The variation of microfibril angle in South African grown *Pinus patula* and its influence on the stiffness of structural lumber

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Abstract

Reduction in the rotation ages of softwood saw log plantations in South Africa is causing increased proportions of low stiffness sawn lumber at final harvest. It has been shown for some species that the microfibril angle (MFA) of the S2 layer of tracheids is strongly related to the modulus of elasticity (MOE) of wood, even more so than wood density, especially in wood formed during juvenile growth. The objectives of this study were to describe the variation in MFA in young *Pinus patula* trees and to determine the relationship between MFA and the dynamic MOE of sawn *Pinus patula* lumber. Thirty 16-20 year old trees from six compartments from the Mpumalanga escarpment were processed into discs and lumber. MFA, density and ring width were measured at two height levels using Silviscan 3. The average annual ring MFA varied between 7^{o} and 29^{o}; the pattern of variation depending mainly on height level and the ring number from the pith. The MFA in *P. patula* followed the same within-tree variation trends as in New Zealand-grown *Pinus radiata* but the average MFA was lower in absolute terms and differences between height levels were less pronounced. MFA and density exhibited highly significant Pearson correlations of 0.73 and 0.70 respectively with board dynamic MOE. A multiple regression model, which included MFA, density and ring width, explained 71% of the variation in the dynamic MOE of boards. A sensitivity analysis on the model showed that MFA and density had approximately similar influences on predicting the dynamic MOE of *Pinus patula* boards.

Keywords: density, modulus of elasticity, juvenile wood

Introduction

Approximately 70% of the sawn timber produced in South Africa is sold as building or structural grade lumber (Crickmay and Associates 2011) and is mainly used in roof truss manufacture. For softwood sawmill processors it is therefore important that a high percentage of the lumber produced conforms to the structural grade requirements. Stiffness and bending strength are the two most important mechanical properties in lumber used for residential roof truss constructions in South Africa

(Petersen and Wessels 2011). Stiffness or the modulus of elasticity (MOE) determines the resistance to deflection when subjected to bending stress as well as the compressive load that slender members can withstand.

As a result of accelerated growth due to the effects of tree breeding and improved silvicultural practices, the mean age of trees for sawlog production in South Africa dropped from 14.1 years in 1983 to 11.3 years in 2003 (Crickmay and Associates 2004). The mean age in a normal plantation forest is usually half that of the harvesting age, suggesting a mean harvesting age reduction from about 28 years in 1983 to about 23 years in 2003. The younger harvesting ages resulted in increased proportions of juvenile wood and, as a result, a significant reduction in average MOE of structural lumber, as well as increased proportions of lumber not conforming to the minimum strength and stiffness requirements for structural lumber (Burdzik 2004; Wessels et al. 2011; Dowse and Wessels 2013).

In South Africa *Pinus patula* is the most important commercial plantation softwood resource with a total of 338 923 ha planted with this species (DAFF 2009). The Mpumalanga escarpment is the largest saw log growing area in South Africa with *Pinus patula* the main species being planted. Studies by Dowse and Wessels (2013) and Wessels et al. (2014) showed that the mean lumber stiffness of 16-20 year-old *Pinus patula* from the Mpumalanga escarpment was about 25% lower than required for the lowest SANS structural grade.

Many studies have emphasized the influence of microfibril angle (MFA) of the S2 layer of tracheids on the MOE of wood (i.e. Cave 1968 and 1969, Cave and Walker

1994, Megraw et al. 1999, Evans and Ilic 2001, Downes et al. 2002, Evans and Kibblewhite 2002). Cave and Walker (1994) argued that microfibril angle is the only property that can explain the large variation in MOE in *Pinus radiata* from the pith outwards and that MFA “is a principal predictor of timber quality, with density behaving as an auxiliary variable”. Most studies were performed on small clear wood specimens but only a few of these studies attempted to relate average MFA to the stiffness of sawn lumber (i.e. Downes et al. 2002, McKinley et al. 2004, Vikram et al. 2011).

In species such as *Pinus radiata* and *Pinus taeda* the variation in MFA has been studied extensively and is well understood (Donaldson 1992 and 1996, Cown et al. 1999, Megraw et al. 1999, Xu and Walker 2004; Burdon et al. 2004, Isik et al. 2008). In *Pinus radiata* the general trend of variation in MFA is a rapid decrease from the pith up to ring 10, followed by a transition phase, and then little change after ring 20 (Figure 1). MFA decreases from the base to the upper parts of the stem. Similar trends were found in *Pinus taeda* (Burdon et al. 2004, Megraw 1985, Megraw et al. 1998 and 1999).

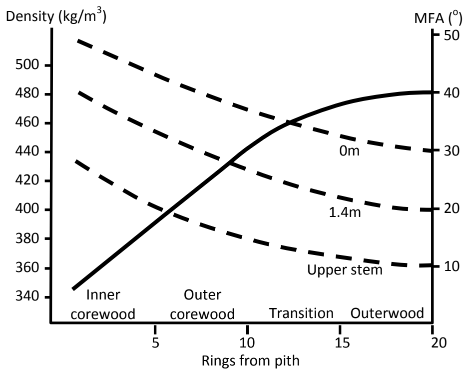

Figure 1. Typical variation of density and microfibril angle in *Pinus radiata* (adapted from Burdon et al. 2004). The broken lines indicate MFA and the solid line density.

Despite the importance of MOE, and its known close relationship with MFA, very little attention has been given to the within and between-tree differences in this property in the South African softwood industry. The only study conducted to date in South Africa involved the use of near infrared spectroscopy technology (Zbonak and Bush 2006). In this study calibration models were developed to predict the MFA at breast-height in 14-year old *Pinus patula* trees from KwaZulu-Natal, but no attempt was made to describe the variability along the radius or along the longitudinal axis of the tree, or to relate MFA to the MOE of the wood.

The purpose of this study was twofold: Firstly, to describe the variation in MFA in different *Pinus patula* growth sites radially at different heights and secondly, to determine the relationship between MFA and the MOE of sawn *Pinus patula* lumber.

Materials and methods

Sample trees were selected from six compartments along the Mpumalanga escarpment, South Africa. The escarpment area is characterised by strong local relief, with variable slopes and aspects. The study area is underlaid by strata from the Transvaal sequence including Nelspruit Granite, Malmani Dolomite, and Timeball Hill Shale. Details of the sites sampled are given in Table 1. The plots received the normal commercial management treatments of weeding, thinning and pruning. All the plots were planted at 1372 stems per hectare except for plot N which was planted at 816 stems per hectare. Thinning treatments were applied around years 8, 13 and 18 with a final stem density of roughly 275 stems per hectare. Each plot received at least three prunings up to a height of 7m.

Table 1. Sample sites details and site means.

Sample plot identification	Plantation	Age (yrs)	Mean DBH (cm)	Mean height (m)	Site Index at age 10 (m)	Mean annual precipitation (mm)	Mean annual temperature (°C)
A (E66)	Nelshoogte	17	36.0	20.5	14.3	1061	16.0
F (E55a)	Uitsoek	20	34.8	20.9	14.6	1151	13.7
G (E36c)	Uitsoek	19	32.0	23.1	16.8	902	14.0
K (E35)	Berlin	16	30.2	18.0	16.5	1006	17.2
N (D74)	Morgenzon	19	24.6	16.6	9.6	997	16.2
R (J20)	Wilgeboom	19	33.4	23.7	16.8	1299	18.5

A stratified sampling procedure in terms of tree diameters was followed so that the sample trees represented the productive timber volume available from the compartments. Ten trees were selected from each compartment. One tree was randomly selected from the first quartile (small diameter), two trees from the second quartile, three trees from the third quartile and four trees from the fourth quartile (large diameters). These sample trees were also used by other researchers for previous studies related to strength and stiffness variation, structural grading and pulping properties (Kipuputwa et al. 2010, Dowse and Wessels 2013, Wessels et al. 2014). Five of the ten trees per compartment were randomly selected for the purposes of this study, giving thirty trees for the whole study.

From each tree sample, discs were removed at breast height (1.3m) and at 6m height levels (Figure 2). A saw log of 2.2m in length was removed between the two discs. All saw logs were processed into boards of 40x120mm (green dimensions) and kiln dried to a target moisture content of 12%.

The static MOE on the flat side of each board (MOE_{flat}) was determined according to SANS 10149 (2002). The acoustic resonance frequency of each board was measured using the A-Grader Portable software from Falcon Engineering

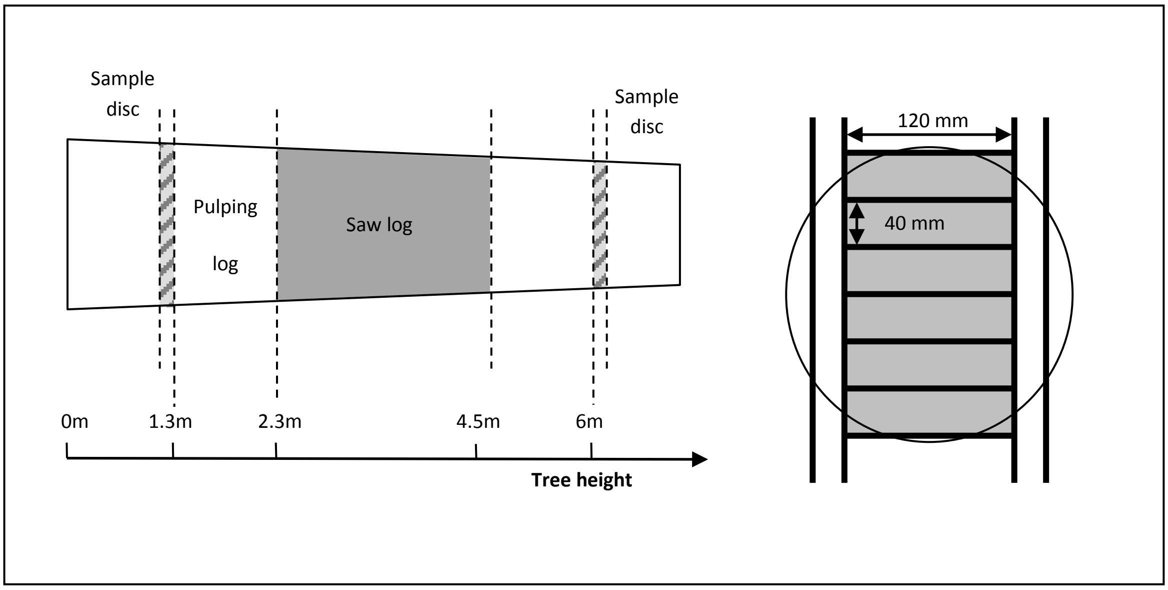

Figure 2. Sample discs, saw log position and the sawing pattern used.

(http://www.falcon-eng.co.nz). This value was used to calculate the dynamic MOE (MOE_{dyn}) for each board:

$$MOE_{dyn} = \rho \cdot (2 \cdot l \cdot f)^2$$

where:

MOE_{dyn}	Dynamic modulus of elasticity, in MPa;
ρ	Density of the test specimen at the moisture content at the time of testing, in kg/m^3;
l	Length of the test specimen in meters to the closest mm; and
f	Resonance frequency of the test specimen, in Hertz.

MFA and wood density measurements were conducted on radial strips taken from both the breast-height and 6m discs, using Silviscan 3 (Evans et al. 1999), at resolutions of 2mm and 0.025mm respectively. The MFA and density values were recorded on an annual ring basis using the radial density profile to demarcate different annual rings.

Annual rings on both ends of each of the boards were dated by reconstructing individual logs and counting the rings from the outside where the barkside surface layer was still visible on the boards. If the stem surface was not visible the ring width patterns from the Silviscan output was used to date individual rings on board ends.

The MFA and density of specific rings were determined as the mean from the two discs. For every board a mean density ($Density_{SS}$) and mean MFA was calculated based on the annual rings present in the board. A mean ring width ($RingWidth_{SS}$) was calculated for each board from the Silviscan ring width data of both heights. Mean ring age per board (RingAge) was calculated based on the age of tree rings on both ends of each board. The ring age started at one for the outer ring next to the bark and increased towards the pith.

A mixed model repeated measures ANOVA was performed using Statistica software (www.statsoft.com) to test the statistical significance of the effect of compartment, ring-age and height as main factors, and their interactions, on MFA and density. Multiple regression models were developed to predict individual board MOE_{dyn} from the MFA, wood density and ring width. Stepwise forward, backward and best subsets selection criteria were used to identify those factors that contributed significantly to the models. Sensitivity analyses were performed on the model to determine the relative influence of varying the independent variables, one at a time, on MOE_{dyn} (Pannel 1997).

A path analysis was performed using SmartPLS version 2.0 to examine the direct and indirect effects of the independent variables MFA, $Density_{SS}$ and $RingWidth_{SS}$ on the MOE_{dyn} of lumber. Correlation analysis quantifies the linear relationship between two variables, but does not specify any cause/effect relationship. Path analysis partitions a correlation coefficient into a direct effect of the causal variable and indirect effects through the pathways to the response. Standardized partial regression coefficients are used to indicate strength and direction of effects (Ivković et al. 2009).

Results

In the mixed model repeated measures ANOVA, trees were used as a random effect and the other factors as fixed effects. Results for the ANOVA on MFA showed that there was a significant three-way interaction between compartment, height and rings from the pith (Table 2). Due to the complexity involved only the two-way interactions were interpreted. There was a highly significant interaction between rings and height and a moderately significant interaction between compartment and rings from the pith. The variation in MFA per annual ring from the pith and for each height level is

Table 2. ANOVA table for MFA and density of the annual rings with compartment, height and rings from pith as factors.

Source of variation			**MFA**		**Density**	
	Numerator DF	Denominator DF	F	p	F	p
Compartment	5	24	1.9079	0.130341	4.24746	0.006586
Height	1	24	19.8627	0.000165	28.86990	0.000016
Rings from pith	11	264	249.4173	0.000000	81.70313	0.000000
Compartment*Height	5	24	0.1922	0.962580	3.26880	0.021636
Compartment*Rings from pith	55	264	1.5550	0.012291	5.27747	0.000000
Height*Rings from pith	11	258	5.0686	0.000000	2.36930	0.008361
Compartment*Height*Rings from pith	55	258	1.6693	0.004488	1.28312	0.103536

illustrated in Figure 3. Take note that only rings 0 to 11 were considered in the ANOVA as some disks at 6m height had 11 annual rings only.

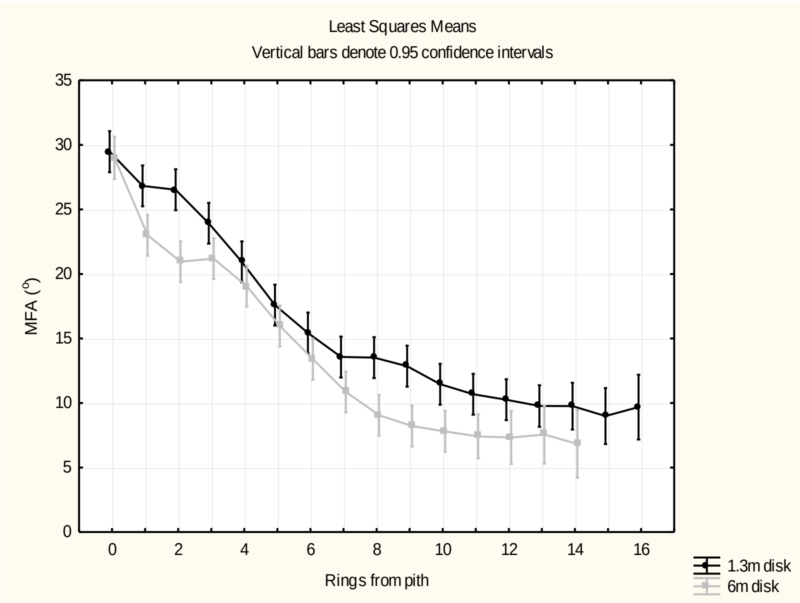

Figure 3. Variation in MFA at different heights and rings from the pith.

Density per annual ring was significantly influenced by all the two-way interactions (Table 2). Figure 4 shows the variation in density as a function of annual rings and height.

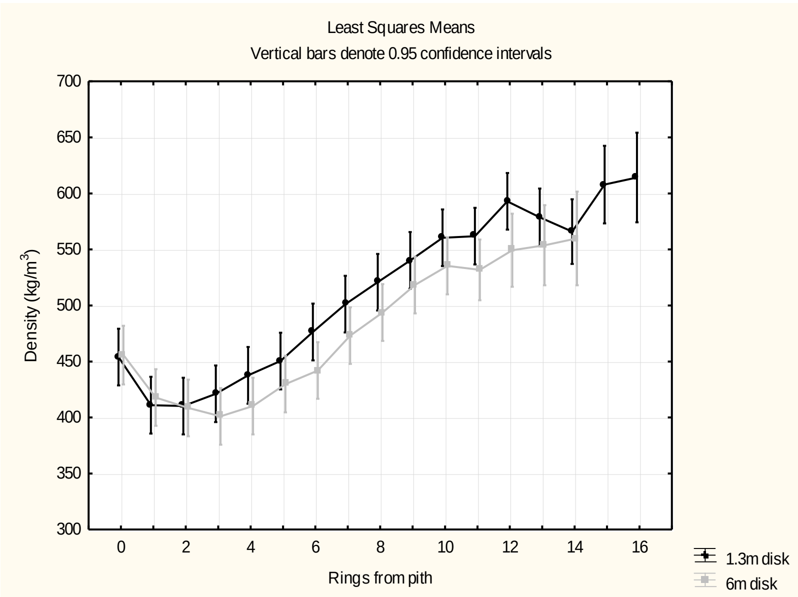

Figure 4. Variation in density at different heights and rings from the pith.

Table 3. Pearson correlations between various properties measured or calculated for individual boards (*, **, *** significant at 0.05, 0.01, and 0.001 probability levels, respectively).

	MOE$_{dyn}$	**MOE$_{flat}$**	**Density$_{SS}$**	**MFA**	**RingAge**	**RingWidth$_{SS}$**	**Density$_{board}$**
MOE$_{dyn}$	1.0000	.90***	.70***	-.73***	-.49***	-.71***	.69***
MOE$_{flat}$		1.0000	.68***	-.64***	-.50***	-.59***	.68***
Density$_{SS}$			1.0000	-.47***	-.36***	-.58***	.90***
MFA				1.0000	.61***	.69***	-.39***
RingAge					1.0000	.63***	-.23*
RingWidth$_{SS}$						1.0000	-.51***
Density$_{board}$							1.0000

Pearson correlations between the various properties measured and calculated for individual boards are presented in Table 3. A multiple regression model was developed for MOE$_{dyn}$ using the calculated board properties from Silviscan measurements as inputs. MFA and Density$_{SS}$ were highly significant ($p<0.001$) and RingWidth$_{SS}$ was a significant parameter ($p<0.05$) – see Table 4. The model could explain 71% of variation in MOE$_{dyn}$. The observed vs. predicted values are shown in Figure 5. The model slightly under-predicts high MOE$_{dyn}$ values and over-predicts low MOE$_{dyn}$ values.

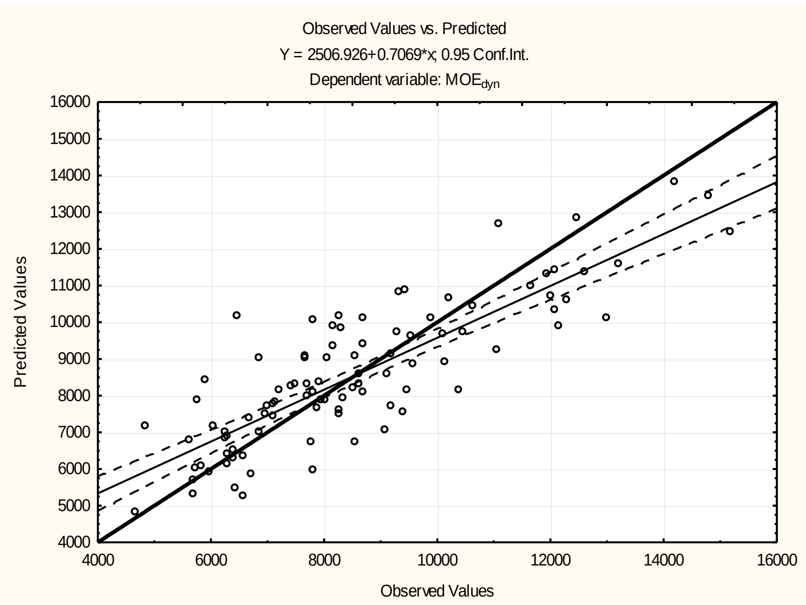

Figure 5. Predicted vs. observed values of a multiple regression model for MOE$_{dyn}$ (Table 4). The model and 0.95 confidence intervals and the 1:1 line are indicated.

Table 4. A multiple regression model for the MOE_{dyn} of *Pinus patula* lumber ($R^2 = 0.71$). Sensitivity analysis results show the relative influence of each independent variable in the model. Parameters marked with *, **, *** were significant at the 0.05, 0.01 and 0.001 probability levels, respectively.

Regression model		**Sensitivity analysis**				
	Parameters	**Mean**	**5^{th} percentile**	**95^{th} percentile**	**ΔMOE_{dyn}**	**Influence (%)**
Intercept	6404.8***					
$Density_{SS}$	16.3***	452	377 kg/m^3	553 kg/m^3	2868 MPa	39.9%
MFA	-203.8***	17.5	10.1^o	24.2^o	-2884 MPa	40.1%
$RingWidth_{SS}$	-151.2*	10.9	6.1 mm	15.6 mm	-1441 MPa	20.0%

A sensitivity analysis was performed on the regression model (Table 4). The mean, 5^{th} percentile and 95^{th} percentile was determined from the observed values for each of MFA, $Density_{SS}$ and $RingWidth_{SS}$. In the model a specific variable was changed from its 5^{th} percentile value to the 95^{th} percentile value while the other variables were kept constant at their mean observed values. The change in MOE_{dyn} from the model as a result was expressed in absolute terms (ΔMOE_{dyn}) and as a percentage influence (Influence) of each variable in the model (Table 4). For example, by changing MFA from its 5^{th} percentile observed value of 10.1^o to its 95^{th} percentile observed value of 24.2^o in the regression model the predicted MOE_{dyn} decreased by 2884 MPa.

A path analysis showed that the effect of $RingWidth_{SS}$ on MOE_{dyn} was mediated through MFA and $Density_{SS}$ but that $RingWidth_{SS}$ also had a direct effect on MOE_{dyn} (Figure 6). All path coefficients were significant ($p<0.05$).

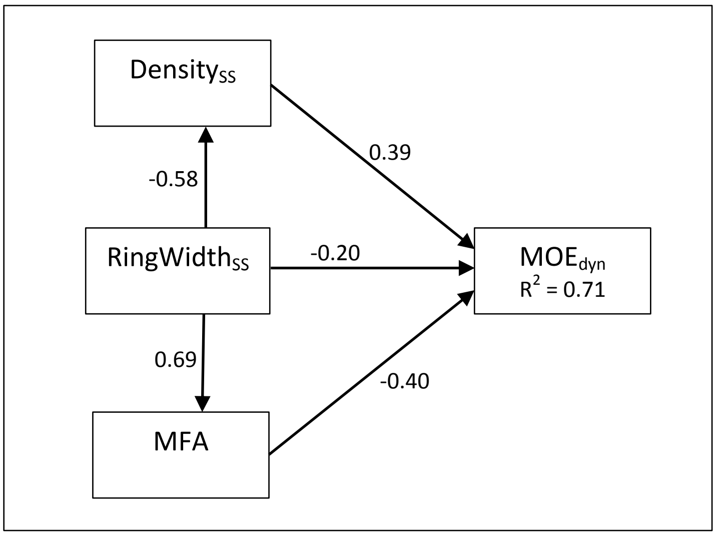

Figure 6. Path analysis for the MOE_{dyn} of *Pinus patula* lumber. All path coefficients were significant ($p<0.05$).

Discussion and Conclusions

The mean MFA per annual ring in *Pinus patula* varied between 7 ^{o} and 29^o along the first 16 annual rings from the pith. There were significant differences in MFA within the tree depending on the height in the tree and ring number from the pith (Figure 3). Average MFA varied from about 10^o at the 16th annual ring at 1.3m height above ground level to nearly 30^o at the pith. (Figure 3). At 6m height above ground level the average MFA was about 2^o - 5^o lower than at breast height except at the pith where the average MFA was approximately the same at the two height levels.

Compared to New Zealand-grown *Pinus radiata* the MFA of *Pinus patula* at 1.3 m was roughly 10^o smaller at similar annual rings from the pith (Figures 1 and 3). The differences at the different height levels were less pronounced compared to NZ *Pinus radiata*, showing differences in MFA of up to 10^o between breast height and upper stem compared to 2^o - 5^o for *Pinus patula*.

Density was significantly different at various rings, heights and compartments. It varied from just over 400 kg/m^3 per ring next to the pith to around 600 kg/m^3 at ring 16 (Figure 4). The trends are similar to that of *Pinus radiata* although in absolute terms *Pinus patula* density was roughly 100 kg/m^3 higher at similar ring positions (Figure 1).

The MOE_{dyn} measured on each board was closely related to MOE_{flat} (r=0.9), the most common method used for machine grading of lumber (Table 3). $Density_{SS}$, as calculated from Silviscan measurements, also had a strong correlation with the density of the full board (r=0.9) despite the fact that no attempt was made to correct the $Density_{SS}$ calculation for the relative volume of each ring in a board. Due to pith eccentricity, logs that were not centred correctly in the primary and secondary breakdown saws, the taper of the log, and the curvature of rings, the actual volume of a ring in a board was too complex to determine. For this study the MFA and density of each annual ring that appears in a board counted the same weight in terms of its contribution to the calculated mean MFA and density ($Density_{SS}$) of that board.

The board properties calculated from Silviscan measurements MFA, $Density_{SS}$ and $RingWidth_{SS}$ had similar and highly significant correlation coefficients with MOE_{dyn} of 0.73, 0.70 and 0.71 respectively (Table 3). The RingAge also had a significant correlation with MOE_{dyn} of 0.49.

The multiple regression model (Table 4) which included MFA, $Density_{SS}$ and $RingWidth_{SS}$ explained 71% of the variation in the MOE_{dyn} of the boards. Sensitivity analysis on the model showed that MFA was the most influential variable in the model (40.1%), followed by $Density_{SS}$ (39.9%) and $RingWidth_{SS}$ (20.0%). Both the Pearson correlations and the sensitivity analysis on the regression model thus suggest that microfibril angle and density are of roughly equal importance in explaining the MOE_{dyn} of the boards. When separating boards according to their distance from the pith, for boards closer to the pith the Pearson correlation coefficients show that density and MOE_{dyn} were slightly better correlated (r = 0.66) than MFA and MOE_{dyn} (r = 0.60) – these correlations are not shown in the Results section. This is contrary to results obtained from studies on small clear samples of *Pinus radiata* where MFA was found more influential in corewood (i.e Cave and Walker 1994; Walker and Butterfield 1996; Dickson and Walker 1997). It must be mentioned that the few results available from studies on full sized lumber seem to partially contradict those on small clear specimens. In a study on *Pinus radiata* Downes et al. (2002) found that both density and MFA were correlated to board MOE for one of the sites considered. In the case of another site the effect of density on MOE was more dominant than the effect of MFA. Vikram et al. (2011) found that density had a greater direct effect on the static MOE of Douglas-fir lumber than MFA. The tendency of the multiple regression model to over –and underpredict outside of the mid-range can possibly be corrected by adding interaction and quadratic terms in cases where accurate prediction of the absolute values of MOE_{dyn} is required (which was of lesser importance in this study).

The negative correlation of $RingWidth_{SS}$ with MOE_{dyn} (Table 3) and the fact that $RingWidth_{SS}$ also entered the multiple regression model as a negative parameter (Table 4) is noteworthy. The sensitivity analysis suggests that $RingWidth_{SS}$ is about half as influential as $Density_{SS}$ and MFA in determining MOE_{dyn}. Path analysis confirmed the independent influence of ring width on MOE_{dyn} by showing that ring width had both a direct effect on MOE_{dyn} as well as an indirect effect mediated through MFA and $Density_{SS}$ (Figure 6). The independent effect of ring width might be related to the fact that smaller ring widths ensure that older, more mature rings will be present in boards cut at or close to the pith. The composition of ring ages, and subsequently ring properties, in boards is therefore influenced by the ring widths. The effect of ring width on MOE_{dyn} was probably in part due to the relationship between $RingWidth_{SS}$ and the slenderness of trees. The sum of the annual ring widths at breast height of a tree will be equal to the diameter at breast height (DBH). The slenderness of a tree is defined as the ratio of the DBH : Heigth of the tree. Several studies found a strong relationship between tree slenderness and wood stiffness (i.e. Lasserre et al. 2005, Watt et al. 2006, Roth et al. 2007, Lasserre et al. 2009). Slender trees need wood of higher stiffness in order to prevent buckling of the stem under its own weight.

Results to date suggest that the establishment of trees at higher planting densities with the objective to encourage the development of more slender trees, might be a useful practical plantation management tool to increase the production of stiffer and stronger wood, especially of the wood produced during juvenile growth. Higher planting densities also result in less exposure to wind – it has been shown that wind exposure results in less stiff wood (Bascuñán et al. 2006). While this approach will most certainly impair diameter growth, the financial gains that will result from the improved quality of the wood produced might surpass the negative effects (if any) caused by the reduced growth rate. Higher planting density and the resultant reduction in growth rate may not necessarily have an adverse effect on volume production per unit forest area and may even increase it, depending on species and site conditions (Van Laar 1978). Further work is required to investigate the economic, market and practical feasibility of higher planting densities.

Microfibril angle, together with density, are clearly important properties in terms of their influence on the stiffness of sawn lumber from young *Pinus patula.* The potential use of MFA data by tree growers and processors depends on the application. Some authors suggested that tree breeders refrain from measuring and selecting for MFA due to the cost and that much cheaper acoustic stress wave methods, and density rather be used because of their excellent ability to predict MOE (Vikram et al. 2011). However, in another study by the author on the same sample material it was found that acoustic velocity assessments performed on standing trees explained considerably less of the variation in MOE_{dyn} than MFA (Wessels CB Unpubl. data).

Measurement of MFA for *Pinus patula* can be particularly useful in studies where the effect of time-dependent treatments such as thinning or fertilising on wood properties needs to be evaluated. Since MFA can be measured on individual annual rings, the effect of a treatment on MFA can be evaluated very effectively over a growth period.

Given the problems associated with reduced rotation ages on the stiffness of plantation grown *Pinus patula* in South Africa, the use of MFA information of this species in both research and industrial studies can be beneficial in managing these problems.

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