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EFFECT OF FASTER GROWTH ON TIMBER QUALITY OF TEAK

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SUMMARY

Teak(*Tectona grandis* L.f.) is the most preferred timber species for forest/commercial plantation programmes in the tropics including India. The main objective of teak plantation mangement is to produce high quality timber to meet the market demands. The term "quality" refers to the suitability of timber for particular end-uses which in the current context include sawn wood of desired dimensions for structural uses and veneer. The factors which dictate timber quality criteria of teak plantations are: tree height and diameter, bole shape (taper, buttressing, fluting, etc.), branchiness (knot size and frequency), grain angle (degree and pattern of spirality), juvenile and tension wood proportions, heartwood-sapwood ratio and heartwood characteristics (e.g. colour, extractives), proportion and arrangement of tissues including earlywood and latewood and cell dimensions. To enhance the productivity of teak plantations the choice of management techniques envisaged include: genetic selection, wide planting spacement and /or thinning, pruning, fertilizer treatment, irrigation, etc.

Scope of the Present Study and Terminolgy

To achieve the results in a focussed manner within a relatively short period of 3 years, target was set in the present study to elucidate the effects of faster growth on selected wood quality parameters such as heartwood percentage, ring width, tissue proportion, cell dimensions, microfibrillar orientation and static bending and compression strength properties. While the heartwood proportion (percentage) of individual tree is important to assess the natural durability and fix the timber price, strength properties with anatomical features such as ring width, cell dimensions, microfibrillar orientation and tissue proportions are the useful indicators of timber quality inluding dimensional stability of juvenile and mature wood. Due to the non-availability of harvestable trees from intensively managed commercial plantations, the study has resorted to sample the

trees from forest plantations of important teak producing locations of Kerala and Karnataka. The term "faster grown timber " in the context of this study refers to any tree which has put up higher than the average growth and yield (tree size) in a population/plantation. The main sources of faster growth in sampled trees are: assumed genetic superiority of individual trees (candidate plus tress - CPT), plantation locations (sites), fertilizer treatment as well as clonal and provenance selection.

Effects of genetic selection

Faster growth by CPT selection

Faster growth, in CPT trees of 13-, 21-, 55- and 65-year-old plantations, did not adversely affect the heartwood percentage, wood density and strength properties. The magnitude of wood property differences due to growth rate varied with age of the trees. Heartwood percentage in individual trees increased with growth rate in 13- and 21-year-old trees while no significant differences were noticed in more mature 55- and 65-year-old trees. Tissue percentages, cell dimensions and microfibrillar angle showed relatively small differences which seem to have only positive effects instead of lowering the timber value of fast grown trees.

Provenance and clonal selection

Wood density differences observed among the six 60-year-old provenance trials (viz. Nilambur, Anamali, Travancore, South Bombay, South Burma and North Burma) were too small. The fast grown Nilambur provenance displayed the basic density (oven dry weight to green volume basis) of 539 kg/m^3 while the slow grown North Burma provenance had nearly the same value of 538 kg/m^3 This indicates that the selection of fast growing provenance does not affect the wood density of teak. Similarly, the clonal testing from Palappilly and Arippa seed orachrds showed that there were no significant differences in wood density and anatomical properties among the clones. The results also reveal that in genetic improvement of teak wood density, tree-to-tree variation offers more avenues for selection than the provenances. However, it is cautioned that selection of wood density alone will be misleading, if overall genetic improvement of timber quality is envisaged, due to its inconsistent relationships with the strength properties of teak.

Fertilizer effects

Fertilizer treatment had prononced effect on the growth increment in 5-year-old trees following the application during the second year. Ring width increased by 100% while vessel diameter and fibre wall thickness did not show significant changes. Increase in ring width was accompanied by slight reduction in vessel percentage and small increase in fibre percentage. These preliminary results indicate the scope for growth acceleration of teak trees by fertilizer application without altering anatomical properties and decreasing density although more data are warranted from high input management.

Plantation location (site) effects

Relatively slow grown teak of Konni plantation showed higher bending strength, while that of North Kanara was slightly weaker, than Nilambur and Arienkavu locations. However, differences in heartwood percentage and other mechanical properties such as maximum longitudinal crushing strength observed were not of much practical value.

Utilisation potential of thinnings/short rotation timber/juvenile wood

The result showing consistent increase of heartwood volume with tree age suggests that the yield of sapwood per tree will be higher from thinnings as well as the relatively small timber harvested below the age of 21-22 years than from the traditional rotations of 55-65 years. The mean sapwood proportions observed in 13- and 21-year-old trees are 52% and 40% in contrast to 16% and 15% in 55- and 65-year-old trees respectively. This means that the estimated growing stock of 1.6 million m^3 of small timber above 10 years in Kerala alone will yield about 0.64-0.8 million m^3 of sapwood. The sapwood of 13- and 21-year-old- trees was not significantly different in strength properties. However, reduced natural durability of sapwood can pose problems in structural/solid wood uses unless the material is adequately treated with environment-freindly preservatives. With higher penetrability, sapwood is easier to treat with preservatives than the refractory heartwood. Utilisation potential of short rotation teak wood is also evident from the following observations:

- Teak can attain optimum timber strength properties in 21-year-old forest plantations as recorded from Nilambur.
- Mean annual increment (MAI) recorded for shorter rotations of 20-30 years is almost double (10-20 m^3/ha) that of traditional 60-year-rotations.
- Faster growth is correlated with higher heartwood percentage of juvenile trees. Plantation managers therefore can aim at producing larger diameter logs with greater yield (larger cylinder) of heartwood per tree by accelerating tree growth of short rotation plantations. This means that grower can fetch better timber price for each fast grown tree of ,larger size if it can meet the property/processing requirements of high-value products such as veneer and sawn wood of desired dimensions.

Practical Significance of Research Results

Because of the complexity of site conditions as well as the genetic and environmental interactions, the results of this short term study cannot be expected to evolve a specific strategy for high input management. Nevertheless, they offer scope for using intensive techniques such as genetic selection and fertilizer treatment for higher yield without reducing the timber value. Perhaps, one of the options is to grow teak in most suitable sites to tap the maximum biological potential of the trees and to assess the economic returns of high input management.

Some tips for teak timber management and future research

- Plantation managers can produce larger diameter logs with greater yield (larger cylinder) of heartwood per tree by accelerating the tree growth in short rotation plantations.
- Teak can produce the timber of optimum strength in relatively short rotations of 21 years.
- Fast growing provenances can be selected for teak management without reducing timber weigh/density.
- Selection of individual trees within a specifiied provenance can provide greater avenues than selection of provenances in breeding programmes for improvement of wood density of teak.
- Wood density is not always the best single indicator of overall genetic improvement of timber quality.
- Faster growth in relatively young forest plantations with judicious fertilizer application/genetic inputs can turn out to be advantageous in terms of heartwood volume per tree and timber strength.
- More research is warranted on timber durability, preservative treatment of sapwood, strength properties as well as quality standard/grading rules of fast grown teak under high input management.

Keywords: *Tectona grandis,* faster growth, timber quality, tree-to-tree variation, locality effect, fertilizer effect, clonal and provenance variation, heritability, genetic gain, wood anatomy, heartwood/sap wood yield, strength properties, plantation management.

1. Introduction

Teak (*Tectona grandis* L.f.) is one of the most widely planted timbers of the tropical countries including India. Of the projected figure of 60 million ha of tropical tree plantations for the year 2000 (Evans 1992), teak alone will account for well above 3 million ha at the estimated proportion of 5% of the total tropical forest plantation area (FAO 1993). The actual figure seems to be much higher in view of the recent massive plantation programmes, with the involvement of private sectors, to invest on high yielding timber in farm/agricultural lands as well as waste lands. The aim of such managed stands is to maximise timber production per unit land area by genetic selection and intensive silvicultural techniques which accelerate tree growth for early harvesting. The important sources by which faster growth and harvestable size achieved are : tree genotypes, provenances, geographic locations / site conditions, wider spacement / thinning, irrigation, fertilization, shorter rotation, etc. The pertinent question then is whether timber quality of faster grown teak is inferior to that of trees grown under the normal conditions of natural forests / plantations.

The timber quality likely to be affected by quicker growth of teak, depends partly on tree form and partly on wood structure and strength properties. The major influencing structural factors are: tree height and diameter, bole shape (taper, buttressing, fluting, etc.), knot size and frequency, grain angle (degree and pattern of spirality), tension wood and juvenile wood proportions, heartwood-sapwood ratio and characteristics (e.g. colour, extractives), proportion and arrangement of tissues including earlywood and latewood and cell dimensions.

2. Literature Review

The literature search on the effects of faster growth reveals that data available are scanty and often conflicting. The topic - "quality of quickly grown teak wood" is not new. It has been debated as early as 1895, when Bourdillon supported the arguments of Lushington (1895) and John Lindley, the contemporary authority in silviculture who attempted to prove that faster-grown timber was the strongest. Subsequently, several studies have been conducted in view of the fact that the comparative value of rapidly and slow grown teak has not yet been determined in a satisfactory manner.

Some of the early studies of this century showed negative correlation between growth rate and wood density and the general notion still prevailing among the teak wood-users is that faster-grown tree produces only light, weak and spongy wood (Chowdhury 1953; Bryce 1966). In contrast, Bhat *et al.* (1987) recently indicated 14% higher wood density for faster growing dominant trees than suppressed trees of the same stand. This result supports numerous authors who reported that wood density and strength properties were superior in faster grown ring-porous species (Nair and Mukheji 1957; Harris 1981). Another school of thought argues that no significant relationships exist between quick growth and tissue proportions and strength properties (Rao *et al.* 1966; Mukherji and Battacharya 1963; Rajput *et al.* 1991).

The controversy over the effect of growth rate on wood quality persists even among other ring-porous timbers of temperate zone. For instance, Wheeler (1987) reports a positive correlation between growth rate and wood density arguing that wider rings contain more latewood with fewer vessels. However, juvenile wood formed near the pith or mature wood of some oaks do not necessarily follow this pattern (Polge and Keller 1973; Taylor and Wooten 1973).

2.1 Geographic/Provenance/Site Effects

The quality of Myanmar teak is considered to be superior in view of straighter and cylindrical stems although from northern part they are often crooked and cross-grained (Tint and Kyu Pe 1995). Teak also displays wide variations among different growing conditions and regions in India. The malabar teak (Nilambur, Kerala), generally having good growth and log dimensions with desirable figure, is reputed for ship-building (Nair 1991). The slow-growing trees in drier localities, which resist forest fire and tend to develop twisted/wavy grain, were known to yield heavier, stronger and close-grained wood with beautiful figure. From a preliminary study, it was found that percentage of logs with flutes and knots was greater in generally quicker growing location (Nilambur) than in slow-growing area (Konni) in India (Balasundaran and Gnanaharan 1991).

The test results on teak samples obtained from different countries such as Bangladesh, India and Myanmar indicate that strongest wood is produced from modest radial growth of 4-5 mm annually (Limaye 1942). Smeathers (1951) observed that the timber produced in plantations from Trinidad was not inferior in mechanical properties to the samples of Myanmar. According to Bryce (1966), the mechanical properties of 51-year-old Tanzania-grown teak were 15% inferior to the teak wood of Myanmar and Trinidad. Teak samples from West Africa were found to be harder and heavier than those from Asian region (Sallenave 1958).

Enough evidences are available from different parts of the world to show that plantation-grown teak is not inferior to naturally grown timber in strength properties, though in some localities naturally grown teak shows superiority or vice versa (Nair and Mukherji 1957; Sekhar *et al.* 1960; Sono and Rativanich 1965; Weimann 1979; Durand 1983; Sanyal *et al.* 1987; Shukla and Mohan Lal 1994; Tint and Kyu Pe 1995).

For any genetic improvement programme, knowledge of the pattern of inheritance of a particular character is essential. Variation among trees, sites and provenances is of interest to tree breeders. An understanding of the variability of wood characters is quite essential, if wood quality and yield are to be manipulated. It was reported by many workers that among trees wood variation has been found to be large (Zobel and Talbert 1984). Since wood density has a major effect on yield and quality of the final product, this character deserves more research attention. Genetic aspects of wood quality in teak received little attention with the exceptions of a few like effect of locality and seed origin on wood density (Purkayastha and Satyamurthi 1975) and effect of seed origin on fibre length (Kedharnath *et al.* 1963).

2.2 Effects of fertilization

Effects of fertilization on wood quality were less widely studied in broad-leaved trees (hardwoods) than in conifers. The data available for hardwoods are those of temperate region ; the density of ring-porous woods tends to be slightly increased by fertilization as seen in red oak and white ash (Mitchell 1972; Szopa *et al.* 1977). Limited studies have also dealt with the impact of fertilizer treatment on vessel-to-fibre ratio, fibre length and machining properties. Generally no change in vessel-to-fibre ratio but a slight increase in vessel proportions was indicated from those studies (Haygreen and Bowyer 1989). Fibre length has been found to remain unchanged or to increase slightly.

2.3 Effects of Irrigation .

While some unpublished data from mechanical testing indicated considerably higher values for bending and compression strength values from river bank plantations of two different localities (Karnataka and Tamilnadu) than the standard teak , another study reported lower values in the trees irrigated with sewage water in Maharashtra (Table 1).

Table 1. Mean values of selected mechanical properties (air dry) of irrigated teak from three locations compared with average values of Indian teak as control

Property	Control [1]	Irrigation plantations		
		Tamil Nadu [2]	Karnataka [2]	Maharashtra [3]
Density, kg-m3	645	591	564	479
Static bending MOR, N-mm^2	86.5	121.2	129.4	60
MOE, N-mm^2	10745	17215	17147	6921
Max. Compressive stress (parallel to grain), N-mm^2	47.7	57.9	51.2	29

[1] Rajput and Gulati 1983; [2] Ashwathnarayana 1994 personal commun. [3] Gogate 1995.

2.4 Effects of thinning treatment

No adequate data are available in the literature on the effects of thinning. Preliminary studies from India and Myanmar indicated that very heavy and moderate thinning treatments did not alter the strength properties (La1 1943; Kadambi 1972).

2.5 Effects of shorter rotation

As practiced in Malaysia and Thailand, in commercial teak plantations of private sectors trees will be grown very rapidly so as to reduce the rotations to 20-30 years instead of 50-80 years. However, two major factors that influenced sawn wood grade and recovery in Ivory Coast plantations were hollow knots and deep flutes in small diameter logs (Durand 1983). Sim *et al* (1979) and Sangkul (1995) reported 55% and 51% of sawnwood recovery from 25-year-old (Malaysia) and 20-year-old trees (Thailand) respectively, with a log diameter range of 9-20.5 cm.

Such a short rotation timber is expected to contain higher proportion of juvenile wood. The new evidences presented by Bhat (1995a) suggest that the differences between juvenile and mature wood are not so large as to affect many end-users' requirements. This is because several physical and mechanical properties of juvenile wood are not necessarily inferior and processing and drying problems are relatively few. The only anticipated problems are reductions in natural resistance (due to lower heartwood content and extractives) and lower recovery of sawn wood and veneer due to growth stresses and smaller log diameter as well as higher proportion of knots and flutes.

2.6 Insect defoliation control

Higher yield of teak plantations, due to insect defoliation control over a period of 4 years, has been demonstrated by Nair *et al* (1985) in 8-year-old trees. This has resulted in higher percentage of heartwood without altering anatomical properties such as cell wall percentage and diameter and percentage of vessels (Bhat 1995b; Priya and Bhat 1997).

3. Scope and Objectives

To achieve the results in a focused manner within a reasonable period of 3 years, target was set in the present study to elucidate the effects of faster growth on selected important wood quality parameters such as heartwood percentage, ring width, tissue proportion, cell dimensions, microfibrillar orientation and static bending and compression strength properties. While the heartwood proportion (percentage) of individual tree is important to assess the natural durability and fix the timber price, strength properties with anatomical features such as ring width, cell dimensions, microfibrillar orientation and tissue proportions are the useful indicators of timber weight and strength as well as dimensional stability of juvenile and mature timber. Due to the non-availability of harvestable trees from intensively managed plantations, study has resorted to confine to forest plantations of important teak producing locations of Kerala and Karnataka. The term “faster grown timber ” in the context of this study refers to any tree which has put up higher than average growth and yield (tree size). The main sources of faster growth in sampled trees are: assumed genetic superiority of individual trees (candidate plus tress - CPT), plantation locations (sites), fertilizer treatment as well as clonal and provenance selection. As trees induced to grow faster by silvicultural treatment often have their wood affected differently from genetic manipulation (Zobel and van Buijtenen 1989), the study envisages to evaluate the effects of faster growth on timber quality separately for each treatment.

4. Materials and Methods

4.1 Field sampling

4.1.1 Location and fertilizer effects

Plantations were located for sampling from three important teak producing areas in Kerala , viz. Nilambur (Location I), Arienkavu (Location II) and Konni (Location III) . In addition, one important teak growing area (Location IV) of Karnataka (Karwar Forest Division, North Kanara) was covered for field sampling of 21-year-old trees. Some of the important site factors recorded are given in Table 2.

Three fast-grown dominant and three slow-grown trees, with straight cylindrical bole showing no visible defects, have been chosen within an area of 20 x 20 m in specified plantation to compare the wood of fast and slow-grown trees in each plantation. This sampling strategy was followed with an assumption that influence of environmental factors in such a small area is negligible and between -treatment growth differences are due to genetic variation (Hedegart 1976). To ascertain the magnitude of variation among three treatments, viz. fast, slow- and medium growth, three additional trees of average growth have been sampled from each plantation in Location I.

Table 2. Field sampling locations and recorded site factors

Factor	Nilambur (Location I)	Arienkavu (Location 11)	Konni (Location 111)	North Kanara (Location IV)
North latitude	11° 12’-11°32’	8°4’-9° 14’	9°3’ -9°85’	15°30’-15°40’
East longitude	75°82’-76°32’	76°59’-77°16’	76°4 1-77°6’	74°40-74°50’
Temperature range, °c	17-37	13 -33	12-35	17-35
Mean rainfall, mm	2600	2700	2900	2900
Soil type	River alluvial	Sandy loam rich in organic matter	Sandy loam	Sandy loam rich in organic matter
Drainage	Good	Good	Good	Good

Source: Working Plans, Kerala Forest Department

To study the effects of growth rate in both young (juvenile) and mature wood, trees were sampled from four different age groups (13-year, 21 -year, 55-year and 65-year) of the plantations of the same geographic location (Nilambur). After ascertaining the trend in Nilambur, further sampling has been limited to fast and slow grown trees of the corresponding age groups in other locations (Table 2). Basal logs of about 1.5 m length were collected from each tree for wood property investigations. About 10 cm thick cross sectional discs were removed from breast height level (1.37 m from stump level) to study anatomical and physical properties and adjacent basal billets to prepare the wood specimens for mechanical testing.

To assess the effects of fertilizer application, five dominant trees each were sampled from fertilized and control stands at the age of 5 years in Aravallikavu (Nilambur). The growth increments were studied following the second year of fertilizer (NPK 1:1:1) application.

4.1.2 Genetic Studies

Since cross sectional discs from clones and provenances could not be collected by non-destructive means, core samples were used for our experiments and hence the study has mainly concentrated on wood density and anatomical properties such as tissue proportions and cell dimensions, leaving the other characters unexplored. Teak clones from two localities (20 from Palappilly and 25 from Arippa) were examined. These 13-year- old clones have originated from Nilambur, Arienkavu and Konni areas. Further, six different provenance trial plots (viz. Nilambur, Anamalai, Travancore, South Bombay, South Burma and North Burma) maintained in Nilambur were used for assessing the provenance effects on growth and wood density of 60-year-old teak..

Five healthy trees were selected at random for each clone and provenance. The girth was measured at breast height and wood core samples were collected from the outermost growth increment. As soon as the samples were collected, they were wrapped in polythene bags and taken to the laboratory for wood density determination by gravimetric methods.

Analysis of variance was done and the derived variance components were used for computation of coefficient of variation. Broad-sense heritability (H^2) and genetic gain ($iH^2\sqrt{p}$) were estimated following the appropriate procedure (Wright 1976).

4.2 Laboratory Investigations

4.2.1 Anatomy

To compare the wood anatomy of fast and slow grown teak, 15-20 μm thick cross sections were taken, using a sliding microtome, from pith to periphery comprising different rings to cover radial variation. Standard microtechnique procedure was followed to prepare the sections for microscopic observation. Important anatomical properties studied are ring width, vessel diameter, fibre length, fibre wall thickness and proportions of fibres, vessels and parenchyma (ray and axial parenchyma combined). Microfibril angle was measured using Senft and Bendtsen's technique (1985). Leica Image Analysis System (quantimet 500+) has been employed for precise quantification of wood anatomical features. For the estimation of fibre and vessel dimensions, at least 50 largest cells were measured to obtain mean values per ring. Heartwood percentage was estimated following the procedure described in an earlier report (Bhat *et al*. 1985).

4.2.2 Mechanical testing

The basal billets of 1.4 m length were converted into scantlings of 3 x 3 cm cross section to prepare test samples from pith to periphery in one radial direction selected randomly just below the breast height. From each radius, samples (with the size of 2 x 2 x 30 cm) were tested for static bending (fibre stress at elastic limit-FS-EL, modulus of rupture-MOR, modulus' of elasticity - MOE) and compression parallel to grain (maximum crushing stress - MCS). The sample size of 2 x 2 x 10 cm has been used for compression test. Small pieces from tested samples were cut to determine the wood density in air dried condition. Mechanical testing has been done using a Universal Testing Machine.

5. Results and Discussion

5.1 Tree Size

Size of the sampled trees of faster, medium and slow growth can be assessed from the mean values of dbh presented in Table 3. It is clear that radial growth is slow and tree size small in Konni and Karwar plantations as compared to other geographic locations, viz. Nilambur and Arienkavu . Generally, dbh increased with tree age and rate of increase was more rapid in young trees below the age of 21 years than mature trees above 55 years. The relatively faster-grown 55-year-old trees, sampled from riverside plantations in Nilambur, displayed greater dbh than 65-year-old trees of the same locality probably due to the availability of more moisture in the soil.

Table 3. Mean dbh (cm) of trees sampled from different age groups and geographic locations

Age, yr	Location I			Location II		Location III		Location IV	
	Fast	Medium	Slow	Fast	Slow	Fast	Slow	Fast	Slow
13	23.8	15.2	10.2	-	-	-	-	-	-
21	28.0	20.5	14.3	34.4	14.6	-	-	18.5	11.5
55	57.5	46.8	22.0	-	-	-	-		-
65	54.1	43.6	29.3	59	27.0	44.0	24.8		

5.2 Effects of Age *vis-a-vis* Growth Rate

5.2.1 Heartwood Percentage

The mean heartwood percentages of faster-, medium - and slow-grown trees within the 13-, 21-,55- and 65-year-old plantations of Location I are presented in Table 4 and

Figure 1. Heartwood percentage increased consistently with tree age although differences between ages 55 and 65 years were not significant (Tables 4 and 5). The mature trees selected at the age of 55 and 65 years for faster growth did not show marked differences in heartwood percentage as compared to the trees which had medium- and slow-growth. In contrast, in juvenile trees at ages 13 and 21 years, growth rate was positively correlated with heartwood percentage and faster grown trees displayed significantly higher heartwood percentages in Nilambur and Karwar locations (Tables 4 and 7). The effects of growth rate on heartwood-sapwood ratio appear to get minimised with tree age (Fig. 1). The trend was similar in other locations (Arienkavu and Konni), as exhibited by 65-year-old trees (Appendices I and II). Similarly, heartwood percentage increased with the increase of growth rate owing to the control of insect defoliation in 8-year-old teak (Bhat 1995b). Thus it is evident that tree age is a more important factor than the growth rate in influencing heartwood percentage of teakwood (Table 4). The other sources of variation in heartwood percentage such as individual trees within a treatment (faster *vs* slow grown trees) and interaction terms of age and tree and age and treatment were not significant (Table 5).

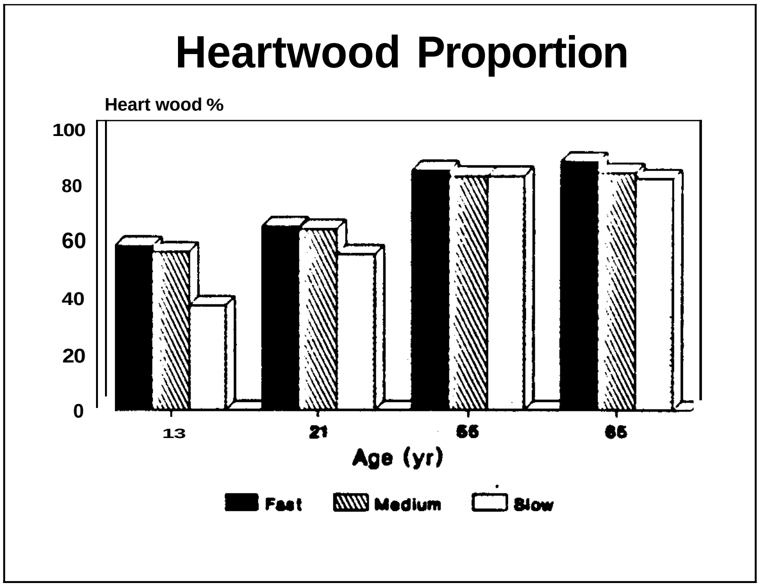

Fig. 1 Mean heartwood percentages of fast, medium and slow grown teak from Nilambur.

Table 4. Comparison of mean heartwood percentages of faster-, and slow-grown trees in Location I (Nilambur)

Age,yr	Faster	Slow	Test of significance
13	58.3	36.5	**
21	65.0	55.2	**
55	85.1	82.8	ns
65	87.8	81.6	ns

** Significant at 1% level; ns Insignificant

Table 5. Analysis of variance of heartwood percentage of teak trees sampled from Location I (Nilambur)

Source of variation	d.f	M.S.S	F
Between - Age	3	2504.109	32.359**
Between - Treatment (Faster, Medium and slow grown trees)	2	313.578	4.052*
Between - Tree	2	69.686	0. .900^{ns}
Age x Treatment	6	79.242	1.024^{ns}
Age x Tree	6	42.547	0.550^{ns}
Treatment x Tree	4	76.422	0.988^{ns}
Error	12	77.386	
Total	35	292.683	

** Significant at 1% level; * Significant at 5% level ; ^{ns} Not significant

Table 6. Comparison of mean heartwood percentage among 4 age groups within the Location I

13-yr (I)	21-yr (II)	55-yr (III)	65-yr (IV)	Bar diagram
50.4	61.3	83.1	84.2	I II $\overline{\text{III IV}}$

Bars connecting the age groups indicate non-significant differences

Table 7. Mean heartwood percentages of teak in two age groups of different Locations

Age, yr	Location I			Location II		Location III		Location IV	
	Fast	Medium	Slow	Fast	Slow	Fast	Slow	Fast	Slow
21	65	64	55	67	58	-		75	51
65	87	84	82	86	79	87	85		

5.2.2 Anatomical properties

In 13-year-old juvenile wood faster growth was associated with significantly wider rings, higher fibre %, lower vessel % and thicker fibre wall while the differences in vessel diameter, fibre length and parenchyma % were not statistically significant (Table 8). In contrast, in quickly grown 65-year-old trees, the differences in mean tissue percentages and vessel diameter were not significant although growth rings were wider and fibre walls thicker. Obviously, anatomical differences due to growth rate are not of the same magnitude in young and mature wood. However, within-tree (pith-to-bark) and between-tree variations in most of the anatomical properties were significant in 13- and 65-year-old trees although between-location differences were insignificant (Appendices III -VII)

Microfibrillar angle in S_2 (middle) layer of the cell wall decreased from the pith outwards and the faster-grown 65-year-old trees displayed lower angle than slow-grown trees (Fig. 2). This implies that faster-grown and mature timber has greater dimensional stability and structural performance than slow-grown wood. This is because higher angle of cellulose microfibrils with cell axis results in lower stability and excessive checks or heart shakes.

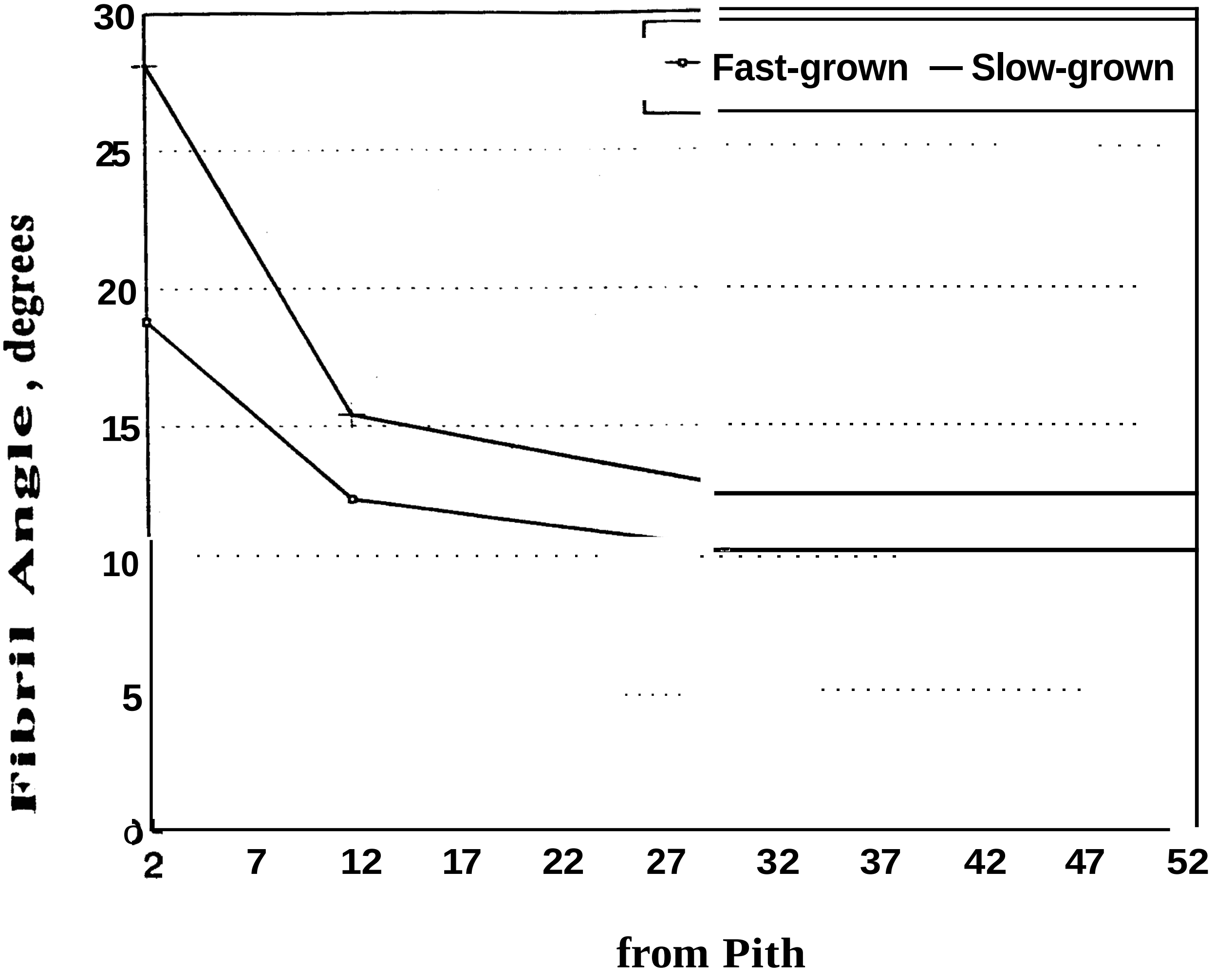

Fig. 2. Radial pattern of variation in microfibril angle of faster- and slow-grown 65-year-old trees of Location I (Nilambur)

Table 8. Comparison of anatomical properties of fast and slow grown trees

Property	Faster grown			Slow grown			t-value
	Mean	SD	CV	Mean	SD	CV	
			13-year-old trees (Location I)				
Ring width, mm	5.5	3.6	65.4	1.3	1.6	123.0	4.38**
Vessel diameter, µ m	141.1	26.6	18.8	147.1	41.5	28.2	0.51^{ns}
Fibre %	71.5	4.5	6.2	52.9	16.7	31.5	4.55**
Vessel %	12.4	3.3	26.6	28.0	14.7	52.5	4.40**
Parenchyma %	16.0	4.6	28.7	18.9	5.0	26.4	1.84^{ns}
Fibre length, mm	1.179	.38	31.0	1.102	.14	13.0	1.79^{ns}
Fiber wall thickness, µ m	4.9	1.0	20.4	3.3	0.7	21.2	5.41**
			65-year-old trees (Locations I & III combined)				
Ring width, mm	3.8	2.2	57.8	1.9	1.4	71.7	3.39**
Vessel diameter,µ m	165.9	27.9	16.8	166.5	30.1	18.0	-0.07^{ns}
Fibre %	66.5	7.2	10.8	65.3	8.8	13.4	0.51^{ns}
Vessel %	17.8	6.2	34.8	18.6	7.3	39.2	-0.46^{ns}
Parenchyma %	15.7	2.9	18.4	15.9	3.2	20.1	-0.35^{ns}
Fibre length,mm	1.341	.30	22.0	1.29	.17	13.0	1.84^{ns}
Fibre wall thickness, µm	5.6	0.8	13.7	5.1	0.8	15.6	2.12*

** Significant at 1%level; * Significant at 5% level ; ^{ns} Not significant

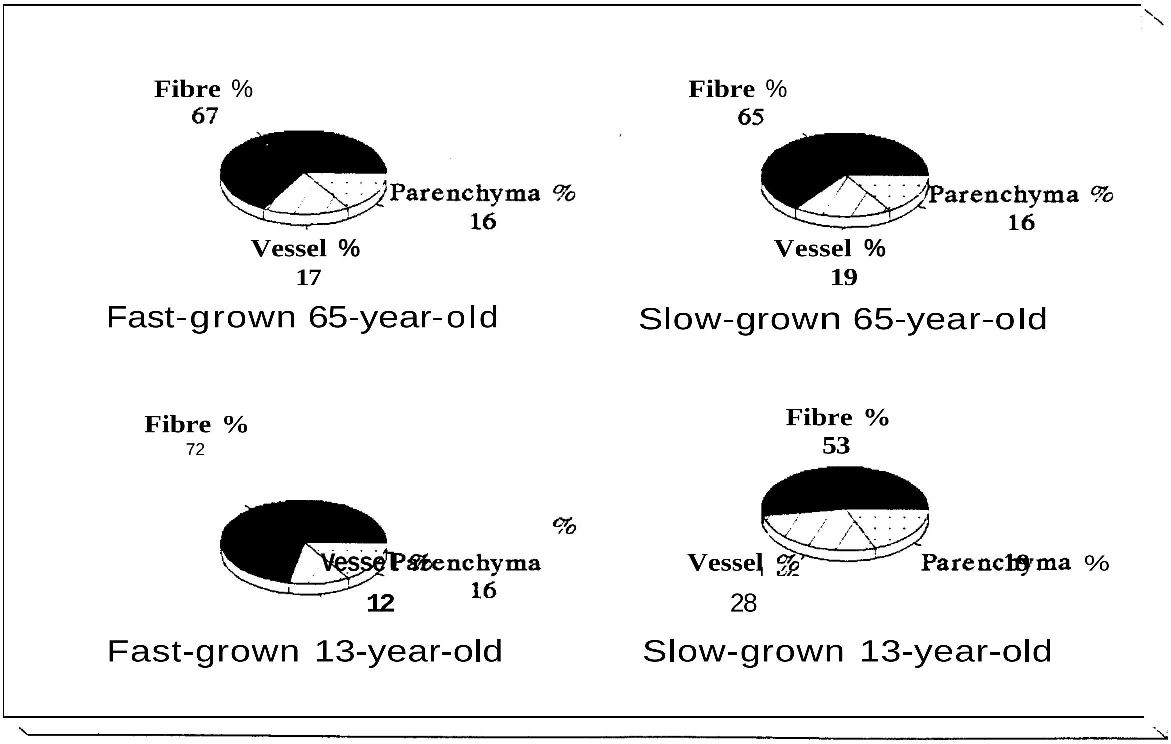

Fig. 3. Tissue composition of fast and slow-grown trees in mature and young trees (locations combined)

5.2.3 Strength Properties

Trees selected for faster, medium and slow growth in 13-, 21-, 55- and 65-year-old plantations within the same geographic location (Nilambur) displayed mostly non-significant differences in mechanical properties such as wood density, FS-EL, MOR, MOE and MCS (Figs 4-7 and Appendix VIII). The only exceptions were slightly lower static bending strength values (MOR and MOE) of faster-grown 55-year-old trees which grew in riverside plantations.

Although, wood density variation was insignificant, age was an important source of variation in FS-EL, MOR, MOE and MCS in Nilambur- location I (Tables 9 ,10 and Appendices IX and X). However, FS-EL was distinctly inferior in 13-year-old wood and superior in 21-year-old wood to that of 55- and 65-year-old timbers (Table 10). Also, MOR of 21-year-old wood was significantly higher than that of other three age groups. MOE followed the same trend except in 65-year-old trees which showed slightly higher values. With regard to MCS, two strength groups existed , i.e. 13- and 55-year-old timbers come under one strength group and their figures were lower than those of 21- and 65-year-old trees. Obviously, important mechanical properties reach to the maximum values by the age of 21 years and then either remain more or less constant or show declining trend with age up to 65 years. This pattern of variation suggests that mechanical maturity of teak timber is attained before or at the age of 21 years(Figs.5-7.).

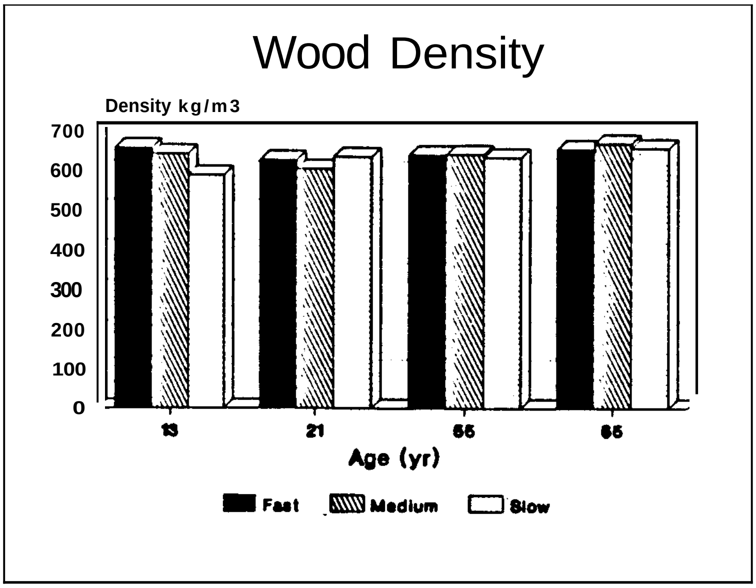

Fig.4 Mean wood density of fast, medium and slow grown trees from Nilambur

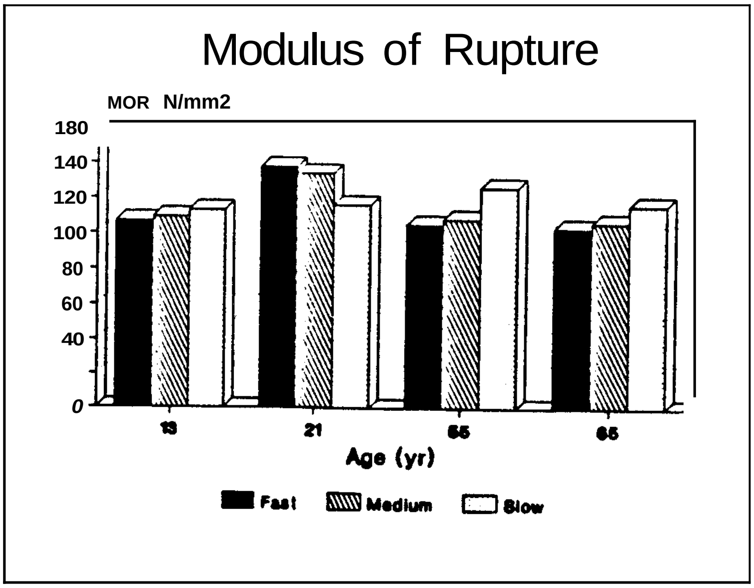

Fig. 5. Mean MOR of teak wood of fast, medium and slow grown trees from Nilambur

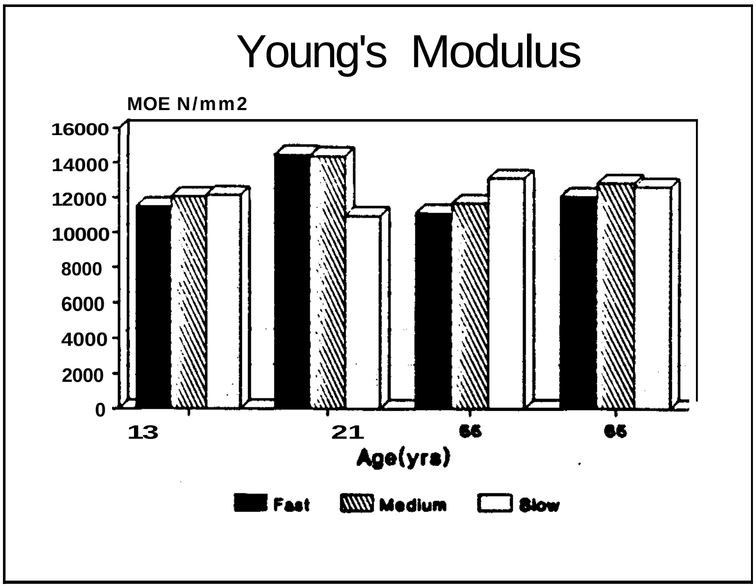

Fig. 6. Mean MOE of teak wood wood of fast, medium and slow grown trees from Nilambur

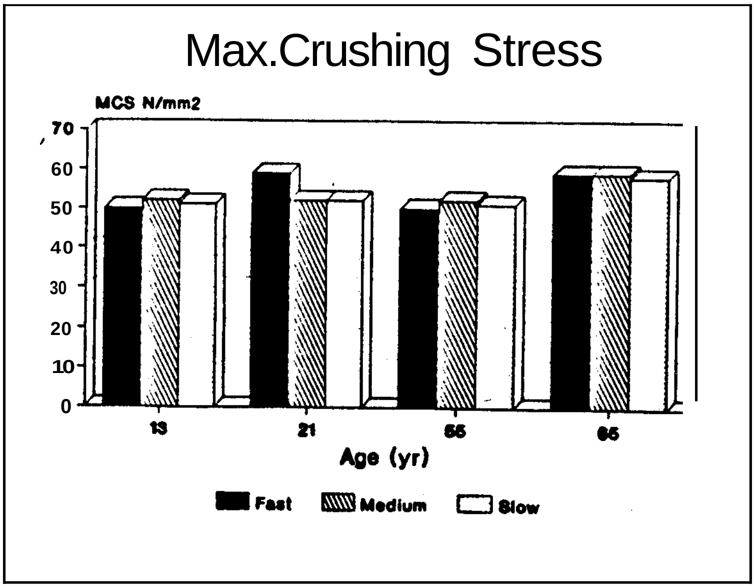

Fig. 7. Mean MCS of teak wood of fast, medium and slow grown trees from Nilambur

Table 9. Summary of the results of analysis of variance of strength properties of teak

Source of variation	d.f	F-value				
		FS-EL	MOR	MOE	MCS	Density
				Location I		
Between - Age	3	9.70**	9.23**	5.01**	9.19**	0.43ns
Between - Tree	2	0.32ns	0.72ns	2.07ns	4.69**	2.65ns
Between - Segment	2	0.25ns	1.56ns	2.93ns	4.08*	1.38ns
Age x Tree	6	0.56ns	1.34ns	0.86ns	1.71ns	5.51**
Age x Segment	6	0.93ns	2.11ns	1.20ns	1.82ns	1.02ns
Tree x Segment	4	0.75ns	1.57ns	2.02ns	2.63ns	1.63ns
				Location II		
Between - Age	2	0.37ns	0.72ns	1.77ns	3.42ns	0.57ns
Between - Tree	2	0.84ns	0.76ns	0.75ns	1.60ns	3.16ns
Between - Segment	2	2.02ns	3.78ns	3.26ns	3.58ns	4.57**
Age x Tree	4	1.94ns	1.46ns	0.41ns	1.15ns	1.20ns
Age x Segment	4	2.76ns	1.59ns	1.92ns	0.48ns	0.74ns
Tree x Segment	4	1.13ns	0.46ns	1.80ns	0.49ns	3.66ns

** Significant at 1% level; *Significant at 5% level ; ^{ns} Not significant; Segment indicates radial position

Table 10. Strength property variation among four age groups of Location I

Property	13-year I	21-year II	55-year III	65-year IV	Bar diagram
Density kg m-3	632	626	643	640	$\overline{\text{I II III IV}}$
FS-EL N mm^{-2}	64	112	85	86	I II III IV
MOR N mm^{-2}	108	134	104	100	$\overline{\text{I III IV}}$ II
MOE N mm^{-2}	1468	14129	10564	12335	I II III IV
MCS N mm^{-2}	49	56	51	59	I III II IV

Bars connecting the age groups display non-significant differences
FS-EL = Fibre stress at elastic limit
MOR = Modulus of rupture
MOE = Modulus of elasticity
MCS = Maximum compressive stress (parallel to grain)

5.3 Effects of Location *vis-a-vis* Growth Rate

5.3.1 Heartwood Percentage

Comparison of heartwood percentage of 65-year-old, trees from Nilambur with that of Konni revealed no significant differences although trees grew relatively faster in the former location. (Tables 3 and 11). Similarly , 21-year-old trees of Location IV , which had relatively slow growth rate, did not exhibit significantly higher volume of heartwood than those of Nilambur and Arienkavu . This implies that heartwood volume in faster growing locations, is not adversely affected although Ferguson (1934) indicated that for the same stem diameter there was higher proportion of sap wood if growth rate was faster due to improved site quality. His conflict finding was probably due to the fact that age factor was not taken into consideration.

Table 11. Comparison of mean heartwood percentage among the geographic locations in two age groups of teak plantations

Age,yr	Location I	Location II	Location III	Location IV	Significance of F value
---21	61.3	62.2	-	62.8	ns
65	84.2	82.8	86.1	-	ns

5.3.2 Strength properties

It is clear from Table 12 that 21-year-old trees of Location IV grew slower than those of Locations I and II. Except wood density, all the properties tested were inferior in Location IV to those of Locations I and 11 (Appendix XI). Similarly, the strength properties of teak from North Kanara were reported to be inferior to those from Nilambur (Tewari 1992). On the contrary, in mature (65-year-old) trees of Konni, which grew slower, properties, excepting density and MCS, were superior to those of Locations I and 11 (Table 12 and Fig. 6). These results suggest that not only growing site but also tree age (juvenile-mature condition) is important in determining the of growth rate on timber quality.

Table 12. Strength property variation among the locations at two different ages

Property	Location I	Location II	Location III	Location IV	Bar diagram
			21-year-old		
DBH, cm	20.9	24.5		15	$\overline{\text{I II}}$ IV
Density kg m-3	618.7	605.5	-	681.5	$\overline{\text{I II}}$ IV
FS-EL N-mm^2	108.1	78.4		65.5	I $\overline{\text{II IV}}$
MOR N-mm^2	133.2	105.8		91.8	I $\overline{\text{II IV}}$
MOE N-mm^2	13643	12525	-	8436	$\overline{\text{I II}}$ IV
MCS N-mm^2	53.9	44 7		44.6	I $\overline{\text{II IV}}$
			65-year-old		
DBH ,cm	42.2	43.3	34.4	-	$\overline{\text{I II}}$ III
Density kg m-3	*655.0*	643.0	665.0	-	$\overline{\text{I II}}$ III
FS-EL N-mm^2	85.0	85.8	125.6	-	$\overline{\text{I II}}$ III
MOR N-mm^2	103.8	103.6	136 [illegible]	-	$\overline{\text{I II}}$ III
MOE N-mm^2	125.12	13395	17560	-	$\overline{\text{I II}}$ III
MCS N-mm^2	*59.0*	43.1	48.0	-	I $\overline{\text{II III}}$

Bars connecting the locations display non-significant differences
FS-EL=Fibre stress at elastic limit; MOR= Modulus of rupture
MOE=Modulus of elasticity;MCS=Maximum compressive stress (parallel to grain)

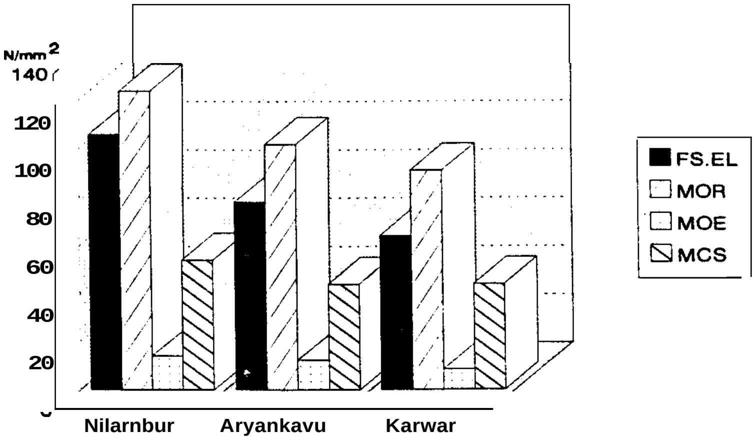

Fig. 8. Strength property variation in 21 -year-old teak wood among three locations (MOE in 000s)

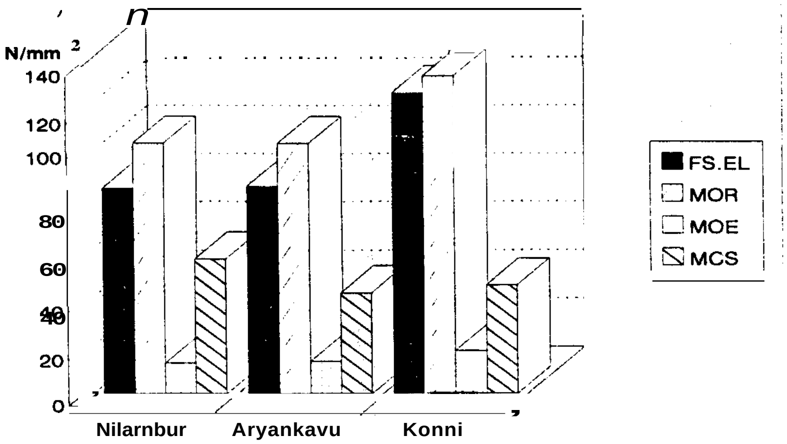

Fig. 9. Strength property variation in 65-year-old teak wood among locations (MOE in 000s)

5.4 Effects of Fertilizer Treatment

Effects of fertilizer treatment were studied in the growth increment following the second year of application in 5-year-old trees. Ring width increased by 100% while vessel diameter and fibre wall thickness did not show significant changes. Increase in ring width was accompanied by slight reduction in vessel percentageand small increase in fibre percentage. This is due to the fact that in ring-porous timber, latewood percentage with more fibres and fewer vessels, is more closely related with ring width than earlywood percentage (Bhat 1995a) resulting in the formation of denser and more uniform wood. Similarly, in European oak and beech, increase in the proportion of fibres and decrease in that of vessels was reported with increasing ring width (Knigge and Koltzenburg 1965). Although the differences were significant at 5% level, the alteration of cell length especially of vessel elements and fibres was very small with fertilizer application (Table 13). Therefore, enhancing the growth rate by modest fertilizer treatment does not necessarily decrease wood density of teak wood. However, this preliminary finding needs to be supported by further studies with different dosages of nutrients under different growing conditions including and different tree ages. More research is also warranted on changes in tissue composition and cell dimensions of extremely rapid growing trees due to irrigation or any other high input management practice as irrigation may alter the proportion of vessels.

Table 13. Comparison of selected properties of wood formed in the 5th growth increment of control and fertilizer treated 5-year-old teak trees

Property	Control			Fertilized			t-value
	Mean	SD	CV%	Mean	SD	CV%	
Diameter at breast height, cm	7.8	0.9	11.9	11.0	0.6	5.3	**
Wood density, kg/m3	444.1	35.0	7.9	478.2	24.8	5.2	**
Ring width, mm	2.8	1.1	40.1	6.0	1.6	28.0	**
Vessel element length ,mm	0.27	0.06	2.1	0.3	0.01	3.8	*
Vessel diameter,μ m	136.3	7.4	5.4	136.4	14.9	10.9	ns
Fibre %	63.5	3.2	5.0	66.9	2.4	3.6	*
Vessel %	18.5	3.9	21.2	14.0	2.8	20.3	*
Parenchyma %	17.8	2.2	12.5	19.2	1.7	9.2	ns
Fibre length,mm	1.17	0.02	1.7	1.04	0.06	5.7	*
Fibre wall thickness , μ m	4.3	0.6	14.2	4.6	0.5	11.2	ns

** Significant at 1% level; * Significant at 5% level; ns Not significant

5.5 Effects of genetic selection

5.5.1 Clonal variation

The analysis of variance shows that there is no significant difference between the clones in wood density at 5 % and 1% levels (Table 14). Phenotypic coefficient of variation (PCV) was as low as 8.3% at Arippa and 8.2% at Palappilly (Table 15). Genotypic coefficient of variation (GCV) was zero in clones planted at Arippa where as it was 3.1% at Palappilly which shows that GCV is quite negligible.

Table 14. Clonal variation in wood density

Source	Palappilly MSS	Palappilly % Variation	Palappilly F value	Arippa MSS	Arippa % Variation	Arippa F value
Treatment	0.0032	50.8	1.68	0.0018	45.1	0.96
Within -clone	0.0029	49.2	1.0	0.0018	54.9	1.0

Table 15. Phenotypic and genotypic coefficient of variation, heritability and genetic gain for wood density

Clones at	PCV %	GCV %	Heritability Individual tree basis	Heritability Clone-mean basis	Genetic gain (K = 2.06) Individual tree basis	Genetic gain (K = 2.06) Clone-mean basis
Palappilly	8.17	3.13	0.146	0.407	0.01 (1.74%)	0.019 (3.3%)
Arippa	8.29	0.00	0.00	0.00	0.00	0.00

Figures in parenthesis are gains in percentage of mean

Broad-sense heritability (H^2) of wood density was found to be zero at Arippa and 0.146 (individual - tree basis) at Palappilly which shows that heritability is very low. Heritability on clone-mean basis was found to be 0.407 at Palappilly. Several workers in the past reported slight differences in estimates of heritability in other species at different locations (Namkoong *el al;* 1972, Namkoong and Conkle, 1976 and Franklin, 1979). Here it is to be noted that estimates of heritability is only a relative indication of genetic control and is not absolute or invariant (Zobel and Talbert, 1984).

The genetic gain was found to be 0.01 (1.74 as % of mean) on individual tree-basis and 0.019 (3.3 as % of mean) on clone-mean basis. Though heritability on clone-mean basis was higher than individual tree basis, the genetic gain is only 3.3 percent. This is due to the low coefficient of variance shown by the clones. If good clones are identified and suitable environmental conditions are given wood density can be improved. The anatomical properties also did not differ appreciably among the clones (Appendix XII).

The wood density of clones varied from Palappilly to Arippa. At Palappilly it was slightly higher (575 kg/m3) than at Arippa(513 kg/m3). Some of the clones are common to both areas and even in those, density was higher at Palappilly. This type of geographic difference in wood density were noted in a number of studies involving several species (Howe, 1974, Talbert and Jett, 1981). Harris (1966) reported that the latitude where the trees are grown has a strong influence on the wood density produced in radiata pine. Ledig et al (1975) noted that the effect of environment on the wood density of forest trees has been extensively studied and the results are often confusing and contradictory. The phenotypic correlation between wood density and girth at breast height ($r = 0.1$) was found to be very weak which is indicative of negligible effect of growth rate on density.

5.5.2 Provenance variation

The analysis of variance shows that there was no significant difference in wood density between the six provenances studied. (Table 16). However, within-provenance variation was quite high as 80.9% where as the variation within clones was 49.2% (Palappilly) to 54.9% (Arippa). The variation due to provenances was only 19.1% while clonal variation was 45.1 (Arippa) to 50.8% (Palappilly). The results show that the within-provenance variation was much higher than between- provenance variation which is determined by anatomical properties (Appendix XIII). Purkayastha and

Satyamurthi (1975) also reported that seed origin contributed very little to percentage of variation in density although the study was based on the limited data with only two provenances.

Table 16. Provenance-variation in wood density

Source	MSS	% of variance	F value
Treatment	0.0019	19.1	0.63
Within-provenance	0.0030	80.9	1

The Phenotypic coefficient of variation was found to be 10.2% while there was no genotypic coefficient of variation and hence the heritability and genetic advance were zero. For the genetic improvement of wood density, provenance selection will not be much effective, instead the within-provenance variation (tree-to-tree variation) needs to be exploited.

5.6 Interrelationships Among Wood Properties

Simple correlation coefficients computed to examine the relationships between wood density and other strength properties revealed that wood density was not correlated with mechanical properties in both 21- and 65-year-old trees (Table 17). Also, MCS did not correlate with bending strength properties of 65-year-old timber although the relationship was significant in 21-year-old trees . This implies that in genetic improvement programme, selection of wood density or any one strength property will not suffice for the overall improvement of teak wood quality of mature trees.

Table 17. Simple correlation coefficients for interrelationships among selected mechanical properties of 21- (n = 44) and 65-year-old (n = 69) teak

Age / property	MOR	MOE	MCS	Density
21-yr				
FS-EL	0.85**	0.77**	0.64**	-0.05^{ns}
MOR	1.00	0.76**	0.66**	0.03^{ns}
MOE	-	1.0	0.59**	-0.17^{ns}
MCS	-	-	1.0	0.12^{ns}
65-yr				
FS-EL	0.92**	0.84**	-0.16^{ns}	0.15^{ns}
MOR	1.0	0.82**	-0.07^{ns}	0.21^{ns}
MOE	-	1.0	-0.09^{ns}	0.21^{ns}
MCS	-	-	1.0	0.12^{ns}

FS-EL = Fibre stress at elastic limit; MOR = Modulus of rupture

MOE = Modulus of elasticity; MCS = Maximum compressive stress (parallel to grain)

** Significant at 1% level; ^{ns} Not significant

5.7 Implications in Plantation Management and Utilisation

The preliminary results of the present study and the recent data available in the literature indicate that silvicultural practices such as fertilizer treatment and irrigation have varied effects on timber quality parameters. Although fast-grown timber is not always necessarily inferior, growth rate has undoubtedly some effects on wood quality, for instance, wider rings of faster grown wood will result in different grain and texture influencing wood figure and aesthetic value. Further, no adequate data are available from intensively managed plantations where trees display extremely rapid growth rate. Growth-wood property relationships appear to be quite complex since wood formation phenomenon responds differently under diverse environmental conditions. The results of the current study are therefore too limited to recommend a specific strategy for high input management. Nevertheless, they are indicative of the scope for using intensive techniques such as genetic selection and fertilizer treatment for higher yield of timber per tree without necessarily reducing timber value of forest-plantations. On the other hand, some of the management practices such as fertilizer treatment will lead to quick growth resulting in high proportion of latewood/fibres and greater wood density. Yet, it is not advisable to generalise the effects of any management practice on the type of wood produced due to the complexity of site conditions as well as the genetic and environmental interactions. Perhaps, one of the options is to grow trees in selected sites to know what kind of wood is produced with high input management.

5.7. I Utilisation potential of thinnings/short rotation timber/juvenile wood

The result showing consistent increase of heartwood volume with tree age suggests that the yield of sapwood per tree will be higher in thinning material and in the timber harvested below the age of 21-22 years than the timber harvested in traditional rotations of 55-65 years. For instance, the mean sapwood proportions observed in 13- and old trees are 52% and 40% in contrast to 16% and 15% in 55- and 65-year-old trees respectively (Table 4). This means that the estimated growing stock of 1.6 million m^3 of small timber above 10 years in Kerala (KFRI 1997) alone will yield about 0.64-0.8 million m^3 of sapwood. Although the results indicate that sapwood of 13- and 21-year-old- trees is not much inferior in strength properties, reduced natural durability can pose problems in structural/solid wood uses unless the material is adequately treated with preservatives. However, greater sapwood pecrentage (or lower percentage of resistant heartwood content) is advantageous for pulping and preservative treatment of thinning material for enhanced durability of the products. Scope for utilisation of short rotation teak wood is also evident from the following observations:

- Teak wood has the potential of attaining mechanical maturity (optimum strength properties) of the timber in 21-year-old forest plantations as recorded from Nilambur.
- The productivity of short rotation teak plantations is not necessarily low as the mean annual increment (MAI) reported for shorter rotations of 20-30 years is almost double (10-20m3/ha) that of traditional 60-year rotations (Centeno 1997).
- Faster growth is correlated with higher heartwood percentage of juvenile trees. Plantation managers therefore can aim at producing larger diameter logs with greater yield (larger cylinder) of heartwood per tree by accelerating tree growth in short rotation plantations. This means that grower can fetch better timber price for each fast grown tree of larger size to make suitable for processing and manufacture of high-value products such as veneer and sawn wood of desired dimensions. The newer research technologies are therefore likely to concentrate more on individual trees to exploit the biological potential of the trees. For example, the genetic manipulation of juvenile wood for greater natural durability of the timber is one such area of future research.

5.7.2 Genetic improvement of timber quality

The results further imply that for genetic improvement of wood density, provenance selection will not be much effective, instead, tree-to-tree variation within the selected provenance needs to be exploited. For instance, two dominant trees of the same age grown in the same plantation showed different patterns of pith-to-bark variation in density probably due to genetic difference (Bhat *et a1* 1989). It is important to take advantage of this source of variation in selecting and producing timber of desired weight and strength with more uniform distribution of density from pith to bark regions for structural purposes. However, it is cautioned that selection of wood density alone in genetic improvement of timber quality will be misleading due to its inconsistent relationships with mechanical properties.

6. Conclusions

Growth rate had varied effects on timber quality of teak depending on different factors such as tree age, growing site (location), fertilizer treatment and genetic differences. The generalised finding of the present study is that faster growth is not always associated with inferior quality timber. The specific conclusions drawn from the results include:

1. Faster growth rate of the trees within the same stand, attributed to genetic differences, did not adversely affect the properties such as heartwood percentage, wood density, dimensions and percentage of fibres as well as static bending and compression (along the grain) strengths. It was in fact correlated with higher heartwood percentage in 13- and 21-year-old juvenile trees.
2. Relatively slow grown teak of 65-year-old Konni plantation was superior in bending strength by 31% to relatively fast grown teak of the same age in Nilambur and Arienkavu plantations while the longitudinal compression strength was about

22% greater in Nilambur than in the former location. Trees of 21-year-old plantation in Nilambur produced stronger timber (in bending and compression) than those of the same age of Arienkavu and North Kanara although trees grew slower in North Kanara.

3. Teak from Nilambur exhibited mechanical maturity of the timber at or before the age of 21 years offering scope for utilisation of short rotation wood without compromising the quality in terms of timber strength.
4. With wider growth rings, anatomical properties such as fibre length, wall thickness and fibre percentages were slightly higher and vessel lower in fast growing juvenile wood either due to fertilizer treatment (5- year-old trees) or due to phenotypic selection. These differences seem to have little practical value in utilisation except that they encourage accelerated tree growth.
5. Between-provenance and between-clonal variability, heritability and genetic gain of wood density, evaluated in clonal trials, were rather low. Tree-to-tree variation (within the selected provenance), rather than the between-provenance variation, should therefore be exploited if genetic improvement of wood density is designed in breeding programme. As wood density was not correlated with mechanical properties, it would not be a reliable predictor of overall genetic improvement of timber strength .
6. Because teak trees perform differently with different site conditions and because the results of this study are derived from limited localities of forest plantations, more research is needed on trees grown in specified sites to know what kind of wood the trees produce with high input management. Particularly important are the studies which deal with producing timber that meets grading rules for veneer and sawn wood, by minimising knots, flutes, taper and by enhancing girth and natural durability of short rotation teak wood.

7. Faster growth in forest plantations, due to judicious fertilizer application genetic inputs, appears to be advantageous in terms of heartwood yield per tree and strength properties.

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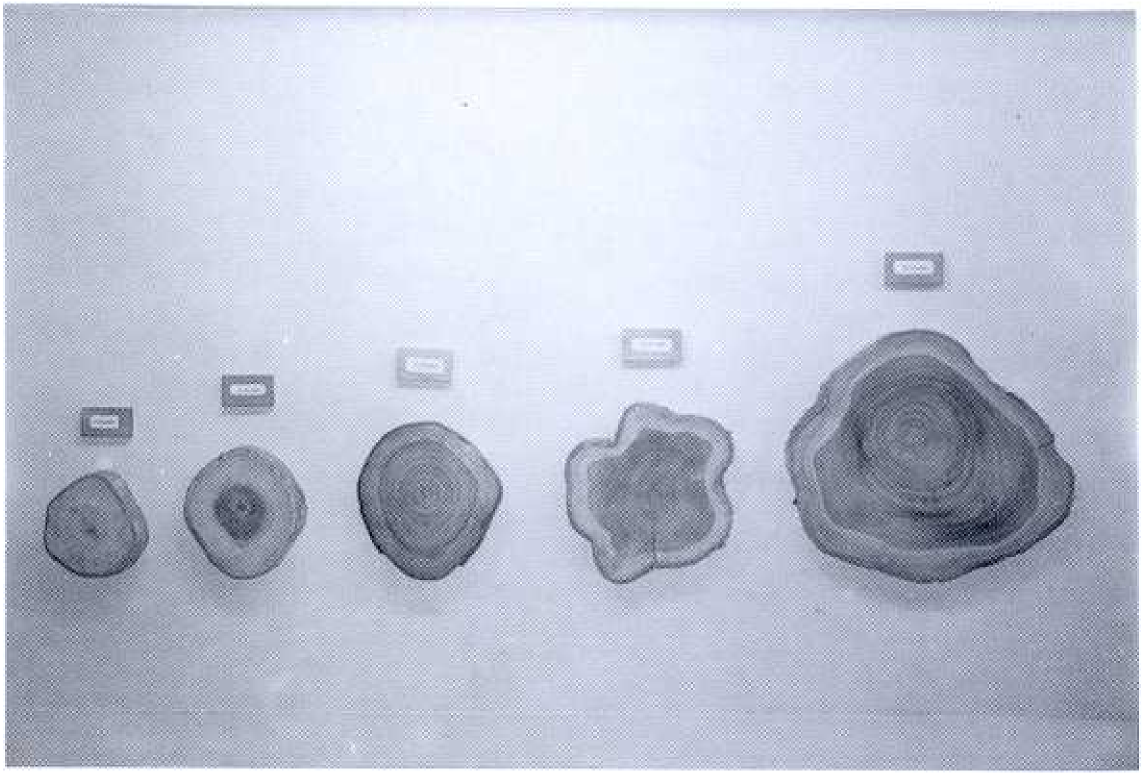
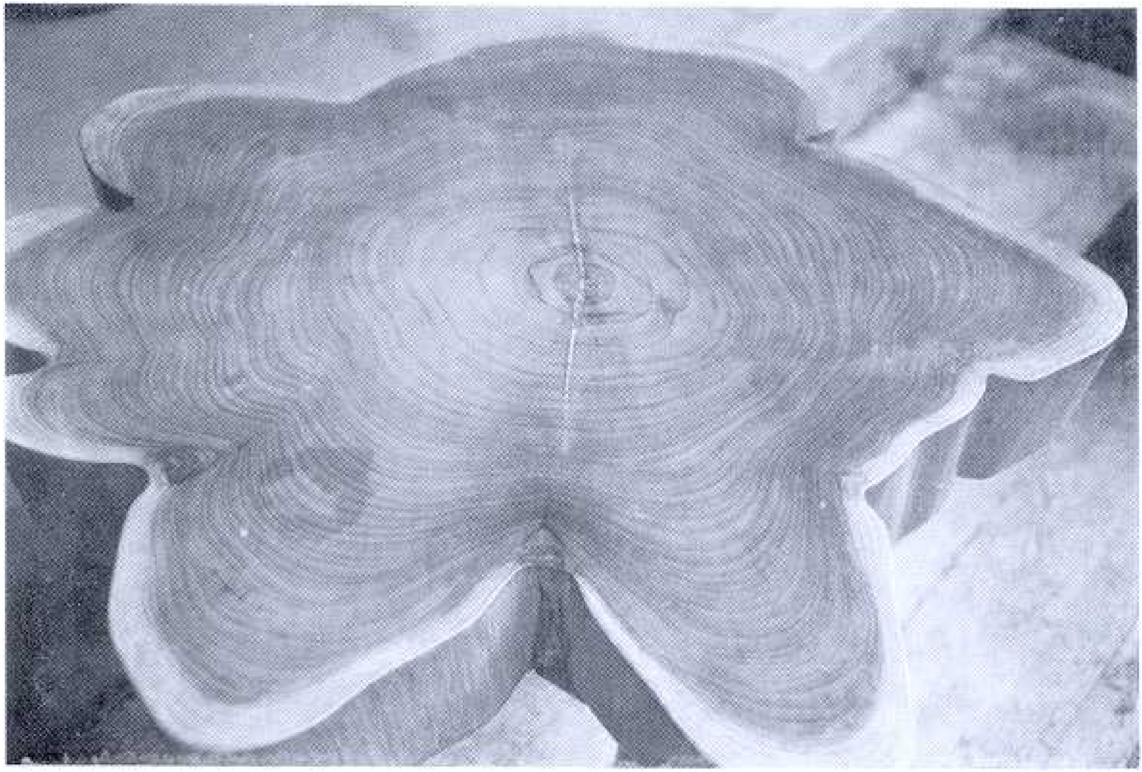
9. PLATES



Cross sectional discs showing consistent increase in heartwood percentage with age from 5-year- to 21-year-old teak wood through 8-year-, 12-year- and 18-year-old samples.



A cross sectional disc (7.5 cm thick) of 55-year-old teak showing the occurrence of heart check/shake in the juvenile wood portion extending up to 15 rings from pith.

10. Appendices

Appendix I

Analysis of variance of heartwood percentage of teak trees grown in Arienkavu

Source of variation	DF	MSS	F ratio
Between - Age	2	676.414	32.383**
Between - Treatment (Faster, Medium and slow)	1	203.616	9.748*
Between - Tree	2	11.957	0.572ns
Age X Treatment	2	10.662	0.510ns
Age X Tree	4	14.304	0.685ns
Treatment X Tree	2	26.725	1.279ns
Error	4	20.888	
Total	17	105.641	

** Significant at 1% level; * Significant at 5% level; ns Not significant

Appendix II

Heartwood percentage variation among three age groups in Location 11: Arienkavu

Age I (21-yr)	Age II (33-yr)	Age III (65-yr)	F-value	Significance	Bar diagram
62.2	76.6	82.8	37.6	**	– – – I II III

Appendix III

Anatomical variation in six radial positions (ring number 1,5,9,10,11 & 12 from pith) in 13-year -old trees (Nilambur)

Property	Ring	Faster grown	Slow grown
Ring width, mm	1	6.9	2.2
	2	11.9	4.3
	3	3.5	0.5
	4	3.6	0.3
	5	4.0	0.4
	6	3.0	0.2
Vessel diameter, µ m	1	90.2	70.9
	2	143.0	133.8
	3	151.1	170.8
	4	161.4	186.5
	5	149.0	164.9
	6	152.0	155.8
Fibre %	1	78.0	76.4
	2	71.0	70.0
	3	68.7	46.8
	4	68.9	39.2
	5	71.6	43.0
	6	70.6	42.2
Vessel %	1	10.2	10.2
	2	10.6	12.6
	3	13.1	34.5
	4	15.0	40.3
	5	12.6	34.7
	6	13.1	36.0
Parenchyma %	1	11.7	13.5
	2	18.4	17.4
	3	18.2	18.6
	4	16.0	20.5
	5	15.6	22.1
	6	16.3	21.8
Fibre wall thickness µ m	1	4.6	4.1
	2	5.3	3.7
	3	4.4	3.0
	4	4.9	3.0
	5	5.0	2.7
	6	4.8	2.9

Appendix IV
Analysis of variance of anatomical properties between and within 13- year- old trees

Property	Source of variation	DF	Mean square	F-value
Ring width	Between	5	33.0	101.9**
	Within	5	38.9	14.2**
	Error	25	2.7	
Vessel diameter	Between	5	381.4	1.4ns
	Within	5	6611.0	24.9**
	Error	25	265.3	
Fibre %	Between	5	655.2	7.1**
	Within	5	524.9	5.7**
	Error	25	91.5	
Vessel %	Between	5	531.2	7.5**
	Within	5	329.5	4.7**
	Error	25	70	
Parenchyma %	Between	5	73.9	5.8**
	Within	5	35.6	2.8*
	Error	25	12.8	
Fibre wall thickness	Between	5	7.8	26.9**
	Within	5	0.6	2.0ns
	Error	25	0.3	

** Significant at 1% level; * Significant at 5% level; ^{ns}Not significant

Appendix V

Anatomical variation in four radial positions (4th, 20th,40th and 65th rings from pith) in 65-year-old trees

Property	Ring	Faster grown	Slow grown
Ring width , mm	1	6.3	3.5
	2	4.3	1.8
	3	3.2	1.5
	4	1.4	1.3
Vessel diameter, µm	1	142.0	134.0
	2	156.5	171.2
	3	167.0	167.9
	4	198.3	192.4
Fibre %	1	70.3	69.4
	2	69.8	68.4
	3	64.0	62.0
	4	62.0	61.4
Vessel %	1	13.9	14.2
	2	14.2	15.8
	3	18.8	20.9
	4	24.2	23.6
Parenchyma %	1	15.8	16.3
	2	15.9	15.7
	3	17.2	17.0
	4	13.8	14.9
Fibre wall thickness, µm	1	4.7	5.0
	2	5.8	5.1
	3	6.2	5.6
	4	5.8	4.7

Appendix VI

Analysis of variance of anatomical properties between and within 65-year-old trees (Nilambur and Konni locations combined)

Property	Source of variation	DF	Mean square	F-value
Ring width	Between	11	5.3	3.18**
	Within	3	28.6	17.00 **
	Error	33	1.7	
Vessel diameter	Between	11	474.0	1.13ns
	Within	3	6632.7	15.88**
	Error	33	417.6	
Fibre %	Between	11	88.4	2.07*
	Within	3	207.2	4.85**
	Error	33	42.6	
Vessel %	Between	11	57.0	2.60*
	Within	3	296.6	11.36**
	Error	33	21.9	
Parenchyma %	Between	11	8.6	0.89ns
	Within	3	15.0	1.56ns
	Error	33	9.6	
Fibre wall thickness	Between	11	1.2	3.04**
	Within	3	2.2	5.47**
	Error	33	0.4	

** Significant at 1% level; * Significant at 5% level; ^{ns} Not significant

Appendix VII

Analysis of variance of anatomical properties of 65-year-old trees among three locations (Nilambur, Arienkavu and Konni)

Property	Source of variation	DF	Mean square	F-value
Vessel diameter	Between	2	321.4	0.501^{ns}
	Within	2	523.0	0.816^{ns}
	Error	4	641.2	
Fibre%	Between	2	19.9	0.857'"
	Within	2	24.4	1.05lns
	Error	4	23.2	
Vessel%	Between	2	6.7	0.732ns
	Within	2	0.5	0.062ns
	Error	4	9.1	
Parenchyma%	Between	2	12.5	2.460ns
	Within	2	19.7	3.870ns
	Error	4	5 .0	

** Significant at 1% level; * Significant at 5% level; ^{ns} Not significant

Appendix VIII
Comparison of strength properties of fast- and slow-grown teak (Nilambur)

Age, yr	Fast	Slow	Test of Significance
	Air-dry density, kg/m3		
13	656	586	ns
21	627	635	ns
55	639	633	ns
65	655	658	ns
	Modulus of rupture, N/mm2		
13	107	113	ns
21	138	116	ns
55	105	126	*
65	103	116	ns
	Young's Modulus, N/mm2		
13	11495	12150	ns
21	14464	10990	ns
55	11164	13150	*
65	12130	12664	ns
	Maximum crushing stress, N/mm2		
13	50	51	ns
21	59	52	*
55	50	51	ns
65	59	58	ns

ns Not significant; * Significant at 5% level

Appendix IX

Variation in mean values of strength properties of teak among four age groups (Nilambur)

Properties	Age-groups			
	13-yr	21-yr	55-yr	65-yr
FS-EL, N -mm^2	64.2	108.1	85.1	86.2
MOR, N -mm^2	108.1	133.8	103.7	99.5
MOE, N -mm^2	11272	14128	10565	12335
MCS, N -mm^2	48.5	56.4	50.9	58.6
Density ,kg-m^3	632.1	625.9	642.8	639.8

Appendix X

Variation in strength property values of teak among three age groups (Arienkavu)

Properties	Age-groups		
	21-yr	33-yr	65-yr
FS-EL, N -mm^2	78.4	85.7	80.0
MOR, N -mm^2	101.9	108.3	94.7
MOE , N -mm^2	11695	13218	12763
MCS , N -mm^2	45.7	46.4	39.2
Density, kg-m^3	608.9	619.0	622.0

Appendix XI

Mean values of strength properties of teak in three locations from Kerala

Age,yr	Location I			Location II			Location III		
	Faster	Medium	Slow	Faster	Medium	Slow	Faster	Medium	Slow
Air-dry density, kg/m3									
21	656	642	586	611	-	608	-	-	
65	655	670	658	627	-	646	653	-	663
Modulus of rupture, N/mm2									
21	137	132	115	107	-	110	-		-
65	102	105	115	96	-	116	139	-	127
Young's Modulus, N/mm2									
21	14323	14238	10822	11891	-	13965	-	-	-
65	12011	12762	12540	13176	-	13594	17567	-	16625
Maximum crushing stress, N/mm2									
21	58	51	50	46	-	46	-	-	-
65	58	59	58	39	-	47	46		51

Appendix XII

Analysis of variance of anatomical properties among 20 clones (3 trees each)

Property	Source of variation	DF	Mean square	F-value
Ring width	Between	19	1.8	1.18^{ns}
	Within	2	0.6	0.44^{ns}
	Error	38	1.5	
Vessel diameter	Between	19	680.5	1.73^{ns}
	Within	2	12.2	0.03^{ns}
	Error	38	391.2	
Fibre %	Between	19	46.6	0.79^{ns}
	Within	2	13.0	0.22^{ns}
	Error	38	58.9	
Vessel %	Between	19	41.3	0.81^{ns}
	Within	2	4.0	0.07^{ns}
	Error	38	51.0	
Parenchyma %	Between	19	5.3	1 .02^{ns}
	Within	2	36.4	6.99**
	Error	38	5.2	
Fibre wall thickness	Between	19	0.8	1.29^{ns}
	Within	2	1.0	1.64ns
	Error	38	0.6	

Significant at 1% level; * Significant at 5% level; ^{ns} Not significant

Appendix XIII

Anatomical comparison of Nilambur and Arienkavu provenances (Clones Collected from Arippa)

Property	Nilambur			Arienkavu			t-value
	Mean	SD	CV	Mean	SD	CV	
Vessel diameter, µm	169.8	16.8	9.8	175.9	30.7	17.4	-0.52^{ns}
Fibre%	63.3	4.5	7.1	55.5	13.5	24.3	1.65^{ns}
Vessel%	20.5	3.5	17.0	24.0	11.2	46.6	-0. 90^{ns}
Parenchyma%	16.2	3.5	21.6	17.6	2.9	16.4	-0.92^{ns}

** Significant at 1% level; * Significant at 5% level; ^{ns} Not significant