7	64.9	85.3	73.6	60.0	72.6	85.3	77.7	75.0	73.1	91.7	82.6	69.9	80.4	117.3	97.8
14	48.6	62.9	93.6	76.8	54.0	56.5	84.0	70.0	56.6	76.9	98.3	85.6	58.0	49.4	90.2	70.6
15	49.6	68.4	85.8	75.2	61.1	63.8	116.4	89.8	47.2	81.3	92.6	83.5	40.5	39.0	67.1	53.2
16	69.2	71.1	75.5	73.1	55.0	82.9	90.4	83.8	59.1	79.5	109.0	92.2	86.6	93.5	98.3	95.2
17	50.8	54.6	100.0	76.9	60.5	76.4	125.9	99.6	54.3	66.1	77.5	70.6	55.1	72.1	100.8	84.7
18	59.9	76.5	124.3	98.8	69.2	90.7	115.8	101.1	65.4	69.6	107.9	88.3	69.9	92.3	112.7	100.2
19	76.6	71.0	96.9	84.5	66.7	74.6	86.0	79.5	70.8	81.6	102.8	91.1	94.4	97.8	119.4	108.3
20	84.7	95.6	106.7	100.1	70.9	87.3	111.3	97.7	72.2	81.3	109.6	94.6	67.9	85.3	114.0	97.9
21	45.2	84.3	101.6	89.0	70.2	73.4	88.0	80.4	78.2	101.1	125.5	111.0	60.4	63.8	108.4	85.8
22	42.5	75.6	86.5	77.8	67.5	84.1	103.8	92.3	79.7	81.9	88.5	85.0	52.5	84.6	103.6	90.9
23	53.8	74.2	110.8	90.5	63.6	73.8	107.3	89.5	50.9	79.6	115.3	94.6	59.5	78.7	108.5	91.7
24	45.2	55.9	64.5	59.1	53.1	63.1	82.5	71.8	43.7	43.1	77.4	60.3	61.9	72.4	65.4	67.9
25	36.6	41.0	60.4	50.2	65.0	99.5	101.2	96.9	54.2	79.1	90.4	82.2	59.2	81.0	99.4	88.0
26	52.2	65.2	87.2	74.9	58.8	78.6	84.5	79.6	55.1	76.2	112.7	92.4	61.2	57.2	83.6	70.8

Appendix 1.5 Modulus of elasticity (MPa) of *Eucalyptus* wood of the basal bolt in each radial position and the weighted average in each of four sites.

Clone	Southern Bahia				São Mateus 1				São Mateus 2				Aracruz			
	Inner	Inter	Outer	Mean	Inner	Inter	Outer	Mean	Inner	Inter	Outer	Mean	Inner	Inter	Outer	Mean
1	8320	9535	8830	9061	8055	9003	10191	9502	9397	10496	10572	10424	7453	7905	8880	8347
2	8324	9860	11524	10538	8355	9964	11829	10736	6653	9176	11218	9945	7339	9713	11141	10190
3	6069	8117	8554	8131	7602	8370	10454	9335	7346	8273	9460	8774	7767	7226	8562	7948
4	8231	9780	12074	10772	7714	9376	12296	10670	7467	9471	11116	10093	7171	10309	11639	10660
5	7982	9092	10111	9491	8151	9935	11941	10760	8394	9180	9767	9395	8874	10383	11344	10713
6	7546	8882	8280	8447	7972	9475	9943	9559	9280	10481	10227	10234	9781	10314	10096	10151
7	8688	9638	9996	9722	10810	9923	10442	10271	9213	9232	12080	10654	11031	10209	11174	10774
8	9397	10542	14610	12461	8375	11162	12899	11752	8236	10533	12324	11199	9476	10567	13379	11864
9	8361	9698	11277	10354	8379	8849	11989	10372	9845	9914	13058	11479	7744	9781	11092	10233
10	7884	8446	10348	9341	6138	6452	8766	7577	8042	7167	8739	8040	6420	7124	8880	7931
11	5369	6382	7188	6684	6838	9239	9454	9106	6790	6439	9130	7820	6704	9102	9786	9204
12	7106	8986	12108	10359	9095	11675	8716	9938	9319	11812	10487	10900	7433	10729	11197	10633
13	7478	7244	9709	8500	6840	8671	9319	8812	8082	9120	9632	9272	7463	8713	7556	8010
14	7710	9127	10925	9884	5449	6649	11239	8824	6470	8356	9484	8732	6573	6676	8809	7732
15	6304	7671	8760	8078	6053	8736	8319	8259	7394	7940	10032	8931	6764	8273	11142	9557
16	7344	8126	9378	8674	6583	7620	9181	8297	6728	9662	10903	9989	8608	10645	10295	10266
17	7689	8253	10599	9370	8477	8413	10901	9663	7688	9213	10993	9951	8684	10042	11204	10487
18	9541	11060	12578	11667	6716	8954	9653	9080	7730	11010	10894	10624	7038	8902	11229	9879
19	6167	7838	8136	7820	6886	7839	9568	8608	9161	9960	10087	9943	6609	6920	9397	8127
20	9228	10401	10625	10526	7710	10441	12676	11286	6727	9681	10224	9657	8134	11491	12604	11712
21	7863	9638	11338	10310	7937	8670	11046	9785	6708	8000	9983	8863	6174	7869	11929	9729
22	6545	8240	9411	8656	7375	7650	9468	8531	7289	9125	10161	9460	7949	9948	12111	10830
23	6712	8465	11618	9866	6986	7474	13016	10196	7681	8219	10423	9267	7641	9207	12663	10778
24	5755	7243	8120	7533	5917	7996	9988	8784	7089	7245	6706	6960	6102	6369	7897	7106
25	6218	6605	9338	7933	9402	8173	11813	10116	8817	9300	11011	10107	6913	6692	8889	7813
26	8100	6465	6903	6848	7089	7806	11074	9368	6806	9614	10671	9862	7595	8254	8461	8292

Appendix 1.6 Modulus of elasticity (MPa) of *Eucalyptus* wood of the top bolt in each radial position and the weighted average in each of four sites

Clone	Southern Bahia				São Mateus 1				São Mateus 2				Aracruz			
	Inner	Inter	Outer	Mean	Inner	Inter	Outer	Mean	Inner	Inter	Outer	Mean	Inner	Inter	Outer	Mean
1	7514	8841	10342	9459	8669	9475	9805	9559	8843	9243	11491	10327	8247	11207	11662	11139
2	7900	9731	11355	10360	9909	11590	12350	11802	7843	10476	12208	11079	7143	9359	11295	10105
3	6914	8615	9859	9067	8938	9287	7656	8437	7063	9227	10225	9510	7939	7903	10254	9082
4	8532	9783	11116	10324	9936	10406	13399	11856	8059	11591	13075	11980	7941	10625	12786	11437
5	13760	10320	10611	10810	8072	10137	12647	11186	10631	11563	11924	11650	10007	11292	12834	11935
6	7572	10110	10270	9936	9036	8676	10181	9465	9752	10971	10304	10516	8516	9659	10437	9934
7	9131	9918	10951	10356	8362	10721	12539	11394	8616	10320	12628	11304	8561	10958	11708	11093
8	11231	11506	13861	12656	10967	11287	13330	12277	10871	12975	13020	12787	9566	11227	14221	12558
9	8176	9444	12153	10672	9630	10669	12849	11655	10897	11429	16088	13705	8759	12561	13740	12770
10	7925	9224	10908	9936	8413	8557	10890	9709	7924	8622	10346	9414	7574	8415	9850	9048
11	7136	8560	9719	8997	7634	8917	10461	9561	7662	8845	11759	10184	7853	6730	9871	8413
12	7746	9726	10989	10160	9811	10039	12869	11431	7576	10771	11379	10756	7913	9938	12785	11159
13	6932	8939	10495	9516	7198	8306	9565	8825	8821	9015	13759	11368	9276	9252	12594	10925
14	7150	8733	10481	9449	6001	7231	9794	8390	7097	9255	10935	9879	6935	6612	10720	8698
15	7826	11163	10229	10362	8326	8991	11847	10353	8162	9799	10417	9944	5545	4649	8880	6854
16	7920	8803	9703	9165	7627	9136	10083	9459	8107	9511	11632	10431	9820	9838	10602	10218
17	6821	8871	11351	9906	8397	10983	12874	11670	8364	10594	10209	10179	9015	10007	11802	10805
18	8058	10223	13847	11819	8541	9779	12757	11144	7253	10452	11568	10690	9066	10305	12877	11467
19	8673	8934	10126	9504	7525	8904	8737	8683	9557	10632	11798	11108	9262	9913	11780	10781
20	11111	11920	12197	11978	9078	10504	12323	11271	8966	10892	12266	11386	8678	10823	12691	11543
21	6758	10806	11781	10889	9728	9083	11185	10199	8366	11188	13361	11992	7601	9165	12623	10738
22	7674	9039	10417	9592	8801	9892	11202	10438	8783	9894	9929	9800	8135	10845	12066	11185
23	7090	9303	12353	10607	7805	8634	11516	9992	7215	9772	13083	11172	8043	9374	12345	10726
24	6071	7179	6913	6935	6364	6791	8631	7668	6268	7441	8402	7804	6691	7717	7916	7714
25	6788	7800	9262	8430	9476	12424	10337	11086	8457	9991	11056	10370	7514	9625	11165	10184
26	7542	8998	10824	9765	8794	8946	10805	9860	8827	10118	12603	11231	8525	9526	12008	10667

Appendix 1.7 Resilience (kJ.m^{-3}) of *Eucalyptus* wood of the basal bolt in each radial position and the weighted average in each of four sites

Clone	Southern Bahia				São Mateus 1				São Mateus 2				Aracruz			
	Inner	Inter	Outer	Mean	Inner	Inter	Outer	Mean	Inner	Inter	Outer	Mean	Inner	Inter	Outer	Mean
1	9.6	12.0	8.1	9.8	10.3	13.8	17.9	15.5	6.2	7.9	9.9	8.7	6.0	7.4	14.1	10.6
2	14.0	15.0	23.1	18.9	15.1	18.9	24.3	21.2	10.5	15.7	17.4	16.0	16.2	16.0	26.3	21.2
3	9.8	9.3	14.4	11.9	7.7	11.5	13.3	12.0	6.9	6.9	10.2	8.6	8.1	9.4	15.5	12.3
4	18.2	21.7	22.0	21.5	13.2	8.7	17.4	13.5	9.4	15.0	21.0	17.4	15.3	15.6	22.8	19.2
5	10.4	9.1	9.6	9.5	13.9	19.6	16.5	17.5	11.3	10.3	11.5	11.0	17.7	21.1	24.2	22.3
6	9.4	8.8	14.8	11.9	14.7	14.9	13.6	14.2	10.2	7.6	14.2	11.1	13.6	11.6	13.9	13.0
7	8.9	8.4	10.7	9.6	14.1	21.6	36.6	28.3	10.7	17.9	21.6	19.0	19.5	17.8	25.1	21.6
8	14.5	13.6	17.9	15.8	18.5	17.0	25.3	21.3	9.8	17.6	15.8	15.9	17.1	20.6	25.4	22.6
9	11.8	12.3	14.8	13.5	15.9	13.7	22.7	18.4	9.1	10.3	20.8	15.4	17.5	23.5	29.5	25.9
10	8.8	10.5	15.7	12.9	8.7	9.9	12.2	10.9	10.3	11.4	12.9	12.1	9.4	9.4	8.7	9.0
11	5.3	6.5	10.2	8.2	6.7	13.0	15.1	13.4	9.0	9.2	14.0	11.6	16.5	23.9	21.5	22.0
12	7.5	10.2	18.9	14.3	21.6	19.1	12.5	16.0	10.9	10.9	18.5	14.7	11.1	8.7	13.3	11.2
13	7.4	6.9	11.9	9.5	5.4	11.9	8.3	9.5	9.6	14.1	15.8	14.5	6.8	9.6	10.0	9.5
14	6.0	13.2	17.3	14.5	6.9	6.5	13.9	10.2	8.6	7.7	14.1	11.0	6.1	7.4	9.7	8.4
15	6.1	9.0	12.9	10.7	7.6	9.3	12.7	10.8	8.8	8.3	10.8	9.6	3.5	4.5	10.4	7.4
16	13.3	14.5	15.8	15.0	6.0	9.1	11.6	10.1	9.8	7.8	8.9	8.5	12.3	11.3	15.5	13.5
17	5.3	5.8	12.3	9.0	16.6	18.5	24.8	21.5	6.8	11.9	15.3	13.1	9.4	9.5	18.8	14.1
18	7.4	13.9	18.5	15.5	9.1	11.6	11.2	11.1	14.8	20.7	27.2	23.4	7.7	10.5	15.4	12.7
19	5.8	7.0	12.1	9.4	8.3	11.5	9.9	10.4	8.7	12.0	15.6	13.5	16.1	13.6	19.0	16.5
20	8.7	11.0	15.1	12.8	5.0	14.3	10.8	11.6	6.1	11.5	13.3	11.9	6.8	12.2	18.4	14.8
21	11.5	17.7	21.4	19.0	6.8	13.7	16.6	14.5	5.3	10.3	8.6	8.9	7.6	14.8	12.1	12.7
22	10.2	13.0	12.5	12.4	6.9	12.4	12.7	12.0	9.2	13.7	19.2	16.0	8.8	9.3	16.9	13.0
23	5.6	5.4	15.9	10.6	5.9	9.3	17.7	13.2	6.0	9.1	8.8	8.7	10.0	13.3	24.6	18.6
24	7.2	7.1	21.0	14.1	12.3	11.1	11.9	11.6	9.8	18.9	19.1	18.1	16.4	17.2	13.7	15.4
25	6.2	16.2	9.5	11.9	23.3	16.4	23.4	20.6	15.5	15.1	21.6	18.4	6.9	7.4	11.5	9.4
26	5.0	7.0	11.3	9.0	10.6	7.8	9.6	9.0	9.4	10.9	16.3	13.5	10.8	4.9	14.1	10.1

Appendix 1.8 Resilience (kJ.m^{-3}) of *Eucalyptus* wood of the top bolt in each radial position and the weighted average in each of four sites

Clone	Southern Bahia				São Mateus 1				São Mateus 2				Aracruz			
	Inner	Inter	Outer	Mean	Inner	Inter	Outer	Mean	Inner	Inter	Outer	Mean	Inner	Inter	Outer	Mean
1	5.8	7.2	10.6	8.8	8.9	8.4	10.2	9.4	10.3	9.7	13.1	11.5	8.5	14.3	13.1	13.1
2	16.4	18.2	24.6	21.2	8.3	17.0	14.1	14.7	7.0	11.5	18.6	14.6	11.6	20.1	21.6	20.0
3	7.6	9.8	14.7	12.0	13.5	9.7	11.5	11.0	7.8	13.5	12.2	12.3	9.5	9.2	16.3	12.8
4	6.4	14.9	17.9	15.6	13.6	21.1	16.7	18.1	9.1	11.9	22.3	16.8	6.5	13.8	16.6	14.5
5	10.7	8.9	10.7	10.0	12.5	11.3	11.7	11.6	13.4	8.9	10.7	10.3	13.0	19.6	26.3	22.3
6	6.2	11.3	17.9	14.1	15.3	12.5	10.5	11.8	10.5	10.0	15.2	12.6	5.7	12.4	11.2	11.1
7	12.2	12.7	13.7	13.1	10.5	12.3	15.0	13.4	12.6	11.7	13.7	12.8	19.3	18.8	21.5	20.2
8	16.6	14.9	19.5	17.4	20.2	17.9	21.6	19.9	15.8	21.9	19.9	20.3	9.7	11.9	16.0	13.7
9	6.7	9.8	11.0	10.1	23.8	15.9	19.6	18.5	15.4	10.8	21.5	16.6	17.0	24.0	30.2	26.4
10	11.5	8.1	10.6	9.7	16.8	13.3	15.8	14.9	12.5	8.6	11.5	10.4	10.1	10.9	15.3	13.0
11	7.6	9.1	12.7	10.7	8.3	10.7	16.6	13.4	6.0	8.1	14.1	10.9	16.2	20.5	23.6	21.6
12	7.7	8.7	16.8	12.6	14.6	18.5	23.2	20.4	9.6	10.6	13.8	12.1	10.2	10.1	14.8	12.5
13	3.8	6.0	9.8	7.7	4.9	7.1	6.6	6.6	10.7	8.2	14.3	11.5	10.8	9.3	18.6	14.1
14	5.8	8.3	17.3	12.5	6.7	5.1	6.5	6.0	8.9	6.9	13.6	10.4	7.6	6.1	10.0	8.2
15	4.7	4.8	10.0	7.4	7.3	8.4	16.3	12.2	8.9	9.8	18.4	14.0	3.7	4.5	6.2	5.3
16	9.8	10.5	11.6	11.0	5.6	8.6	12.7	10.3	7.5	6.3	11.8	9.2	12.4	12.9	16.0	14.4
17	4.7	7.2	9.0	7.8	10.7	17.8	31.0	23.7	5.0	8.3	9.0	8.3	7.4	8.4	11.7	10.0
18	5.2	11.5	20.8	15.5	8.9	6.9	15.3	11.3	11.6	21.8	24.4	22.1	7.5	12.4	21.3	16.3
19	7.2	6.0	13.4	9.8	5.0	6.7	9.4	7.9	10.3	10.3	11.3	10.8	14.4	12.1	22.6	17.6
20	11.0	9.6	13.6	11.7	7.9	11.3	12.8	11.7	5.7	8.8	12.4	10.3	7.9	10.8	12.8	11.5
21	6.7	15.4	18.0	15.8	6.1	6.6	11.0	8.8	14.1	19.1	26.5	22.3	4.8	10.5	13.2	11.2
22	5.1	8.5	8.3	8.1	6.5	6.7	12.1	9.4	8.7	11.2	6.5	8.6	6.6	9.4	10.7	9.8
23	4.7	6.4	8.4	7.2	6.2	6.1	13.6	9.8	4.2	6.9	10.7	8.5	9.0	11.1	14.4	12.5
24	8.7	11.5	12.9	12.0	6.4	7.2	9.7	8.4	16.7	7.4	18.0	13.6	11.0	12.7	15.1	13.7
25	4.8	4.0	6.4	5.3	9.2	15.1	17.3	15.6	3.5	8.2	11.2	9.2	7.5	9.0	9.9	9.3
26	5.6	6.3	9.2	7.7	7.1	12.5	10.3	10.8	4.3	6.5	11.7	8.9	9.3	6.0	9.9	8.3

Appendix 1.9 Compression strength parallel to grain (MPa) of *Eucalyptus* wood of the basal bolt in each radial position and the weighted average in each of four sites.

Clone	Southern Bahia				São Mateus 1				São Mateus 2				Aracruz			
	Inner	Inter	Outer	Mean	Inner	Inter	Outer	Mean	Inner	Inter	Outer	Mean	Inner	Inter	Outer	Mean
1	43.2	51.9	52.6	51.4	43.9	48.1	60.6	53.9	41.8	54.4	64.3	58.1	39.1	47.6	61.9	53.9
2	41.3	50.3	59.8	54.1	47.1	54.6	72.3	62.7	42.6	54.2	65.6	58.7	41.2	52.3	58.3	54.2
3	41.2	44.3	51.9	47.8	41.8	50.1	61.5	55.0	38.4	42.7	52.4	47.1	41.5	47.4	63.1	54.6
4	47.3	57.1	70.5	62.8	44.5	58.2	72.6	64.0	48.1	61.2	71.3	64.9	43.8	54.0	61.4	56.6
5	42.9	47.1	57.8	52.0	49.6	55.5	66.1	60.2	51.2	50.8	62.5	56.7	47.1	52.8	60.6	56.1
6	44.2	47.4	47.6	47.2	49.5	51.4	57.4	54.2	46.9	52.6	55.9	53.7	49.8	50.3	60.0	55.1
7	41.8	49.0	55.3	51.4	52.5	62.5	67.1	63.8	57.1	56.4	71.7	64.1	42.8	48.8	60.3	53.9
8	48.1	54.5	68.9	61.1	47.5	56.8	76.6	65.8	46.6	57.1	63.6	59.3	54.0	59.3	74.0	66.1
9	44.8	50.3	68.0	58.6	45.8	49.6	66.1	57.5	48.8	61.7	69.6	64.3	47.5	56.1	71.3	62.8
10	40.8	44.3	56.9	50.2	35.2	41.9	57.4	48.9	44.9	45.1	51.2	48.1	34.1	41.4	44.5	42.2
11	32.6	39.6	46.9	42.6	43.8	51.2	55.9	52.8	33.9	43.1	56.2	48.8	37.3	49.1	55.3	51.0
12	42.6	56.8	67.3	60.6	49.0	58.4	74.7	65.6	51.3	54.6	58.4	56.2	43.1	63.7	74.6	67.1
13	43.2	45.4	53.7	49.3	35.8	40.2	48.5	43.9	40.7	48.0	50.9	48.7	35.7	41.5	56.2	48.2
14	32.0	46.4	56.9	50.2	32.4	43.0	63.5	52.2	35.7	49.4	61.9	54.3	32.6	43.9	49.7	45.6
15	35.8	41.9	51.8	46.2	41.0	49.8	51.2	49.6	37.0	53.7	59.5	54.9	25.0	50.7	57.3	51.5
16	41.2	44.0	52.7	48.1	35.0	42.6	50.3	45.7	41.0	40.9	54.9	47.9	43.0	49.7	59.3	53.8
17	36.7	43.6	56.2	49.2	47.4	52.5	67.9	59.7	46.9	48.8	54.7	51.6	48.2	51.6	62.1	56.5
18	43.5	55.0	64.3	58.5	48.6	48.3	46.7	47.5	47.0	55.6	76.3	65.1	39.8	52.0	61.3	55.4
19	39.0	45.3	53.9	49.0	40.6	45.2	57.1	50.7	52.3	53.2	56.4	54.7	44.4	47.8	56.0	51.6
20	55.4	59.1	63.1	60.7	40.6	54.0	63.3	57.3	50.3	54.7	54.6	54.2	43.4	49.8	66.0	57.3
21	43.2	53.9	60.3	56.0	42.7	49.1	65.2	56.5	37.6	52.7	60.9	55.3	38.7	47.0	61.8	53.6
22	41.6	49.8	56.9	52.5	32.7	43.5	51.6	46.5	36.4	46.3	56.2	50.2	43.0	52.9	63.9	57.4
23	35.4	44.0	60.6	51.4	38.2	39.4	65.7	52.5	35.1	44.2	51.6	47.0	39.1	47.8	64.6	55.3
24	35.7	36.8	44.0	40.3	36.1	38.2	55.5	46.6	32.7	42.7	41.6	41.1	36.2	36.8	39.2	37.9
25	33.4	40.8	50.6	44.9	53.9	58.9	63.1	60.5	39.7	49.3	54.4	50.9	37.1	39.3	51.0	44.9
26	35.4	43.3	42.6	42.2	37.4	51.4	58.4	53.5	41.3	54.5	62.4	57.1	38.9	43.9	58.8	50.9

Appendix 1.10 Compression strength parallel to grain (MPa) of *Eucalyptus* wood of the top bolt in each radial position and the weighted average in each of four sites

Clone	Southern Bahia				São Mateus 1				São Mateus 2				Aracruz			
	Inner	Inter	Outer	Mean	Inner	Inter	Outer	Mean	Inner	Inter	Outer	Mean	Inner	Inter	Outer	Mean
1	43.6	44.7	52.3	48.4	47.5	48.7	56.1	52.2	46.6	44.9	63.8	54.5	48.6	52.2	59.8	55.6
2	42.5	52.7	61.7	56.2	51.9	63.6	71.2	66.2	52.5	61.5	70.9	65.3	38.8	51.6	64.0	56.5
3	41.8	46.7	57.7	51.7	45.7	51.3	60.7	55.4	41.0	48.9	58.9	53.1	49.1	50.5	60.0	55.1
4	26.4	58.7	73.2	62.7	55.9	58.9	67.1	62.7	52.7	62.0	69.6	64.9	50.8	61.5	66.9	63.1
5	44.1	51.4	57.2	53.5	50.5	56.3	64.9	60.0	54.2	52.3	60.9	56.8	49.9	54.9	67.7	60.8
6	47.0	53.9	55.4	54.0	54.3	54.4	58.3	56.4	52.7	56.6	57.9	56.9	53.2	57.4	41.5	49.0
7	47.3	51.7	55.5	53.2	51.4	50.8	65.4	58.1	49.9	54.2	65.0	59.2	41.5	53.2	62.4	56.6
8	52.8	61.1	65.1	62.2	56.1	51.9	65.5	59.1	59.8	64.9	67.4	65.6	51.7	58.0	68.8	62.7
9	45.2	51.3	61.7	55.9	56.2	52.5	71.0	62.1	51.7	57.0	76.8	66.3	48.2	60.1	70.3	64.0
10	42.4	43.0	55.4	49.1	47.1	47.7	65.2	56.4	46.5	48.0	56.8	52.2	45.8	49.9	54.9	52.0
11	40.5	50.1	54.8	51.5	48.0	53.8	56.9	54.7	41.7	51.7	59.1	54.4	41.2	45.7	51.7	48.2
12	39.8	49.0	59.1	53.1	47.9	49.5	67.8	58.5	48.0	51.1	59.4	55.0	43.2	55.1	64.1	58.4
13	35.5	44.7	51.2	47.0	39.1	41.8	46.3	43.8	40.2	45.1	55.5	49.8	44.0	53.9	66.3	59.1
14	35.1	44.0	54.2	48.2	34.6	39.8	49.2	44.0	39.2	50.9	64.3	56.4	43.2	38.4	52.7	46.0
15	42.3	55.3	59.1	55.9	47.9	60.6	65.4	61.7	47.8	56.4	61.2	58.0	29.5	33.1	47.9	40.2
16	39.5	42.5	49.1	45.5	43.0	46.1	57.5	51.5	46.8	47.8	55.6	51.6	53.4	51.9	55.2	53.7
17	41.6	45.7	56.1	50.5	45.8	54.9	71.2	62.1	45.1	51.5	54.9	52.6	43.8	48.3	53.7	50.6
18	50.8	60.2	68.6	63.4	45.4	55.7	71.5	62.5	50.5	60.2	74.0	66.1	47.9	56.7	70.2	62.5
19	40.7	47.6	60.3	53.2	42.8	45.6	56.5	50.8	53.8	55.7	60.6	57.9	49.6	56.5	65.1	60.1
20	47.9	52.3	57.6	54.5	47.3	53.1	64.8	58.4	48.2	55.9	62.9	58.6	46.3	50.7	60.2	55.0
21	43.6	56.4	66.2	60.0	45.0	51.8	62.0	56.3	53.0	58.8	68.6	63.1	41.5	51.0	62.5	55.8
22	41.0	45.3	48.9	46.6	44.7	51.0	59.4	54.6	43.2	48.7	56.1	51.9	43.1	52.7	58.7	54.7
23	42.3	47.4	62.8	54.6	43.7	46.8	61.3	53.7	38.9	46.1	61.2	52.9	43.4	48.2	61.6	54.4
24	30.8	36.3	35.9	35.6	33.5	39.6	43.0	40.7	35.9	40.5	44.2	41.9	31.4	38.5	42.2	39.6
25	34.6	39.9	49.3	44.1	47.9	59.2	67.1	62.0	41.8	46.2	52.3	48.8	36.7	48.3	56.1	51.0
26	39.2	45.5	51.8	48.0	38.6	46.8	53.8	49.4	43.4	48.2	61.8	54.5	43.0	45.4	57.3	51.1

Appendix 1.11 Janka hardness (N) of *Eucalyptus* wood of the basal bolt in each radial position and the weighted average in each of four sites

Clone	Southern Bahia				São Mateus 1				São Mateus 2				Aracruz			
	Inner	Inter	Outer	Mean	Inner	Inter	Outer	Mean	Inner	Inter	Outer	Mean	Inner	Inter	Outer	Mean
1	3225	4214	4692	4354	3743	4469	6468	5396	3750	4862	5452	5046	2635	3887	5695	4666
2	2922	3273	4487	3845	3774	3809	7157	5479	3807	3993	5002	4479	3065	3723	5300	4446
3	3770	2462	2946	2835	2855	3278	5811	4502	3780	3169	5863	4577	2780	2510	2710	2637
4	3675	4260	5842	4993	5335	5348	7284	6315	4280	4825	6637	5676	4575	6200	7000	6438
5	4205	4134	5445	4797	5338	4399	7571	6079	4539	4703	5899	5284	4530	5691	6902	6181
6	4303	4259	5190	4729	4788	4578	5911	5265	3875	5035	5181	4992	4898	4982	6638	5802
7	3808	4003	4474	4219	4618	5163	7208	6131	3725	4560	5586	4990	4710	5080	5518	5262
8	3363	3246	4912	4091	4755	4370	5792	5119	5128	5602	5705	5606	3951	4132	5476	4786
9	3725	4551	6088	5237	4825	4774	8726	6755	4925	5196	8653	6898	5095	5232	8479	6842
10	3663	3901	4865	4359	4495	3735	4808	4348	3833	3523	5576	4580	3258	4361	4845	4493
11	2902	3540	4472	3942	3790	6265	6312	6041	3198	3215	5298	4255	3253	4188	5918	4959
12	3415	3885	6656	5224	4455	5420	8133	6680	4400	5885	5325	5457	5335	5320	4737	5030
13	3965	3575	5281	4467	2950	3635	4716	4107	3253	3703	5130	4372	4560	4611	4840	4720
14	3793	4134	6471	5268	2908	3720	6970	5264	3475	5223	7444	6158	3164	5031	6164	5411
15	3138	4029	5130	4490	3583	5603	5888	5543	3945	4503	6663	5527	3135	3155	6400	4776
16	3735	3419	4338	3910	3353	3140	4493	3838	2920	2913	4830	3872	4875	4296	7787	6099
17	2865	2807	4629	3724	6159	5103	9345	7329	3080	3430	6463	4911	5760	4090	5832	5128
18	3095	3522	4203	3819	3135	4003	4633	4231	2775	3100	5325	4180	2653	3825	6259	4925
19	3498	3253	4480	3891	3025	2698	5081	3922	4173	3705	4733	4266	3720	3168	4528	3903
20	4625	4920	5229	5045	3988	3999	6826	5412	3135	4925	4921	4744	2657	3690	5070	4277
21	4041	4920	5503	5124	3660	4743	7408	5967	3160	4565	4420	4352	3816	3450	5824	4674
22	4265	4080	5010	4564	3223	3668	4307	3943	4560	4615	5148	4876	4160	5010	7038	5939
23	2675	2644	5162	3906	2468	3028	5133	4024	2913	3620	3784	3631	2586	3220	5227	4160
24	1810	2035	2775	2383	3505	3313	4475	3913	3360	3302	3930	3622	2800	2955	2728	2826
25	2390	2968	4053	3453	3980	2957	3200	3181	2765	4298	5985	4988	3298	3325	4566	3943
26	4095	3477	4435	4018	3658	4020	5363	4655	3783	3990	6025	4987	4278	4147	5395	4784

Appendix 1.12 Janka hardness (N) of *Eucalyptus* wood of the top bolt in each radial position and the weighted average in each of four sites

Clone	Southern Bahia				São Mateus 1				São Mateus 2				Aracruz			
	Inner	Inter	Outer	Mean	Inner	Inter	Outer	Mean	Inner	Inter	Outer	Mean	Inner	Inter	Outer	Mean
1	2908	3226	3958	3560	4080	3387	4211	3868	4520	3313	5351	4453	2753	3635	4320	3889
2	3078	3611	4953	4229	3530	4823	7123	5844	3643	4053	5341	4656	3088	3548	4485	3970
3	2490	2318	3675	3014	3303	3490	4128	3790	2488	3210	4463	3764	2150	2578	3790	3141
4	3250	4160	4905	4442	5025	4448	5899	5231	3925	6340	5640	5749	4755	4906	6017	5446
5	3185	3243	4443	3837	3090	3622	4688	4102	4550	3608	4266	4031	5078	4255	6341	5380
6	3890	4173	5272	4694	3920	4615	4861	4669	3666	3943	4920	4404	3921	4015	4903	4450
7	3333	3484	4109	3781	4408	4175	5397	4809	3610	4483	5038	4673	3713	3971	5140	4530
8	3778	3534	4936	4259	4658	4488	5832	5177	5320	5105	4307	4727	3793	4258	5978	5071
9	4098	4016	6018	5025	6305	4721	7075	6057	5220	5173	8204	6693	4800	5245	6256	5706
10	3535	3113	4425	3811	3908	3877	6137	5010	4205	3350	5024	4273	4113	3885	4548	4239
11	2918	3554	4878	4152	3940	3950	5155	4552	3375	3367	5304	4336	3408	3275	4468	3885
12	2820	3078	4319	3672	3763	4010	6915	5438	3275	3855	4803	4271	3440	4081	6329	5141
13	2760	3240	4725	3935	2938	2623	3740	3213	3435	2627	4278	3533	3290	3140	4649	3910
14	2805	3224	6155	4647	2670	2400	3995	3225	3341	4705	6530	5481	4870	2731	5149	4154
15	2979	5020	4388	4500	4158	3950	6053	5022	3970	4750	5605	5100	2318	2368	3718	3038
16	3131	2839	3706	3302	2750	3370	3999	3622	3320	3065	4490	3803	3580	3768	5115	4423
17	2480	2923	4068	3451	2970	3898	7548	5630	3325	3285	3160	3227	3195	3368	4824	4078
18	2695	3503	4620	3981	3090	3885	6040	4883	2470	3925	4860	4247	4910	4215	7526	5940
19	2875	2841	4982	3915	2203	2727	4004	3313	3655	3058	4205	3691	3160	3141	4680	3912
20	3987	4473	4842	4609	3423	3839	5087	4421	3370	3620	4935	4253	2705	3660	5201	4335
21	3324	4329	5970	5049	3641	3340	4739	4070	3913	4201	6998	5571	3093	3753	4968	4294
22	2967	3514	4203	3803	2883	3123	4171	3623	3500	4163	3802	3916	3117	3773	5822	4732
23	2135	2825	3695	3191	2693	2723	4565	3641	2373	2789	4456	3581	2933	2978	4814	3892
24	2204	2416	3216	2795	2668	2688	4785	3735	2368	3618	3683	3525	2673	2457	2765	2632
25	2193	2640	3508	3029	2930	2947	4160	3552	2853	3207	4040	3588	3378	3454	4939	4189
26	2929	2921	4091	3507	3253	3450	4098	3754	2970	3838	5195	4430	3963	3575	4817	4235

Appendix 1.13 Grain angle (mm in 100 mm) of *Eucalyptus* wood of the basal bolt in each radial position and the weighted average in each of four sites

Clone	Southern Bahia				São Mateus 1				São Mateus 2				Aracruz			
	Inner	Inter	Outer	Mean	Inner	Inter	Outer	Mean	Inner	Inter	Outer	Mean	Inner	Inter	Outer	Mean
1	1.13	2.44	1.64	1.91	2.73	3.01	2.53	2.74	1.65	2.79	3.07	2.81	0.60	3.03	2.00	2.27
2	2.38	3.29	2.58	2.84	2.44	2.53	2.52	2.52	2.67	5.32	2.64	3.72	4.58	3.68	3.60	3.73
3	3.28	3.25	2.42	2.84	1.30	1.73	2.16	1.90	3.00	2.54	2.03	2.33	2.65	2.53	0.90	1.73
4	4.18	2.77	5.30	4.18	1.80	1.58	2.15	1.89	1.90	1.50	0.87	1.22	7.15	3.53	2.00	3.13
5	1.95	3.01	4.18	3.48	1.58	3.78	7.90	5.62	3.76	6.99	3.60	4.97	0.63	5.46	8.12	6.31
6	1.68	4.56	4.37	4.18	4.75	3.35	3.94	3.78	2.97	1.43	4.16	2.95	3.00	4.35	6.57	5.32
7	3.98	2.93	3.31	3.22	0.95	4.63	4.02	3.95	4.10	3.78	2.80	3.32	2.30	4.55	3.59	3.85
8	2.48	3.26	3.60	3.35	1.98	0.83	1.37	1.21	2.53	2.40	3.20	2.81	1.24	1.79	3.83	2.75
9	1.43	3.61	5.55	4.36	6.85	3.71	7.10	5.72	2.45	5.41	4.35	4.59	4.61	4.21	5.06	4.67
10	0.69	6.61	3.47	4.45	4.35	5.81	3.55	4.54	2.95	4.30	4.39	4.21	5.00	4.17	4.16	4.25
11	4.90	4.11	4.19	4.23	3.75	4.28	5.07	4.62	1.35	5.40	4.19	4.39	5.25	3.57	4.33	4.11
12	3.10	6.20	1.90	3.74	1.35	1.70	1.72	1.67	1.22	2.40	1.02	1.59	1.83	1.58	2.00	1.81
13	7.45	2.84	3.69	3.73	1.85	0.65	2.23	1.56	2.05	2.93	3.50	3.13	3.20	2.76	2.57	2.71
14	3.10	2.72	3.63	3.21	2.70	7.23	2.84	4.58	3.16	2.23	2.95	2.68	3.35	4.86	4.11	4.34
15	4.45	3.56	3.92	3.83	4.80	0.75	3.93	2.74	3.00	2.95	2.47	2.71	4.60	4.65	6.95	5.80
16	3.31	3.88	5.55	4.66	2.40	2.05	3.88	3.00	2.00	1.75	1.45	1.63	3.75	3.83	3.98	3.90
17	0.50	4.31	2.08	2.81	3.65	4.60	4.52	4.46	1.65	4.10	1.93	2.77	2.68	2.32	3.67	3.03
18	1.55	6.44	5.88	5.67	1.43	4.16	1.50	2.56	2.20	4.10	1.85	2.79	1.43	5.77	4.72	4.81
19	5.03	4.33	4.13	4.30	2.70	3.08	2.36	2.68	1.93	2.95	3.33	3.04	2.75	2.91	2.78	2.83
20	2.95	2.74	2.79	2.78	1.40	2.00	2.18	2.03	3.15	2.76	3.10	2.97	1.57	4.18	4.70	4.18
21	3.12	5.93	4.27	4.82	2.43	2.45	2.95	2.70	2.80	4.65	3.60	3.94	3.99	3.20	3.25	3.30
22	1.43	6.14	4.20	4.70	3.87	1.83	2.66	2.45	4.73	3.70	3.18	3.54	3.15	3.51	3.93	3.69
23	3.88	5.12	5.80	5.33	2.25	3.47	3.65	3.44	2.18	4.50	3.30	3.67	3.13	3.06	2.98	3.03
24	2.43	0.83	6.25	3.70	2.03	4.89	1.10	2.71	3.40	2.18	2.55	2.49	3.55	2.70	6.63	4.75
25	2.65	3.59	4.46	3.93	3.65	4.13	2.65	3.34	1.50	5.35	1.55	3.07	7.00	4.30	4.53	4.68
26	3.20	3.99	10.18	7.00	1.88	3.15	2.98	2.94	2.73	3.15	5.20	4.13	1.68	1.70	2.38	2.04

Appendix 1.14 Grain angle (mm in 100 mm) of *Eucalyptus* wood of the top bolt in each radial position and the weighted average in each of four sites

Clone	Southern Bahia				São Mateus 1				São Mateus 2				Aracruz			
	Inner	Inter	Outer	Mean	Inner	Inter	Outer	Mean	Inner	Inter	Outer	Mean	Inner	Inter	Outer	Mean
1	4.57	3.79	2.69	3.32	2.73	2.87	2.84	2.84	3.00	2.91	1.85	2.39	2.58	0.80	1.44	1.30
2	1.66	2.55	2.27	2.32	2.03	1.38	1.54	1.52	4.10	3.91	2.77	3.36	2.25	2.71	5.30	3.96
3	2.40	3.20	4.14	3.59	0.70	2.70	1.71	2.01	4.08	2.22	1.37	1.98	2.10	1.69	1.00	1.39
4	3.00	4.09	3.46	3.67	3.80	1.93	1.61	1.96	3.20	0.88	1.98	1.66	4.99	3.80	2.78	3.41
5	1.68	2.20	4.12	3.11	0.60	0.82	2.43	1.60	2.63	2.03	2.56	2.35	3.53	2.78	6.91	4.92
6	4.63	3.33	9.73	6.66	1.93	3.15	3.11	3.01	2.78	3.28	4.89	4.03	3.00	3.40	5.44	4.38
7	5.03	2.15	3.61	3.17	1.50	1.62	1.83	1.71	3.25	1.32	1.86	1.78	3.00	2.57	3.60	3.13
8	3.33	2.85	3.77	3.36	2.13	3.36	4.00	3.56	1.95	1.73	1.42	1.60	2.78	1.94	3.18	2.64
9	9.06	3.43	3.44	4.00	0.50	1.94	4.05	2.85	3.70	1.48	4.91	3.42	8.70	5.35	1.71	3.87
10	4.75	2.29	2.38	2.58	2.45	4.92	6.30	5.36	0.83	2.70	1.41	1.87	1.08	2.67	3.50	2.93
11	2.80	3.44	4.79	4.05	2.40	1.65	1.85	1.83	2.35	2.05	2.54	2.32	2.25	6.00	4.86	5.06
12	4.38	1.83	1.81	2.07	0.75	0.93	1.33	1.11	3.05	2.95	1.59	2.28	2.35	1.63	1.93	1.85
13	3.75	2.66	2.71	2.80	3.38	2.85	2.64	2.80	1.73	3.28	1.95	2.46	1.30	4.03	2.07	2.78
14	5.08	2.14	5.95	4.34	3.98	2.00	2.73	2.56	3.16	2.23	2.95	2.68	2.43	5.64	6.59	5.79
15	2.68	2.80	3.85	3.31	2.65	3.75	1.75	2.64	3.48	2.35	3.08	2.83	3.53	4.18	5.91	4.98
16	2.30	1.46	4.42	3.02	2.50	2.33	4.11	3.24	1.40	1.77	1.32	1.51	4.68	3.23	3.48	3.50
17	4.33	4.02	2.54	3.31	2.65	1.20	3.92	2.70	3.25	1.60	3.03	2.48	2.03	2.67	3.41	2.98
18	4.03	4.78	5.83	5.23	1.58	1.68	5.55	3.60	5.38	3.48	4.65	4.25	1.00	2.94	4.20	3.38
19	2.20	1.79	1.78	1.83	1.23	1.62	3.00	2.27	0.00	0.73	2.80	1.69	3.98	2.24	3.35	2.97
20	2.95	2.74	2.79	2.78	3.77	2.51	3.25	3.01	2.80	2.05	1.75	1.98	4.50	2.86	2.80	3.00
21	3.10	2.34	1.42	1.95	2.58	5.15	3.01	3.82	3.91	3.58	3.47	3.56	3.50	2.80	2.68	2.81
22	3.35	2.98	4.31	3.68	2.45	1.66	1.73	1.78	2.70	3.15	3.07	3.06	1.28	3.18	2.60	2.70
23	0.95	0.93	1.30	1.12	0.70	1.67	1.65	1.56	2.30	1.85	3.20	2.57	4.54	2.58	2.50	2.74
24	1.84	1.66	5.52	3.61	2.40	2.78	2.92	2.81	2.35	4.03	2.73	3.21	1.68	1.63	3.63	2.63
25	3.97	4.03	7.01	5.52	3.18	2.10	4.65	3.48	3.25	1.42	2.32	2.05	3.65	3.18	6.16	4.72
26	3.94	3.78	3.51	3.66	3.10	3.15	1.70	2.42	2.20	1.91	3.40	2.68	1.68	1.70	2.38	2.04

Appendix 1.15 Janka hardness (N) of 26 *Eucalyptus* clones, mean Janka hardness per site and within-site coefficient of variation (CV) over four sites in Brazil (SBA - Southern Bahia; SM1 - São Mateus 1; SM2 - São Mateus 2; ARA - Aracruz).

Clone	Southern Bahia			São Mateus 1			São Mateus 2			Aracruz		
	Base	Top	Mean	Base	Top	Mean	Base	Top	Mean	Base	Top	Mean
1	4354	3560	3957	5396	3868	4632	5046	4453	4749	4666	3889	4277
2	3845	4229	4037	5479	5844	5661	4479	4656	4567	4446	3970	4208
3	2835	3014	2924	4502	3790	4146	4577	3764	4171	2637	3141	2889
4	4993	4442	4717	6315	5231	5773	5676	5749	5712	6438	5446	5942
5	4797	3837	4317	6079	4102	5090	5284	4031	4658	6181	5380	5780
6	4729	4694	4711	5265	4669	4967	4992	4404	4698	5802	4450	5126
7	4219	3781	4000	6131	4809	5470	4990	4673	4831	5262	4530	4896
8	4091	4259	4175	5119	5177	5148	5606	4727	5167	4786	5071	4929
9	5237	5025	5131	6755	6057	6406	6898	6693	6795	6842	5706	6274
10	4359	3811	4085	4348	5010	4679	4580	4273	4426	4493	4239	4366
11	3942	4152	4047	6041	4552	5296	4255	4336	4295	4959	3885	4422
12	5224	3672	4448	6680	5438	6059	5457	4271	4864	5030	5141	5085
13	4467	3935	4201	4107	3213	3660	4372	3533	3952	4720	3910	4315
14	5268	4647	4958	5264	3225	4244	6158	5481	5820	5411	4154	4782
15	4490	4500	4495	5543	5022	5283	5527	5100	5313	4776	3038	3907
16	3910	3302	3606	3838	3622	3730	3872	3803	3838	6099	4423	5261
17	3724	3451	3587	7329	5630	6480	4911	3227	4069	5128	4078	4603
18	3819	3981	3900	4231	4883	4557	4180	4247	4214	4925	5940	5432
19	3891	3915	3903	3922	3313	3618	4266	3691	3978	3903	3912	3908
20	5045	4609	4827	5412	4421	4916	4744	4253	4498	4277	4335	4306
21	5124	5049	5086	5967	4070	5018	4352	5571	4961	4674	4294	4484
22	4564	3803	4183	3943	3623	3783	4876	3916	4396	5939	4732	5335
23	3906	3191	3549	4024	3641	3833	3631	3581	3606	4160	3892	4026
24	2383	2795	2589	3913	3735	3824	3622	3525	3573	2826	2632	2729
25	3453	3029	3241	3181	3552	3366	4988	3588	4288	3943	4189	4066
26	4018	3507	3762	4655	3754	4205	4987	4430	4708	4784	4235	4509
Mean	4257	3930	4094	5132	4394	4763	4859	4384	4621	4889	4331	4610
C.V.(%)	16.91	15.60	15.33	21.10	19.39	18.72	15.49	18.41	15.59	20.20	18.14	17.86

APPENDIX 2 Magnitude of the fibre dimensions and microfibril angle.

Appendix 2.1 Fibre length (mm) of *Eucalyptus* wood in each radial position and the weighted average in each site.

Clone	Southern Bahia				São Mateus 1			
	Inner	Inter	Outer	Average	Inner	Inter	Outer	Average
1	0.953	1.028	1.065	1.039	1.027	1.099	1.104	1.094
2	0.989	1.084	1.111	1.088	0.940	1.069	0.965	1.004
3	1.217	1.231	1.312	1.270	1.056	1.207	1.246	1.211
4	0.949	1.085	1.221	1.140	0.998	0.947	1.164	1.060
5	0.894	1.074	1.313	1.176	0.931	1.091	1.116	1.087
6	0.943	0.984	1.291	1.133	0.909	1.051	1.161	1.092
7	0.893	0.978	1.160	1.061	1.075	1.106	1.118	1.109
8	0.896	1.302	1.314	1.267	0.915	1.150	1.166	1.135
9	1.029	1.012	1.353	1.184	0.840	0.945	0.967	0.945
10	1.044	1.080	1.092	1.082	0.898	0.776	1.234	1.017
18	0.977	1.120	1.127	1.109	1.027	1.087	0.979	1.027
Clone	São Mateus 2				Aracruz			
	Inner	Inter	Outer	Average	Inner	Inter	Outer	Average
1	1.035	1.041	1.085	1.062	0.946	0.953	1.023	0.988
2	0.805	0.969	1.238	1.087	0.907	1.031	1.002	1.004
3	0.886	1.137	1.207	1.147	1.051	1.106	1.119	1.107
4	0.958	1.051	1.079	1.056	0.879	0.940	1.072	1.000
5	0.915	1.039	1.084	1.049	0.915	0.947	1.035	0.988
6	0.869	1.017	1.135	1.061	1.046	1.153	1.176	1.154
7	0.920	1.053	1.195	1.111	1.028	1.061	1.092	1.074
8	0.890	1.037	1.191	1.099	0.912	1.172	1.184	1.152
9	0.939	1.023	1.065	1.036	0.856	0.979	1.128	1.041
10	0.914	0.878	0.956	0.921	0.790	1.068	1.080	1.046
18	0.931	0.951	0.922	0.934	0.934	1.032	1.013	1.013

Appendix 2.2 Fibre diameter (μm) of *Eucalyptus* wood in each radial position and the weighted average in each of four sites.

Clone	Southern Bahia				São Mateus 1			
	Inner	Inter	Outer	Average	Inner	Inter	Outer	Average
1	20.4	22.3	23.7	22.84	22.1	17.4	19.6	18.98
2	18.7	20.5	20.2	20.15	16.4	19.8	18.0	18.56
3	20.5	20.5	23.9	22.18	21.9	23.2	22.9	22.91
4	18.5	21.1	21.6	21.10	18.2	17.9	16.2	17.08
5	17.3	15.5	21.2	18.56	19.5	17.8	17.2	17.70
6	20.1	18.8	20.9	19.99	18.1	20.0	19.9	19.74
7	18.9	18.4	18.7	18.60	18.7	17.0	17.7	17.52
8	19.2	21.1	18.3	19.53	18.1	19.0	16.2	17.52
9	19.5	19.6	21.1	20.32	17.7	20.8	15.1	17.62
10	17.9	18.0	22.2	20.05	19.8	17.6	20.1	19.07
18	21.2	19.5	17.2	18.52	17.3	18.6	18.6	18.50
Clone	São Mateus 2				Aracruz			
	Inner	Inter	Outer	Average	Inner	Inter	Outer	Average
1	19.8	18.5	17.1	17.92	16.5	17.7	16.9	17.23
2	15.3	16.7	18.8	17.63	17.8	17.9	17.5	17.69
3	16.2	19.2	19.5	19.08	21.6	21.8	19.1	20.41
4	20.9	20.2	19.5	19.92	15.9	18.4	20.1	19.00
5	15.3	18.1	15.9	16.71	15.6	15.9	15.6	15.72
6	16.9	19.5	19.1	19.04	18.8	20.8	19.1	19.78
7	15.2	17.5	17.4	17.24	15.2	19.0	17.0	17.61
8	14.5	17.3	17.3	17.01	19.8	17.9	17.1	17.66
9	16.2	17.5	16.8	16.99	17.8	18.6	17.0	17.71
10	17.4	17.5	19.1	18.30	16.0	16.5	17.7	17.05
18	15.8	18.0	18.2	17.87	19.8	16.8	17.1	17.28

Appendix 2.3 Lumen diameter (μm) of *Eucalyptus* wood in each radial position and the weighted average in each site.

Clone	Southern Bahia				São Mateus 1			
	Inner	Inter	Outer	Average	Inner	Inter	Outer	Average
1	15.7	15.5	16.0	15.8	15.5	10.6	12.0	11.8
2	12.9	14.7	14.5	14.4	10.7	13.5	12.2	12.6
3	12.2	11.7	14.1	13.0	15.3	16.4	15.7	15.9
4	10.2	12.1	11.1	11.4	11.6	11.6	9.2	10.4
5	11.3	8.8	13.6	11.5	13.1	10.6	9.7	10.4
6	12.9	12.1	12.3	12.3	11.4	13.2	11.4	12.1
7	12.7	11.9	12.1	12.1	12.2	10.6	11.0	11.0
8	10.1	10.7	8.8	9.7	10.8	11.6	7.4	9.4
9	9.9	10.1	9.6	9.8	10.8	13.3	5.4	9.1
10	11.4	11.6	15.1	13.4	13.7	11.3	13.4	12.6
18	14.7	12.8	9.1	11.1	11.2	10.0	9.6	9.9
Clone	São Mateus 2				Aracruz			
	Inner	Inter	Outer	Average	Inner	Inter	Outer	Average
1	13.2	11.2	8.9	10.3	10.4	10.8	9.8	10.2
2	8.9	8.9	10.3	9.6	12.1	11.8	12.4	12.2
3	10.6	12.1	12.7	12.2	14.9	14.8	12.7	13.8
4	11.9	11.1	10.2	10.7	8.8	11.7	11.9	11.5
5	8.5	11.6	9.2	10.1	9.1	8.6	6.0	7.3
6	10.3	12.0	11.6	11.6	12.5	14.4	11.4	12.7
7	8.0	8.7	7.7	8.1	8.5	12.2	9.9	10.7
8	8.2	8.4	9.6	9.0	12.6	10.1	7.9	9.2
9	8.9	9.0	7.3	8.1	11.1	11.1	7.2	9.2
10	9.9	11.0	12.6	11.7	9.0	8.4	10.7	9.6
18	9.2	11.6	11.8	11.5	13.1	9.7	9.5	10.0

Appendix 2.4 Fibre wall thickness (μm) of *Eucalyptus* wood in each radial position and the weighted average in each of four sites.

Clone	Southern Bahia				São Mateus 1			
	Inner	Inter	Outer	Average	Inner	Inter	Outer	Average
1	2.3	3.4	3.9	3.5	3.3	3.4	3.8	3.6
2	2.9	2.9	2.9	2.9	2.9	3.1	2.9	3.0
3	4.1	4.4	4.9	4.6	3.3	3.4	3.6	3.5
4	4.1	4.5	5.3	4.8	3.3	3.1	3.5	3.3
5	3.0	3.3	3.9	3.6	3.2	3.6	3.8	3.6
6	3.6	3.4	4.3	3.9	3.3	3.4	4.2	3.8
7	3.1	3.2	3.3	3.3	3.2	3.2	3.3	3.3
8	4.5	5.2	4.8	4.9	3.7	3.7	4.4	4.0
9	4.8	4.7	5.7	5.2	3.4	3.8	4.9	4.3
10	3.2	3.2	3.5	3.3	3.1	3.1	3.4	3.2
18	3.3	3.3	4.0	3.7	3.0	4.3	4.5	4.3
Clone	São Mateus 2				Aracruz			
	Inner	Inter	Outer	Average	Inner	Inter	Outer	Average
1	3.3	3.7	4.1	3.8	3.0	3.5	3.6	3.5
2	3.2	3.9	4.3	4.0	2.9	3.1	2.5	2.8
3	2.8	3.5	3.4	3.4	3.3	3.5	3.2	3.3
4	4.4	4.5	4.6	4.6	3.5	3.4	4.1	3.7
5	3.4	3.2	3.3	3.3	3.3	3.6	4.8	4.2
6	3.3	3.8	3.8	3.7	3.1	3.2	3.8	3.5
7	3.6	4.4	4.9	4.6	3.3	3.4	3.6	3.5
8	3.1	4.5	3.8	4.0	3.6	3.9	4.6	4.2
9	3.6	4.2	4.7	4.4	3.3	3.7	4.9	4.3
10	3.7	3.3	3.2	3.3	3.5	4.1	3.5	3.7
18	3.3	3.2	3.2	3.2	3.3	3.6	3.8	3.7

Appendix 2.5 Microfibril angle (degree) of *Eucalyptus* wood in each radial position and the weighted average in each of four sites.

Clone	Southern Bahia				São Mateus 1			
	Inner	Inter	Outer	Average	Inner	Inter	Outer	Average
1	7.9	6.2	6.4	6.5	6.9	9.6	9.9	9.5
2	6.6	4.0	3.9	4.2	8.8	8.1	8.3	8.3
3	7.1	8.8	8.5	8.5	6.8	8.0	6.5	7.1
4	10.9	9.5	7.5	8.6	7.6	9.6	10.7	10.0
5	6.0	5.4	5.8	5.6	8.7	7.9	8.4	8.2
6	6.5	6.5	7.5	7.0	15.8	11.5	9.0	10.7
7	11.2	6.9	9.8	8.8	7.0	9.4	9.3	9.1
8	10.1	7.1	7.5	7.6	11.5	9.7	9.5	9.8
9	10.4	9.2	6.4	7.9	15.9	10.5	10.2	10.9
10	7.9	7.8	6.1	7.0	12.3	14.2	11.8	12.8
18	10.4	9.2	10.9	10.2	6.4	9.4	9.6	9.2
Clone	São Mateus 2				Aracruz			
	Inner	Inter	Outer	Average	Inner	Inter	Outer	Average
1	7.7	7.7	8.2	7.9	8.8	8.3	9.3	8.8
2	9.7	9.2	6.4	7.9	9.7	7.3	8.3	8.0
3	8.0	6.9	7.2	7.2	8.9	8.2	7.6	8.0
4	6.8	8.7	8.0	8.1	13.2	9.2	8.8	9.4
5	8.4	8.1	7.2	7.7	9.9	11.3	11.9	11.5
6	9.6	8.9	8.3	8.7	7.5	8.4	10.1	9.1
7	8.9	8.7	6.8	7.8	7.9	7.8	8.4	8.1
8	12.1	6.7	6.0	6.9	9.4	8.6	8.9	8.8
9	7.9	8.7	8.1	8.3	16.4	16.0	10.8	13.4
10	9.6	11.7	8.8	10.0	20.2	13.6	13.9	14.4
18	8.7	8.5	8.4	8.5	10.7	9.6	10.2	10.0

APPENDIX 3 Analysis of variance between clones and sites of the nominal density and mechanical properties.

Appendix 3.1 Balanced analysis of variance of nominal density of *Eucalyptus* clones between clones and between sites at the basal and top bolts in each radial position. (ns- no significant at P = 0.05; * P≤ 0.05; ** P≤ 0.01; *** P≤ 0.001).

Property	Source	d.f.	SS	MS	F	P
Nominal	Clone	25	0.173834	0.006953	5.44	***
density	Site	3	0.023122	0.007707	6.04	***
(Inner)	Error	75	0.095778	0.001277		
Base	Total	103	0.292735			
Nominal	Clone	25	0.228148	0.009126	6.10	***
density	Site	3	0.047443	0.015814	10.58	***
(Intermediate)	Error	75	0.112131	0.001495		
Base	Total	103	0.387722			
Nominal	Clone	25	0.307789	0.012312	7.19	***
Density	Site	3	0.083708	0.027903	16.31	***
(Outer)	Error	75	0.128341	0.001711		
Base	Total	103	0.519838			
Nominal	Clone	25	0.1937466	0.0077499	8.47	***
Density	Site	3	0.0308993	0.0102998	11.25	***
(Inner)	Error	75	0.0686469	0.0009153		
Top	Total	103	0.2932928			
Nominal	Clone	25	0.156466	0.006259	4.90	***
Density	Site	3	0.019496	0.006499	5.08	**
(Intermediate)	Error	75	0.095859	0.001278		
Top	Total	103	0.271821			
Nominal	Clone	25	0.209106	0.008364	6.38	***
Density	Site	3	0.017665	0.005888	4.49	**
(Outer)	Error	75	0.098343	0.001311		
Top	Total	103	0.325114			
Nominal	Clone	25	0.230175	0.009207	7.82	***
Density	Site	3	0.057599	0.019200	16.30	***
(Average)	Error	75	0.088329	0.001178		
Base	Total	103	0.376103			
Nominal	Clone	25	0.1667835	0.0066713	7.18	***
Density	Site	3	0.0178002	0.0059334	6.38	***
(Average)	Error	75	0.0697093	0.0009295		
Top	Total	103	0.2542930			

Appendix 3.2 Balanced analysis of variance of modulus of rupture of *Eucalyptus* clones between clones and between sites at the basal and top bolts in each radial position. (ns- no significant at P = 0.05; * P≤ 0.05; ** P≤ 0.01; *** P≤ 0.001)

Property	Source	d.f.	SS	MS	F	P
Modulus of	Clone	25	13626.0	545.0	4.11	***
rupture	Site	3	436.1	145.4	1.10	ns
(Inner)	Error	75	9935.4	132.5		
Base	Total	103	23997.5			
Modulus of	Clone	25	13106.5	524.3	4.68	***
rupture	Site	3	710.4	236.8	2.11	ns
(Intermediate)	Error	75	8402.0	112.0		
Base	Total	103	22218.9			
Modulus of	Clone	25	16873.5	674.9	4.86	***
rupture	Site	3	994.5	331.5	2.39	ns
(Outer)	Error	75	10411.7	138.8		
Base	Total	103	28279.7			
Modulus of	Clone	25	12725.54	509.02	5.18	***
rupture	Site	3	1931.35	643.78	6.55	***
(Inner)	Error	75	7369.82	98.26		
Top	Total	103	22026.72			
Modulus of	Clone	25	15805.1	632.2	5.94	***
rupture	Site	3	1578.9	526.3	4.94	**
(Intermediate)	Error	75	7982.6	106.4		
Top	Total	103	25366.6			
Modulus of	Clone	25	17293.9	691.8	4.44	***
rupture	Site	3	2121.6	707.2	4.54	**
(Outer)	Error	75	11693.6	155.9		
Top	Total	103	31109.1			
Modulus of	Clone	25	12247.08	489.88	6.23	***
rupture	Site	3	785.72	261.91	3.33	*
(Average)	Error	75	5895.04	78.60		
Base	Total	103	18927.84			
Modulus of	Clone	25	13982.03	559.28	6.73	***
rupture	Site	3	1797.69	599.23	7.21	***
(Average)	Error	75	6231.95	83.09		
Top	Total	103	22011.67			

Appendix 3.3 Balanced analysis of variance of modulus of elasticity of *Eucalyptus* clones between clones and between sites at the basal and top bolts in each radial position. (ns- no significant at P = 0.05; * P≤ 0.05; ** P≤ 0.01; *** P≤ 0.001)

Property	Source	d.f.	SS	MS	F	P
Modulus of	Clone	25	69705759	2788230	3.57	**
elasticity	Site	3	1636585	545528	0.70	ns
(Inner)	Error	75	58538606	780515		
Base	Total	103	129880949			
Modulus of	Clone	25	109804395	4392176	5.10	***
elasticity	Site	3	3887445	1295815	1.50	ns
(Intermediate)	Error	75	64596932	861292		
Base	Total	103	178288772			
Modulus of	Clone	25	141244104	5649764	4.89	***
elasticity	Site	3	3807448	1269149	1.10	ns
(Outer)	Error	75	86672790	1155637		
Base	Total	103	231724342			
Modulus of	Clone	25	90186483	3607459	3.81	***
elasticity	Site	3	3964872	1321624	1.40	ns
(Inner)	Error	75	70920321	945604		
Top	Total	103	165071676			
Modulus of	Clone	25	106643866	4265755	4.53	***
elasticity	Site	3	8298933	2766311	2.94	*
(Intermediate)	Error	75	70667749	942237		
Top	Total	103	185610548			
Modulus of	Clone	25	161511697	6460468	7.68	***
elasticity	Site	3	12963740	4321247	5.14	**
(Outer)	Error	75	63094926	841266		
Top	Total	103	237570364			
Modulus of	Clone	25	99384861	3975394	6.02	***
elasticity	Site	3	2167242	722414	1.09	ns
(Average)	Error	75	49528827	660384		
Base	Total	103	151080930			
Modulus of	Clone	25	116324029	4652961	8.73	***
elasticity	Site	3	7975135	2658378	4.99	**
(Average)	Error	75	39988886	533185		
Top	Total	103	164288050			

Appendix 3.4 Balanced analysis of variance of resilience of *Eucalyptus* clones between clones and between sites at the basal and top bolts in each radial position. (ns- no significant at P = 0.05; * P≤ 0.05; ** P≤ 0.01; *** P≤ 0.001)

Property	Source	d.f.	SS	MS	F	P
Resilience	Clone	25	8.9780	0.3591	2.41	**
	Site	3	1.5397	0.5132	3.45	*
(Inner)	Error	75	11.1564	0.1488		
Base	Total	103	21.6740			
Resilience	Clone	25	9.2380	0.3695	1.87	*
	Site	3	0.9619	0.3206	1.62	ns
(Intermediate)	Error	75	14.8085	0.1974		
Base	Total	103	25.0085			
Resilience	Clone	25	15.1900	0.6076	2.12	**
	Site	3	1.0598	0.3533	1.23	ns
(Outer)	Error	75	21.4732	0.2863		
Base	Total	103	37.7230			
Resilience	Clone	25	9.5087	0.3803	2.76	***
	Site	3	1.1071	0.3690	2.68	*
(Inner)	Error	75	10.3268	0.1377		
Top	Total	103	20.9426			
Resilience	Clone	25	10.5375	0.4215	2.51	***
	Site	3	1.2991	0.4330	2.58	ns
(Intermediate)	Error	75	12.5870	0.1678		
Top	Total	103	24.4236			
Resilience	Clone	25	12.5668	0.5027	1.84	*
	Site	3	1.2416	0.4139	1.52	ns
(Outer)	Error	75	20.4668	0.2729		
Top	Total	103	34.2752			
Resilience	Clone	25	10.6516	0.4261	2.38	**
	Site	3	0.9509	0.3170	1.77	ns
(Average)	Error	75	13.4493	0.1793		
Base	Total	103	25.0518			
Resilience	Clone	25	10.1792	0.4072	2.36	**
	Site	3	1.1363	0.3788	2.19	ns
(Average)	Error	75	12.9586	0.1728		
Top	Total	103	24.2741			

Appendix 3.5 Balanced analysis of variance of compression strength parallel to grain of *Eucalyptus* clones between clones and between sites at the basal and top bolts in each radial position. (ns- no significant at P = 0.05; * P≤ 0.05; ** P≤ 0.01; *** P≤ 0.001)

Property	Source	d.f.	SS	MS	F	P
Compression	Clone	25	2201.15	88.05	4.75	***
strength	Site	3	117.61	39.20	2.11	ns
(Inner)	Error	75	1391.30	18.55		
Base	Total	103	3710.06			
Compression	Clone	25	2409.36	96.37	5.95	***
strength	Site	3	147.38	49.13	3.03	*
(Intermediate)	Error	75	1214.29	16.19		
Base	Total	103	3771.03			
Compression	Clone	25	3688.68	147.55	4.62	***
Strength	Site	3	312.07	104.02	3.26	*
(Outer)	Error	75	2395.14	31.94		
Base	Total	103	6395.89			
Compression	Clone	25	2097.11	83.88	4.57	***
Strength	Site	3	512.97	170.99	9.32	***
(Inner)	Error	75	1376.38	18.35		
Top	Total	103	3986.46			
Compression	Clone	25	2514.82	100.59	5.34	***
Strength	Site	3	150.41	50.14	2.66	*
(Intermediate)	Error	75	1412.25	18.83		
Top	Total	103	4077.47			
Compression	Clone	25	3993.96	159.76	7.46	***
Strength	Site	3	372.77	124.26	5.80	***
(Outer)	Error	75	1605.75	21.41		
Top	Total	103	5972.48			
Compression	Clone	25	2745.01	109.80	6.50	***
Strength	Site	3	175.24	58.41	3.46	*
(Average)	Error	75	1267.00	16.89		
Base	Total	103	4187.25			
Compression	Clone	25	2832.14	113.29	7.70	***
Strength	Site	3	274.35	91.45	6.22	***
(Average)	Error	75	1102.74	14.70		
Top	Total	103	4209.23			

Appendix 3.6 Balanced analysis of variance of Janka hardness of *Eucalyptus* clones between clones and between sites at the basal and top bolts in each radial position. (ns- no significant at P = 0.05; * P≤ 0.05; ** P≤ 0.01; *** P≤ 0.001)

Property	Source	d.f.	SS	MS	F	P
Janka hardness	Clone	25	33353498	1334140	3.22	***
	Site	3	2746286	915429	2.21	ns
(Inner)	Error	75	31106195	414749		
Base	Total	103	67205979			
Janka hardness	Clone	25	43627791	1745112	4.58	***
	Site	3	5811064	1937021	5.08	**
(Intermediate)	Error	75	28594915	381266		
Base	Total	103	78033771			
Janka hardness	Clone	25	81929902	3277196	3.88	***
	Site	3	20425647	6808549	8.07	***
(Outer)	Error	75	63298468	843980		
Base	Total	103	165654017			
Janka hardness	Clone	25	34844838	1393794	4.45	***
	Site	3	5345031	1781677	5.69	***
(Inner)	Error	75	23495355	313271		
Top	Total	103	63685224			
Janka hardness	Clone	25	33061772	1322471	5.16	***
	Site	3	2978893	992964	3.87	**
(Intermediate)	Error	75	19237401	256499		
Top	Total	103	55278066			
Janka hardness	Clone	25	46480365	1859215	2.68	***
	Site	3	5888768	1962923	2.83	*
(Outer)	Error	75	52037354	693831		
Top	Total	103	104406487			
Janka hardness	Clone	25	52639982	2105599	5.60	***
	Site	3	10799492	3599831	9.58	***
(Average)	Error	75	28179452	375726		
Base	Total	103	91618926			
Janka hardness	Clone	25	35047828	1401913	4.34	***
	Site	3	3823250	1274417	3.94	**
(Average)	Error	75	24228907	323052		
Top	Total	103	63099986			

APPENDIX 4 Analysis of variance for grain angle

Appendix 4.1 Analysis of variance between clones and sites for each radial position and weighted average for wood from the basal bolt

Analysis of Variance for inner

Source	DF	SS	MS	F	P
Clone	25	52.911	2.116	1.09	0.374
Site	3	6.740	2.247	1.16	0.331
Error	75	145.477	1.940		
Total	103	205.128			

Analysis of Variance for Intermediate

Source	DF	SS	MS	F	P
Clone	25	77.712	3.108	1.98	0.012
Site	3	8.553	2.851	1.82	0.151
Error	75	117.492	1.567		
Total	103	203.758			

Analysis of Variance for Outer

Source	DF	SS	MS	F	P
Clone	25	105.492	4.220	2.31	0.003
Site	3	28.632	9.544	5.23	0.002
Error	75	136.923	1.826		
Total	103	271.047			

Analysis of Variance for W-Average

Source	DF	SS	MS	F	P
Clone	25	56.9522	2.2781	2.66	0.001
Site	3	14.2323	4.7441	5.54	0.002
Error	75	64.2170	0.8562		
Total	103	135.4015			

Appendix 4.2 Analysis of variance between clones and sites for each radial position and weighted average for wood from the top bolt

Analysis of Variance for inner

Source	DF	SS	MS	F	P
Clone	25	55.485	2.219	1.26	0.221
Site	3	22.974	7.658	4.35	0.007
Error	75	132.161	1.762		
Total	103	210.620			

Analysis of Variance for Intermediate

Source	DF	SS	MS	F	P
Clone	25	28.042	1.122	1.00	0.473
Site	3	8.486	2.829	2.53	0.063
Error	75	83.780	1.117		
Total	103	120.308			

Analysis of Variance for Outer

Source	DF	SS	MS	F	P
Clone	25	100.477	4.019	2.43	0.002
Site	3	24.006	8.002	4.84	0.004
Error	75	124.085	1.654		
Total	103	248.568			

Analysis of Variance for W-Average

Source	DF	SS	MS	F	P
Clone	25	41.9504	1.6780	2.07	0.008
Site	3	15.4165	5.1388	6.35	0.001
Error	75	60.7014	0.8094		
Total	103	118.0683			

APPENDIX 5 Analysis of variance of the fibre dimensions between radial positions

Appendix 5.1 One-way analysis of variance of the fibre length between radial position per site

Southern Bahia

Source	DF	SS	MS	F	P
Factor	2	0.3019	0.1509	15.06	0.000
Error	30	0.3006	0.0100		
Total	32	0.6025			

São Mateus 1

Source	DF	SS	MS	F	P
Factor	2	0.11768	0.05884	5.92	0.007
Error	30	0.29824	0.00994		
Total	32	0.41592			

São Mateus 2

Source	DF	SS	MS	F	P
Factor	2	0.19995	0.09998	16.63	0.000
Error	30	0.18041	0.00601		
Total	32	0.38036			

Aracruz

Source	DF	SS	MS	F	P
Factor	2	0.13259	0.06630	11.55	0.000
Error	30	0.17222	0.00574		
Total	32	0.30481			

Appendix 5.2 One-way analysis of variance of the fibre diameter between radial position per site.

Southern Bahia

Source	DF	SS	MS	F	P
Factor	2	0.84	0.42	0.09	0.910
Error	30	133.35	4.44		
Total	32	134.19			

São Mateus 1

Source	DF	SS	MS	F	P
Factor	2	19.15	9.57	1.96	0.159
Error	30	146.92	4.90		
Total	32	166.07			

São Mateus 2

Source	DF	SS	MS	F	P
Factor	2	2.91	1.46	0.54	0.590
Error	30	81.37	2.71		
Total	32	84.28			

Aracruz

Source	DF	SS	MS	F	P
Factor	2	11.07	5.53	1.23	0.307
Error	30	135.25	4.51		
Total	32	146.32			

Appendix 5.3 One-way analysis of variance of the lumen diameter between radial position per site

Southern Bahia

Analysis of Variance

Source	DF	SS	MS	F	P
Factor	2	14.51	7.25	2.31	0.116
Error	30	94.01	3.13		
Total	32	108.51			

São Mateus 1

Analysis of Variance

Source	DF	SS	MS	F	P
Factor	2	3.00	1.50	0.39	0.681
Error	30	115.77	3.86		
Total	32	118.78			

São Mateus 2

Analysis of Variance

Source	DF	SS	MS	F	P
Factor	2	15.88	7.94	3.72	0.036
Error	30	64.07	2.14		
Total	32	79.95			

Aracruz

Analysis of Variance

Source	DF	SS	MS	F	P
Factor	2	2.82	1.41	0.46	0.633
Error	30	90.96	3.03		
Total	32	93.78			

Appendix 5.4 One-way analysis of variance for wall thickness between radial position per site

Southern Bahia

Analysis of Variance

Source	DF	SS	MS	F	P
Factor	2	2.713	1.356	2.12	0.138
Error	30	19.229	0.641		
Total	32	21.942			

São Mateus 1

Analysis of Variance

Source	DF	SS	MS	F	P
Factor	2	2.029	1.015	5.68	0.008
Error	30	5.360	0.179		
Total	32	7.389			

São Mateus 2

Analysis of Variance

Source	DF	SS	MS	F	P
Factor	2	1.310	0.655	2.27	0.121
Error	30	8.653	0.288		
Total	32	9.962			

Aracruz

Analysis of Variance

Source	DF	SS	MS	F	P
Factor	2	1.808	0.904	4.23	0.024
Error	30	6.411	0.214		
Total	32	8.219			

APPENDIX 6 Estimation of the microfibril angle for each clone, using the fibre dimensions as predictors and each site as a replicate. (FL- fibre length; FD- fibre diameter; LD- lumen diameter; WT- fibre wall thickness).

Clone	Predictor	Model	R^2	F	b0	b1	b2	b3
	FL	Quadratic	0.917	5.56 ns	1009.3	-1936	4 935	
Clone 01	FD	Quadratic	0.776	1.73 ns	-61.1	7.3	-0.2	
	LD	Quadratic	0.913	5.23 ns	-31.6	6.7	-0.3	
	WT	Cubic	0.132	0.08 ns	-401.1	167.5		-4.1
	FL	Linear	0.401	1.34 ns	31.7	-23.6		
Clone 02	FD	Quadratic	1.000	1561 *	-384.2	43.0	-1.2	
	LD	Quadratic	0.981	25.3 ns	-43.0	9.3	-0.4	
	WT	Linear	0.079	0.17 ns	4.1	0.9		
	FL	Quadratic	1.000	13454 **	273.3	-451	190.9	
Clone 03	FD	Quadratic	0.734	1.38 ns	-135.8	13.7	-0.3	
	LD	Quadratic	0.683	1.08 ns	-51.8	8.6	-0.3	
	WT	Quadratic	0.953	10.0 ns	85.5	-40.5	5.2	
	FL	Linear	0.135	0.31 ns	14.5	-5.2		
Clone 04	FD	Linear	0.707	4.83 ns	16.7	-0.4		
	LD	Quadratic	0.998	311.4 *	800.8	-144	6.5	
	WT	Quadratic	0.924	6.12 *	30.6	-9.7	1.1	
	FL	S	0.902	18.3 *	-1.7	4.1		
Clone 05	FD	Linear	0.816	8.87 ns	38.7	-1.8		
	LD	Linear	0.955	42.5 *	21.4	-1.3		
	WT	Quadratic	0.828	2.40 ns	131.3	-70.6	10.0	
	FL	Linear	0.085	0.19 ns	21.1	-11.1		
Clone 06	FD	Cubic	0.900	4.52 ns	-3962	306.4		-0.3
	LD	Linear	0.000	0.00 ns	8.5	0.03		
	WT	Linear	0.077	0.17 ns	19.4	-2.8		
	FL	Linear	0.004	0.00 ns	10.1	-1.5		
Clone 07	FD	Cubic	0.387	0.32 ns	-293.4	25.0		-0.03
	LD	Linear	0.591	2.89 ns	5.5	0.3		
	WT	Quadratic	0.933	6.95 ns	60.6	-26.4	3.3	
	FL	Quadratic	0.831	2.46 ns	-525.6	900.5	-378.5	
Clone 08	FD	Quadratic	0.816	2.22 ns	-623.5	69.2	-1.9	
	LD	Quadratic	0.967	14.5 ns	-1551	332.7	-17.7	
	WT	Quadratic	0.283	0.20 ns	-170.4	81.2	-9.2	
	FL	Quadratic	0.333	0.25 ns	-78.6	180.4	-90.7	
Clone 09	FD	Quadratic	0.882	3.73 ns	-773.8	84.6	-2.3	
	LD	Quadratic	0.812	2.16 ns	-457.8	104.7	-5.8	
	WT	Quadratic	0.873	3.44 ns	658.9	-271	28.0	
	FL	Quadratic	0.716	1.26 ns	-920.8	1884	-947.8	
Clone 10	FD	Linear	0.645	3.63 ns	49.6	-2.1		
	LD	Linear	0.595	2.93 ns	29.4	-1.6		
	WT	Quadratic	0.976	20.2 ns	1871.7	-1076	155.0	
	FL	Linear	0.682	4.29 ns	0.5	8.8		
Clone 18	FD	Cubic	0.794	1.93 ns	819.6	-67.8		0.1
	LD	Quadratic	0.912	5.18 ns	-420.5	81.5	-3.8	
	WT	Quadratic	0.997	180.5 *	-55.0	34.1	-4.5	

APPENDIX 7 Relationships between density, anatomical and mechanical characteristics

Appendix 7.1 Coefficients of correlation of the nominal density and mechanical properties with the nominal density (ND), fibre length (FL), fibre diameter (FD), lumen diameter (LD), fibre wall thickness (WT), grain angle (GA) and microfibril angle (MF) for eleven clones over four different sites. [* - P ≤ 0.05; **- P≤ 0.01; **- P≤ 0.01 ns - non-significant]. (MOR = modulus of rupture, MOE = modulus of elasticity, CP = compression strength parallel to the grain)

Site		ND	FL	FD	LD	WT	GA	MF
	ND		0.331	-0.157	-0.758**	0.741**	-0.460	0.279
Southern	MOR	0.780**	0.357	-0.034	-0.640*	0.714*	-0.410	0.601
Bahia	MOE	0.572	0.221	-0.311	-0.579	0.394	-0.204	0.455
	CP	0.744**	0.273	-0.122	-0.546	0.526	-0.445	0.234
	ND		0.311	-0.396	-0.273	-0.136	-0.299	-0.482
São	MOR	0.362	0.273	-0.230	-0.190	-0.007	-0.441	-0.248
Mateus 1	MOE	0.542	0.153	-0.515	-0.439	0.014	-0.429	-0.230
	CP	0.677*	0.498	-0.098	0.017	-0.223	-0.454	-0.588
	ND		-0.189	-0.600	-0.660*	0.332	0.426	-0.070
São	MOR	0.471	0.092	-0.434	-0.654*	0.482	0.140	-0.094
Mateus 2	MOE	0.533	0.408	-0.529	-0.757**	0.534	0.099	-0.433
	CP	0.722*	-0.152	-0.565	-0.637*	0.336	0.301	-0.433
	ND		-0.055	-0.316	-0.626*	0.828**	0.250	0.453
Aracruz	MOR	0.362	0.307	-0.103	-0.301	0.471	-0.234	-0.016
	MOE	0.142	0.427	-0.094	-0.181	0.236	-0.448	-0.377
	CP	0.645*	-0.158	-0.024	-0.185	0.347	-0.020	0.098

Appendix 7.2 Analysis of regression to estimate the nominal density ($g.cm^{-3}$) of wood of 11 clones produced over four sites, using anatomical characteristics as predictors (FL = fibre length, mm; FD = fibre diameter, μm; LD = lumen diameter μm; WT= fibre wall thickness, μm).[* - P ≤ 0.05; **- P≤ 0.01; ns - non-significant].

Site	Predictor	Model	R^2	F (sig)	b0	b1	b2
	FL	Linear	0.549	9.72 (**)	-0.0472	0.5146	
Southern	FD	Quadratic	0.178	0.87 (ns)	-3.4916	0.3986	-0.00098
Bahia	LD	Quadratic	0.691	8.95 (**)	1.4653	-0.1324	0.0045
	WT	Linear	0.553	11.14 (**)	0.3389	0.0474	
	FL	Linear	0.298	3.39 (ns)	0.016	0.513	
São	FD	Linear	0.282	3.14 (ns)	1.167	-0.0334	
Mateus 1	LD	Linear	0.075	0.73 (ns)	0.6401	-0.0074	
	WT	Quadratic	0.193	0.95 (ns)	-1.1293	0.9402	-0.1294
	FL	Quadratic	0.138	0.64 (ns)	-3.3221	7.8359	-3.9063
São	FD	Quadratic	0.515	4.24 (*)	9.6745	-0.9660	0.0255
Mateus 2	LD	Linear	0.433	6.87 (*)	0.8629	-0.0274	
	WT	Quadratic	0.291	1.64 (ns)	2.3409	-0.9544	0.1271
	FL	Linear	0.003	0.03 (ns)	0.6285	-0.0611	
Aracruz	FD	Linear	0.101	1.01 (ns)	0.8480	-0.0158	
	LD	Linear	0.464	6.92 (*)	0.729	-0.0168	
	WT	Linear	0.715	20.05 (**)	0.202	0.0962	

Appendix 7.3 Multiple linear regression to estimate the nominal density (ND: g.cm^{-3}) of wood produced over four sites, using anatomical characteristics as predictors (FL = fibre length, mm; FD = fibre diameter, µm; LD = lumen diameter, µm; WT = fibre wall thickness, µm). [* - P ≤ 0.05; **- P≤ 0.01; **- P≤ 0.01; ns - non-significant].

Site	Equation	F	S
Southern Bahia	ND = 0.959** - 0.380 FL* - 0.0159 FD* + 0.0806 WT**	**	0.024
São Mateus 1	ND = 0.459* + 0.534 FL* - 0.0255 FD*	*	0.039
São Mateus 2	ND = 0.0552 FD** - 0.0402 LD(ns)	**	0.074
Aracruz	ND = 0.0703 FD** - 0.0657 LD**	**	0.041

Appendix 7.4 Analysis of regression to estimate the compression strength parallel to the grain (CP, MPa) of wood of 11 clones produced over four sites, using nominal density (ND, g.cm^{-3}) and anatomical characteristics as predictors (FL = fibre length, mm; FD = fibre diameter, µm; LD = lumen diameter µm; WT= fibre wall thickness, µm; GA = grain angle, mm in 100 mm and MF = microfibril angle, degree). [* - P ≤ 0.05; **- P≤ 0.01; ns - non-significant].

Site	Predictor	Model	R^2	F (sig)	b0	b1	b2
Southern Bahia	ND	Linear	0.556	11.26 (**)	5.7819	90.2395	
	FL	Linear	0.321	3.76 (ns)	-2.06	49.62	
	FD	Linear	0.015	0.14 (ns)	63.7342	-0.5152	
	LD	Inverse	0.369	5.26 (*)	29.0590	290.742	
	WT	Linear	0.278	3.47 (ns)	37.556	3.971	
	GA	Linear	0.198	2.23 (ns)	62.4220	-2.5978	
	MF	Linear	0.160	1.52 (ns)	38.440	1.896	
São Mateus 1	ND	Linear	0.454	7.48 (*)	11.3990	79.7288	
	FL	Linear	0.434	6.13 (*)	-22.720	74.220	
	FD	Linear	0.010	0.09 (ns)	62.7043	-0.3744	
	LD	Linear	0.000	0.009 (ns)	55.1450	0.0506	
	WT	Quadratic	0.132	0.61 (ns)	-68.108	71.202	-10.09
	GA	Linear	0.206	2.34 (ns)	61.60	-1.77	
	MF	Linear	0.485	7.54 (*)	88.49	-3.326	
São Mateus 2	ND	Linear	0.521	9.81 (**)	7.5563	86.4458	
	FL	Linear	0.023	0.22 (ns)	74.5036	-15.856	
	FD	Linear	0.320	4.23 (ns)	129.281	-3.9756	
	LD	Linear	0.915	86.07 (**)	99.574	-4.222	
	WT	Linear	0.814	30.72 (**)	7.167	12.958	
	GA	Linear	0.090	0.89 (ns)	53.7163	1.1430	
	MF	Linear	0.113	1.02 (ns)	26.29	4.111	
Aracruz	ND	Linear	0.417	6.44 (*)	29.7579	43.2355	
	FL	Linear	0.025	0.23 (ns)	65.9761	-11.242	
	FD	Linear	0.001	0.01 (ns)	56.2357	-0.1161	
	LD	Linear	0.033	0.30 (ns)	58.7001	-0.4296	
	WT	Linear	0.676	14.64 (**)	32.700	6.315	
	GA	Linear	0.218	2.23 (ns)	56.504	-0.983	
	MF	Linear	0.742	23.1 (**)	37.609	1.826	

Appendix 7.5 Multiple linear regression to estimate the compression strength parallel to the grain (CP, MPa) of wood produced over four sites, using nominal density (ND, g.cm^{-3}) and anatomical characteristics as predictors (FL = fibre length, mm; FD = fibre diameter, µm; ld = lumen diameter; WT = fibre wall thickness, µm; GA = grain angle, mm in 100mm; MF = microfibril angle degree). [* - P ≤ 0.05; **- P≤ 0.01; **- P≤ 0.01; ns - non-significant].

Site	Equation	F	S
Southern Bahia	CP = 1.58 LD** + 8.49 WT**	**	6.596
São Mateus 1	CP = 2.15 LD* + 8.53 WT*	**	8.358
São Mateus 2	CP = 4.23 LD** + 3.75 GA*	**	11.58
Aracruz	CP = 107 ND** - 40.7 FL* + 3.30 LD** - 1.87* GA + 0.801MF(ns)	**	2.550
	CP = 71.6 ND** + 1.30 LD**	**	3.377

Appendix 7.6 Analysis of regression to estimate modulus of rupture (MOR, MPa) of wood of 11 clones produced over four sites, using nominal density (ND, g.cm^{-3}) and anatomical characteristics as predictors (FL = fibre length, mm; FD = fibre diameter, µm; LD = lumen diameter µm; WT= fibre wall thickness, µm; GA = grain angle and MF = microfibril angle). [* - P ≤ 0.05; **- P≤ 0.01; ***- P≤ 0.001 ns - non-significant].

Site	Predictor	Model	R^2	F	b0	b1	b2
	ND	Linear	0.612	14.20 (**)	-55.677	290.441	
	FL	Linear	0.128	1.32 (ns)	1.175	84.358	
Southern	FD	Linear	0.002	0.02 (ns)	108.532	-0.551	
Bahia	LD	Linear	0.635	13.94 (**)	219.78	-10.296	
	WT	Linear	0.687	17.6 (**)	23.91	17.830	
	GA	Linear	0.168	1.82 (ns)	123.02	-7.331	
	MF	Linear	0.359	5.04 (*)	48.238	6.605	
	ND	Linear	0.586	11.30 (**)	-20.63	220.34	
	FL	Linear	0.075	0.73 (ns)	47.893	47.225	
São	FD	Linear	0.154	1.45 (ns)	206.22	-5.901	
Mateus 1	LD	Linear	0.037	0.34 (ns)	112.39	-1.223	
	WT	Linear	0.000	0.00 (ns)	97.171	0.358	
	GA	Linear	0.194	2.17 (ns)	109.89	-3.427	
	MF	Linear	0.058	0.56 (ns)	117.09	-1.940	
	ND	Linear	0.397	5.27 (*)	24.14	127.39	
	FL	Quadratic	0.131	0.60 (ns)	-924.17	1982.87	-959.33
São	FD	Linear	0.591	11.94 (**)	276.26	-9.860	
Mateus 2	LD	Linear	0.428	6.73 (*)	158.55	-6.090	
	WT	Linear	0.796	27.3 (**)	-14.40	30.193	
	GA	Linear	0.067	0.58 (ns)	98.643	-1.584	
	MF	Linear	0.045	0.37 (ns)	113.95	-2.555	
	ND	Linear	0.851	(***)	-41.0	230.0	
	FL	Quadratic	0.368	2.33 (ns)	2927.3	-5400.9	2554.4
Aracruz	FD	Linear	0.010	0.10 (ns)	100.34	-1.047	
	LD	Linear	0.099	0.99 (ns)	106.00	-2.308	
	WT	Linear	0.565	9.09 (*)	8.77	21.067	
	GA	Linear	0.055	0.52 (ns)	87.181	-1.604	
	MF	Linear	0.000	0.00 (ns)	82.56	-0.099	

Appendix 7.7 Multiple analysis of regression to estimate the modulus of rupture (MOR, MPa) of wood produced over four sites, using nominal density (ND, $g.cm^{-3}$) and anatomical characteristics as predictors (FL = fibre length, mm; FD = fibre diameter, µm; WT = fibre wall thickness, µm; GA = grain angle, mm in 100mm; MF = microfibril angle, degree). [* - P ≤ 0.05; **- P≤ 0.01; **- P≤ 0.01 ns - non-significant].

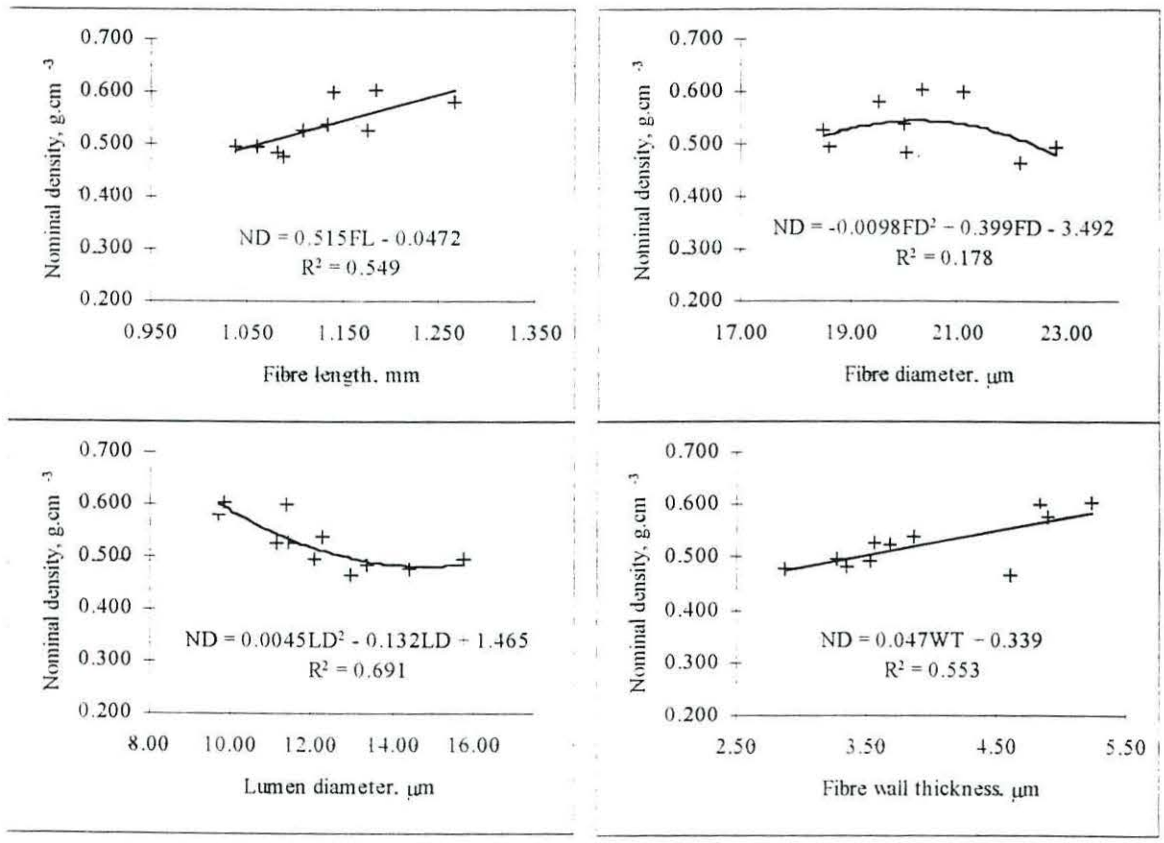
Site	Equation	F	S
Southern Bahia	MOR = 146 ND** - 6.20 GA* + 5.70 MF*	**	9.78
São Mateus 1	MOR = 198* -116 FD* + 112 LD* + 220 WT* - 5.65 GA*	ns	9.15
São Mateus 2	MOR = 84.2 FL** - 6.20 LD* + 8.80 MF*	**	11.77
Aracruz	MOR = 9.42 FD** - 8.25 LD*	**	12.39

Appendix 7.8 Analysis of regression to estimate the modulus of elasticity (MOE, MPa) of wood of 11 clones produced over four sites, using nominal density (ND, $g.cm^{-3}$) and anatomical characteristics as predictors (FL = fibre length, mm; FD = fibre diameter, µm; LD = lumen diameter µm; WT= fibre wall thickness, µm; GA = grain angle, mm in 100 mm; MF = microfibril angle, degree). [* - P ≤ 0.05; **- P≤ 0.01; ***- P≤ 0.001; ns - non-significant].

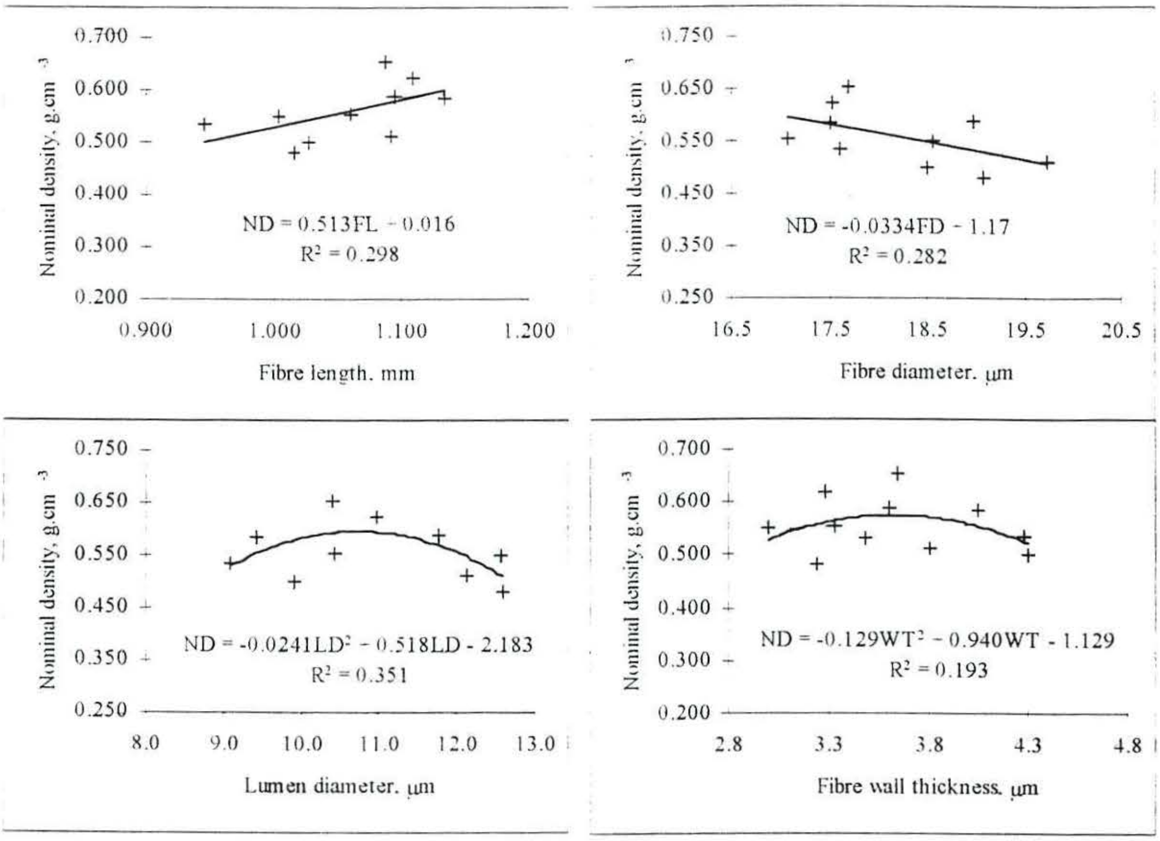
Site	Predictor	Model	R^2	F (sig)	b0	b1	b2
Southern Bahia	ND	Linear	0.616	12.85 (**)	987.00	17154	
	FL	Linear	0.579	9.63 (*)	-3517.0	12089	
	FD	Linear	0.101	1.01 (ns)	16884.3	-325.21	
	LD	Quadratic	0.793	13.4 (**)	43480	-5061	186.4
	WT	Linear	0.424	5.88 (*)	6462.0	891.1	
	GA	Linear	0.369	4.68 (ns)	12325	-676	
	MF	Quadratic	0.371	2.36 (ns)	15913.0	-2118.1	175.84
São Mateus 1	ND	Linear	0.516	8.54 (*)	-1561	21327	
	FL	Linear	0.024	0.22 (ns)	7286.45	2601.73	
	FD	Linear	0.249	2.65 (ns)	22821.0	-693.0	
	LD	Linear	0.194	2.17 (ns)	13198.1	-274.57	
	WT	Linear	0.000	0.00 (ns)	9971.28	28.0193	
	GA	Linear	0.406	5.47 (*)	11936	-496	
	MF	Quadratic	0.524	4.41 (*)	-14473	5227.80	-271.9
São Mateus 2	ND	Linear	0.390	5.11 (*)	2621	13245	
	FL	Linear	0.632	12.01 (**)	-3237	12786	
	FD	Linear	0.279	3.49 (ns)	21709.6	-641.20	
	LD	Linear	0.768	26.6 (***)	17971	-775.00	
	WT	Linear	0.608	12.4 (**)	2743.0	1995.6	
	GA	Quadratic	0.365	2.01 (ns)	12875.9	-1957	282.1
	MF	Quadratic	0.268	1.47 (ns)	-10074	5449.30	-360.55
Aracruz	ND	Linear	0.380	4.90 (*)	-262.00	15913	
	FL	Linear	0.354	4.38 (ns)	-4136	11706	
	FD	Linear	0.009	0.08 (ns)	9896.15	-85.668	
	LD	Linear	0.037	0.34 (ns)	9686.04	-125.28	
	WT	Linear	0.052	0.50 (ns)	6054.56	627.818	
	GA	Quadratic	0.571	4.66 (*)	11299	-1766	190
	MF	Linear	0.143	1.50 (ns)	10422.3	-207.14	

Appendix 7.9 Multiple linear regression to estimate the modulus of elasticity (MOE, MPa) of wood produced over four sites, using nominal density (ND, g.cm^{-3}) and anatomical characteristics as predictors (FL = fibre length, mm; FD = fibre diameter, μm; WT = fibre wall thickness, μm; GA = grain angle, mm in 100mm; MF = microfibril angle, degree). [* - P ≤ 0.05; **- P≤ 0.01; **- P≤ 0.01; ns - non-significant].

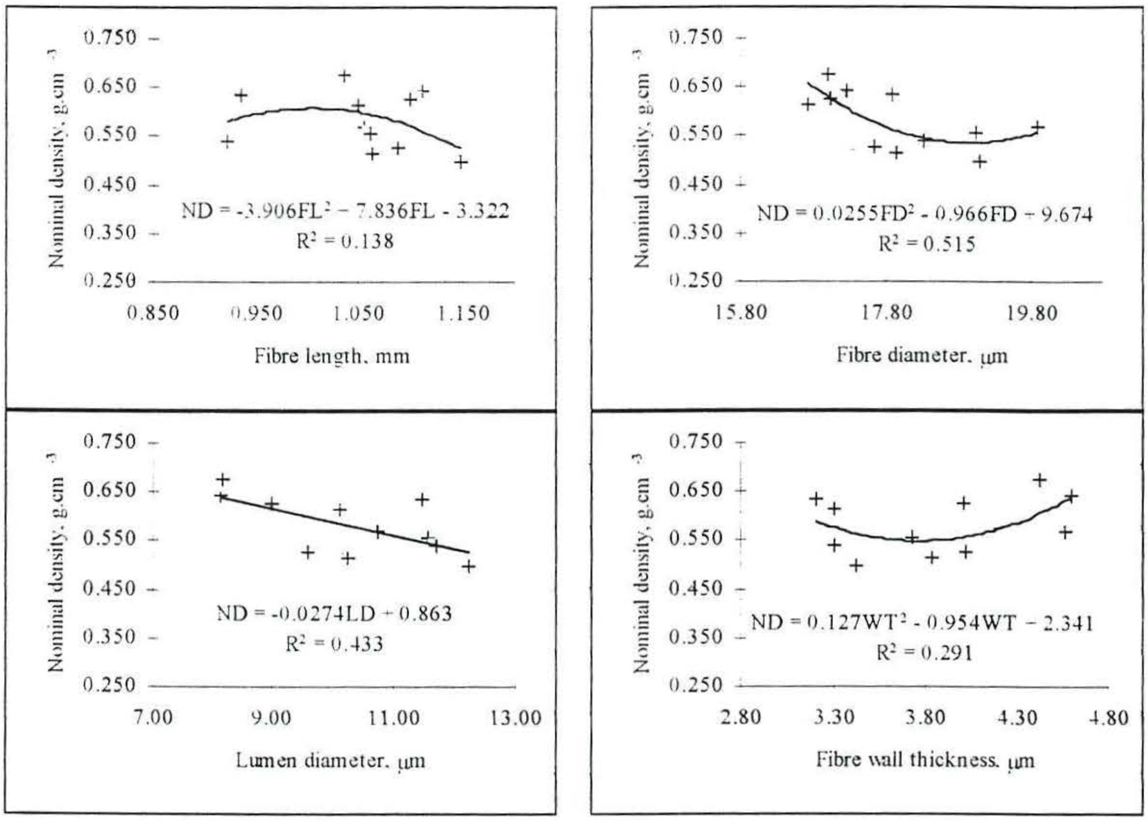
Site	Equation	F	S
Southern Bahia	MOE = 309 LD* + 866 MF**	**	1756
São Mateus 1	MOE = 14410 FL** - 473 LD*	**	1071
São Mateus 2	MOE = 9046 ND* + 4701 FL*	**	950
Aracruz	MOE = 15541 FL** - 471 LD* - 303 MF*	**	866



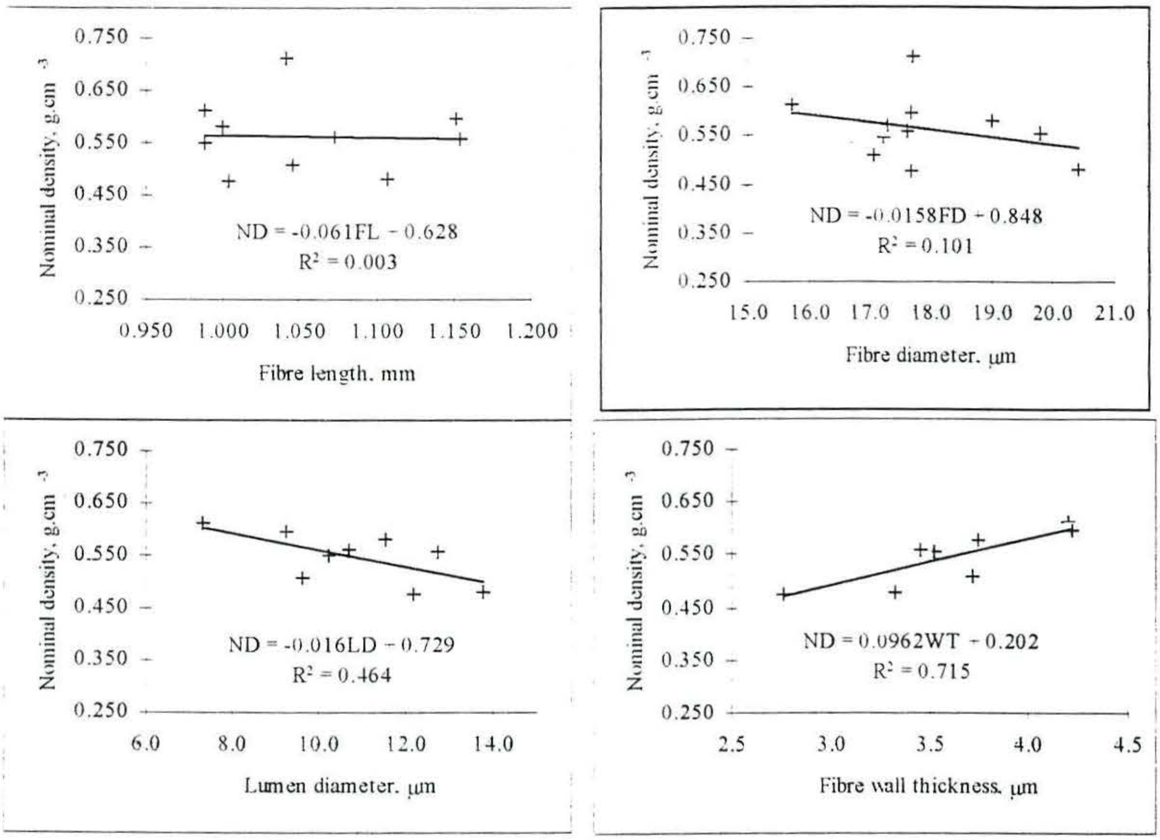
Appendix 7.10 Models selected to estimate the nominal density (ND, g.cm^{-3}) of the 11 clones grown over Southern Bahia site, using fibre length (FL, mm), fibre diameter (FD, μm), lumen diameter (LD, μm) and fibre wall thickness (WT, μm) as predictors.



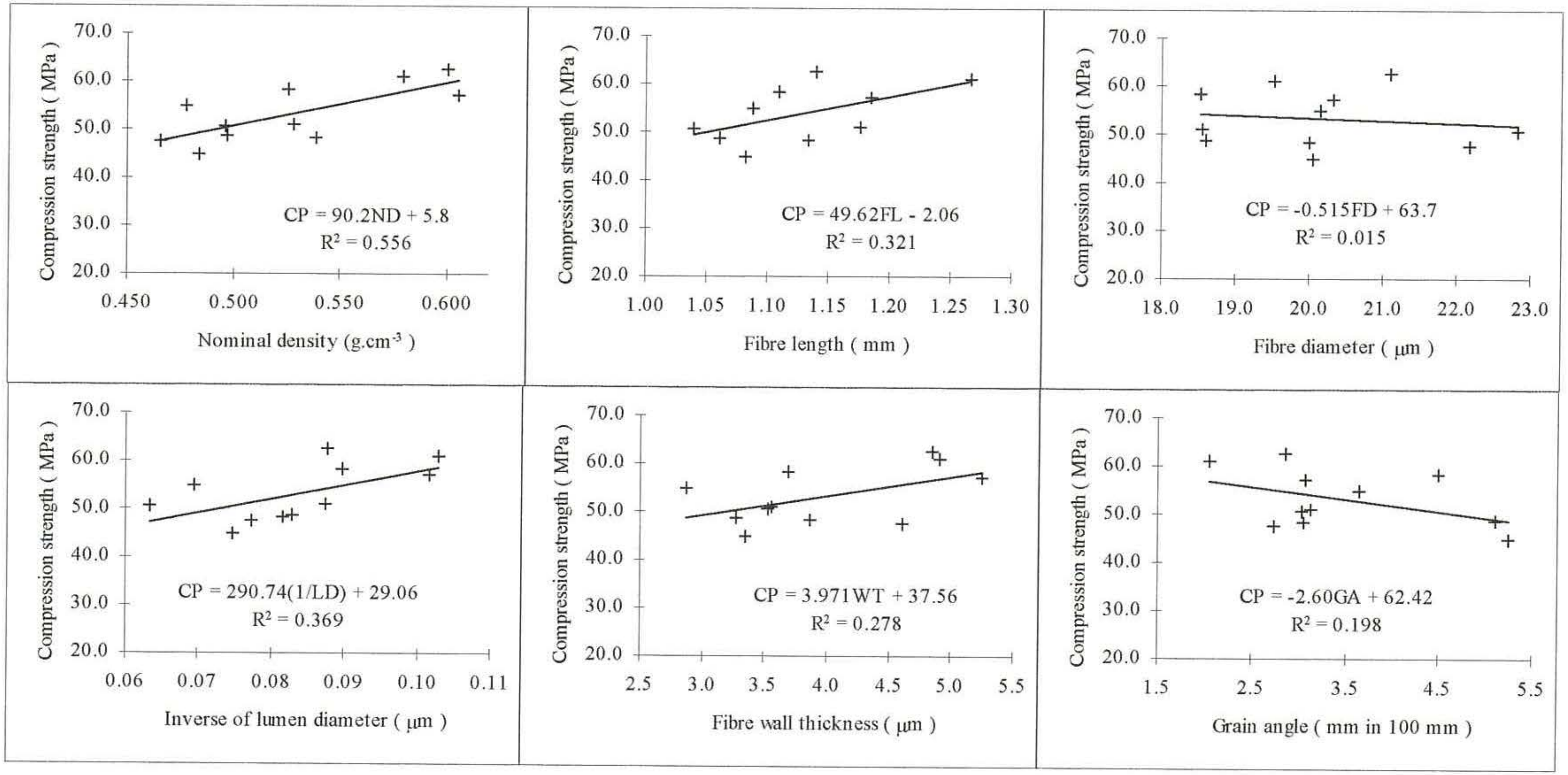
Appendix 7.11 Models selected to estimate the nominal density (ND, g.cm^{-3}) of the 11 clones grown over São Mateus 1 site, using fibre length (FL, mm), fibre diameter (FD, µm), lumen diameter (LD, µm) and fibre wall thickness (WT, µm) as predictors.



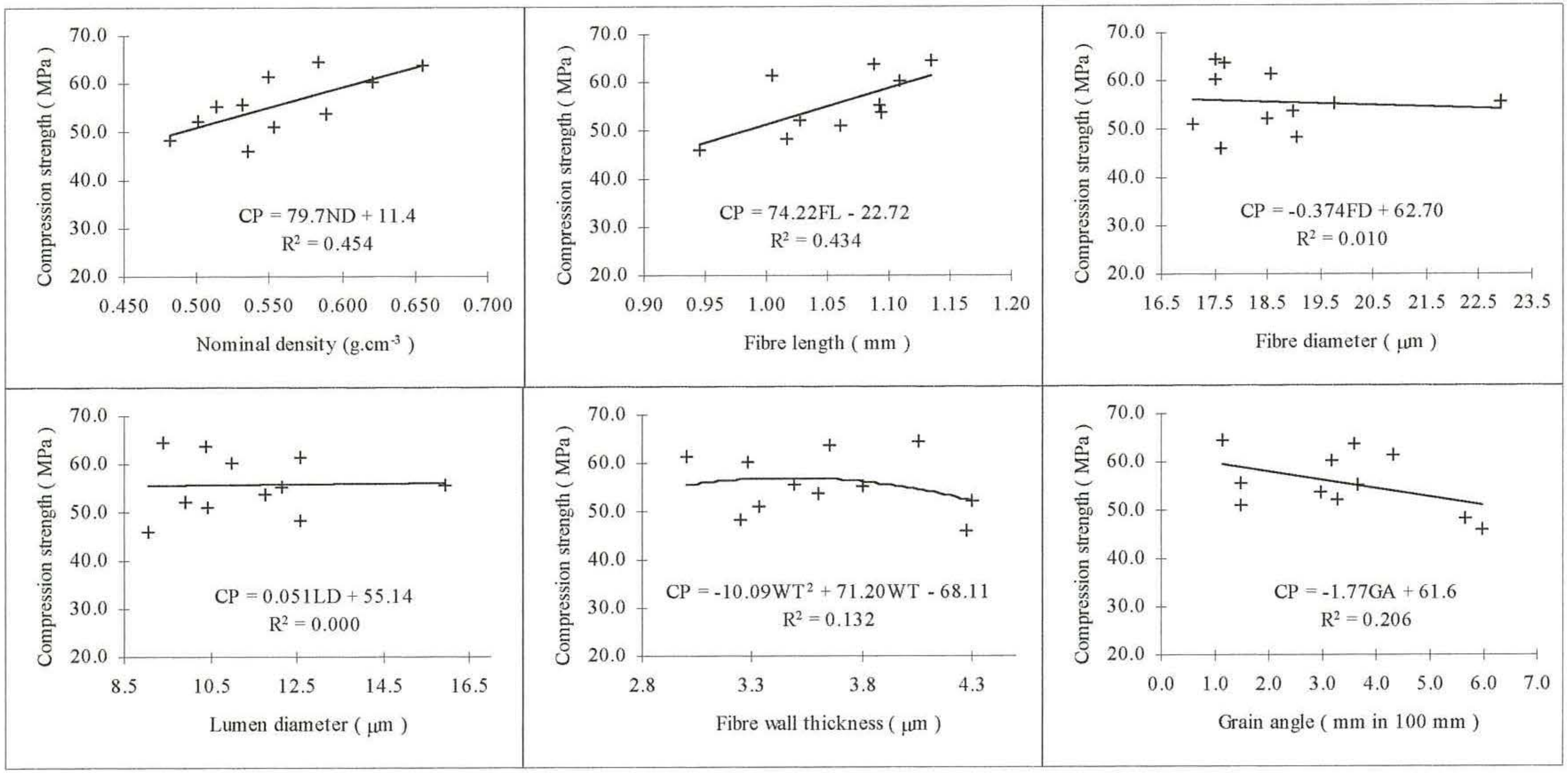
Appendix 7.12 Models selected to estimate the nominal density (ND, g.cm^{-3}) of the 11 clones grown over São Mateus 2 site, using fibre length (FL, mm), fibre diameter (FD, µm), lumen diameter (LD, µm) and fibre wall thickness (WT, µm) as predictors.



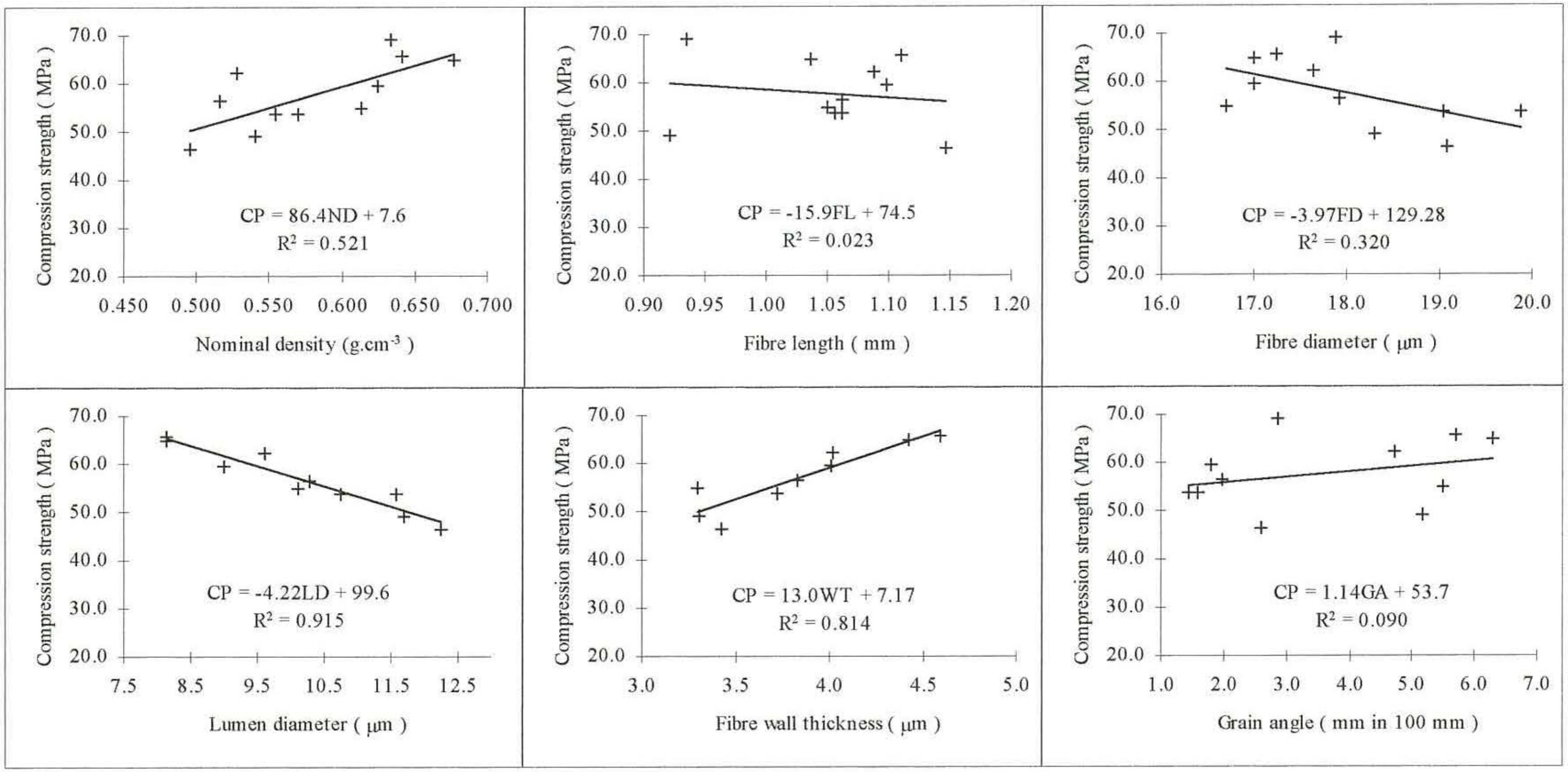
Appendix 7.13 Models selected to estimate the nominal density (ND. g.cm^{-3}) of the 11 clones grown over Aracruz site, using fibre length (FL, mm), fibre diameter (FD, µm), lumen diameter (LD, µm) and fibre wall thickness (WT, µm) as predictors.



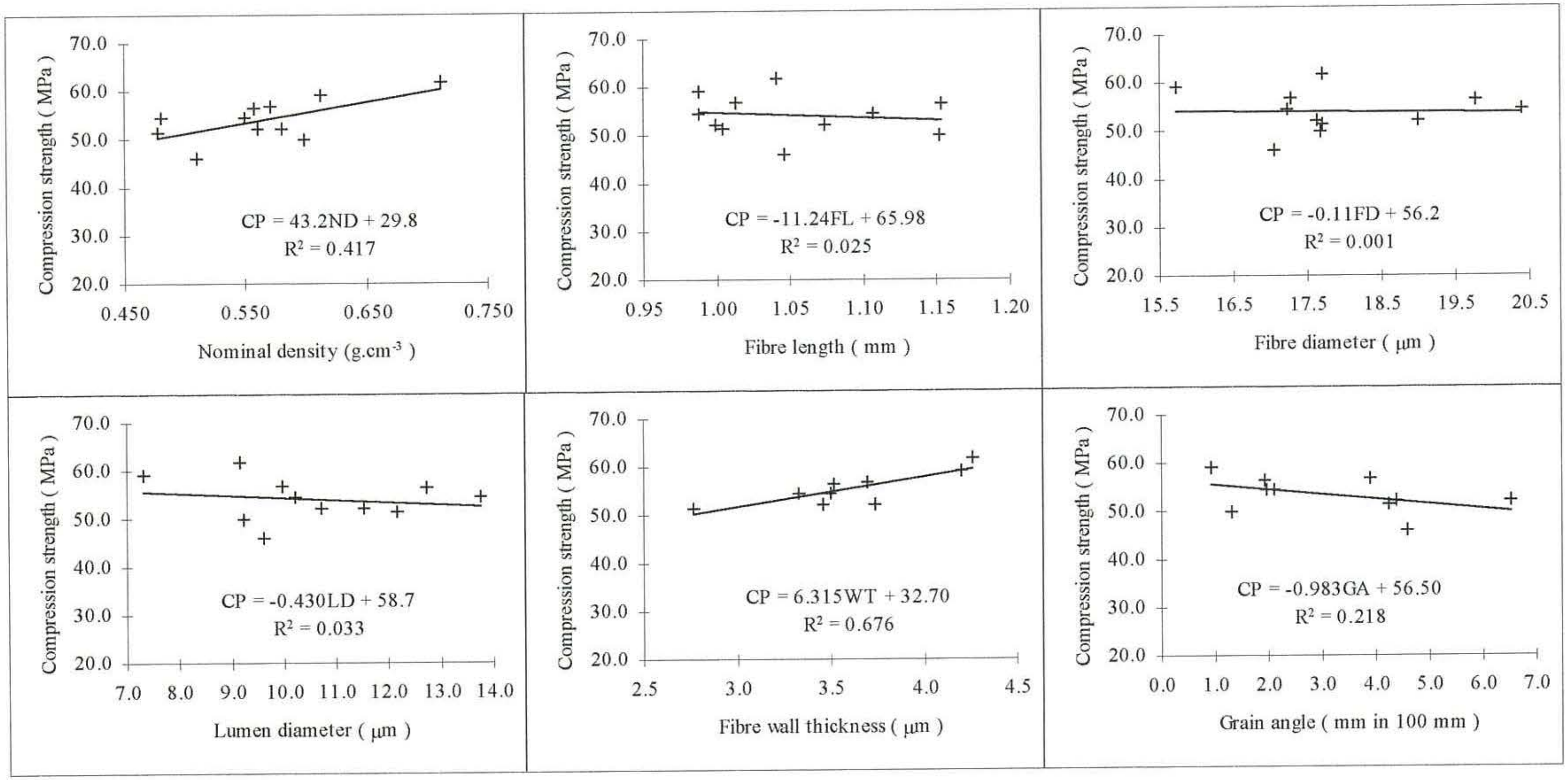
Appendix 7.14 Models selected to estimate the compression strength parallel to the grain (MPa) of the 11 clones grown over Southern Bahia site, using nominal density (g.cm^{-3}), fibre length (FL, mm), fibre diameter (FD, μm), lumen diameter (LD, μm), fibre wall thickness (WT, μm) and grain angle (mm in 100mm).



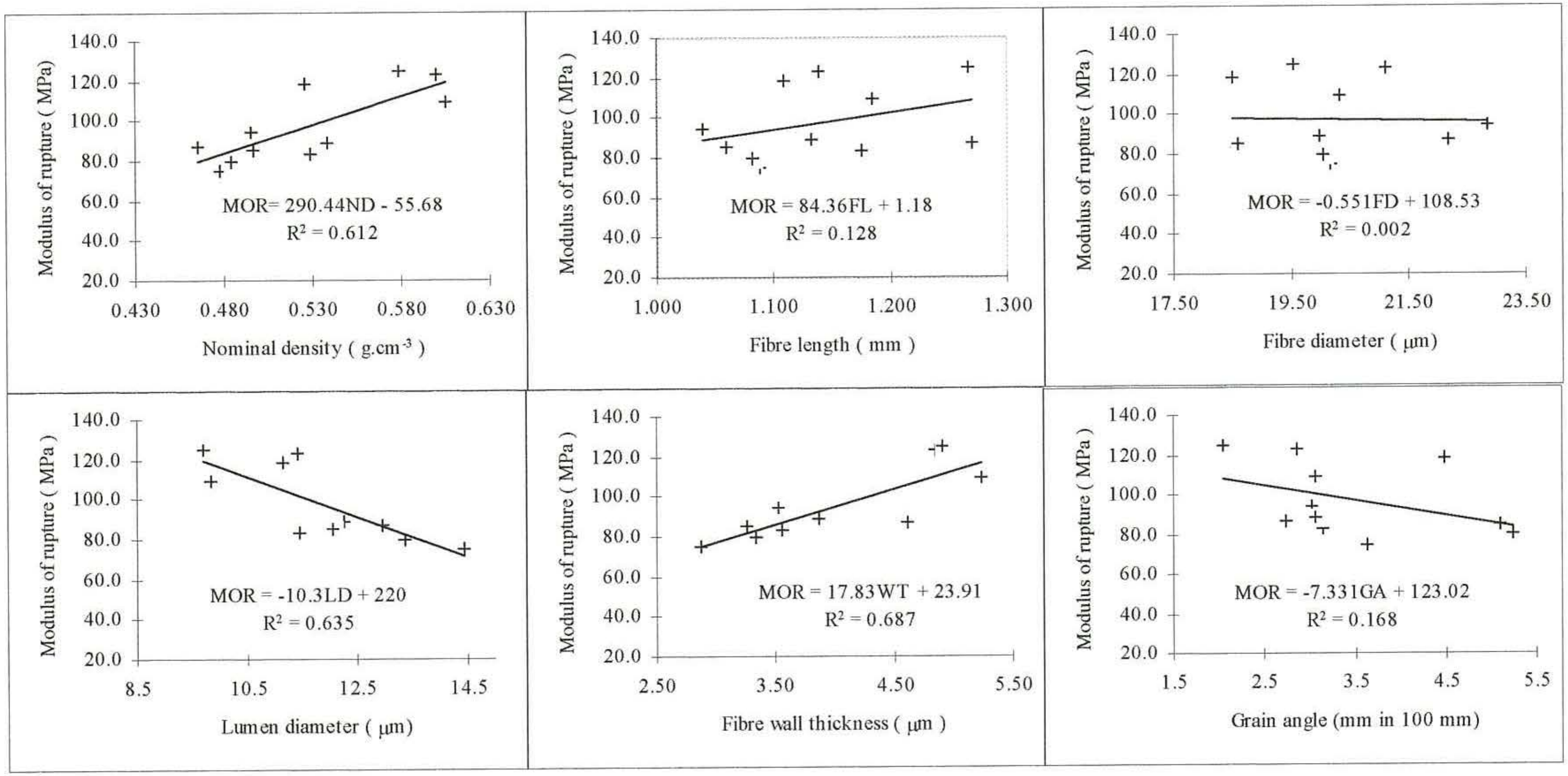
Appendix 7.15 Models selected to estimate the compression strength parallel to the grain (MPa) of the 11 clones grown over São Mateus 1 site, using nominal density ($g.cm^{-3}$), fibre length (FL, mm), fibre diameter (FD, µm), lumen diameter (LD, µm), fibre wall thickness (WT, µm) and grain angle (mm in 100 mm) (degree) as predictors.



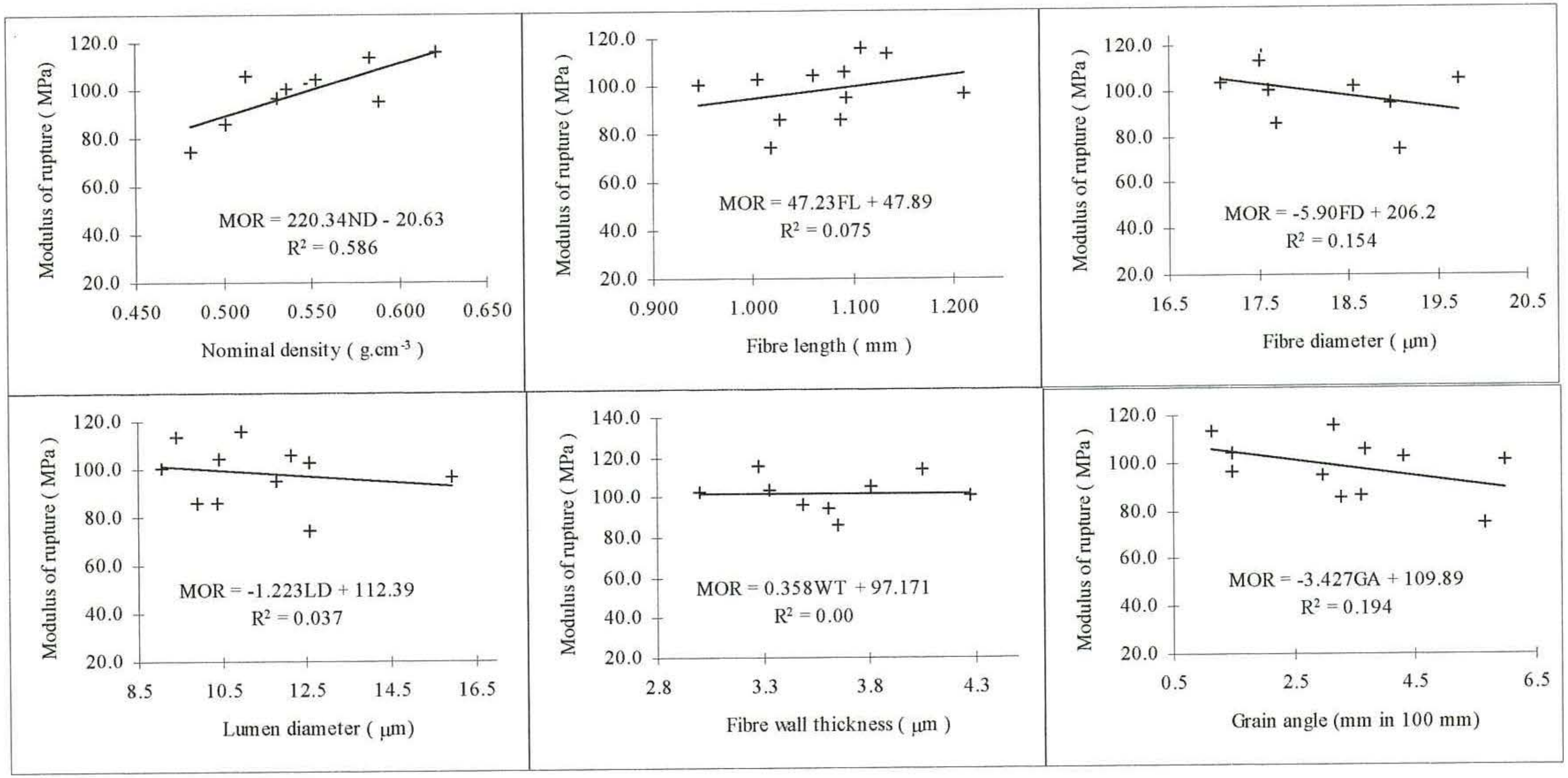
Appendix 7.16 Models selected to estimate the compression strength parallel to the grain (MPa) of the 11 clones grown over São Mateus 2 site, using nominal density ($g.cm^{-3}$), fibre length (FL, mm), fibre diameter (FD, µm), lumen diameter (LD, µm), fibre wall thickness (WT, µm) and grain angle (mm in 100 mm) as predictors.



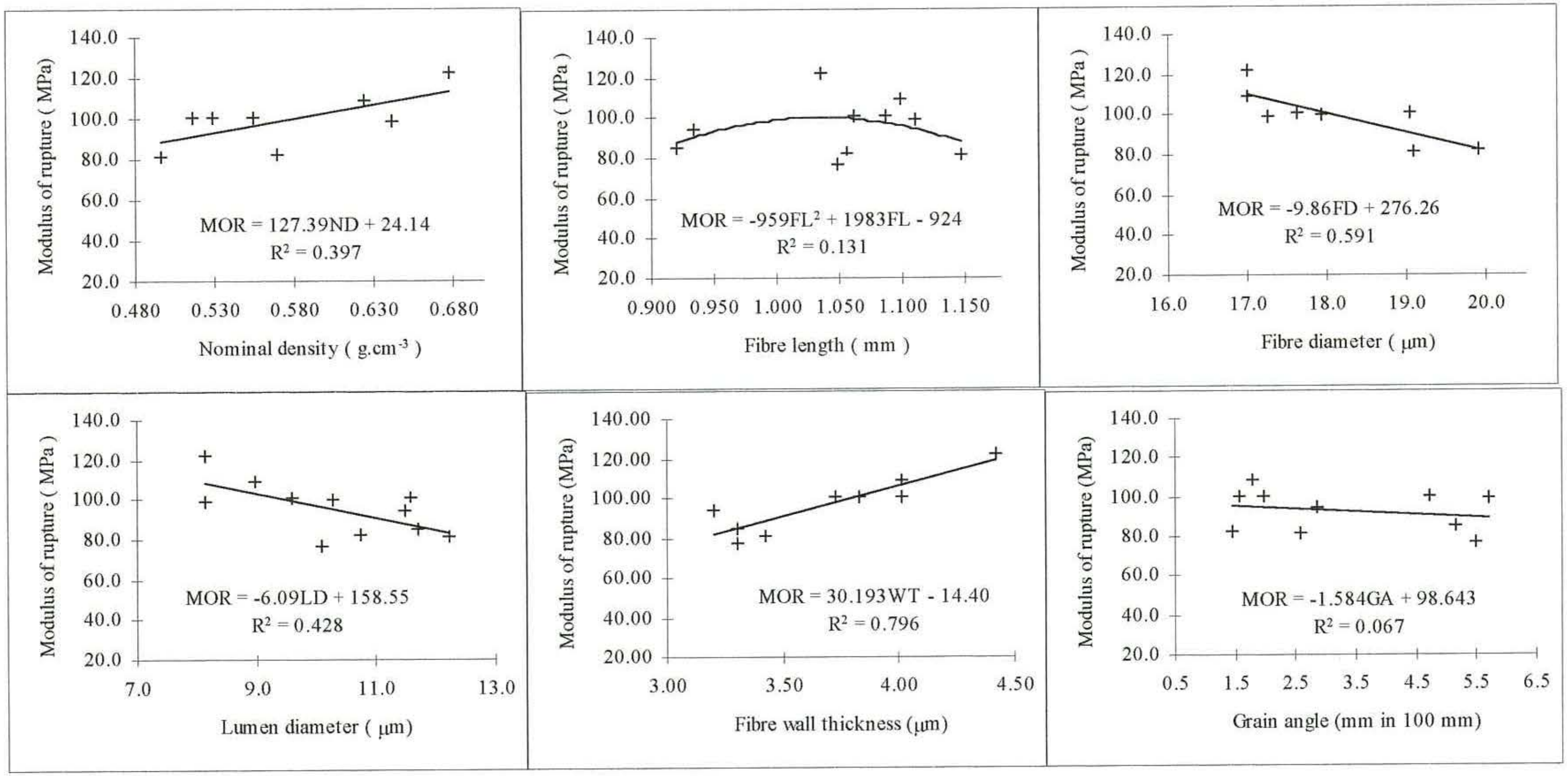
Appendix 7.17 Models selected to estimate the compression strength parallel to the grain (MPa) of the 11 clones grown over Aracruz site, using nominal density ($g.cm^{-3}$), fibre length (FL, mm), fibre diameter (FD, µm), lumen diameter (LD, µm), fibre wall thickness (WT, µm) and grain angle (mm in 100 mm) as predictors.



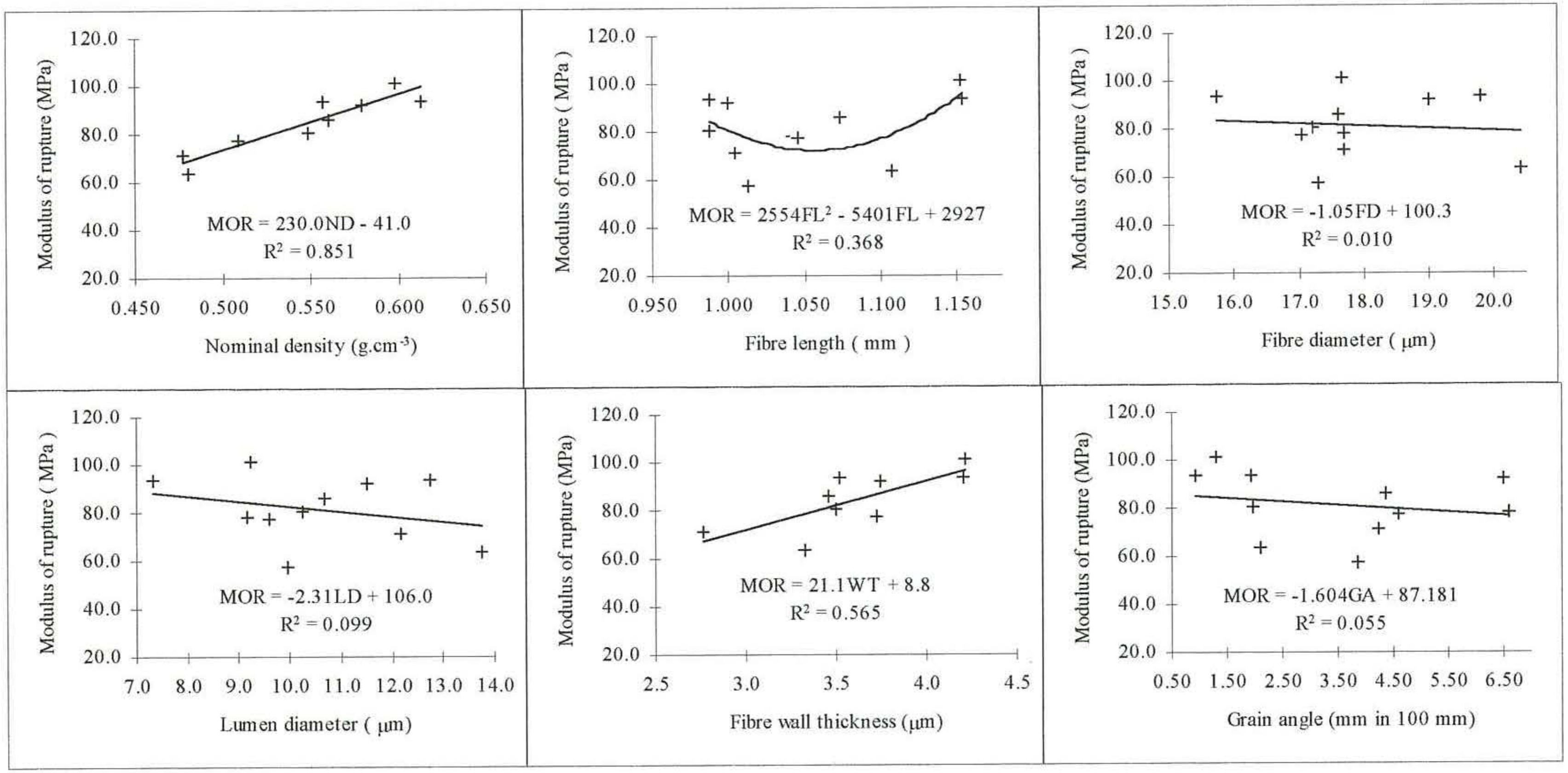
Appendix 7.18 Models selected to estimate the modulus of rupture (MPa) of the 11 clones grown over Southern Bahia site, using nominal density ($g.cm^{-3}$), fibre length (FL, mm), fibre diameter (FD, μm), lumen diameter (LD, μm), fibre wall thickness (WT, μm) and grain angle (mm in 100 mm) as predictors.



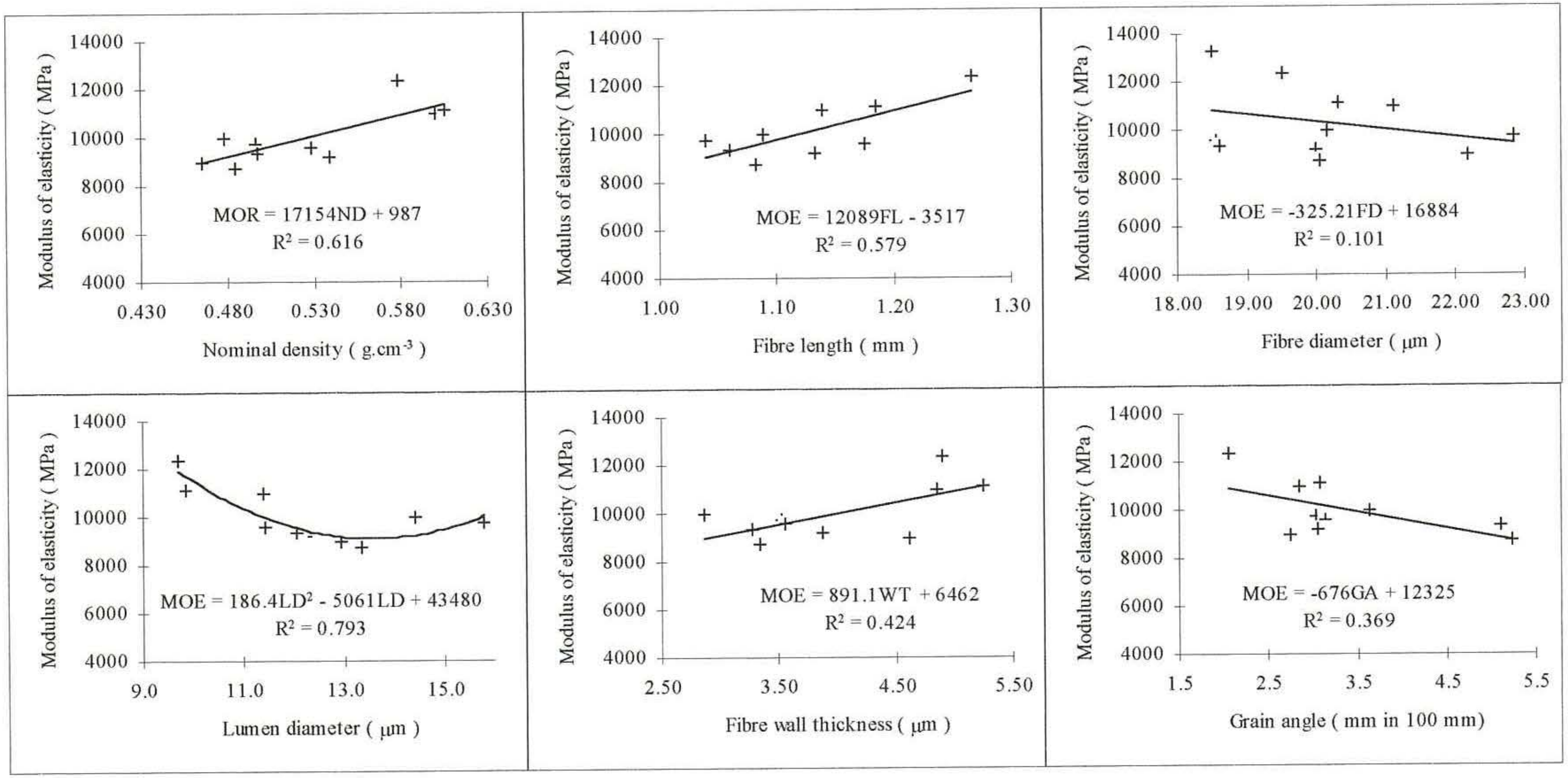
Appendix 7.19 Models selected to estimate the modulus of rupture (MPa) of the 11 clones grown over São Mateus 1 site, using nominal density ($g.cm^{-3}$), fibre length (FL, mm), fibre diameter (FD, µm), lumen diameter (LD, µm), fibre wall thickness (WT, µm) and grain angle (mm in 100 mm) as predictors.



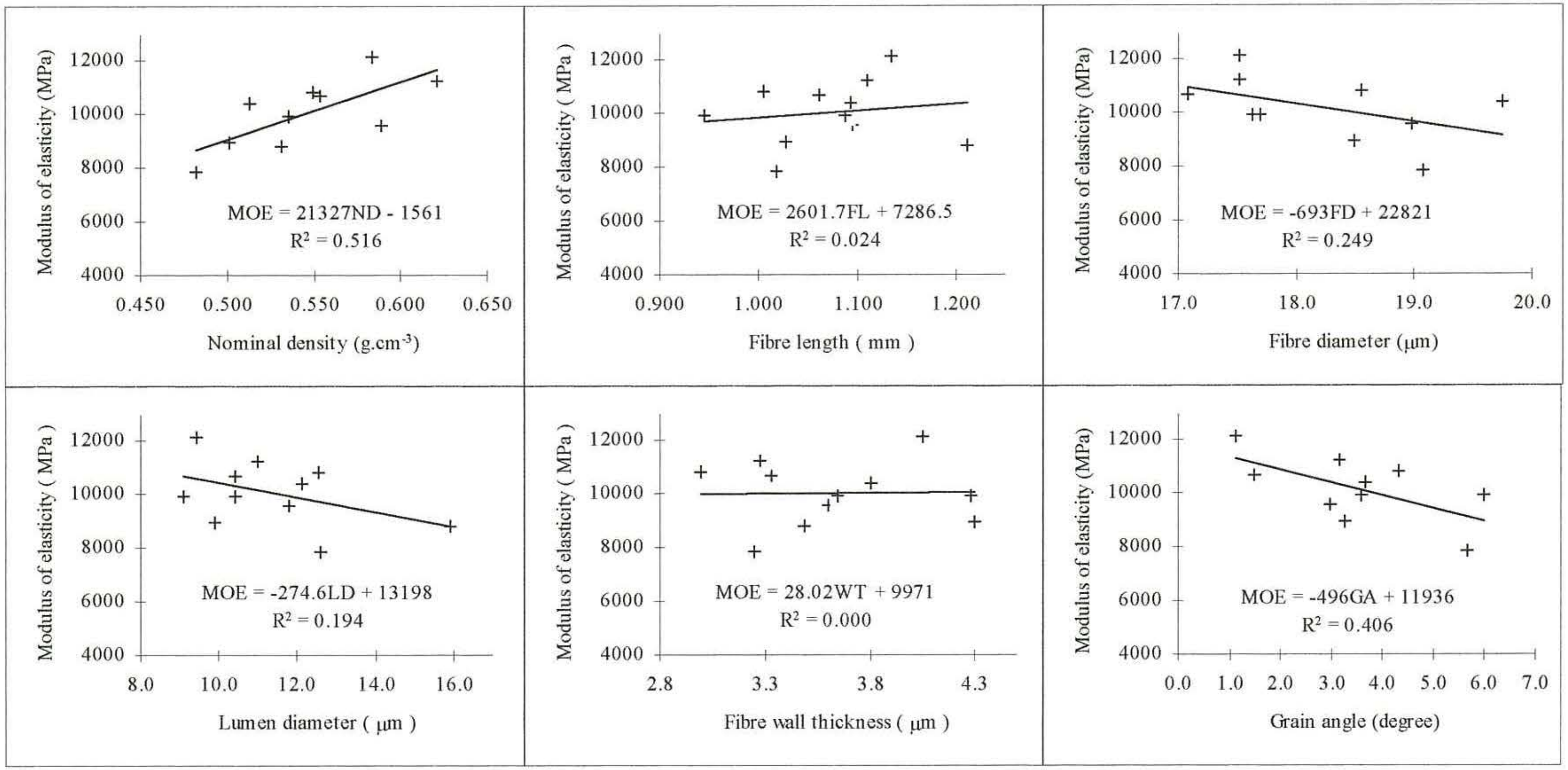
Appendix 7.20 Models selected to estimate the modulus of rupture (MPa) of the 11 clones grown over São Mateus 2 site, using nominal density (g.cm^{-3}), fibre length (FL, mm), fibre diameter (FD, µm), lumen diameter (LD, µm), fibre wall thickness (WT, µm) and grain angle (mm in 100 mm) as predictors.



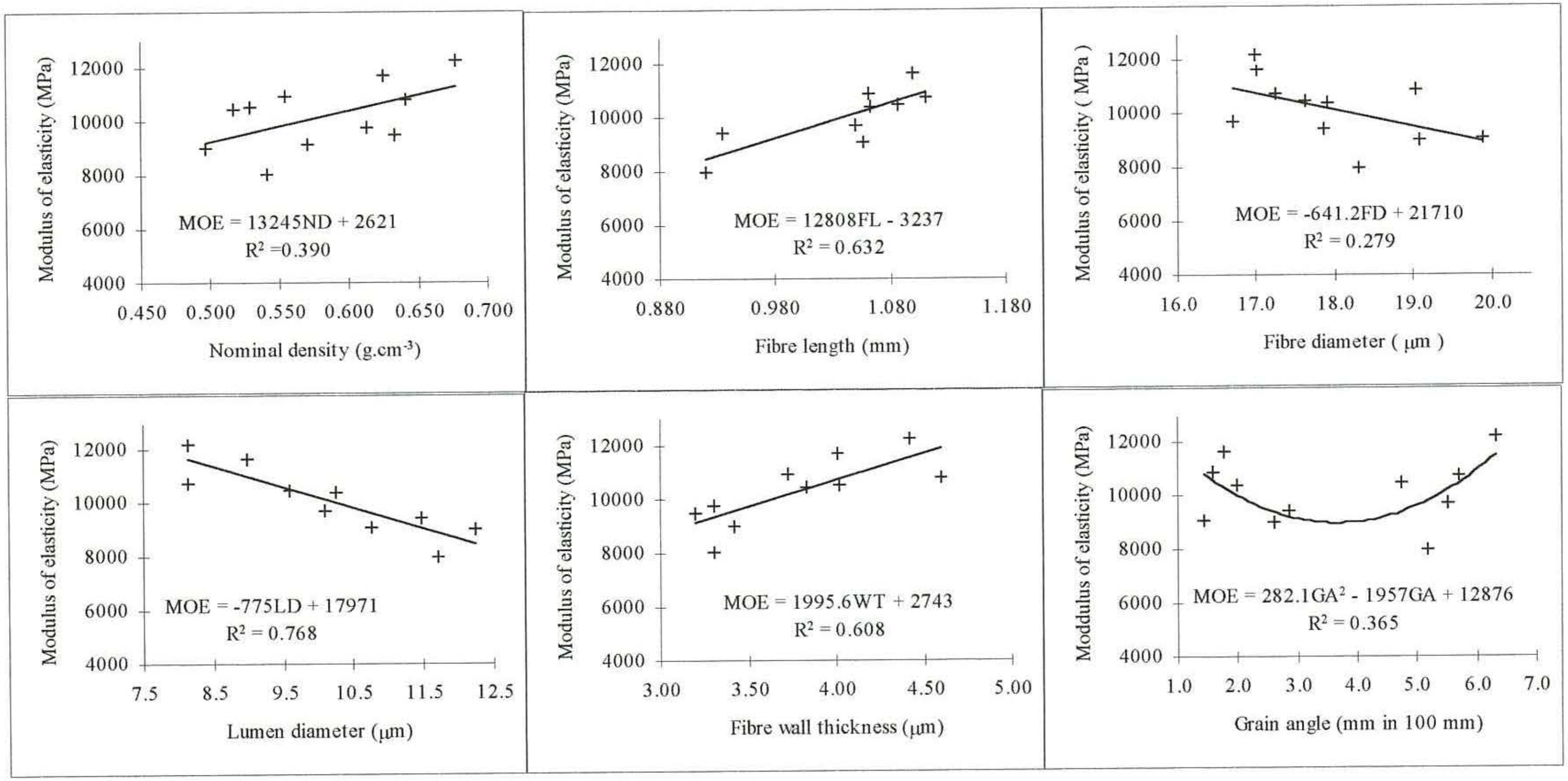
Appendix 7.21 Models selected to estimate the modulus of rupture (MPa) of the 11 clones grown over Aracruz site, using nominal density (g.cm^{-3}), fibre length (FL, mm), fibre diameter (FD, µm), lumen diameter (LD, µm), fibre wall thickness (WT, µm) and grain angle (mm in 100 mm) as predictors.



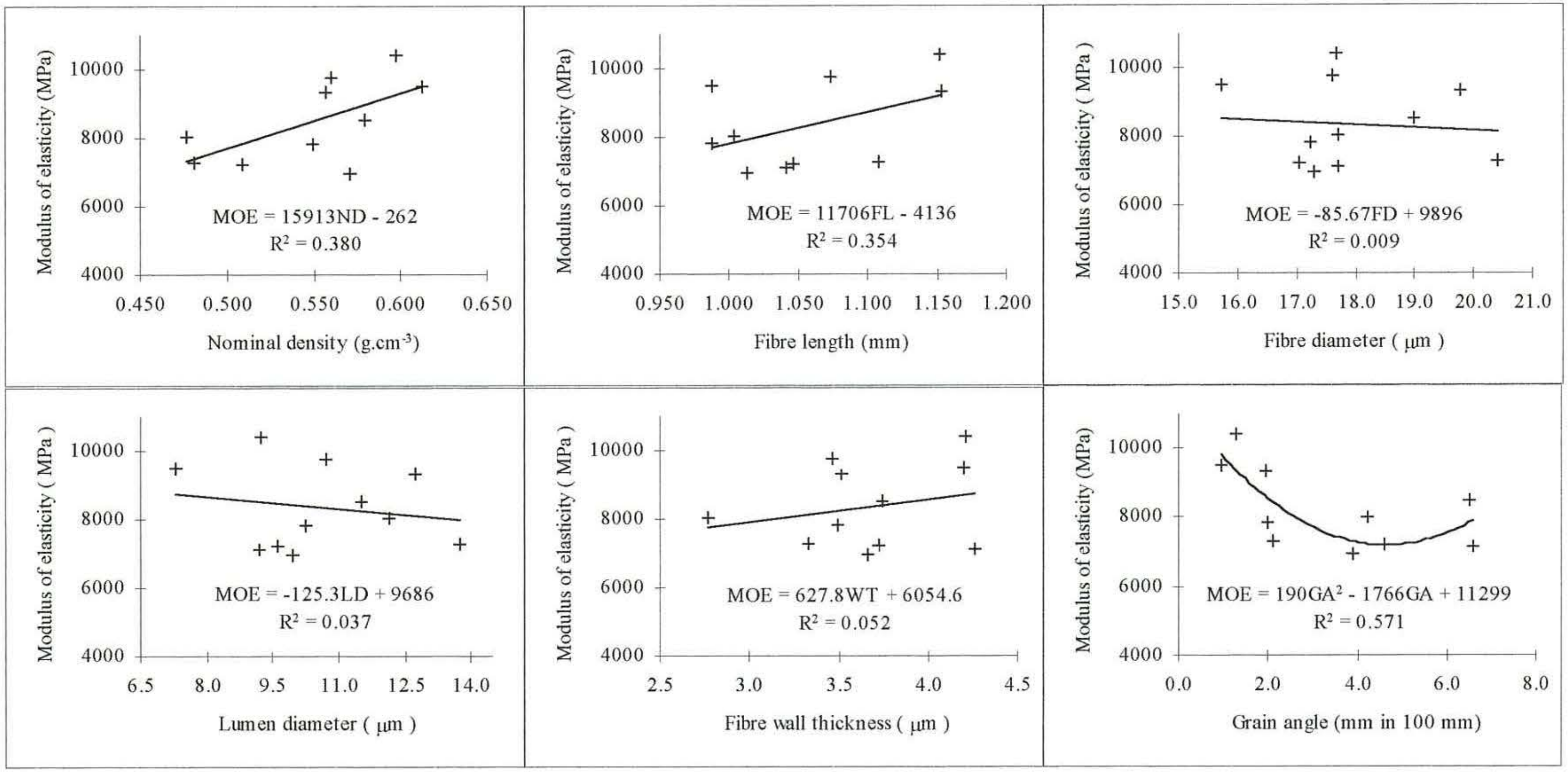
Appendix 7.22 Models selected to estimate the modulus of elasticity (MPa) of the 11 clones grown over Southern Bahia site, using nominal density ($g.cm^{-3}$), fibre length (FL, mm), fibre diameter (FD, µm), lumen diameter (LD, µm), fibre wall thickness (WT, µm) and grain angle (mm in 100 mm) as predictors.



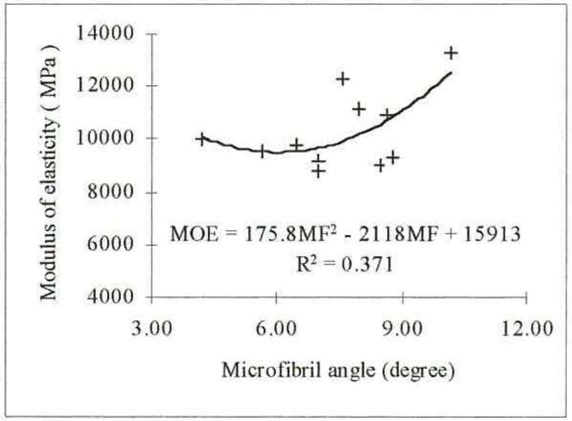
Appendix 7.23 Models selected to estimate the modulus of elasticity (MPa) of the 11 clones grown over São Mateus 1 site, using nominal density (g.cm^{-3}), fibre length (FL, mm), fibre diameter (FD, µm), lumen diameter (LD, µm), fibre wall thickness (WT, µm) and grain angle (mm in 100 mm) as predictors.



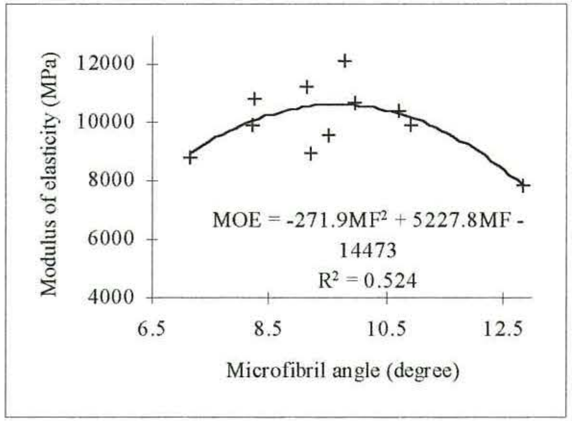
Appendix 7.24 Models selected to estimate the modulus of elasticity (MPa) of the 11 clones grown over São Mateus 2 site, using nominal density (g.cm^{-3}), fibre length (FL, mm), fibre diameter (FD, µm), lumen diameter (LD, µm), fibre wall thickness (WT, µm) and grain angle (mm in 100 mm) as predictors.



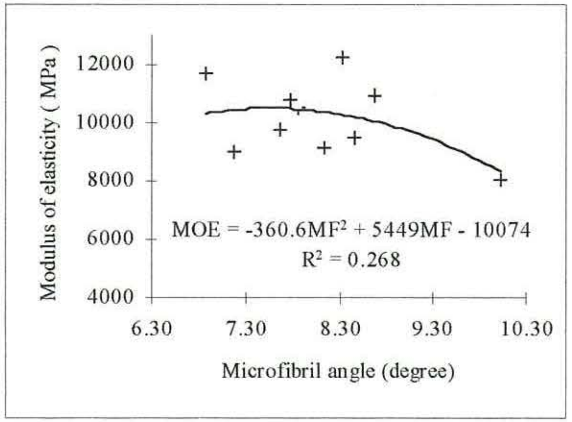
Appendix 7.25 Models selected to estimate the modulus of elasticity (MPa) of the 11 clones grown over Aracruz site, using nominal density (g.cm^{-3}), fibre length (FL, mm), fibre diameter (FD, µm), lumen diameter (LD, µm), fibre wall thickness (WT, µm) and grain angle (mm in 100 mm) as predictors.



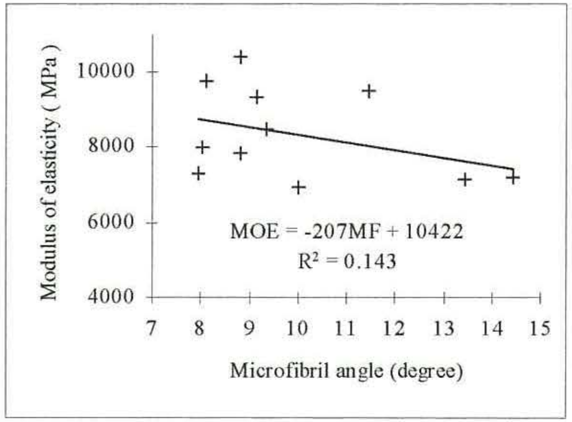
Southern Bahia



São Mateus 1

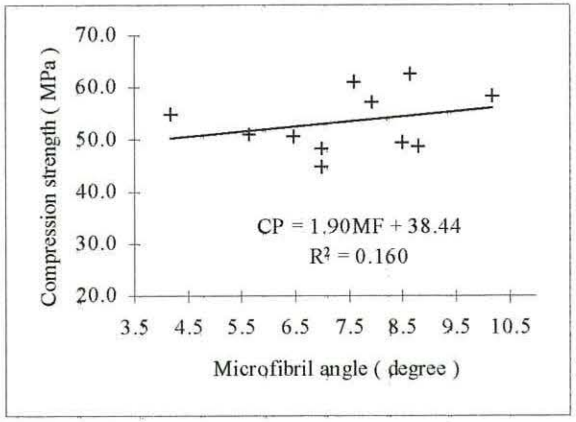


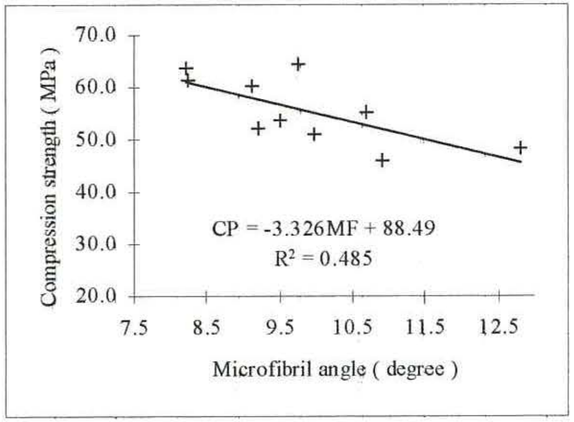
São Mateus 2



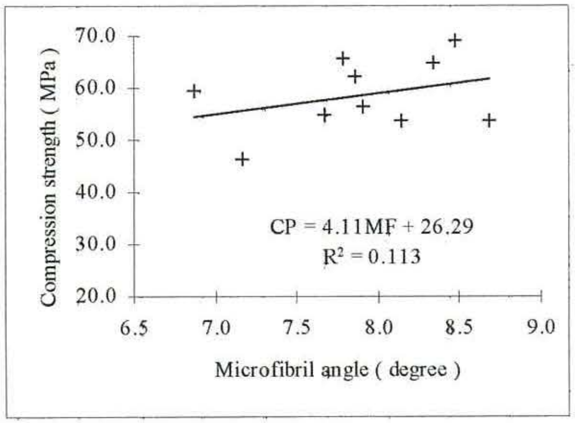
Aracruz

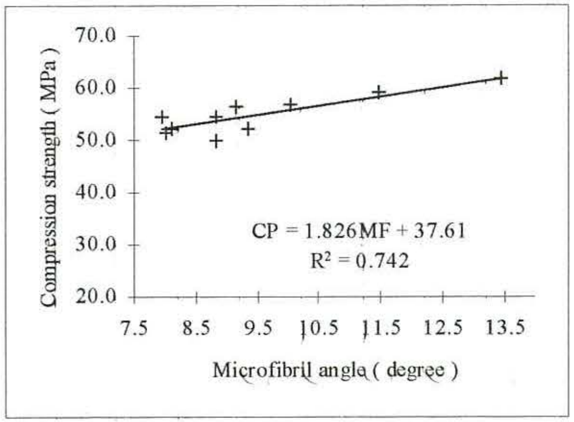
Appendix 7.26 Influence of the microfibril angle in the modulus of elasticity in each sites.





Southern Bahia São Mateus 1





São Mateus 2 Aracruz

Appendix 7.28 Influence of the microfibril angle in the compression strength parallel to grain in each sites.