DESTRUCTIVE AND NON-DESTRUCTIVE EVALUATION OF WOOD PROPERTIES IN SELECTED TIMBERS OF KERALA

By

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2010-17-102

THESIS

Submitted in partial fulfillment of the requirement for the degree of

MASTER OF SCIENCE IN FORESTRY

Faculty of Agriculture

Kerala Agricultural University

DEPARTMENT OF WOOD SCIENCE
COLLEGE OF FORESTRY
KERALA AGRICULTURAL UNIVERSITY
VELLANIKKARA, THRISSUR – 680 656
KERALA, INDIA

2012

DECLARATION

I hereby declare that this thesis entitled **"Destructive and non-destructive evaluation of wood properties in selected timbers of Kerala"** is a bonafide record of research done by me during the course of research and that the thesis has not previously formed the basis for the award of any degree, diploma, fellowship or other similar title, of any other University or Society.

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ACKNOWLEDGMENT

With deep admiration I evince my heartfelt gratitude and unforgettable owe to my major advisor Dr. E.V. Anoop, Associate Professor and head, Dept. of Wood Science and Chairman of my advisory committee for his meticulous help, forbearance, affectionate advice, valuable guidance, constructive suggestions, unfailing patience, friendly approach and timely help at various stages of my study programme.

I extend my wholehearted thanks to Dr. P.K. Ashokan, Professor, Dept. of Tree Physiology and Breeding and member of my advisory committee for his keen interest and valuable suggestions he has provided throughout the course of my study.

My earnest thanks to Dr. N.K. Vijayakumar, Associate Dean (Retd.), College of Forestry and advisory committee member for his cooperation and intellectual advice to me during the course of study.

I express my heartfelt gratitude to Dr. A.V. Santhoshkumar, Associate Professor and Head Dept. of Tree Physiology and breeding and member of my advisory committee for his wholehearted co-operation and worthful advice extended to me throughout the study.

I am greatly indebted to Dr. Shakti Singh Chauhan, Scientist, Institute of Wood Science and Technology, Bangalore for guiding me throughout the project.

I take this opportunity to render my sincere gratitude to Dr. B. Mohankumar, Associate Dean, College of Forestry and Dr. K. Sudakara, Professor and Head Dept of Silviculture and Agroforestry for their constant support during the course of my study.

I sincerely thank Dr. T. K. Kunhamu, Associate Professor, Dept. of Silviculture and Agroforestry, College of Forestry and Dr. P.O. Nameer, Associate Professor and Head, Dept. of Wildlife Sciences, College of Forestry for their valuable help and advice during the course of my study period.

I am wholeheartedly obliged to Dr. K. Vidyasagaran, Associate Professor and Head, Dept. of Forest Management and Utilization, College of forestry; Mr. S. Gopakumar, Assistant Professor, dept. of Forest Management and utilization, College of Forestry; Dr. V. Jamaludeen, Assistant professor, Dept. of Silviculture and Agroforestry, College of Forestry for their valuable advice extended to me during the study.

I wish to express my gratitude to Dr. Sunandha for their guidance throughout the statistical analysis and interpretation of the data.

I owe my sincere thanks to all the staffs of Kerala Forest department for their whole hearted co-operation, help and valuable suggestions during the various stages of my study.

I express my sincere gratitude to the owner, Shri Shaji and staff of TRC Saw Mill, Thrissur for their support during my filed days.

I extend my unreserved thanks to Mrs. Jayasree, Rubber Research Institute, Kottayam, for her timely advice and help for the mechanical testing of wood specimens.

The help rendered by Ms. Prema, Ms. Khadeeja, Ms. Anju, Mrs. Mini, Mrs. Jyothi, Ms. Sajitha, Ms. Soumya and Mr. Adarsh are also remembered with gratitude.

The love, support, care and encouragement of my dear friends Sindhumathi, Delphy and Sukanya gave me enough mental strength to get through all difficult circumstances.

Words can't express my gratitude towards my friends; Shiran, Sreejith, Aneesh, Sreehari, R, Sreehari V.S, Shine and Sneha for their heartfelt help and support rendered throughout the study.

The support and timely help provided by my junior friends, Vishnu, Anish, Iqbal, Arun Raj, Parvathy, Anju, Surya, Vinu and Mereena are gratefully acknowledged.

A word of apology to those who has not been mentioned in person and a note of thanks to one and all who worked for the successful completion of this endeavor.

At this juncture, I express my deep love to my parents and sister without whose moral support, blessings and affection this would not have been a success.

Above all I bow my head before the God, ALMIGHTY whose blessings enabled me to undertake this venture successfully.

Dhanya P

CONTENTS

CHAPTER NO.	TITLE	PAGE NO.
1	INTRODUCTION	1-4
2	REVIEW OF LITERATURE	5-27
3	MATERIALS AND METHODS	28-41
4	RESULTS	42-73
5	DISCUSSION	74-80
6	SUMMARY	81-83
7	REFERENCES	i- xviii
8	ABSTRACT	

LIST OF TABLES

Table No.	Title	Page No.
1	Details of the logs sampled for study	32
2	Variation in specific gravity (oven dry) between the selected tree species	43
3	Results of static bending test of the selected tree species	43
4	Variation in compression strength parallel to grain of the selected tree species	46
4	Variation in compression strength perpendicular to grain of the selected tree species	46
6	Results of hardness test of the selected tree species	49
7	Variation in tensile strength parallel to grain of the selected tree species	49
8	Variation in shear strength of the selected tree species	52
9	Variation in penetration depth of the selected tree species	52
10	Variation in stress wave velocity obtained by using treesonic microsecond timer of the selected tree species	53
11	Correlation between penetration depth and specific gravity (oven dry) at pith, middle and periphery positions in *Acacia auriculiformis*	53
12	Correlation between penetration depth and specific gravity (oven dry) at pith, middle and periphery positions in *Artocarpus hirsutus*	55
13	Correlation between penetration depth and specific gravity at pith, middle and periphery positions in *Artocarpus heterophyllus*	55
14	Correlation between penetration depth and specific gravity (oven dry) at pith, middle and periphery positions in *Swietenia macrophylla*	57
15	Correlation between penetration depth and specific gravity (oven dry) at pith, middle and periphery positions in *Xylia dolabriformis*	57
16	Correlation between penetration depth and specific gravity (oven dry) at pith, middle and periphery positions in *Hevea brasiliensis*	58
17	Correlation between penetration depth and specific gravity (oven dry) at pith, middle and periphery positions in *Tectona grandis*	58
18	Correlation between pilodyn penetration depth and specific gravity (oven dry) of each species	60

LIST OF TABLES (CONTD)

Table No.	Title	Page No.
19	Correlation between penetration depth and specific gravity (air dry) at pith, middle and periphery positions in *Acacia auriculiformis*	60
20	Correlation between penetration depth and specific gravity (air dry) at pith, middle and periphery positions in *Artocarpus hirsutus*	62
21	Correlation between penetration depth and specific gravity (air dry) at pith, middle and periphery positions in *Artocarpus heterophyllus*	62
22	Correlation between penetration depth and specific gravity (air dry) at pith, middle and periphery positions in *Swietenia macrophylla*	63
23	Correlation between penetration depth and specific gravity (air dry) at pith, middle and periphery positions in *Xylia dolabriformis*	63
24	Correlation between penetration depth and specific gravity (air dry) at pith, middle and periphery positions in *Hevea brasiliensis*	64
25	Correlation between penetration depth and specific gravity (air dry) at pith, middle and periphery positions in *Tectona grandis*	64
26	Correlation between specific gravity (air dry) and penetration depth in the selected species	66
27	Correlation of dynamic MOE, stress wave velocity and penetration depth with mechanical parameters and specific gravity	68
28	Results of regression in case of specific gravity (air dry) and penetration depth	71
29	Measurements obtained when transducers were inserted along the same side of teak log at 1 m interval	73
30	Measurements obtained when transducers were inserted on the opposite side of teak log at 1 m interval	73

LIST OF FIGURES

Fig. No.	Title	Between pages
1	Positions in the teak log at which measurements were taken by inserting the transducers of treesonic timer at 1 m interval starting from A to G on the same side	40-41
2	Positions in the teak log at which measurements were taken by inserting the transducers of treesonic timer at 1 m interval on the opposite side	40-41
3	Relation between specific gravity (oven dry) and penetration depth in *Acacia auriculiformis*	69-70
4	Relation between specific gravity (oven dry) and penetration depth in *Artocarpus hirsutus*	69-70
4	Relation between specific gravity (oven dry) and penetration depth in *Artocarpus heterophyllus*	69-70
6	Relation between specific gravity (oven dry) and penetration depth in *Swietenia macrophylla*	69-70
7	Relation between specific gravity (oven dry) and penetration depth in *Xylia dolabriformis*	70-71
8	Relation between specific gravity (oven dry) and penetration depth in *Hevea brasiliensis*	70-71
9	Relation between specific gravity (oven dry) and penetration depth in *Tectona grandis*	70-71
10	Relation between average specific gravity (oven dry) and average penetration depth in each of the species	70-71
11	Relation between Static MOE and Dynamic MOE of each species	70-71

LIST OF PLATES

Fig. No.	Title	Between pages
1	Cross cutting the logs of species to required size	32-33
2	Crosscutting of discs of species to desired size	32-33
3	Using pilodyn for indirect assessment of density in species	32-33
4	Pilodyn 6J (Fujiteck Corp.) used for the study purpose purpose purpose showing (a) pin, (b) housing, (c) trigger, (d) scale and (e) loading rod	32-33
5	The positions at which measurements were taken at the end cross section of log using pilodyn	32-33
6	Measurements taken in rubber (*Hevea brasiliensis*) using pilodyn	32-33
7	Start and stop transducers inserted into a pyinkado (*Xylia dolabriformis*) log	32-33
8	Measurements taken in teak (*Tectona grandis*) log using treesonic microsecond timer	32-33
9	Positions on the end cross section of log at which measurements were taken using treesonic microsecond timer	33-34
10	Conversion of logs to planks before making them to small clear specimens	33-34
11	Scantlings assembled before conversion to small clear specimens	33-34
12	Specific gravity module attached to electronic balance (Shimadzu AUY 220)	33-34
13	Wood samples used for specific gravity estimation	33-34
14	Universal Testing Machine (UTM)	37-38
15	Wood samples kept for conditioning	37-38
16	Static bending test	37-38
17	Test for compression strength parallel to grain	37-38
18	Test for compression strength perpendicular to grain	39-40
19	Test for hardness	39-40
20	Test for shear strength	39-40
21	Test for tensile strength parallel to grain	39-40
22	Teak log having hollow inside used for the study purpose	40-41
23	Measurements taken in teak (*Tectona grandis*) log having hollow inside by inserting the transducers at 1 m interval along the same side of the log	40-41
24	Measurements taken in teak (*Tectona grandis*) log having hollow inside by inserting the transducers at 1 m interval on the opposite side of the log	40-41
25	The extent of hollow and shake inside the teak log	40-41

Dedicated to My Family

Introduction

INTRODUCTION

Wood is a naturally durable material that has long been recognized for its versatile and attractive structural properties (Feist, 1990). It outperforms all other materials combined in the total annual tonnage used worldwide (Brostow et al., 2010). Because of its natural origin, wood frequently exhibits an unusually wide degree of variability in physical and mechanical properties as a result of its genetic source, environmental factors (climate, soil, water, available nutrients etc.) and also its complex internal multicomponent structure (anisotropy). These variations influence the suitability of wood for a variety of purposes. Consequently manufacturers and users of wood products are frequently confused about these wide variations in wood properties and they need to know the properties and potential of wood as a raw material for conversion to various products (Dundar et al., 2012).

The main quality requirements for solid wood products are stiffness, strength, dimensional stability and lack of internal checking, crook and bow (Raymond and Apiolaza, 2004). In general, the fundamental wood properties determining these product properties are basic density, modulus of elasticity (stiffness) and modulus of rupture (wood strength) (Karlinasari et al., 2008).

For growers and processors of trees intended for structural timber production, the accurate prediction of mechanical properties of standing trees has various benefits (Wessels et al., 2011). This helps in improved wood quality assessments (Kabir et al., 2002; Cown, 2005; Chauhan and Walker, 2006), log segregation into quality classes (Dickson et al., 2004; Amishev, 2008), board segregation into stiffness classes and early screening for genetic heritability (Wei and Borralho, 1997; Kumar et al., 2002).

The mechanical and physical properties of timber are affected by natural characteristics (orientation of loading regarding fibre orientation, density, knots and slope of grain) and by service conditions (moisture content, load duration), which makes the strength assessment of timber in service (residual strength) extremely difficult. Presently, estimation of physical and mechanical properties that directly affect the strength can be assessed meaningfully only by destructive means. In many species, especially in priced timbers, it is extremely difficult to gather specimens either due to non-availability of samples to satisfy the minimum sampling requirements or the higher costs involved in adopting destructive sampling. The sample preparation is also time consuming. Many a times, the logs used in such tests cannot be retrieved for further utilization, incurring high losses.

Currently, worldwide research and development efforts are underway to examine the potential use of a wide range of non-destructive (NDT) and semi-destructive techniques (SDT) for evaluating wood and wood-based materials from the assessment of standing trees to in-place structures (Brashaw et al., 2009). These techniques will not only save precious resources without sacrificing logs for testing, but have been found to be reasonably good predictors of timber properties under field conditions and detection of decay. In the case of wood products, nondestructive methods are often used for process control, quality assurance measurements, and grade classification (during and after processing). Non-destructive techniques have also found application in the evaluation of existing wood buildings and built-up components and in the periodic inspection of other essential facilities and structures such as wood utility poles, scaffold planks, mine timbers etc. (Falk et al., 1990). Also, proper application of non-destructive techniques allows for a more confident assessment of material properties and, in turn, structural integrity and residual capacity.

Non-destructive evaluation (NDE) of materials is, by definition, the science of identifying the physical and mechanical properties of a piece of material without altering its end-use capabilities (Ross et al., 1998). Such evaluations rely upon nondestructive testing (NDT) techniques or tools to provide accurate information pertaining to the properties and performance of the material in question (Ross and Pellerin, 1994).

Non-destructive testing techniques for wood differ greatly from those for homogeneous, isotropic materials such as metals, glass, plastics, and ceramics. In such nonwood-based materials, whose mechanical properties are known and tightly controlled by manufacturing processes, NDT techniques are used to detect the presence of discontinuities, voids, or inclusions. Because wood is a biological material, these irregularities occur naturally and, further, may occur because of agencies of degradation in the environment. Hence, NDT techniques for wood are used to measure how natural and environmentally induced irregularities interact in a wood to determine its mechanical properties (Ross, 1992).

Many physical NDE techniques exist such as electrical resistance, dielectric and vibrational properties, acoustical emission, wave propagation, X-ray etc. (Ross et al., 1998). The use of such technologies could lead to greater profitability for the forest industry. Acoustic technologies have been well established as material assessment means in the past several decades, and their use has become widely accepted by the wood industry for quality control and product grading (Wang et al., 2007a). However, there is a pertinent need to standardize these methods before recommending for widespread usage under field conditions. There is, hence a need to correlate actual strength performance using destructive techniques with those obtained by non-destructive and semi-destructive methods in species currently used in the state.

Also, methods to determine internal defects and detection of putridity (decay) in various stages using non-destructive techniques in standing trees are non-existent under the prevailing conditions in our state.

Considering the above, the proposed investigation envisages a detailed study of the physical and mechanical properties of wood in timber species such as: acacia (*Acacia auriculiformis* A. Cunn. ex Benth.), anjily (*Artocarpus hirsutus* Lamk.), jack (*Artocarpus heterophyllus* Lamk.), mahogany (*Swietenia macrophylla* King), pyinkado (*Xylia dolabriformis* Benth.), rubber (*Hevea braziliensis* (H.B.K.) M. A.) and teak (*Tectona grandis* L.f.) using destructive and non-destructive testing methods. These timbers are currently used in our state for furniture making and other purposes.

The study also aimed at evaluating the suitability of non-destructive techniques (NDT) and semi-destructive techniques (SDT) as predictors of timber properties under field conditions.

Review of Literature

REVIEW OF LITERATURE

Wood is an extremely versatile material with a wide range of physical and mechanical properties. For growers and processors of trees intended for structural timber production, the accurate prediction of the mechanical properties of standing trees has various benefits (Wessels et al., 2011). Amongst others, such information can be used to assist in taking decisions related to the allocation of trees to different processing facilities (Matheson et al., 2002; Wang et al., 2007) for processing production planning (Uusitalo, 1997; Wessels et al., 2006), to study the effect of site and silviculture factors on wood quality (Wang et al., 2000b; Grabianowski et al., 2004; Wang et al., 2005) and to assist tree breeders to screen and select for superior breeding material (Launay et al., 2002; Lindstrom et al., 2002; Ivkovic et al., 2009).

2.1 PHYSICAL PROPERTIES

The physical properties of timbers relate to inherent qualities such as appearance, colour, density, etc., of wood and also its reaction to sound, heat, light, electricity, etc. According to Sekhar (1988) the knowledge of physical properties decides the wood working qualities. The wood property varies from species to species. It is observed that no two species are identical with regard to all wood properties.

2.1.1 Wood Density or Specific Gravity

The terms density and specific gravity are both used to describe the mass of a material per unit volume. These terms are often used interchangeably although they each have precise and different definitions (Bowyer and Smith, 1998). Both terms are defined by Haygreen and Bowyer (1996), Zobel and van Buijtenen

(1989) and Hoadley (2000). Wood specific gravity is the sum total of the wood substance proper, extraneous matter and wood content (Sekhar, 1988).

Wood density is considered the best single index of wood quality because it is the most dependable characteristic for predicting timber strength (Shirin et al., 1998). It has been a desirable trait to include in tree improvement programs because of its economic value and high degree of genetic control (Sprague et al., 1983) and is one of the most studied wood quality traits (Downes et al., 1997; Downes and Raymond, 1997; Peszlen, 1998; McKinley et al., 2003; Jordan et al., 2008). Basic density is commonly assessed using a core taken near breast height, which has been shown to be highly correlated to whole tree values (Lausberg et al., 1995; Raymond and Muneri, 2001; Kube and Raymond, 2002). It affects various products of wood, such as pulp and paper properties, wood strength, and wood quality (Zobel and van Buijtenen, 1989). It can be used as a predictor of yield and quality of pulp and paper products (Dadswell and Wardrop, 1959; Barefoot et al., 1970). High densities are advantageous since they correspond to higher pulp yields on a raw material volume basis, and to a better use of digester capacity (Miranda et al., 2001). Density appears to influence machinability, conversion, strength, paper yield and many other properties (Wimmer at al., 2002). Most mechanical properties of wood are closely related to specific gravity and density (Walker, 1993; Haygreen and Bowyer, 1996).

Wood density can be changed by silvicultural manipulations (Williams and Hamilton, 1961). Specific gravity varies with species and provenance. Edaphic, climatic and topographic factors profoundly influence specific gravity of wood. Parolin and Ferriera (1998) studied thirty five central Amazonian tree species and concluded that the specific gravity of wood from soils with low nutrient status was generally higher than that of wood grown in soils with higher nutrient status. Tree age is another factor which influences specific gravity. It was reported that increase in tree age increased the specific gravity from 0.47 to 0.56 in the case of *Acacia mangium* (Siagian et al., 1999).

In a species, the wood density is the most important wood characteristic because knowledge about it allows the prediction of a greater number of properties than any other trait (Bowyer and Smith, 1998). Jerome et al. (2006) reported that wood density is the single best descriptor of wood; it correlates with numerous morphological, mechanical, physiological and ecological properties. Some wood properties that are closely related to wood specific gravity are: strength, dimensional stability with moisture content change, ability to retain paint, fibre yield per unit volume, suitability for making particleboard and related wood composite materials, and suitability as a raw material for making paper (Bowyer and Smith, 1998).

Shanavas and Kumar (2006) found that the presence of lignin and other denser fractions and/or complex wood ultra structure, apparently enhances wood density, which explains the observed interspecific variations. As regards within tree variation, mean specific gravity of heartwood is greater than sapwood and bark, presumably because of higher lignification in the former. In *Artocarpus heterophyllus*, the specific gravity of heart wood, sap wood and bark are 0.534, 0.588 and 0.415 respectively. In *Artocarpus hirsutus*, the specific gravity of heart wood, sap wood and bark are 0.523, 0.482 and 0.400 respectively.

Shukla et al. (2007) assessed the specific gravity of plantation grown 8, 12 and 13 year old trees of *Acacia auriculiformis* from Sirsi, Karnataka, India. Average standard specific gravity was highest in 13 year old trees (0.62) followed by 12 year (0.60) and 8 year old trees (0.57). In other studies, 14 year old trees from Mudigere, Karnataka, had an average specific gravity of 0.72 (air-dry) (Kumar et al., 1987), whereas 9 year old trees from Gaya, Bihar, had a specific gravity of 0.62 (Shukla et al., 1990). Verghese et al. (1999) reported that specific gravity was 0.59 for 15 year old plantations from Wada, Maharashtra. Keating and Bolza (1982) reported that the specific gravity of timber obtained from Indonesia was 0.58– 0.64. Mahat (1999) reported variation in specific gravity (0.53–0.61) of different provenances tested in Malaysia. Thus specific gravity appears to be widely influenced by age, environmental factors and seed origin.

Seen at the anatomical level, density is the combined result of a number of characteristics including cell wall thickness, cell diameter, growth ring width, amount of ray and vessel elements, and the ratio of earlywood to latewood in a growth ring. It is a complex feature influenced by cell wall thickness, the proportion of different kind of tissues, and the percentage of lignin, cellulose and extractives (Valente et al., 1992). Strength and stiffness prediction methods using the width of growth rings are, therefore, also included as a density dependent prediction method.

Wood density varies within the species. Raymond and Macdonald (1998) assessed the longitudinal patterns of within tree variation for basic density in *Eucalyptus globulus* (ages 5 and 10 years) and *E. nitens* (ages 5, 10 and 15 years) plantations growing in three geographic areas in Tasmania. Each tree was sampled by taking discs from a combination of percentage heights (0, 10, 20 to 70%) and fixed height samples (0.5 m, 0.7 m to 1.5 m). Both species showed an initial drop in density between the felling cut (zero height) and 0.5 m, followed by a linear increase in density between 10% and 70% of tree height. Density at all fixed heights was highly correlated with whole tree values for *E. globulus*, but results were variable across sites for *E. nitens*. For *E. globulus*, the optimal sampling height was 1.3 m above ground and for *E. nitens*, optimal sampling height was 1.5 m above ground.

There are several methods to determine density from increment core samples. Gravimetric methods for density determination make use of the accurate determination of the volume and mass of the sample at specific moisture content (Yao, 1968). A relatively easy and popular way of determining the density of small samples, like those from increment cores, is the maximum moisture content method developed by Smith (1954). This method uses the mass of a sample when saturated with water, its oven-dry mass and the absolute density of wood cell wall material (1.53 g/cm^3), to determine the basic density of small sections. In some wood species, extractives, which is not part of the wood substance and which contribute nothing to wood strength, need to be extracted from the wood to ensure more reliable density values for predictive purposes (Tsoumis, 1991).

2.2 MECHANICAL PROPERTIES OF WOOD

The mechanical properties of wood are its fitness and ability to resist applied or external forces. They include elastic properties, which characterize resistance to deformation and distortion, and strength properties, which characterize resistance to applied loads. Mechanical property values are given in terms of stress (force per unit area) and strain (deformation resulting from the applied stress). The mechanical property values of wood obtained from laboratory tests of lumber of straight-grained clear wood samples without natural defects that would reduce strength, such as knots, checks, splits, etc. (Winandy, 1994). It is largely such properties that determine the use of wood for structural and building purposes and innumerable other uses of which furniture, vehicles, implements, and tool handles are a few examples.

Strength properties of different timbers are evaluated on the basis of different tests carried out for bending and compression. Since one individual timber is not likely to be better or worse than the other under all the tests and all the properties evaluated from these tests, suitability indices are derived by combining several properties relevant to a particular use and expressing them as percentage of reference timber so as to obtain a single figure for comparison. By compiling the suitability indices for 246 Indian timber species, Sekhar and Gulati (1972) revised the suitability indices prepared by Limaye (1954) which in turn was based on only 207 species. Various factors influence the strength properties of wood. The variability of wood strength between species or within a species can be due to environmental and genetic factors (Schniewind, 1989). Bhat et al. (1999) citing the example of *Tectona grandis* and *Gmelina arborea* showed that in some species, age plays no influential role in altering mechanical properties. Mechanical property within a tree varies even with position of sample. In most cases, strength initially increases and then decreases again in a radial direction from pith to periphery (Sekhar and Negi, 1966; Sekhar, 1988). Presence of knots in tissue sample is an important factor affecting timber strength (Rajput et al., 1998). Dry samples are found to have higher strength than green samples (Kumar et al., 1987). However, above fibre saturation point, the mechanical properties are not much affected by moisture content.

2.2.1 Static Bending Test

The properties of static bending tests are useful in all engineering constructions and also in deciding suitability of various species for beams, deckings, axles and wood poles (Sekhar, 1988). Lohani and Sharma (2003) investigated the stiffness-strength relationships in *Albizzia procera* and *Prosopis juliflora* by subjecting the samples to static bending test. The modulus of elasticity and modulus of rupture obtained from these tests revealed their efficacy for machine grading. In a study conducted on plantation grown and natural tamarack (*Larix laricina*), the static bending and compression parallel to grain in plantation grown tamarack were found to be significantly lower than naturally grown tamaracks (Beaudoin et al., 1989). Shukla et al. (1988) by studying the strength properties (static bending, compression parallel to grain and hardness) of 16 year old *Eucalyptus tereticornis* concluded that overall strength properties increased from pith to periphery in the heartwood and decreased in the sapwood region.

Bhat and Thulasidas (1997) analyzed the physical and mechanical properties of *Eucalyptus grandis* and *E.tereticornis*, grown in Kerala. They reported that the bending strength of *E. tereticornis* grown in Kerala was 11 percent weaker than that grown in drier localities of north India. Studies on the bending properties of *Pinus radiata* wood growing in silvo pastoral systems revealed that the frequency of fertilizer application had no significant effect on the mechanical properties but stem height had significant effect on stress at proportional limit and modulus of rupture (Ramirez et al., 2001). Kretschmann and Green (1996) analyzed various mechanical properties of clear southern pine at different moisture contents. From these findings, it was reported that the elastic modulus increased with decreasing moisture content from green to four per cent moisture content.

In a study on the mechanical properties of rubber wood from a 35-year-old plantation in central Kerala by Gnanaharan and Dhamodaran (1992), it was reported that rubber wood from the 35-year-old trees grown in the central region of Kerala had a mean MOR of 98.4 N mm^{-2}, MOE of 15.7 kN mm^{-2}, MCS of 52.7 N mm^{-2} and density of 580 kg m^{-3}. This study concluded that rubber wood from 35-year-old trees of the central region of Kerala has strength values comparable with those of many structural timbers.

Olufemi and Malami (2011) reported the bending strength of *Eucalyptus camaludensis* Denhn (river red gum) grown in North-western Nigeria. The study revealed that *E. camaludensis* has an average density of 977.58 kg m^{-3} and has bending strength of 133.33 Nmm^{-2}. The modulus of elasticity (stiffness) was

15219.89 Nmm^{-2}. Comparison between the density and bending strength of *E. camaludensis* with other wood species commonly utilized as timber in Nigeria revealed that the wood is suitable for timber production.

Kubojima et al. (2000) examined the load-deflection curve for static bending and the force-time curve for impact bending of heat-treated wood. Bending strength increased at the initial stage of the heat treatment and decreased later. It decreased more in air than in nitrogen. The work needed for rupture decreased steadily as the heating time increased. It decreased more in nitrogen than in air. It was concluded that heat-treated wood was more brittle than untreated wood in the static bending test. This means that the main factors contributing to the reduction of the work needed for rupture were viscosity and plasticity, not elasticity.

Sadegh and Rakhshani (2011) analysed the static bending strength of beech wood (*Fagus orientalis* Lipsky) and compared them with other beech species. In the tests randomly selected logs taken from the trunk 2-4 m height were obtained from trees naturally growing in Noshahr region (North of Iran) and tested according to ASTM Standard. The results showed that the static bending strength of beech was 1292 kg cm-^{2}. These results were compared with other available values in the literature. This comparison revealed that beech trees growing in Iran and those growing elsewhere have similar values for mechanical properties and density.

Yoshihara and Fakuda (1998) studied the influence of loading point on the static bending test of *Liriodendron tulipifera* wood. They observed that when depth/span ratio is high, loading point had little influence in Young's and shear moduli. Also, when specimen had a high depth/span ratio, bending strength increased with increase in the radius of the loading nose. Studies on the variation pattern of mechanical property of *Dendrocalamus latiflorus* timber revealed that site condition had no effect on bending strength (Lin et al., 1999). Age profoundly influences bending strength properties. In a study conducted on red pine (*Pinus resinosa*), modulus of elasticity and modulus of rupture was 22 to 90 percent greater in mature wood than in juvenile wood (Shepard and Schottafer, 1992). From the studies on the thermal behavior of wood during static bending tests, Naito et al. (1998) found that in specimens of yellow cedar (*Chamaecyparis lawsoniana*) the temperature raised upto an average of 0.6°C immediately below the loading point after the load reached the proportional limit. Ayarkwa et al. (2001) evaluated modulus of rupture of solid and finger jointed tropical African hardwoods using longitudinal vibration. They concluded that although static bending is generally recognized as a more desirable method of determining modulus of rupture, the longitudinal vibration technique may also be useful as a non destructive technique for predicting modulus of rupture of solid and finger jointed African hardwood timbers.

2.2.2 Compression Parallel to Grain

The properties determined under this test are useful for design of columns and evaluating suitability of timber species for post and other industrial purposes where forces act in a direction parallel to the grain of timber (Sekhar, 1988). Kolin (1988) investigated compression strength parallel to grain in woods of *Fagus sylvatica*, *Quercus pedunculata*, poplar, fir and spruce at different moisture content of 4% to 24% and at different temperature between 20^{o} to 80^{o}C. He found that compression strength decreased with increase in moisture content and temperature. Variation of strength properties along pith to periphery was studied in *Eucalyptus terreticornis*. It was observed that compression strength parallel to grain increased from pith to periphery in heartwood and decreased in sapwood region (Shukla et al., 1988). Shukla and Khanduri (1990) from their studies on the effect of rate of loading on ultimate bending and compressive strength of wood conducted on

Eucalyptus, *Mangifera indica* and *Tsuga dumosa*, established relation between these two strength parameters and rate of loading. It was found that rate of loading has greater influence on maximum crushing stress under compression than on modulus of rupture in static bending. In another study to determine the variation of specific gravity and compression parallel to grain among different clones of *Populus deltoids*, it was reported that maximum crushing stress differed significantly between clones and with radial position. Along radial position maximum crushing stress at central position was weaker than outer position (Rajput et al., 1997). Rate of growth and age of trees also affects compression parallel to grain. Razali and Hamami (1993) reported a mean maximum crushing stress of 43.4 N/mm^2 for 12- year old *Acacia mangium*, whereas Damodaran and Chacko (1999) reported a mean maximum crushing stress of 30.4 N/mm^2 for 8 –year old and 10-year old *Acacia mangium* trees. Oh (1997) studied the relationship between anatomical properties and compression parallel to grain in *Pinus densiflora*. From these studies he reported that compression strength parallel to grain increased with increase in tracheid length and wall thickness.

2.2.3 Compression Perpendicular to Grain

Compression strength perpendicular to grain is often critical in timber design. It is usually most severe at the ends of deep, narrow beams and in connecting members at the top and bottom of short, heavily loaded columns. In this test, force is applied on the radial longitudinal surface only. The properties evaluated in this test are useful for selecting timber species for uses where timber is loaded on its lateral surface such as furniture, railway sleeper, instruments and some type of sports goods (Sekhar, 1988). Beaudoin et al. (1989) by studying the mechanical properties of plantation grown and natural tamarack timbers concluded that compression perpendicular to grain and hardness did not differ significantly between plantation grown and naturally grown tamarack woods. Like other properties viz., bending strength, compression parallel to grain and modulus of elasticity, it was found in clear southern pine that compression perpendicular to grain increased with decreasing moisture content from green to four percent moisture content (Kretschmann and Green, 1996).

Compressive stress at limit of proportionality (CS at LP), compressive stress at maximum load (CS at ML), and modulus of elasticity (MOE) in compression perpendicular increased from inner to outer positions in *Acacia mangium*. (Shanavas and Kumar, 2006).

2.2.4 Hardness

Shukla et al. (2007) assessed the physical and mechanical properties of timber of plantation grown 8, 12 and 13 year old trees of *Acacia auriculiformis* A.Cunn. ex Benth. from Sirsi, Karnataka, India. It was found that the hardness and tension values determined in radial, tangential and end directions and tension perpendicular to the grain appear to be independent of age, whereas the shear values were found to be age related, being highest for the 13 year old specimens. The timber of the 13 year old trees was dense, very strong, moderately tough, stable in service and hard, and it compared favorably with teak in several properties. The results suggest that it can be used for tool handles, oars, paddles, packing cases, ammunition boxes, etc. It was also found suitable for the rural construction industry where timbers of small diameter can be used. If trees are allowed to grow older to attain greater size the range of potential uses will increase. Rokeya et al. (2010) assessed the hardness of hybrid Acacia (*Acacia auriculiformis* and *Acacia mangium*). It was found that the hardness of hybrid Acacia is less (458 kg) than that of *A. auriculiformis* (572 kg), but the value is greater than that of *A. mangium* (337 kg). Shanavas and Kumar (2006) assessed the hardness of *Acacia auriculiformis*, *A. mangium* and *Grevillea robusta.* Hardness in radial and tangential planes, besides end surface hardness of *A. auriculiformis* was higher than that of *A. mangium* and *G. robusta*. Wood specimens from the mid position of *A. auriculiformis* had significantly higher radial and tangential hardness values than that of inner and outer positions, while the other species did not show any predictable pattern. End-hardness decreased progressively from inner to outer positions in *A. auriculiformis,* but *A. mangium* showed a divergent pattern.

2.2.5 Shear Strength

Maximum shearing stress is useful in the design of various articles such as agricultural implements, lorry bodies, bearing and packing blocks etc (Sekhar, 1988). This test is carried out generally by block shear test using universal testing machine. Yoshihara and Satoh (2003) put forward off axis tension test method to determine shear strength by analysing the strength properties of *Fraxinus spaethiana*. They however concluded that this method is not suitable to determine shear properties of wood. Recent studies were carried out by Sretenovic et al. (2004) on Norway spruce and European larch to check the suitability of modified shear test set up upon block shear test. Test results indicated that for determination of shear strength and shear modulus, modified shear test is very suitable. Muller et al. (2004) used the new method to determine the longitudinal shear modulus and shear strength of solid wood in a single test. They observed that the shear properties of normal wood and compression wood of *Larix decidua* were related to their microstructure i.e. density, microfibril angle and lignin content. Their analytical models prove that the effect of increased microfibril angle and higher lignin content on longitudinal shear modulus in cell wall balance each other to a large degree. Studies were conducted in western hemlock (*Tsuga heterophylla* Sarg.) to examine whether the shear stress can be used to describe the shear strength. It was concluded that in short beam test under asymmetric four point loading, the value of the maximum shear stress is an effective parameter for comparing the shear strength of materials with each other. Lin et al. (1999) analysed the variation pattern of mechanical properties of *Dendrocalamus latiflorus*. They concluded that site has no significant effect on shearing strength parallel to grain but age has a positive influence on shearing strength. They also found that this property was better at upper position f culms followed by middle and lower positions. Rokeya et al. (2010) in his study reported that the strength values of wood for compression perpendicular to grain, hardness and shear parallel to grain in air–dry condition are higher than that of the green values except nail withdrawal.

2.2.6 Tensile Strength Parallel to Grain

Krestchmann and Green (1996) studied the moisture content-mechanical properties relationships in clear southern pine. It was found that the tensile stress parallel and perpendicular to grain increased with decreasing moisture content from green to a peak between 7% and 13% moisture content. Rokeya et al. (2010) in their study on the physical and mechanical properties of hybrid Acacia (*Acacia auriculiformis* x *Acacia mangium*) reported that the values of tension perpendicular to grain are lower than those of green conditions. Hildebrandt (1960) emphasized the importance of chemical composition and its influence in mechanical wood properties. He reported that as the amount of lignin increases, the tensile strength, resistance to rupture and shock decreases.

2.3 NON DESTRUCTIVE EVALUATION

Nondestructive materials evaluation (NDE) is the science of identifying the physical and mechanical properties of a piece of material without altering its end-use capabilities (Ross and Pellerin, 1994). Non-destructive methods are becoming an important alternative for predicting wood characteristics. The primary advantages of such tests are speed of data collection, low cost and ability to evaluate large numbers of samples, which favors the selection of superior genotypes, even in field conditions (Gomes et al., 2011). These techniques have contributed to the advancement of knowledge of the natural variability of wood, allowing the identification of wood material that is free from internal defects, which helps in their appropriate use.

NDE can be classified in two distinct groups: Global Test Methods (GTM) and Local Test Methods (LTM) (Bertolini et al., 1998; Ceraldi et al., 2001). GTM include visual inspection and species identification, ultrasonic stress wave method / ultrasound pulse velocity (UPV), ultrasonic array imaging, sonic stress waves and IR thermography. LTM testing can be used for determination of the element residual section and loss of mass. LTM include resistance drilling, drill sampling, penetration test, screw withdrawal resistographic measurement, hardness test, videoscopy, X-Ray and micro-CT.

Generally, timber testing methods can be divided into following groups with regard to the test destructivity level: non-destructive tests (NDT): visual inspection, ultrasound pulse velocity (UPV), vibration methods, sonic stress wave, thermography, X-ray, etc. and semi-destructive / minor-destructive tests (MDT): resistance drilling, penetration test, videoscopy, small non-standard sample testing, etc.

2.3.1 Pilodyn

The pilodyn is the only instrument that has been used extensively in the field to assess wood density of both softwoods and hardwoods. The pilodyn drives, with predetermined force, a flat-nosed, spring-loaded pin of 2.5 mm diameter into wood and is free of operator bias. Only two observations per tree would be required using pilodyn for indirect selection of density (Greaves et al. 1996). The penetration depth can be used as an indirect measure of the density of the outer section of the stem (Cown, 1978). The depth of penetration is negatively correlated with basic density (Greaves et al., 1996; Raymond and MacDonald, 1998; Raymond et al., 1998; Muneri and Raymond, 2000; Chauhan and Aggarwal, 2011).

A number of comparative analyses have shown high correlation between pilodyn estimates and wood density estimates. Cown (1978) correlated the pilodyn readings and outer wood density of radiate pine of different ages and could obtain a correlation coefficient of 0.97. Micko et al. (1982) compared the pin penetrations in both debarked and unpeeled standing white spruce (*Picea glauca* (Moench) Voss) trees with outerwood specific gravity determined from actual core samples taken near the Pilodyn test spots. High degrees of correlation were found for Pilodyn penetration measurements and the outerwood specific gravities. His tests confirmed that the Pilodyn tester can be used in tree specific gravity estimation as part of a selection program for tree improvement. Moura et al. (1987) also found good correlations between wood density and Pilodyn penetration in several eucalyptus species. Taylor (1981) also reported a high correlation coefficient (-0.81) between PP depth and wood density using 35 individual *Pinus taeda* . Hall (1988) reported correlation coefficients between the Pilodyn results and wood density of -0.48 in *Picea mariana*, -0.62 in *Picea glauca* and - 0.48 in *Larix laricina*. Yamashita et al. (2007) reported a correlation coefficient of -0.82 between penetration depth and the wood density of wood blocks from *Cryptomeria japonica*. The correlation was stronger for sapwood density than for heartwood density, which was consistent with the fact that the pilodyn pin penetrated into only the outside of the trunk of a tree. Notivol et al. (1992) found good correlations between pilodyn and wood density (0.73) for *Pinus pinaster* provenances in a sample of 60 trees of 34 years of age.

Raymond and Macdonald (1998) correlated the basic density of *Eucalyptus globulus* (ages 5 and 10 years) and *E. nitens* (ages 5, 10 and 15 years) disks taken at percentage heights (0, 10, 20 to 70%) and fixed height samples (0.5 m, 0.7 m to 1.5

m) with pilodyn taken from each of the 4 aspects. Both species were found to contain trees which produced aberrant pilodyn readings. For *E. globulus*, the optimal sampling height was 1.3 m above ground and the mean pilodyn reading was found to predict whole tree density with an accuracy of ±21 kg/m3. For *E. nitens*, optimal sampling height was 1.5 m above ground. However, pilodyn readings around the stem were not very repeatable and correlations with whole tree density were lower, resulting in the accuracy of prediction of whole tree density as ± 26 kg/m^3.

Studies were also carried out to define correlations with mechanical properties. Relations between resistance to superficial penetration and a three point loading test were found but more studies are needed to corroborate these results, due to its empirical nature and to the local and superficial character of the results obtained (Togni, 1995). Pilodyn penetration correlated well with crushing strength and MOE besides density in the case of hardwood species like maple and oak (Chudnoff et al., 1984). Wu et al. (2010) tested the effectiveness of pilodyn in evaluating wood basic density, outer wood density, heartwood density, and modulus of elasticity (MOE) in 22 four year old eucalyptus clones in Guangxi, China. Results indicated that the mean value of pilodyn penetration, wood basic density and MOE ranged from 9.44 to 15.41 mm, 0.3514 to 0.4913 g cm^{-3} and 3.94 to 7.53 GPa, respectively. There were significant differences (1% level) in pilodyn penetration between different treatments, different directions and among the clones. Generally strongly negative correlations were found between pilodyn penetration and wood properties, and the coefficients ranged from -0.433 to -0.755.The results confirmed that pilodyn is an effective and efficient means of estimating wood properties.

Studies were done to understand the genetic correlation between pilodyn penetration depth and wood density to assess the usefulness of pilodyn for genetic improvement. Fukatsu et al. (2011) assessed the genetic correlation in 12 clones of *Cryptomeria japonica* in 10 test sites in Kanto breeding region in Japan and he could obtain a genetic correlation of -0.88. In his result, the indirect selection using the pilodyn realized 87% of the genetic gain obtained by the direct selection of wood density. Kube and Raymond (2002) also assessed the genetic correlation between basic density and Pilodyn penetration in 12 year old *Eucalyptus nitens* progeny trials across three sites in Tasmania. He also obtained a strong negative relationship (-0.90) basic density and Pilodyn penetration.

Linear relationships between pilodyn penetration and wood density of nearby cores or discs have been demonstrated repeatedly (Greaves et al., 1996, 1997b; Raymond and MacDonald, 1998; Muneri and Raymond, 2000). Nevertheless, heritability estimates for pilodyn penetration have been smaller than corresponding estimates for density of wood cores or discs (Greaves et al., 1996; Muneri and Raymond 2000). Reported narrow-sense heritability (h^2) for pilodyn penetration of *Eucalyptus globulus* and *E. nitens* vary from around 0.20 (Muneri and Raymond, 2000) to around 0.60 (Greaves et al. 1996, 1997b). Muneri and Raymond (2000) cited the lower heritability for pilodyn together with a finding that *E. globulus* sub-races ranked differently for pilodyn and wood cores to argue that cores should be preferred to pilodyn for indirect assessment of whole-tree wood density. However, the cost effectiveness of pilodyn remains compelling and Muneri and Raymond's (2000) postulation that genetic ranking was disturbed by sub-race level differences in wood anatomy has not been verified against possible alternative hypotheses.

Iki et al. (2009) analysed the relationship between pilodyn penetration and mean basic density of a standing tree (*Abies sachalinensis*) with and without bark. Though in both cases significant negative correlation was obtained between pilodyn penetration and mean basic density, it was found that pilodyn penetration with bark was more useful than without bark as it was easier.

There are varying opinions regarding the diameter-pilodyn correlation. The correlations have been reported to be near zero (Gea et al., 1997; Tibbits and Hodge 1998). But in a study by Kube and Raymond (2002) on *Eucalyptus nitens* they were strongly adverse (0.63). In their study they also found that heritabilities and genetic correlations for Pilodyn assessed in summer (shooting into early-wood) and winter (shooting into late-wood) were not significantly different.

Pilodyn can also be used as an indirect method for detecting decay in standing trees and logs. Rongfeg et al. (2010) collected and classified the displaced and partially-decayed larch and pine timber frames from the Hall of Military Prowess, the Palace Museum into five categories of decaying. After measuring the radial and tangential penetrations with pilodyn, the classified wood samples were determined for wood densities and the relationships between pilodyn values and wood densities were analyzed from measurements of 125 larch samples and 60 pine samples. The results showed that wood density decreased and the pilodyn values increased with degree of decaying and there existed significant differences in wood density and the pilodyn values among the decay classes. There were significant linear correlations between the tangential and radial penetrations of pilodyn, and significant power function relationship between wood density and tangential penetration, and between wood density and radial penetration for both wood types (P<0.01). The values of correlation coefficient (r) were -0.67 for larch and -0.76 for pine for the relationship between wood density and pilodyn values of tangential penetration, and -0.55 and -0.69 for the relationship between wood density and pilodyn values of radial penetration. Piirto et al. (1992) could effectively assess the decay of giant sequoia ecosystem using pilodyn wood tester in above and below ground.

Wood moisture and temperature may influence the pin penetration of the pilodyn. According to Bonamini et al. (2001) penetration depth is highly correlated with moisture content. However, above fibre saturation point as in living trees, wood moisture content has no bearing on the test result (Micko et al. 1982). In a test of *Gmelina arborea*, Lauridsen et al. (1983) compared the pilodyn readings in the morning and afternoon in order to check the influence of daily fluctuations on wood moisture. However in line with the studies by Micko et al. (1982), they found no significant differences between the conditions.

Pilodyn penetration is not reported to be temperature dependent at temperatures above freezing point. Cheliak et al. (1984) reported that pin penetration fell rapidly between temperatures of zero and minus 10°C. They suggested that the Pilodyn wood tester should only be used at temperatures above 0°C for estimating relative wood density in standing trees.

Cown (1978) compared the pilodyn results with that of torsiometer results which measures the torque when an increment borer is turned into a tree. Apart from the fact that a torsiometer was slower than a pilodyn, the correlation with density was also worse. A limitation of the pilodyn, however, is that it does not record patterns of wood density variation within a stem because the pin penetrates only 7-16 mm, typically the outermost few growth rings (Moura et al., 1987).

Some studies have found pilodyn precision to be low and unreliable for selecting individual trees (Gough and Barnes, 1984; Raymond et al., 1998; Cown, 1998). But it was also found to be very useful for ranking genotypes or for grouping genotypes or sites into density classes if several trees are sampled (Cown, 1981; Moura et al., 1987; Raymond et al., 1998). However, the low cost and simplicity of this method remain strong advantages and, for this reason, it is still being used.

Jingle et al. 2009 used pilodyn to assess wood traits of standing larch trees (*Larix kaempfri*). It was found that pilodyn penetration (Pa) of *L.*

kaempferi had a significant negative correlation with wood fibre character (latewood fibre length and latewood fibre width). Pilodyn penetration could estimate the average of outerwood density and fibre length and fibre width of latewood in the entire radial direction in a standing tree of *Larix kaempferi*, and it could also estimate the basic wood density in an entire radial direction. Wu et al. (2011) reported that pilodyn can be confidently used to indirectly select for fiber width and basic density.

In the study by Aguiar et al. (2003), it was found that a strongly negative (hence favourable) phenotypic and genetic correlation existed between volume and pilodyn, a result which contradicts a well established negative relation between the two traits. This result further suggests that the pilodyn reading taken at fixed height in small size trees will tend to sample different zones of density depending on their specific size. Small trees will be sampled at a lower density section of the stem (towards the tip), whereas big trees will be sampled at a higher density section (towards the butt). Heritability of pilodyn was very low, suggesting that measurements taken at age 12 of *Pinus pinaster* were not a reliable measure of wood density, probably due to the high proportion of juvenile wood.

A possible broad application of pilodyn is to sort logs into broad density classes, making the prices based not only on log size and visual grading but also on density characteristics (Graves et al., 1996; Watt et al., 1996). In standing trees, pin penetration is likely to vary according to normal density variations patterns present in annual ring of softwoods and ring-porous hardwoods (Sprage et al., 1983). Other applications are the genetic control of species (Aguiar et al., 2003), however there is the need to monitor some field trials for a longer period of time to confirm and support the results.

near the base of trees while both types can be used to obtain acoustic velocity of logs (Wang et al., 2007).The transducers of the timer are equipped with a sliding hammer, resulting in quick operation and patented by Weyerhaeuser Company (Chih-Lin, 2005). One test including moving to the next tree takes 40 seconds. The typical distance between transducers is 1 meter. The stress wave is generated by a hammer impact. The high velocity trees produces high strength wood material, hence high velocity trees are preferred for quality wood production (Divos, 2010). Velocity can be calculated by dividing the distance travelled by the stress wave by the time taken (Mochan, 2009)**.** As the distance between the probes is known the stiffness can be determined using the one-dimensional relationship: $E = \rho \times v^2$. where E is the modulus of elasticity, ρ is the green density of the wood in kg/m^3 and v is the velocity in m/s (Chauhan et al., 2005; Chauhan and Walker, 2006; Lasserre et al., 2007).

The FAKOPP treesonic provided good correlations with bending stiffness in a loblolly pine clonal study with an estimated production rate of 800 trees/day for a two-person crew measuring every tree (Eckard 2007). Huber et al. (2006) estimated 840 trees/day in a 8-yr-old slash pine trial, again with two people measuring every tree. These studies were done in favorable conditions.

Dickson et al. (2003) evaluated the efficacy of FAKOPP microsecond timer as a direct measure of wood stiffness using two age classes (9-year and 25-year-old) of *Eucalyptus dunnii*. Trees were measured before and after harvest, sawn, and all boards tested acoustically prior to and after drying and reconditioning. The speed of sound along logs was sufficiently closely correlated with wood stiffness to allow logs to be sorted into stiffness classes. A highly significant and positive relationship was found for acoustic measurements made on logs while a weaker, but still significant, relationship existed for acoustic measurements made on standing trees. For the sawn boards, sound flight velocity in both green and kiln

Watt et al. (1996) found that the pilodyn is able to predict mean outerwood density values with reasonable accuracy, and offer an alternative to the slower and more costly core sampling. These authors calibrated the pilodyn results in specimens of different size against X-ray densitometer values. Gorlacher (1987) obtained good correlation coefficients between density and depth of penetration of the pilodyn 6J, taking into account that the number of measurements for each specimen must be large. This author proposed empirical relations between the depth of penetration and density, showing that these empirical relations are affected by moisture content. The correlation coefficient varied from 0.74 to 0.92, and depended on a number of measurements and species, therefore, species-based calibrations are required.

2.3.2 Treesonic Timer

Acoustic tools such as FAKOPP's Treesonic, Fibre-Gen's Director HM200™ and the Metriguard 2600™ have become increasingly popular in forest and processing environments (Todoroki, 2010). These tools have the potential for providing a rapid, non-destructive method for identifying trees with high stiffness or modulus of elasticity (Wang et al., 2001; Lindstrom et al., 2002; Matheson et al., 2002; Grabianowski et al., 2006). This provides opportunities for better resource quality assessments (Cown, 2005; Chauhan and Walker, 2006), better log segregation into quality classes (Dickson et al., 2004; Amishev and Murphy, 2008), better board segregation into stiffness classes, and early screening for genetic heritability (Kumar et al., 2002), yielding great potential to add value all along the forest-to products chain.

Fakopp treesonic timer use the time-of-flight method to measure acoustic velocity while other tools (e.g., Fibre-gen HM 200) use a resonance acoustic method. The time-of-flight tools are commonly used to obtain acoustic velocity dried boards was strongly correlated with both stiffness and wood hardness. Correlations were strongest for sound velocity in the green boards indicating that grading of boards could be conducted prior to drying. Boards with low strength or hardness could be segregated at this stage, minimizing expenditure on further processing low grade material. Stiffness was significantly positively correlated with wood hardness at both ages in both logs and boards, indicating that segregation based on increasing stiffness would lead to improvements in hardness.

Eckard (2007) assessed the efficiency of the treesonic time-of-flight acoustic tool at screening young clones of loblolly pine for three economically important solid wood properties: wood density, modulus of elasticity (MOE), and modulus of rupture (MOR). Treesonic stress wave speed measurements (SWS) were highly repeatable (0.85) and had moderate and highly significant clone mean correlations with mechanical wood properties. SWS were largely uncorrelated with wood density. Thus, SWS was highly efficient at selecting clones for MOE (0.81), moderate for MOR (0.59) and poor for density (0.03).

Mahon (2007) compared the acoustic velocities for 100 standing loblolly pine (*Pinus taeda)* trees, obtained with the transmitting and receiving probes placed on the same-face and opposite-faces using FAKOPP's treesonic. Significant differences in velocity between the two methods were found, with velocity determined using the opposite-face method generally dependent on stem diameter, or the amount of wood through which the stress wave must pass. However, velocity does not depend on stem size when using the same-face method. Variation in velocities from hit-to-hit was 62% less using the opposite-face method compared to the same-face method.

Materials and methods

MATERIALS AND METHODS

3.1. MATERIALS

3.1.1 Species under Study

The present investigation aimed at studying the mechanical and physical properties of wood in timber species such as: acacia (*Acacia auriculiformis* A. Cunn. ex Benth.), anjily (*Artocarpus hirsutus* Lamk.), jack (*Artocarpus heterophyllus* Lamk.), mahogany (*Swietenia macrophylla* King), pyinkado (*Xylia dolabriformis* Benth.), rubber (*Hevea braziliensis* (H.B.K.) M. A.) and teak (*Tectona grandis* L.f.) using destructive and non-destructive methods and to evaluate the suitability of nondestructive techniques as predictors of timber properties under field conditions.

3.1.1.1 Acacia auriculiformis **A. cunn. Ex Benth.**

Its trade name is ear pod wattle and local name is acacia. It belongs to the family Leguminosae. It is an exotic from Papua New Guinea and Australia. The wood is moderately hard. There is clear distinction between heartwood and sapwood. Sapwood is yellowish white in colour and heartwood is dark brown. The wood is diffuse porous, coarse textured, with straight grain and fairly distinct growth rings. The wood is used for furniture making and constructional purposes.

3.1.1.2 Artocarpus heterophyllus **Lamk.**

Its trade name is jack. Local name is plavu. It belongs to the family Moraceae. It is distributed in tropical evergreen forests and is widely cultivated. The wood is moderately hard and moderately heavy, lustrous, coarse to medium textured with straight to interlocked grain. Sapwood is greyish or pale yellow. Heartwood is yellow to yellowish brown in colour which darkens on exposure. Growth rings are indistinct. Wood is diffuse porous. It is used for constructional purposes and for making furniture and cabinets, carving, turnery, plywood and veneers, blockboard, musical, mathematical, engineering and drawing instruments, lorry and bus bodies and brushware.

3.1.1.3 Artocarpus hirsutus Lamk.

Its trade name is ayani. Local names are anjily, ayani (Mal.), hessuain (Kan.), dinipilla (Tam.), pejata (Tel.) It belongs to the family Moraceae. It is distributed in tropical evergreen, semi-evergreen and southern moist mixed deciduous forests. The wood is moderately hard and heavy, coarse textured with straight or interlocked grain. Sapwood is greyish white and heartwood is golden yellow to yellowish brown; darkens on exposure to yellowish brown. The wood is diffuse porous with indistinct growth rings. The wood can be used for making window, door frames and ceiling boards, furniture and cabinets, turnery, piles, flush door shutters, plywood, blockboard, tool handles, fence posts, textile mill accessories, cooperage, boat and ship, vehicle bodies, beams and rafters, hurdles for sports, mathematical, engineering and drawing instruments, brushware, carts and carriages.

3.1.1.4 Hevea braziliensis (H.B.K.) M. A

The trade name and local name of *Hevea brasiliensis* is rubber. It belongs to the family Euphorbiaceae. Wood is moderately hard, light to moderately heavy, medium coarse textured with straight grain. Sapwood and heartwood are not distinct. Wood is yellowish white or pale white, brownish or creamy on exposure; diffuse porous with distinct growth rings. Wood is used for making packing cases and boxes, fibreboard, particleboard and low quality furniture.

3.1.1.5 Swietenia macrophylla King

Trade name and local name is mahogany. It is an exotic from tropical American regions and is widely cultivated as avenue tree. It belongs to the family Meliaceae. Wood is moderately hard and moderately heavy; diffuse porous; fine to medium coarse textured, lustrous with straight grain. Heartwood and sapwood is distinct. Sapwood is pale reddish, heartwood reddish brown and darkens on exposure. Growth rings are distinct. Wood is mainly used for furniture making and constructional purposes.

3.1.1.6 Tectona grandis **L.f.**

The trade name is teak. Local name is thekku. Wood is moderately hard and moderately heavy, medium coarse textured with straight grain and ring porous. Heartwood and sapwood are distinct. Sapwood is white or pale yellow, heartwood light golden brown when fresh, turning brown or dark brown on exposure, often with darker streaks. Wood has an attractive figure produced by growth rings. The wood has the odour of old leather. Growth rings are distinct. Wood is well known for its good quality and often used as a standard for comparison for other timbers. It has a wide range of uses from shipbuilding, construction, paneling, interior fittings, railway sleepers, furniture and cabinet making. It is an outstanding timber for joinery. Because of its resistance to chemicals it is used in industrial chemical plants.

3.2 METHODS

3.2.1 Selection of Logs

Mature disease free logs with straight bole and balanced form of the above species were selected from the forest depots and retail outlets in Thrissur. From the selected logs, 1.5 m long billets were crosscut using power saw and used for the study (Plate 1). Midgirths of the selected logs were measured using a linen tape. One disc (5 cm thick) was cut from the base of each log using a power saw (Plate 2). Small clear samples for analyzing the physical properties were sawn out from these discs. Details of the logs sampled for study are shown in Table 1.

3.2.2 Measurements Using Nondestructive Instruments

Pilodyn and treesonic microsecond timer were the two non-destructive equipments used in this study.

3.2.2.1 Pilodyn Measurement

Pilodyn is an instrument used for indirect non-destructive assessment of basic density (Greaves et al., 1996; Raymond and Macdonald, 1998; Hoffmayer, 2007) of logs. The pilodyn drives a steel pin into the tree with a precise force. The depth to which the pin penetrates is indicated on the instrument (Plate 3) and is inversely proportional to the density of the wood (Hansen, 2000). In the present study, Pilodyn 6 J (FUJI TECK, Tokyo, Japan) with 2.5 mm pin diameter (Plate 4) was used for taking measurements. Using pilodyn, four readings were taken each from the pith, middle and periphery portions at the end cross section of the logs (Plate 5 and Plate 6). The penetration depth was recorded while the Pilodyn 6J was still pressed against the tree. The penetration was read in millimetres (0-40 mm) on the scale on one side of the instrument.

3.2.2.2 Treesonic Microsecond Timer Measurement

Treesonic microsecond timer (Fakkopp, Hungary) is used to rapidly predict wood stiffness (MOE) of standing trees (Wang et al., 2000; Lindstrom et al., 2002; Kumar, 2004; Toulmin and Raymond, 2007). The instrument is designed and patented by Weyerhaeuser Co. (Chih-Lin, 2005). The timer consists of two

Table 1. Details of the logs sampled for study

SI. No.	Species	Trade Name	Midgirth (cm)	Age (approx.) (years)
1.	*Acacia auriculiformis* A. Cunn. ex Benth.	Acacia	68	12
2.	*Artocarpus hirsutus* Lamk.	Ayani	100	15
3.	*Artocarpus heterophyllus* Lamk.	Jack wood	90	15
4.	*Swietenia macrophylla* King	Mahogany	159	88
5.	*Xylia dolabriformis* Benth.	Pyinkado	123	40
6.	*Hevea braziliensis* (H.B.K.) M. A.	Rubber	102	30
7.	*Tectona grandis* L.f.	Teak	65	35

Plate 1. Cross cutting the logs of species to required size

Plate 2. Crosscutting of discs of species to desired size

Plate 3. Using pilodyn for indirect assessment of density in species

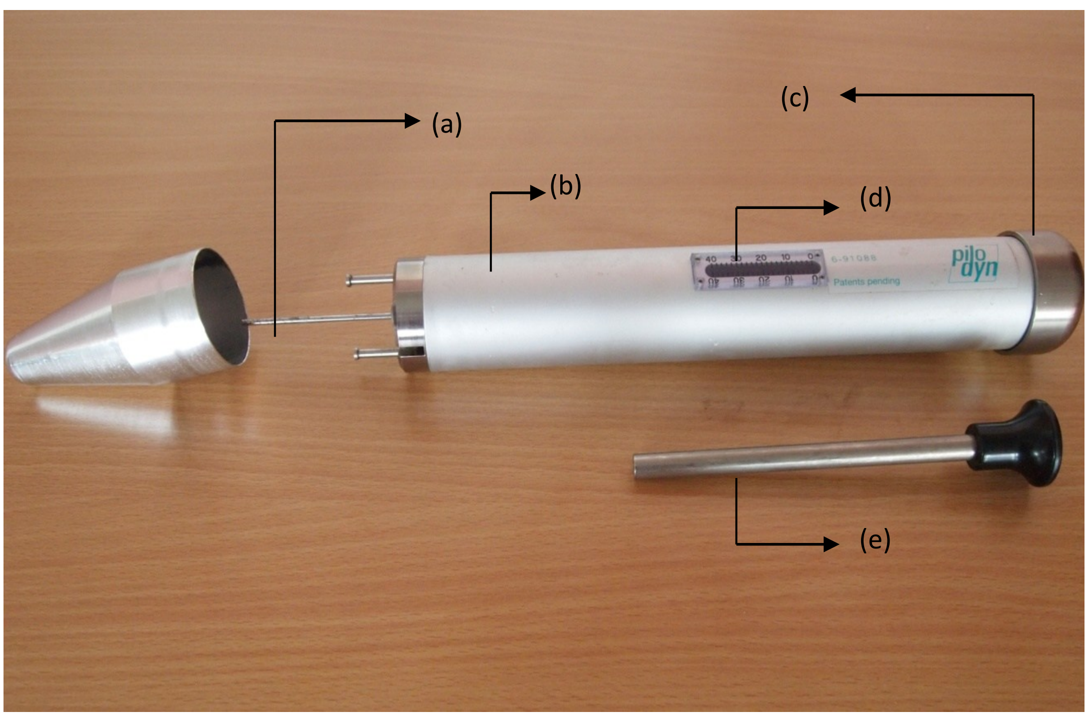

Plate 4. Pilodyn 6J (Fujiteck Corp.) used for the study purpose showing (a) pin, (b) housing, (c) trigger, (d) scale and (e) loading rod

Plate 5. The positions at which measurements were taken at the end cross section of log using pilodyn

Plate 6. Measurements taken in rubber (*Hevea brasiliensis*) using pilodyn

Plate 7. Start and stop transducers inserted into a pyinkado (*Xylia dolabriformis*) log

Plate 8. Measurements taken in teak (*Tectona grandis*) log using treesonic microsecond timer

transducers, the longer and flat shaped transducer is the start and the shorter and cube shaped one is the stop transducer. The transducers were inserted into the end cross section of logs of each of the species (1m length) and the start transducer was hit with a sliding hammer (Plate 7 and 8). The time required for the sound waves to pass from the start transducer to stop transducer through the log was read out from the timer. Five readings were taken from each log (Plate 9). Velocity was calculated by dividing the distance travelled by the stress wave by the time taken (Mochan, 2009)**.** Dynamic MOE (Modulus of Elasticity) or stiffness was determined using the one-dimensional relationship: $E = \rho \times v^2$, where E is the modulus of elasticity, ρ is the actual density of the wood at the time of measurement in kg/m^3 and v is the velocity in m/s (Chauhan et al., 2005; Chauhan and Walker, 2006; Lasserre et al., 2007).

3.2.3 Conversion of Logs

After taking the readings using the pilodyn and treesonic microsecond timer, each of the logs was sawn to scantlings of size 5 cm x 5 cm cross section and 1 m length and 6.25 cm x 6.25 cm cross section and 1 m length (Plate 10 and 11). These scantlings were taken to the Rubber Wood Testing Laboratory of Rubber Research Institute, Kottayam for further conversion to small clear specimens as per IS 2455: 1990 (ISI, 1990) for analyzing the mechanical properties.

3.2.4 Estimation of Physical Properties

3.2.4.1 Wood Specific Gravity

Wood specific gravity of each species was determined using a specific gravity module attached to a precision electronic balance (Shimadzu AUY 220; Plate 12). The samples of size 2 cm x 2 cm cross section and 3 cm length taken

Plate 9. Positions on the end cross section of log at which measurements were taken using treesonic microsecond timer

Plate 10. Conversion of logs to planks before making them to small clear specimens

Plate 11. Scantlings assembled before conversion to small clear specimens

Plate 12. Specific gravity module attached to electronic balance (Shimadzu AUY 220)

Plate 13. Wood samples used for specific gravity estimation

from the disc, representing pith, middle and periphery, were used in the present study (Plate 13). The specific gravity measurements were estimated on air dry and oven dry basis.

To obtain air dry specific gravity, measurements were taken when the samples attained moisture percentage of 12 to 15 per cent (equilibrium moisture condition). Oven dry specific gravity was measured after drying the wood samples in an oven at 102°C±1°C, for such a time as was needed to make its weight constant.

3.2.5 Estimation of Mechanical Properties

The tests for assessing mechanical properties of *Acacia auriculiformis*, *Artocarpus hirsutus*, *Artocarpus heterophyllus*, *Swietenia macrophylla*, *Xylia dolabriformis Hevea braziliensis* and *Tectona grandis* were carried out as per IS 1708: 1986 (ISI, 1986) at the Rubber Wood Testing Laboratory of Rubber Research Institute of India (RRII) Kottayam. Static bending strength, compression strength parallel to grain, compression strength perpendicular to grain, shear, tension parallel to grain and hardness were tested using an automatic 'Universal Testing Machine' (UTM-Shimadzu 100 kg).

3.2.5.1 Testing Instrument

All the mechanical properties were tested using automatic Universal Testing Machine (UTM-Shimadzu 100 kgN). It is a computerized and sophisticated version of the manual UTM. The instrument (Plate 14) used in this study; the automatic Universal Testing machine (UTM, Shimadzu) is an assemblage of different units. The testing units consists of a jig where the samples are loaded for test and a head, whose upward or downward movement applies stress in the sample. The calibration of the instrument is controlled by a control keypad. This set up is associated with a computer installed with the software 'Winsoft", which sense the deflection and stress, and plots the load by deflection curve on the monitor simultaneously along with the test. Before the start of a test, the instrument is calibrated for the type of test, rate of loading, dimensions of sample as per IS 1708: 1986 (ISI, 1986). On completion of the test the stress by strain graph can be directly read from the monitor and various parameters corresponding to the test can be recorded.

3.2.5.2 Preparations of Test Samples

Scantlings of size 5 cm x 5 cm cross section and 1 m length (for static bending, compression strength parallel and perpendicular to grain, tensile parallel test) or 6.25 cm and 6.25 cm cross section and 1 m length (for hardness and shear test) were cut from logs in green condition and allowed to air dry for few days. The scantlings were converted to standard small clear specimens for different tests as per IS 2455: 1990 specified by ISI (1990). The samples were air dried to a moisture content of 12 to 20 percent. The samples were transferred to a conditioning chamber to condition all the samples to a uniform moisture percent of 12±2 per cent (Plate 15).

3.2.5.3 Testing of Samples

3.2.5.3.1 Static Bending Test

Samples of size 2cm x 2cm cross section and 30 cm length were tested as per IS 1708 (part 5): 1986 (ISI, 1986). Before loading the sample for testing, the width and thickness were accurately measured. The samples were loaded such that the stress was on the tangential plane (Plate 16). The machine was calibrated to set the deflection and load at zero and the rate of loading was set at 1mm/minute. Load by deflection curve was read from the monitor. The parameters viz., modulus of elasticity (MOE), modulus of rupture (MOR), maximum load, fibre stress at limit of proportionality (FS at LP) and horizontal shear at limit of proportionality (HS at ML) were recorded for further reanalysis.

Reanalysis of the derived data was done to calculate MOE accurately. The software calculates MOE over a range of deflection at limit of proportionality. To overcome this discrepancy, the tangent of the curve was adjusted to the maximum and deflection corresponding to the proportionality limit was recorded. By substituting the value thus attained in the following formulae, various parameters were reanalyzed.

(a)	Fiber stress at limit of proportionality (kg/cm^2) (FS at LP)	= $3\,PI/2bh^2$
(b)	Modulus of rupture (kg/cm^2) (MOR)	= $3P'I/2bh^2$
(c)	Modulus of elasticity (kg/cm^2) (MOE)	= $PI^3/4\Delta BH^3$
(d)	Horizontal shear stress on neutral plane at limit of proportionality (kg/cm^2) (HS at LP)	= $3P/4bh$
(e)	Horizontal shear stress at maximum load (kg/cm^2) (HS at ML)	= $3P'/4bh$
(f)	Maximum Load (kg) (ML)	= CA"/ lbh

Where,

P = Load in kg at the limit of proportionality which shall be taken as the point in load deflection curve above which the graph deviates from the straight line

I = Span of the test specimen in cm

b = Breadth of test specimen in cm

P' = Maximum load in kg

Δ = Deflection in cm at the limit of proportionality

C = Area constant in kg.cm (the energy represented by one square centimeter which is equal to load in kg, represented by one square centimeter ordinate multiplied by deflection in centimeters, represented by one centimeter abscissa).

A = Area in cm^2 of load deflection curve up to limit of proportionality

3.2.5.3.2 Test for Compression Strength Parallel to Grain

Samples of size 2 cm x 2 cm cross section and 8 cm length were tested as per IS 1708 (part 8): 1986 (ISI, 1986). Before test, the width, thickness and length of the samples were recorded. The rate of loading was calibrated to 0.6 mm/min and the load and deflection was set to zero. The sample was loaded with its longitudinal axis along the direction of movement of head (Plate 17). After the test, data is saved in a folder systematically. Load- deflection curve is analysed through the reanalysis mode. A tangent is drawn in such a way that maximum number of points are in the straight line. Based on the limit of proportionality and maximum load, the Compressive Stress at Limit Proportionality, Compressive Stress at Maximum Load and Modulus of Elasticity was calculated by using the formula given below.

(a) Compressive stress at limit of proportionality (kg/cm^2) (CS at LP) = P/A

Plate 14.Universal Testing Machine (UTM) Plate 15. Wood samples kept for
conditioning

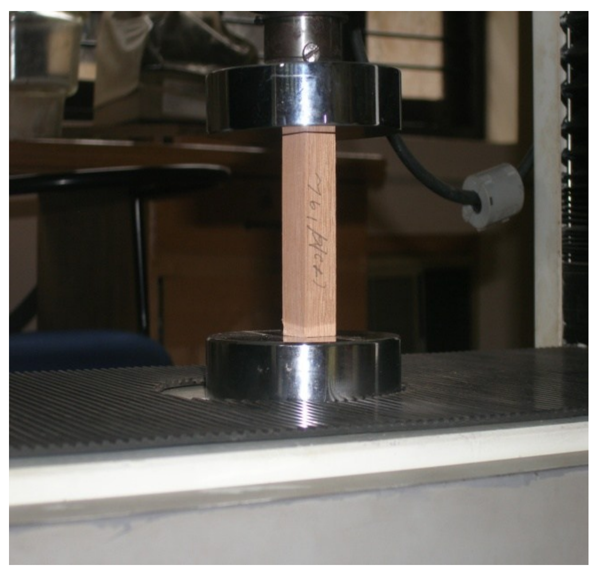

Plate 16. Static bending test Plate 17. Test for compression strength
parallel
to grain

(b) Compressive stress at maximum load (kg/cm^2) (CS at ML) = P'/A

(c) Modulus of elasticity in compression parallel to grain (kg/cm^2) = LP/ΔA

Where,

P = Load at limit of proportionately in kg

A = Cross sectional area of specimen in cm^2

P' = Maximum crushing load in kg

L = Length of the specimen in cm

Δ = Deformation at the limit of proportionately in cm

3.2.5.3.3 Test for Compression Strength Perpendicular to Grain

Samples of size 2 cm x 2 cm cross section and 10 cm length were tested as per IS 1708 (Part 9): 1986 (ISI, 1986). The sample was loaded such that the tangential plane faces the stress (Plate 18). The linear dimensions of the sample were recorded before the test. Rate of loading was calibrated to 0.6 mm/minute and the deflection and load were set to zero. Various parameters were read from the monitor and graph adjusted to reanalyze the MOE. The following parameters were calculated using the formulae.

(a) Compressive stress at limit of proportionality (kg/cm^2) = P/A

(b) Crushing strength at compression of 2.5 mm (kg/cm^2) = P'/A

(c) Modulus of elasticity in compression parallel to grain (kg/cm^2) = P/A x h/Δ

Where,

P	=	Load at limit of proportionately in kg
A	=	Area of cross section normal to the direction of load or area of metal plate used is 3x2 cm.
P'	=	Load at 2.5 mm compression in kg
H	=	Height of the specimen in cm
Δ	=	Deformation at the limit of proportionately in cm

3.2.5.3.4 Hardness Test

Samples of size 5 cm and 5 cm cross section and 15 cm length were tested as per IS 1708 (part 10): 1986 (ISI, 1986) (Plate 19). Load (kN) required to penetrate into the specimen by a steel bar with an hemispherical end or a steel ball of 1.128 cm diameter to a depth of 0.564 cm was recorded. Measurements were made at the centre of the radial, tangential and end faces and no splitting or chipping occurred. The rate of loading was kept constant at 6mm/minute.

3.2.5.3.5 Shear Test

Samples of size 5 cm and 5 cm cross section and 6.25 cm length were tested as per IS 1708 (Part 11): 1986 (ISI, 1986). The specimens were notched at one end to produce shear failure in an area of 5 cm × 5 cm in the radial or tangential plane. The samples were loaded such that the head of the machine rests exactly in the notch (Plate 20). Rate of loading was calibrated to 0.4 mm/minute and the load and deflection were set to zero. Various parameters were analysed by the following formulae. Reanalysis was not done, as the parameters studied were independent of deflection at limit of proportionality.

Maximum shearing stress (kg cm^{-2}) (M.S.S) = P/A

Where

P = Maximum load in Kg

A = Cross section area of specimen in cm^3

3.2.5.3.6 Tensile Strength Parallel to Grain

Samples of 5 cm and 1.5 cm cross section and 32.5 cm in length were tested as per IS 1708 (part 12): 1986 (ISI, 1986) (Plate 21). The machine was calibrated to set the deflection and load at zero and the rate of loading was set at 1 mm/minute. Based on the limit of proportionality and maximum load, TS at LP and TS at ML were calculated by using the formula mentioned below.

Tensile stress at limit of proportionality (kg/cm^2) (TS at LP) = P/A

Tensile stress at maximum load (kg/cm^2) (TS at ML) = P'/A

Where

P = Load at limit of proportionately in kg

P' = Maximum load in kg

A = Cross sectional area of specimen in cm^2

3.2.6 Assessment of Hollow Portion in Teak (*Tectona grandis*) Log

Measurements were taken using the treesonic microsecond timer and pilodyn in teak log to assess the extent of hollow inside (not due to decay) (Plate 22). The length of the log was 6m and the mid girth was 125 cm. The readings were taken by inserting the transducers at 45° of treesonic microsecond timer at 1m interval and hitting the start transducer using hammer starting from the defective end of the log to the other (Fig. 1, Plate 23). Since not much deviation was found in

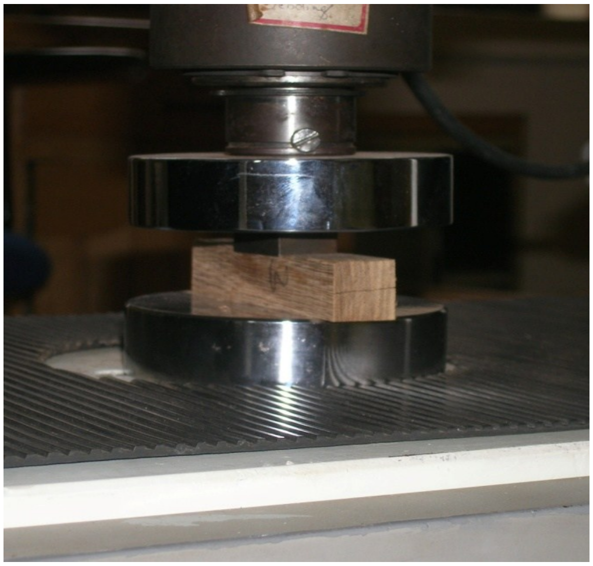

Plate 18. Test for compression strength perpendicular to grain

Plate 19. Test for hardness

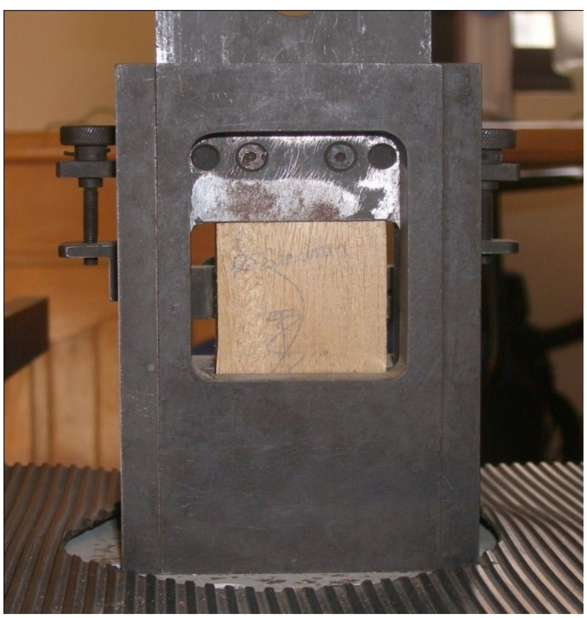

Plate 20. Test for shear strength

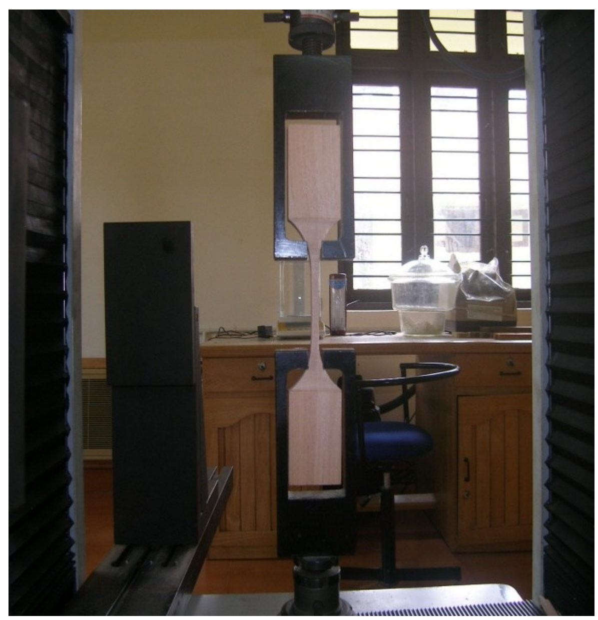

Plate 21. Test for tensile strength parallel to grain

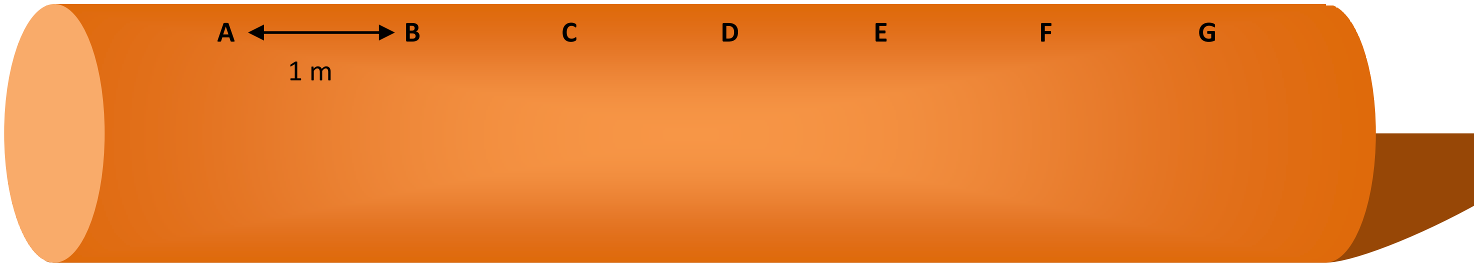

Fig. 1. Positions in the teak log at which measurements were taken by inserting the transducers of treesonic timer at 1 m interval starting from A to G on the same side

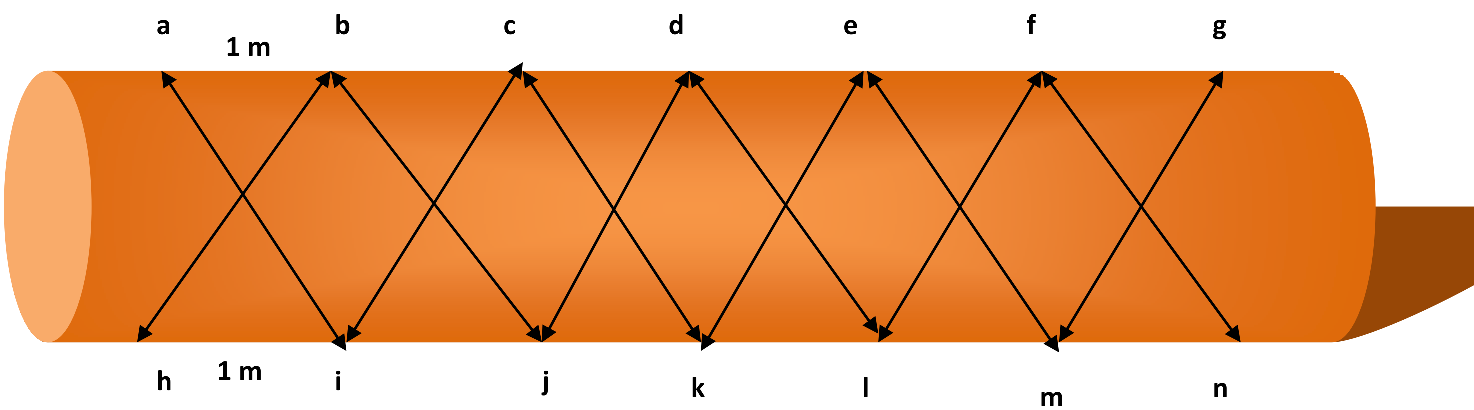

Fig. 2. Positions in the teak log at which measurements were taken by inserting the transducers of treesonic timer at 1 m interval on the opposite side

Plate 22. Teak log having hollow inside used for the study purpose

Plate 23. Measurements taken in teak (*Tectona grandis*) log having hollow inside by inserting the transducers at 1 m interval along the same side of the log

Plate 24. Measurements taken in teak (*Tectona grandis*) log having hollow inside by inserting the transducers at 1 m interval on the opposite side of the log

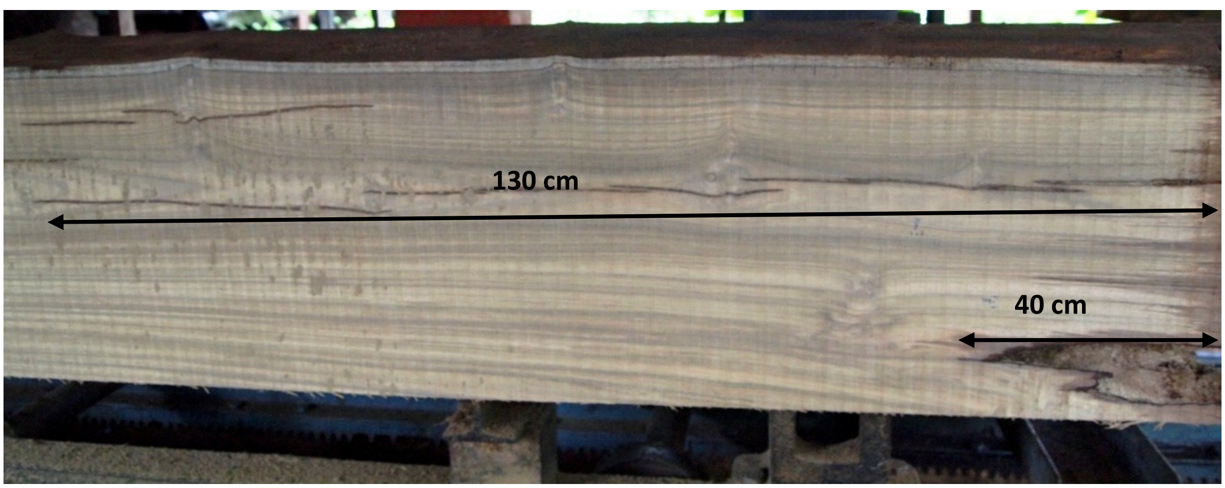

Plate 25. The extent of hollow and shake inside the teak log

the observations to indicate the presence of hollow, measurements were also taken by inserting the transducers at 1m interval on the opposite sides of the log (Fig. 2, Plate 24). After taking the measurements, the log was sawn to planks to actually assess the extent of hollow. There were shakes present inside the wood (Plate 25). Digimizer software was used to measure the actual extent of shake inside the log.

3.2.7 Statistical Analysis

The present study was carried out on seven timber species currently used in Kerala. For each species separate readings were taken using two non-destructive instruments viz., treesonic microsecond timer and pilodyn. Density and mechanical parameters were also found out for each species. Since the study focused mainly on correlating the readings got by non-destructive techniques with density and mechanical parameters, correlations and regressions were done using the statistical software SPSS and SAS. Separate one-way ANOVA was carried out using SPSS for testing the difference between species. Digimizer software was used to find out the extent of shake in teak (*Tectona grandis*) log.

Results

RESULTS

This chapter describes the results of tests conducted destructively and nondestructively (using pilodyn and treesonic microsecond timer) to analyse the wood physical and mechanical properties in acacia (*Acacia auriculiformis*), anjily (*Artocarpus hirsutus*), jack (*Artocarpus heterophyllus*), mahogany (*Swietenia macrophylla*), pyinkado (*Xylia dolabriformis*) rubber (*Hevea brasiliensis*) and teak (*Tectona grandis*).

4.1 PHYSICAL PROPERTIES

4.1.1 **Specific Gravity (Air Dry)**

Specific gravity (air dry) of all the species differed significantly at 1 per cent level (Table 2). *Xylia dolabriformis* was found to have higher mean specific gravity (0.89) followed by *Tectona grandis* (0.78). *Artocarpus hirsutus* (0.70), *Hevea brasiliensis* (0.68), *Acacia auriculiformis* (0.66), and *Artocarpus heterophyllus* (0.64) showed homogeneous values. *Swietenia macrophylla* had the lowest specific gravity (0.54).

4.1.2 **Specific Gravity (Oven Dry)**

Specific gravity of all the species differed significantly at 1 per cent level (Table 2). *Xylia dolabriformis* was found to have higher mean specific gravity (0.85) followed by *Tectona grandis* (0.68). It was also observed that *Hevea brasiliensis* (0.60) and *Acacia auriculiformis* (0.58) showed homogeneous values. *Artocarpus heterophyllus* (0.52) and *Swietenia macrophylla* had the lowest specific gravity (0.47).

Table 2. Variation in specific gravity (oven dry) between the selected tree species

SI. No	Species	Specific gravity (air dry)	Specific gravity (oven dry)
1	*Acacia auriculiformis*	0.66^{c} (0.16)	0.58^{c} (0.15)
2	*Artocarpus hirsutus*	0.70^{c} (0.04)	0.63^{bc} (0.03)
3	*Artocarpus heterophyllus*	0.64^{c} (0.11)	0.52^{d} (0.09)
4	*Swietenia macrophylla*	0.54^{d} (0.02)	0.47^{d} (0.02)
5	*Xylia dolabriformis*	0.89^{a} (0.03)	0.85^{a} (0.04)
6	*Hevea brasiliensis*	0.68^{c} (0.03)	0.60^{c} (0.03)
7	*Tectona grandis*	0.78^{b} (0.06)	0.68^{b} (0.03)

Means with same letters as superscript within a column are at par

Table 3. Results of static bending test of the selected tree species

SI. No	Species	MOR (kg cm-^{2})	Max load (kg cm-^{2})	FS at LP (kg cm-^{2})	HS at LP (kg cm-^{2})	HS at ML (kg cm-^{2})	MOE (kg cm-^{2})
1	*Acacia auriculiformis*	1091.25^{a} (58.55)	203.77^{a} (11.55)	661.92^{b} (82.38)	23.53^{b} (2.98)	38.78^{a} (2.09)	80411.68^{ab} (3762.70)
2	*Artocarpus hirsutus*	602.19^{c} (120.76)	113.21^{c} (22.84)	335.34^{d} (74.77)	11.92^{d} (2.64)	21.41^{c} (4.29)	53485.72^{c} (22078.75)
3	*Artocarpus heterophyllus*	614.48^{c} (170.63)	116.12^{c} (34.51)	348.57^{d} (117.15)	12.41^{d} (4.14)	21.88^{c} (6.11)	59433.65^{c} (30261.31)
4	*Swietenia macrophylla*	742.85^{bc} (50.36)	139.10^{bc} (9.87)	520.21^{c} (49.69)	18.48^{c} (1.79)	26.38^{bc} (1.82)	68827.71^{ab} (3536.41)
5	*Xylia dolabriformis*	1135.11^{a} (183.87)	212.14^{a} (34.28)	718.28^{b} (110.82)	25.50^{b} (3.88)	40.30^{a} (6.52)	80518.58^{ab} (6805.50)
6	*Hevea brasiliensis*	853.85^{b} (44.72)	160.39^{b} (7.27)	532.30^{c} (93.72)	18.90^{c} (3.29)	30.31^{b} (1.45)	57462.96^{c} (1549.94)
7	*Tectona grandis*	1075.99^{a} (85.83)	199.77^{a} (16.58)	822.34^{a} (16.88)	29.10^{a} (0.57)	38.08^{a} (3.09)	96941.41^{a} (15442.15)

Means with same letters as superscript within a column are at par, MOR – Modulus of rupture, Max load - Maximum load, FS at LP – Fibre stress at limit of proportionality, HS at LP – Horizontal shear stress at limit of proportionality, HS at ML – Horizontal shear stress at maximum load, MOE – Modulus of elasticity

4.2 MECHANICAL PROPERTIES

4.2.1 Static Bending Test

4.2.1.1 Modulus of Rupture

The data on variation in modulus of rupture among the species are presented in Table 3. Analysis of variance conducted revealed that all the species differed significantly (1 per cent level) with respect to modulus of rupture. Table 3 reveals that *Xylia dolabriformis* had the highest value (1135.11 kg cm^{-2}) and *Artocarpus hirsutus* (602.19 kg cm^{-2}) had the lowest value.

4.2.1.2 Maximum Load

Maximum load sustained by *Xylia dolabriformis* (1135.11 kg cm^{-2}), *Acacia auriculiformis* (1091.25 kg cm^{-2}) and *Tectona grandis* (1075.99 kg cm^{-2}) were significantly higher than all other species (Table 3). It was also noticed that the load sustained by *Artocarpus hirsutus* (602.19 kg cm^{-2}) and *Artocarpus heterophyllus* (614.48 kg cm^{-2}) were the lowest.

4.2.1.3 Horizontal Shear Stress at Limit of Proportionality

Table 3 shows the variation in horizontal shear stress at limit of proportionality among the species. All the species differed significantly with *Tectona grandis* (29.10 kg cm^{-2}) having the highest value followed by *Xylia dolabriformis* (25.50 kg cm^{-2}) and *Acacia auriculiformis* (23.53 kg cm^{-2}). It was also observed that *Swietenia macrophylla* (18.48 kg cm^{-2}) and *Hevea brasiliensis* (18.90 kg cm^{-2}) had homogeneous values and the values obtained for *Artocarpus hirsutus* (11.92 kg cm^{-2}) and *Artocarpus heterophyllus* (12.41 kg cm^{-2}) were the lowest.

4.2.1.4 Fibre Stress at Limit of Proportionality

Tectona grandis (822.34 kg cm^{-2}) differed significantly from all other species and showed the highest value for fibre stress at limit of proportionality. All the species showed the same trend as was observed in case of horizontal shear stress at limit of proportionality (Table 3).

4.2.1.5 Horizontal Shear Stress at Maximum Load

The data on variation in horizontal shear stress at maximum load among the species are presented in Table 3. Analysis of variance conducted revealed that all the species differed significantly (1 per cent level) with respect to the values. *Xylia dolabriformis* (40.30 kg cm^{-2}), *Acacia auriculiformis* (38.78 kg cm^{-2}) and *Tectona grandis* (38.08 kg cm^{-2}) had higher values compared to other species.

4.2.1.6 Modulus of Elasticity

All the species differed significantly (1 per cent level) with *Tectona grandis* (96941.41 kg cm^{-2}) having the highest value followed by *Xylia dolabriformis* (80518.58 kg cm^{-2}), *Acacia auriculiformis* (80411.68 kg cm^{-2}) and *Swietenia macrophylla* (68827.71 kg cm^{-2}).

4.2.2 Test for Compression Strength Parallel to Grain

4.2.2.1 Compressive Stress at Limit of Proportionality

Table 4 shows the variation in compressive stress at limit of proportionality among the species. It was observed that all the species differed significantly at 1 per cent level. *Xylia dolabriforris* had the highest value (471.35 kg cm^{-2}) and *Hevea brasiliensis* had the lowest value (270.31 kg cm^{-2}).

Table 4. Variation in compression strength parallel to grain of the selected tree species

SI. No	Species	Max Load (kg)	CS at LP (kg cm-^{2})	CS at ML (kg cm-^{2})	MOE (kg cm-^{2})
1	*Acacia auriculiformis*	2224.63^b (140.58)	401.12^b (37.65)	564.56^b (33.88)	54740.93^b (4834.74)
2	*Artocarpus hirsutus*	1847.49^c (171.84)	318.74^c (34.41)	464.98^c (43.30)	46541.51^c (2173.08)
3	*Artocarpus heterophyllus*	1609.36^d (70.48)	278.93^{cd} (18.09)	405.01^d (18.46)	34664.81^d (1375.84)
4	*Swietenia macrophylla*	1501.32^d (34.53)	313.90^c (24.38)	380.24^d (9.01)	43266.86^c (2925.94)
5	*Xylia dolabriformis*	2498.09^a (61.01)	471.35^a (35.59)	636.55^a (18.99)	62308.65^a (3456.02)
6	*Hevea brasiliensis*	1521.85^d (60.47)	270.31^d (30.59)	382.63^d (15.01)	47566.79^c (3724.90)
7	*Tectona grandis*	1555.79^d (147.77)	300.67^{cd} (32.80)	397.44^d (40.49)	59469.31^{ab} (6254.99)

Means with same letters as superscript within a column are at par, CS at LP – Compressive stress at limit of proportionality, CS at ML - Compressive stress at maximum load, MOE – Modulus of elasticity.

Table 5. Variation in compression strength perpendicular to grain of the selected tree species

SI. No	Species	CS at LP (kg cm-^{2})	CS at ML (kg cm-^{2})
1	*Acacia auriculiformis*	104.08^c (8.02)	182.10^c (2.30)
2	*Artocarpus hirsutus*	131.69^b (14.40)	226.75^b (11.84)
3	*Artocarpus heterophyllus*	105.00^c (25.97)	161.74^{cd} (35.06)
4	*Swietenia macrophylla*	170.07^a (13.61)	298.37^a (20.64)
5	*Xylia dolabriformis*	174.57^a (13.75)	301.12^a (17.95)
6	*Hevea brasiliensis*	83.36^d (4.70)	157.42^d (7.68)
7	*Tectona grandis*	131.53^b (13.63)	233.40^b (14.14)

Means with same letters as superscript within a column are at par, CS at LP – Compressive stress at limit of proportionality, CS at ML- Compressive stress at maximum load

4.2.2.2 Maximum Load

Maximum load sustained by *Xylia dolabriformis* (2498.09 kg cm^{-2}) was higher than all other species (Table 4). The values obtained for *Artocarpus heterophyllus* (1609.36 kg cm^{-2}), *Tectona grandis* (1555.79 kg cm^{-2}), *Hevea brasiliensis* (1521.85 kg cm^{-2}) and *Swietenia macrophylla* (1501.32 kg cm^{-2}) were homogeneous and lowest.

4.2.2.3 Compressive Stress at Maximum Load or Maximum Crushing Strength

The data on variation in horizontal shear stress at maximum load among the species are presented in Table 4. Analysis of variance conducted revealed that all the species differed significantly at 1 per cent level with respect to this property. All the species showed the same trend in the values as that obtained for maximum load.

4.2.2.4 Modulus of Elasticity

Modulus of elasticity of *Xylia dolabriformis* was the highest (62308.65 kg cm^{-2}) and differed significantly from all other values (Table 4). The values obtained for *Tectona grandis* (59469.31 kg cm^{-2}) was the second highest and it was followed by *Acacia auriculiformis* (54740.93 kg cm^{-2}). The lowest value for modulus of elasticity was obtained for *Artocarpus heterophyllus* (34664.81 kg cm^{-2}).

4.2.3 Compression Strength Perpendicular to Grain

4.2.3.1 Compressive Stress at Limit of Proportionality

Table 5 shows the variation in compressive stress at limit of proportionality among the species. It was observed that all the species differed significantly at 1 per cent level. The values obtained for *Xylia dolabriformis* (174.57 kg cm^{-2}) and

Swietenia macrophylla (170.07 kg cm^{-2}) was found to be the highest followed by *Artocarpus hirsutus* (131.69 kg cm^{-2}) and *Tectona grandis* (131.53 kg cm^{-2}).

4.2.3.2 Compressive Stress at Maximum Load

The values obtained for *Xylia dolabriformis* (301.12 kg cm^{-2}) and *Swietenia macrophylla* (298.37 kg cm^{-2}) was found to be the highest and differed significantly from the other species (Table 5)

4.2.4 Test for Hardness

4.2.4.1 Radial

The data on variation in radial hardness among the species are presented in Table 6. Analysis of variance conducted revealed that all the species differed significantly at 1 per cent level with respect to the values. The value of radial hardness of *Xylia dolabriformis* (865.53 kg) was the highest. *Acacia auriculiformis* (714.92 kg) obtained higher values compared to *Tectona grandis* (536.63 kg). *Swietenia macrophylla* showed the lowest value (186.90 kg).

4.2.4.2 Tangential

The values obtained for tangential hardness of *Xylia dolabriformis* (859.21 kg) was the highest followed by *Acacia auriculiformis* (694.34 kg). The values of all the species showed the same trend as in case of radial values (Table 6).It should be noted that tangential hardness of anjily (*Artocarpus hirsutus*) (609.27 kg) is higher than that of teak (*Tectona grandis*) (561.19 kg).

4.2.4.3 End

The values of end hardness of all the species showed the same trend as in case of radial and tangential values. *Xylia dolabriformis* (939.78 kg cm^{-2}) had the

Table 6. Results of hardness test of the selected tree species

SI. No	Species	Radial (kg cm-^{2})	Tangential (kg cm-^{2})	End (kg cm-^{2})
1	*Acacia auriculiformis*	714.92^b (93.64)	694.34^b (61.44)	783.57^b (74.98)
2	*Artocarpus hirsutus*	487.09^c (75.11)	609.27^c (57.89)	656.95^c (82.47)
3	*Artocarpus heterophyllus*	342.25^d (59.36)	388.73^d (99.13)	558.93^d (43.22)
4	*Swietenia macrophylla*	186.90^e (26.74)	168.61^e (16.13)	269.25^e (33.15)
5	*Xylia dolabriformis*	865.53^a (23.56)	859.21^a (71.67)	939.78^a (30.99)
6	*Hevea brasiliensis*	384.18^d (27.91)	374.75^d (23.70)	554.13^d (30.81)
7	*Tectona grandis*	536.63^c (45.68)	561.19^c (83.80)	562.29^d (48.08)

Means with same letters as superscript within a column are at par

Table 7. Variation in tensile strength parallel to grain of the selected tree species

SI. No	Species	Max Load (kg)	TS at LP (kg cm-^{2})	TS at ML (kg cm-^{2})
1	*Acacia auriculiformis*	649.94^a (142.87)	384.84^d (26.19)	1273.51^a (220.59)
2	*Artocarpus hirsutus*	228.96^e (27.29)	368.62^d (34.87)	466.21^d (43.72)
3	*Artocarpus heterophyllus*	257.45^{de} (99.70)	393.04^d (111.79)	521.99^d (186.39)
4	*Swietenia macrophylla*	542.12^{ab} (80.55)	556.88^b (111.73)	1107.54^{ab} (166.91)
5	*Xylia dolabriformis*	482.45^{bc} (178.91)	498.70^{bc} (108.43)	973.22^{bc} (340.31)
6	*Hevea brasiliensis*	375.68^{cd} (41.46)	435.25^{cd} (23.74)	741.24^{cd} (56.03)
7	*Tectona grandis*	612.08^{ab} (125.35)	685.25^a (75.45)	1193.98^{ab} (257.04)

Means with same letters as superscript within a column are at par, Max load-Maximum load, TS at LP – Tensile stress at limit of proportionality, TS at ML – Tensile stress at maximum load highest value followed by *Acacia auriculiformis* (783.57 kg cm^{-2}). *Swietenia macrophylla* (186.90 kg cm^{-2}) had the lowest value (Table 6).

4.2.5 Test for Tensile Strength Parallel to Grain

4.2.5.1 Maximum Load

Maximum load sustained by all the species differed significantly at 1 per cent level. The maximum load sustained by *Swietenia macrophylla* (542.12 kg) and *Tectona grandis* (612.08 kg) was found to have similar values (Table 7).

4.2.5.2 Tensile Stress at Limit of Proportionality

At elastic limit, the values obtained for *Artocarpus heterophyllus* (393.04 kg cm^{-2}), *Acacia auriculiformis* (384.84 kg cm^{-2}) and *Artocarpus heterophyllus* (393.04 kg cm^{-2}) was the lowest. *Tectona grandis* (685.25 kg cm^{-2}) had the highest tensile stress at limit of proportionality (Table 7).

4.2.5.3 Tensile Stress at Maximum Load

Table 7 shows the variation in tensile stress at maximum load among the species. It was observed that all the species differ significantly at 1 per cent level. The values obtained for *Acacia auriculiformis* (1273.51 kg cm^{-2}) was found to be the highest followed by *Tectona grandis* (1193.98 kg cm^{-2}) and *Swietenia macrophylla* (1107.54 kg cm^{-2}).

4.2.6 Shear Strength

4.2.6.1 Maximum Load

Maximum load sustained by *Xylia dolabriformis* (4060.59 kg cm^{-2}) was significantly higher than all other species (Table 8). It was also noticed that the load sustained by *Tectona grandis* (2396.04 kg cm^{-2}) and *Swietenia macrophylla* (2225.10 kg cm^{-2}) was the lowest.

4.2.6.2 Maximum Shearing Stress

The values of all the species showed the same trend as observed in case of maximum load sustained by all the species (Table 8). *Xylia dolabriformis* (162.27 kg cm^{-2}) had the highest shearing stress followed by *Artocarpus hirsutus* (138.62 kg cm^{-2}), *Acacia auriculiformis* (137.14 kg cm^{-2}), *Artocarpus heterophyllus* (111.56 kg cm^{-2}), *Hevea brasiliensis* (110.83 kg cm^{-2}), *Tectona grandis* (95.84 kg cm^{-2}) and *Swietenia macrophylla* (89.00 kg cm^{-2}).

4.3 NON DESTRUCTIVE TEST

4.3.1 Penetration Depth Obtained from Pilodyn

Table 9 shows the variation in pilodyn penetration depth among the species. All the species differed significantly at 1 per cent level. The highest penetration depth was obtained for *Artocarpus heterophyllus* (16.75 mm) followed by *Swietenia macrophylla* (13.64 mm). The penetration depth obtained for *Tectona grandis* was 11.83 mm. *Xylia dolabriformis* had the lowest penetration depth (8.42 mm).

4.3.2 Stress Wave Velocity Obtained from Treesonic Microsecond Timer

Table 10 shows the variation in the velocities obtained by using treesonic microsecond timer. The highest velocity was obtained for acacia (*Acacia auriculiformis*) (4781.02 m/s). The velocity obtained for *Acacia auriculiformis* was in par with teak (*Tectona grandis*) (4538.59). Pyinkado (4258.08) had the third highest velocity followed by *Swietenia macrophylla* (3918.40 m/s) *Artocarpus hirsutus* (3357.81 m/s) and *Hevea brasiliensis* (3573.56 m/s).

Table 8. Variation in shear strength of the selected tree species

SI. No.	Species	Max load (kg cm-^{2})	MSS (kg cm-^{2})
1	*Acacia auriculiformis*	3428.45^b (175.24)	137.14^b (7.01)
2	*Artocarpus hirsutus*	3465.42^b (265.57)	138.62^b (10.62)
3	*Artocarpus heterophyllus*	2788.93^c (228.29)	111.56^c (9.13)
4	*Swietenia macrophylla*	2225.10^d (104.95)	89.00^d (4.19)
5	*Xylia dolabriformis*	4060.59^a (419.55)	162.27^a (16.83)
6	*Hevea brasiliensis*	2770.65^c (153.67)	110.83^c (6.15)
7	*Tectona grandis*	2396.04^d (364.34)	95.84^d (14.57)

Means with same letters as superscript within a column are at par, MSS – Maximum shear stress, Max load – Maximum load

Table 9. Variation in penetration depth of the selected tree species

SI. No	Species	Penetration depth (mm)
1	*Acacia auriculiformis*	9.75^d (2.53)
2	*Artocarpus hirsutus*	13.64^c (1.50)
3	*Artocarpus heterophyllus*	16.75^a (4.96)
4	*Swietenia macrophylla*	15.58^{ab} (1.83)
5	*Xylia dolabriformis*	8.42^d (0.90)
6	*Hevea brasiliensis*	12.00^c (1.21)
7	*Tectona grandis*	11.83^c (1.27)

Means with same letters as superscript within a column are at par

Table 10. Variation in stress wave velocity obtained by using treesonic microsecond timer of the selected tree species

SI. No.	Species	Stress wave velocity (m/s)
1	*Acacia auriculiformis*	4781.02[a] (338.87)
2	*Artocarpus hirsutus*	3357.81[d] (94.42)
3	*Artocarpus heterophyllus*	2934.93[e] (123.88)
4	*Swietenia macrophylla*	3918.40[e] (119.67)
5	*Xylia dolabriformis*	4258.08[b] (183.08)
6	*Hevea brasiliensis*	3573.56[d] (142.36)
7	*Tectona grandis*	4538.59[a] (231.86)

Means with same letters as superscript within a column are at par

Table 11. Correlation between penetration depth and specific gravity (oven dry) at pith, middle and periphery positions in *Acacia auriculiformis*

	Pith specific gravity	Middle specific gravity	Periphery specific gravity	Pith penetration depth (mm)	Middle penetration depth (mm)	Periphery penetration depth (mm)
Pith specific gravity	1					
Middle specific gravity	.995**	1				
Periphery specific gravity	0.436	0.464	1			
Pith penetration depth (mm)	-.961*	-0.943	-0.582	1		
Middle penetration depth (mm)	-0.82	-0.783	0.136	0.723	1	
Periphery penetration depth (mm)	-0.658	-0.627	-0.797	0.838	0.31	1

** significant at 1% level; * significant 5% level; others are non significant

4.4 CORRELATION BETWEEN WOOD PHYSICAL AND MECHANICAL PROPERTIES AND NON-DESTRUCTIVE EVALUATION (NDE) PARAMETERS

4.4.1 Correlation with Specific Gravity

4.4.1.1. Correlation between Penetration Depth and Specific Gravity (Oven Dry) at Pith, Middle and Periphery Positions

a. Acacia auriculiformis

There was significant negative correlation between specific gravity taken from pith, middle and periphery regions and penetration depth taken at these positions. The correlation coefficient ranges from -0.783 to -0.961 (Table 11). Pith penetration depth was having significant correlation with pith specific gravity at 5 per cent level.

b. Artocarpus hirsutus

Table 12 shows the correlation coefficients between specific gravity taken from pith, middle and periphery regions and penetration depth taken at these positions. Penetration depths taken at pith, middle and periphery regions were found to be negatively correlated with pith, middle and periphery specific gravity. The correlation coefficient ranges from -0.816 to -0.887.

c. Artocarpus heterophyllus

Specific gravity taken at pith, middle and periphery regions was negatively correlated with penetration depth taken at these positions as shown in Table 13. There is significant negative correlation exists between specific gravity and penetration depth. The correlation coefficient ranges from -0.613 to -0.946.

Table 12. Correlation between penetration depth and specific gravity (oven dry) at pith, middle and periphery positions in *Artocarpus hirsutus*

	Pith specific gravity	Middle specific gravity	Periphery specific gravity	Pith penetration depth (mm)	Middle penetration depth (mm)	Periphery penetration depth (mm)
Pith specific gravity	1					
Middle specific gravity	-0.127	1				
Periphery specific gravity	0.594	-0.853	1			
Pith penetration depth (mm)	-0.932	0.208	-0.324	1		
Middle penetration depth (mm)	0.081	-0.87	0.816	0.132	1	
Periphery penetration depth (mm)	-0.889	0.522	-0.816	0.662	-0.333	1

Table 13. Correlation between penetration depth and specific gravity at pith, middle and periphery positions in *Artocarpus heterophyllus*

	Pith specific gravity	Middle specific gravity	Periphery specific gravity	Pith penetration depth (mm)	Middle penetration depth (mm)	Periphery penetration depth (mm)
Pith specific gravity	1					
Middle specific gravity	0.194	1				
Periphery specific gravity	-0.363	0.795	1			
Pith penetration depth (mm)	-0.926	-0.129	0.269	1		
Middle penetration depth (mm)	0.627	-0.613	-.952*	-0.54	1	
Periphery penetration depth (mm)	0.449	-0.598	-0.946	-0.243	0.923	1

* significant 5% level; others are non significant

d. Swietenia macrophylla

Table 14 shows the correlation coefficients between specific gravity taken from pith, middle and periphery regions and penetration depth taken at these positions. There is significant negative correlation exists between specific gravity and penetration depth. The correlation coefficient ranges from -0.584 to -0.967. Pith penetration depth is having significant correlation with pith specific gravity at 5 per cent level.

e. Xylia dolabriformis

Specific gravity taken at pith, middle and periphery regions was negatively correlated with penetration depth taken at these positions as shown in Table 15. Significant negative correlation exists between specific gravity at taken from pith, middle and periphery regions with pith, middle and periphery penetration depth. The correlation coefficient ranges from -0.793 to -0.943.

f. Hevea brasiliensis

Table 16 shows the correlation coefficients between, middle and periphery specific gravity with pith, middle and periphery penetration depth. Penetration depths taken at pith, middle and periphery regions are negatively correlated with pith, middle and periphery specific gravity as shown in Table 16. The correlation coefficient ranges from -0.707 to -0.940. Pith penetration depth is having significant correlation with pith specific gravity at 1 per cent level.

g. Tectona grandis

Specific gravity taken at pith, middle and periphery regions was negatively correlated with penetration depth taken at these positions as shown in Table 17. Significant negative correlation exists between specific gravity at taken from pith, middle and penetration depth at these positions. The correlation coefficient ranges from -0.845 to -0.927.

Table 14. Correlation between penetration depth and specific gravity (oven dry) at pith, middle and periphery positions in *Swietenia macrophylla*

	Pith specific gravity	Middle specific gravity	Periphery specific gravity	Pith penetration depth (mm)	Middle penetration depth (mm)	Periphery penetration depth (mm)
Pith specific gravity	1					
Middle specific gravity	0.483	1				
Periphery specific gravity	-0.636	0.322	1			
Pith penetration depth (mm)	-.967*	-0.286	0.806	1		
Middle penetration depth (mm)	0.424	-0.584	-0.895	-0.584	1	
Periphery penetration depth (mm)	0.87	0	-0.87	-0.926	0.812	1

* significant 5% level; others are non significant

Table 15. Correlation between penetration depth and specific gravity (oven dry) at pith, middle and periphery positions in *Xylia dolabriformis*

	Pith specific gravity	Middle specific gravity	Periphery specific gravity	Pith penetration depth (mm)	Middle penetration depth (mm)	Periphery penetration depth (mm)
Pith specific gravity	1					
Middle specific gravity	0.608	1				
Periphery specific gravity	0.508	0.548	1			
Pith penetration depth (mm)	-0.793	-0.894	-0.816	1		
Middle penetration depth (mm)	-0.793	-0.894	-0.816	1.000**	1	
Periphery penetration depth (mm)	-0.261	-0.258	-0.943	0.577	0.577	1

** significant at 1% level; others are non significant

Table 16. Correlation between penetration depth and specific gravity (oven dry) at pith, middle and periphery positions in *Hevea brasiliensis*

	Pith specific gravity	Middle specific gravity	Periphery specific gravity	Pith penetration depth (mm)	Middle penetration depth (mm)	Periphery penetration depth (mm)
Pith specific gravity	1					
Middle specific gravity	0.853	1				
Periphery specific gravity	0.313	0.327	1			
Pith penetration depth (mm)	-0.636	-0.426	-0.870	1		
Middle penetration depth (mm)	-0.302	-0.707	0.577	0.302	1	
Periphery penetration depth (mm)	-0.636	-0.853	-0.731	0.636	0.905	1

Table 17. Correlation between penetration depth and specific gravity (oven dry) at pith, middle and periphery positions in *Tectona grandis*

	Pith specific gravity	Middle specific gravity	Periphery specific gravity	Pith penetration depth (mm)	Middle penetration depth (mm)	Periphery penetratio n depth (mm)
Pith specific gravity	1					
Middle specific gravity	.982*	1				
Periphery specific gravity	0.271	0.369	1			
Pith penetration depth (mm)	-0.927	-0.858	0.098	1		
Middle penetration depth (mm)	-0.927	-0.858	0.098	1.000**	1	
Periphery penetration depth (mm)	0.229	0.087	-0.845	-0.577	-0.577	1

** significant at 1% level; * significant 5% level; others are non significant

4.4.1.2 Correlation between Penetration Depth Obtained from All Positions and Specific Gravity (Oven Dry) at All Positions of Each Species

Table 18 gives the correlation coefficient between specific gravity (oven dry) and penetration depth of each species. Significant negative correlation exists between specific gravity (oven dry) and penetration depth in all the species. Penetration depths of all species were found to be negatively correlated with specific gravity on oven dry basis. The correlation coefficient ranges from -0.712 to -0.907. Highest correlation was obtained in *Tectona grandis* (-0.907) followed by *Artocarpus heterophyllus* (-0.883), *Swietenia macrophylla* (-0.873), *Acacia auriculiformis* (-0.859), *Xylia dolabriformis* (-0.842), *Artocarpus hirsutus* (-0.841) and lowest in *Hevea brasiliensis* (-0.712).

4.4.1.3 Correlation between Mean Penetration Depth and Mean Specific Gravity (Oven Dry) of All Species

When Pearson's correlation was done to know the correlation between mean penetration depth and mean specific gravity of each species, correlation coefficient obtained was 0.786.There was significant correlation at 5 per cent level.

4.4.1.4. Correlation between Penetration Depth and Specific Gravity (Air Dry) at Pith, Middle and Periphery Positions

a. Acacia auriculiformis

There is significant negative correlation between specific gravity taken from pith, middle and periphery regions and penetration depth taken at these positions. The correlation coefficient ranges from -0.768 to -0.986 (Table 19).

b. Artocarpus hirsutus

Table 20 shows the correlation coefficients between specific gravity taken from pith, middle and periphery regions and penetration depth taken at these positions. Penetration depths taken at pith, middle and periphery regions were found to be

Table 18. Correlation between pilodyn penetration depth and specific gravity (oven dry) of each species

SI. No	Species	Correlation
1	*Acacia auriculiformis*	-0.859**
2	*Artocarpus hirsutus*	-0.841**
3	*Artocarpus heterophyllus*	-0.883**
4	*Swietenia macrophylla*	-0.873**
5	*Xylia dolabriformis*	-0.842**
6	*Hevea brasiliensis*	-0.712**
7	*Tectona grandis*	-0.907**

** significant at 1% level

Table 19. Correlation between penetration depth and specific gravity (air dry) at pith, middle and periphery positions in *Acacia auriculiformis*

	Pith specific gravity	Middle specific gravity	Periphery specific gravity	Pith penetration depth (mm)	Middle penetration depth (mm)	Periphery penetration depth (mm)
Pith specific gravity	1					
Middle specific gravity	.993**	1				
Periphery specific gravity	0.527	0.465	1			
Pith penetration depth (mm)	-.960*	-0.93	-0.742	1		
Middle penetration depth (mm)	-0.809	-0.768	-0.199	0.723	1	
Periphery penetration depth (mm)	-0.656	-0.604	-.986*	0.838	0.31	1

** significant at 1% level; * significant 5% level; others are non significant

negatively correlated with pith, middle and periphery specific gravity. The correlation coefficient ranges from -0.768 to 1.000

c. Artocarpus heterophyllus

Specific gravity taken at pith and periphery regions was negatively correlated with penetration depth taken at these positions as shown in Table 21. The correlation coefficient ranges from 0.044 to -0.950.

d. Swietenia macrophylla

Table 22 shows the correlation coefficients between specific gravity taken from pith, middle and periphery regions and penetration depth taken at these positions. There is significant negative correlation exists between specific gravity and penetration depth. The correlation coefficient ranges from -0.477 to -0.870.

e. Xylia dolabriformis

Specific gravity taken at pith and middle regions was negatively correlated with penetration depth taken at these positions as shown in Table 23. But the penetration depth at the middle region was positively correlated with middle specific gravity. The correlation coefficient ranges from -0.894 to 0.522.

f. Hevea brasiliensis

Penetration depths taken at pith and middle regions were negatively correlated with pith and middle specific gravity as shown in Table 24. The correlation coefficient ranges from -0.447 to 0.853. Pith penetration depth is having significant correlation with pith specific gravity at 1 per cent level.

g. Tectona grandis

Specific gravity taken at pith, middle and periphery regions was negatively correlated with penetration depth taken at these positions as shown in Table 25. Significant negative correlation exists between specific gravity at taken from pith,

Table 20. Correlation between penetration depth and specific gravity (air dry) at pith, middle and periphery positions in *Artocarpus hirsutus*

	Pith specific gravity	Middle specific gravity	Periphery specific gravity	Pith penetration depth (mm)	Middle penetration depth (mm)	Periphery penetration depth (mm)
Pith specific gravity	1					
Middle specific gravity	-0.067	1				
Periphery specific gravity	-0.211	-0.632	1			
Pith penetration depth (mm)	-0.768	-0.132	-0.168	1		
Middle penetration depth (mm)	0.067	-1.000**	0.632	0.132	1	
Periphery penetration depth (mm)	-0.2	0.333	-0.843	0.662	-0.333	1

** significant at 1% level; * significant 5% level; others are non significant

Table 21. Correlation between penetration depth and specific gravity (air dry) at pith, middle and periphery positions in *Artocarpus heterophyllus*

	Pith specific gravity	Middle specific gravity	Periphery specific gravity	Pith penetration depth (mm)	Middle penetration depth (mm)	Periphery penetration depth (mm)
Pith specific gravity	1					
Middle specific gravity	0.209	1				
Periphery specific gravity	-0.074	-0.052	1			
Pith penetration depth (mm)	-.950*	-0.344	-0.197	1		
Middle penetration depth (mm)	0.808	0.044	-0.629	-0.591	1	
Periphery penetration depth (mm)	0.575	0.052	-0.852	-0.313	0.943	1

* significant 5% level; others are non significant

Table 22. Correlation between penetration depth and specific gravity (air dry) at pith, middle and periphery positions in *Swietenia macrophylla*

	Pith specific gravity	Middle specific gravity	Periphery specific gravity	Pith penetration depth (mm)	Middle penetration depth (mm)	Periphery penetration depth (mm)
Pith specific gravity	1					
Middle specific gravity	0.878	1				
Periphery specific gravity	-0.135	0.197	1			
Pith penetration depth (mm)	-0.477	-0.366	0.782	1		
Middle penetration depth (mm)	-0.651	-0.847	-0.658	-0.185	1	
Periphery penetration depth (mm)	0.258	0.126	-0.87	-.968*	0.42	1

* significant 5% level; others are non significant

Table 23. Correlation between penetration depth and specific gravity (air dry) at pith, middle and periphery positions in *Xylia dolabriformis*

	Pith specific gravity	Middle specific gravity	Periphery specific gravity	Pith penetration depth (mm)	Middle penetration depth (mm)	Periphery penetration depth (mm)
Pith specific gravity	1					
Middle specific gravity	0.585	1				
Periphery specific gravity	0.726	0.405	1			
Pith penetration depth (mm)	-0.757	-0.894	-0.302	1		
Middle penetration depth (mm)	-0.757	-0.894	-0.302	1.000**	1	
Periphery penetration depth (mm)	-0.199	-0.258	0.522	0.577	0.577	1

** significant at 1% level; * significant 5% level; others are non significant

Table 24. Correlation between penetration depth and specific gravity (air dry) at pith, middle and periphery positions in *Hevea brasiliensis*

	Pith specific gravity	Middle specific gravity	Periphery specific gravity	Pith penetration depth (mm)	Middle penetration depth (mm)	Periphery penetration depth (mm)
Pith specific gravity	1					
Middle specific gravity	-0.316	1				
Periphery specific gravity	0.316	-1.000**	1			
Pith penetration depth (mm)	0.674	0.426	-0.426	1		
Middle penetration depth (mm)	-0.447	0.707	-0.707	0.302	1	
Periphery penetration depth (mm)	-0.135	0.853	-0.853	0.636	0.905	1

** significant at 1% level; others are non significant

Table 25. Correlation between penetration depth and specific gravity (air dry) at pith, middle and periphery positions in *Tectona grandis*

	Pith specific gravity	Middle specific gravity	Periphery specific gravity	Pith penetration depth (mm)	Middle penetration depth (mm)	Periphery penetration depth (mm)
Pith specific gravity	1					
Middle specific gravity	0.812	1				
Periphery specific gravity	-0.71	-0.371	1			
Pith penetration depth (mm)	-0.882	-0.931	0.676	1		
Middle penetration depth (mm)	-0.882	-0.931	0.676	1.000**	1	
Periphery penetration depth (mm)	0.436	0.248	-0.911	-0.577	-0.577	1

** significant at 1% level; others are non significant middle and penetration depth at these positions. The correlation coefficient ranges from -0.882 to -0.931.

4.4.1.5 Correlation between Penetration Depth Obtained from All Positions and Mean Specific Gravity (Air Dry) at All Positions of Each Species

Table 26 gives the correlation coefficient between specific gravity (air dry) and penetration depth of each species. Except *Hevea brasiliensis*, correlation coefficients of all other species showed significant negative correlation (1 per cent level) with pilodyn penetration depth. The highest correlation was noticed in *Tectona grandis* (0.94) followed by *Acacia auriculiformis* (0.90) and the lowest correlation was noticed in *Hevea brasiliensis* (0.56).

4.4.1.6 Correlation between Mean Penetration Depth and Mean Specific Gravity of All Species

Pearson's correlation was done to assess the correlation between mean penetration depth and mean specific gravity of all species. Negative correlation was noticed and the correlation coefficient obtained was -0.698.

4.4.2 Correlation with Mechanical Parameters

4.4.2.1 Correlation between Dynamic MOE and Mechanical Parameters

4.4.2.1.2 Correlation between Dynamic MOE and Parameters Obtained from Static Bending Test

A Pearson's correlation analysis was performed to analyze the relationship between dynamic MOE and mechanical parameters. A significant (1 per cent level) correlation was found between dynamic MOE and parameters obtained from static bending test like horizontal shear stress at limit of proportionality, horizontal shear stress at maximum load, fibre stress at limit of proportionality, modulus of rupture and static MOE. The correlation coefficient ranges from 0.883 to 0.949. The correlation coefficient between Static MOE of each species and Dynamic MOE

Table 26. Correlation between specific gravity (air dry) and penetration depth in the selected species

SI. No	Species	Correlation
1	*Acacia auriculiformis*	-0.900**
2	*Artocarpus hirsutus*	-0.829**
3	*Artocarpus heterophyllus*	-0.863**
4	*Swietenia macrophylla*	-0.772**
5	*Xylia dolabriformis*	-0.722**
6	*Hevea brasiliensis*	-0.563
7	*Tectona grandis*	-0.944**

** significant at 1% level

was 0.876 which is significant at 1 per cent level (Table 19). Dynamic MOE showed greatest correlation with modulus of rupture and horizontal shear stress at maximum load (Table 27).

4.4.2.1.3 Correlation between Dynamic MOE and Compressive Strength Parallel to Grain

Modulus of elasticity showed significant correlation with dynamic MOE. Correlation coefficient obtained was 0.919 (Table 27).

4.4.2.1.4 Correlation between Dynamic MOE and Hardness

A significant correlation at 5 per cent level was found between radial and tangential hardness and dynamic MOE (Table 27).

4.4.2.1.5 Correlation between Dynamic MOE and Shear

There was no significant correlation between dynamic MOE and Maximum shearing stress. Correlation coefficient obtained was 0.445 (Table 27).

4.4.2.2 Correlation between Stress Wave Velocity and Mechanical Parameters

Stress wave velocity also showed significant correlation with all the parameters obtained from static bending test like horizontal shear stress at limit of proportionality, horizontal shear stress at maximum load, fibre stress at limit of proportionality, modulus of rupture and static MOE. Stress wave velocity was also correlated with tensile stress at maximum load at 5 per cent level (Table 27).

4.4.2.3 Correlation between Penetration Depth and Mechanical Parameters

It was observed that the penetration depth showed significant negative correlation at 5 per cent level with radial hardness (-0.87) (Table 27). Penetration depth showed significant correlation at 1 per cent level with all the parameters obtained from static bending test like modulus of rupture (0.93) and horizontal

Table 27. Correlation of dynamic MOE, stress wave velocity and penetration depth with mechanical parameters and specific gravity

	HR	HT	MSS	MOR	HS at ML	HS at LP	FS at LP	SMOE	TS at ML	CS MOE	SPG	DMOE	Velocity	PD
HR	1													
HT	.98**	1												
MSS	.83*	.87*	1											
MOR	0.75	0.61	0.31	1										
HS at ML	0.75	0.61	0.31	1.00**	1									
HS at LP	0.56	0.43	0.04	.95**	.94**	1								
FS at LP	0.56	0.43	0.04	.95**	.94**	1.00**	1							
MOE	0.51	0.41	-0.02	.86*	.86*	.95**	.95**	1						
TS at ML	0.30	0.14	-0.15	.79*	.79*	.84*	.84*	.86*	1					
CS MOE	.80*	0.74	0.44	.90**	.90**	.87*	.87*	.80*	0.62	1				
SPG	.84*	.85*	0.69	0.64	0.64	0.55	0.55	0.45	0.11	0.81*	1			
DMOE	.85*	.77*	0.45	.95**	.95**	.89**	.88**	.88**	0.73	.92**	0.69	1		
Velocity	0.58	0.46	0.15	.89**	.89**	.89**	.89**	.89**	.93**	.83*	0.38	.89**	1	
PD	-.87*	-0.75	-0.58	-.93**	-.93**	-.78*	-.78*	-0.64	-0.56	-.90**	-0.79*	-.88**	-.77*	1

Means with same letters as superscript within a column are at par, HR – Radial hardness (kg), HT - compressive stress parallel to grain, SPG – Specific gravity (oven dry), DMOE – Dynamic MOE (kg cm^{-2}) , SPG – Specific gravity (oven dry), PD – Penetration depth (mm) shear at maximum load (0.93) and with the non-destructive instrument treesonic microsecond timer (-0.88).

4.5 REGRESSION ANALYSIS BASED OF PHYSICAL PROPERTIES AND NON DESTRUCTIVE EVALUATION METHODS

4.5.1 Regression between Specific Gravity (Oven Dry) and Penetration Depth in the Selected Species

4.5.1.1 Acacia auriculiformis

Linear relationship exists between specific gravity (oven dry) and penetration depth of *Acacia auriculiformis* as shown in Fig. 3. The R^2 value obtained was 0.74.

4.5.1.2 Artocarpus hirsutus

Linear relationship exists between specific gravity (oven dry) and penetration depth of *Artocarpus hirsutus* (Fig. 4). The R^2 value obtained was 0.71.

4.5.1.3 Artocarpus heterophyllus

Linear relationship exists between specific gravity (oven dry) and penetration depth of *Artocarpus heterophyllus* as shown in Fig. 5. The R^2 value obtained was 0.78.

4.5.1.4 Swietenia macrophylla

Linear relationship exists between specific gravity (oven dry) and penetration depth of *Swietenia macrophylla* (Fig. 6). The R^2 value obtained was 0.76.

4.5.1.5 Xylia dolabriformis

Linear relationship exists between specific gravity (oven dry) and penetration depth of *Xylia dolabriformis* as shown in Fig. 7. The R^2 value obtained was 0.71.

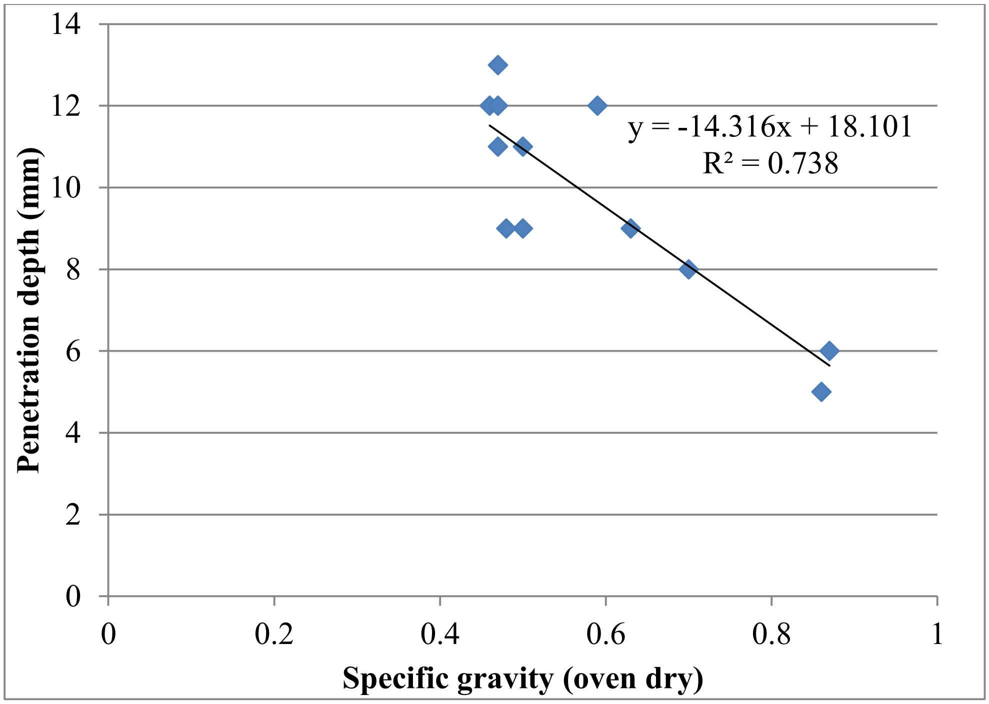

Fig. 3. Relation between specific gravity (oven dry) and penetration depth in *Acacia auriculiformis*

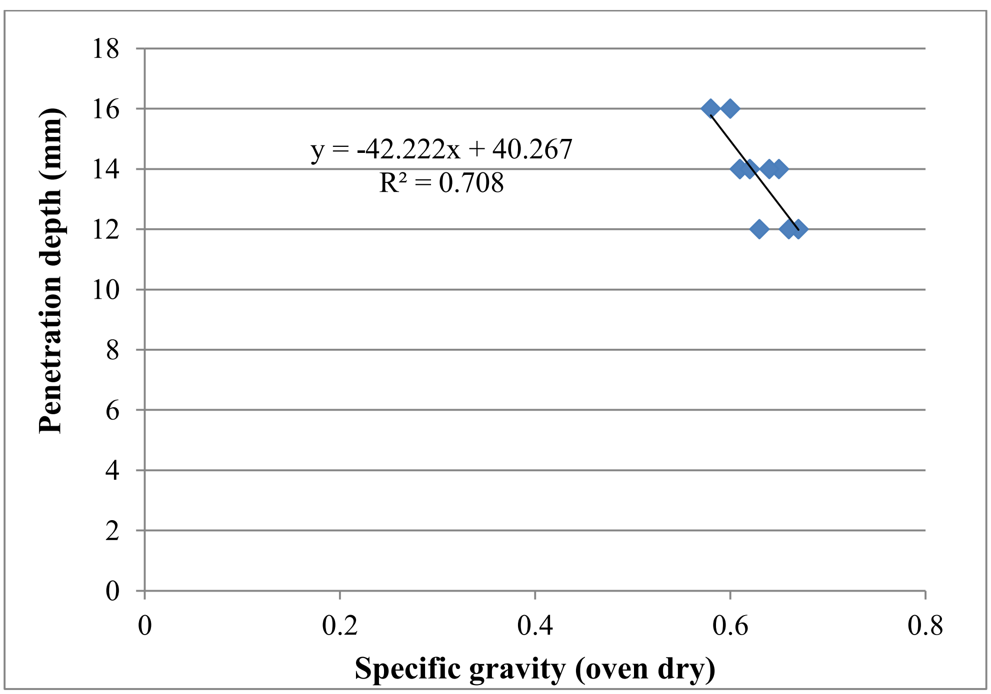

Fig. 4. Relation between specific gravity (oven dry) and penetration depth in *Artocarpus hirsutus*

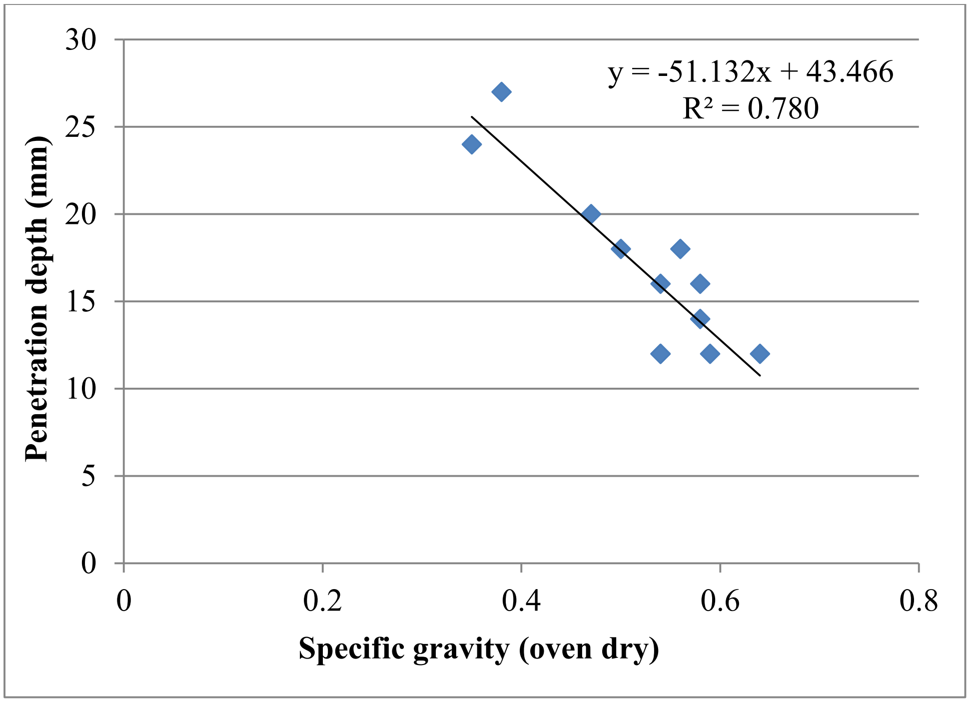

Fig. 5. Relation between specific gravity (oven dry) and penetration depth in *Artocarpus heterophyllus*

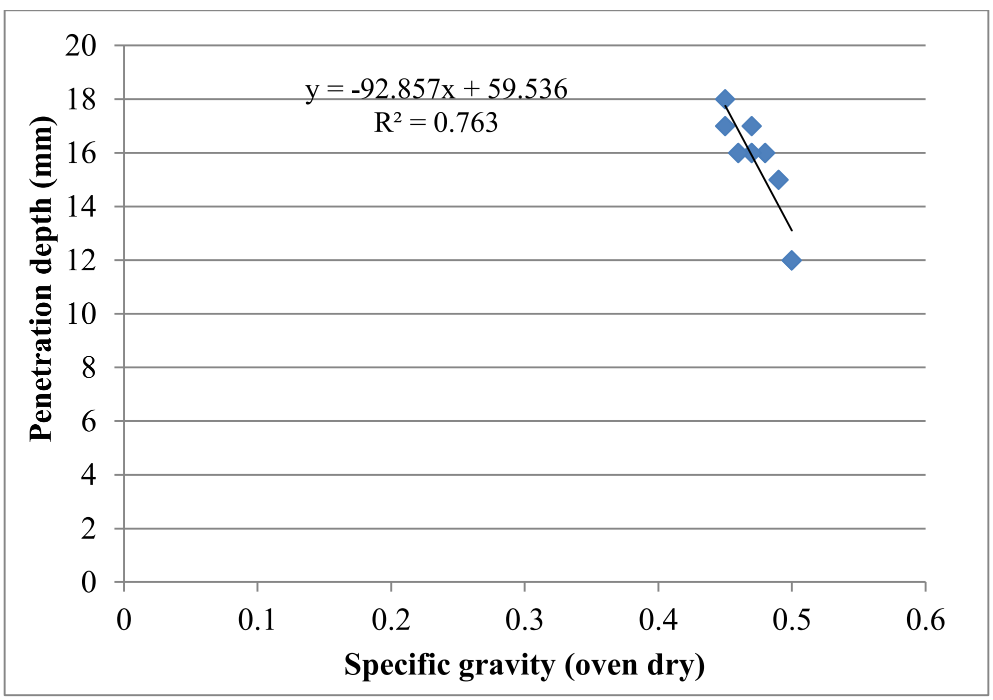

Fig. 6. Relation between specific gravity (oven dry) and penetration depth in *Swietenia macrophylla*

4.5.1.6 Hevea brasiliensis

In *Hevea brasiliensis* also, linear relationship between specific gravity (oven dry) and penetration depth was observed. The R^2 value obtained was 0.51 (Fig. 8).

4.5.1.7 *Tectona grandis*

In *Tectona grandis* also, a linear relationship between specific gravity (oven dry) and penetration depth was noticed. The R^2 value obtained was 0.83 (Fig. 9).

4.5.2 Regression between Average Specific Gravity (Oven Dry) and Average Penetration Depth of Each Species

A linear relationship was observed between average specific gravity (oven dry) and average penetration depth with R^2 value of 0.62 as shown in Fig. 10.

4.5.3 Regression between Specific Gravity (Air Dry) and Penetration Depth in the Selected Species

Regression equations obtained when penetration depth obtained from all positions were correlated with specific gravity (air dry) in each species (Table 28). R^2 value obtained was highest in *Tectona grandis* (0.891) followed by *Acacia auriculiformis* (0.809). Lowest R^2 value was obtained in *Hevea brasiliensis* (0.317).

4.5.4 Regression between Static MOE and Dynamic MOE

A linear relationship exists between static MOE and dynamic MOE with R^2 value of 0.767 as shown in Fig. 10.

4.5.5 Multilinear Regression to Analyze the Influence of Moisture Content on Penetration Depth and Dynamic Modulus of Elasticity

In order to know the influence of moisture content on penetration depth, a multilinear regression was done keeping moisture content and specific gravity as

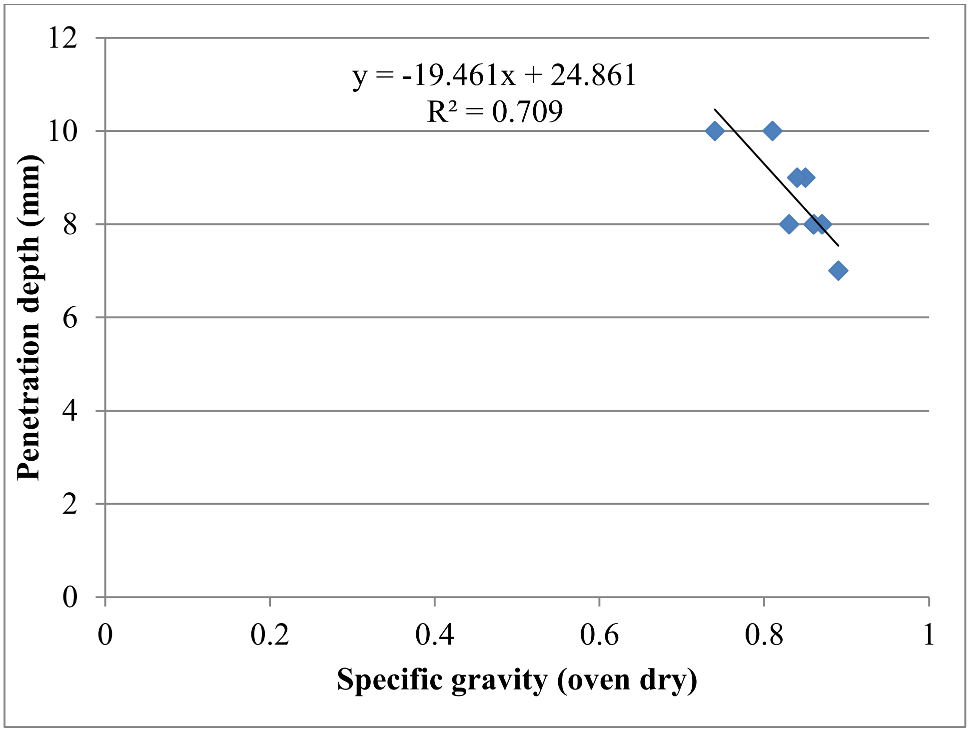

Fig. 7. Relation between specific gravity (oven dry) and penetration depth in *Xylia dolabriformis*

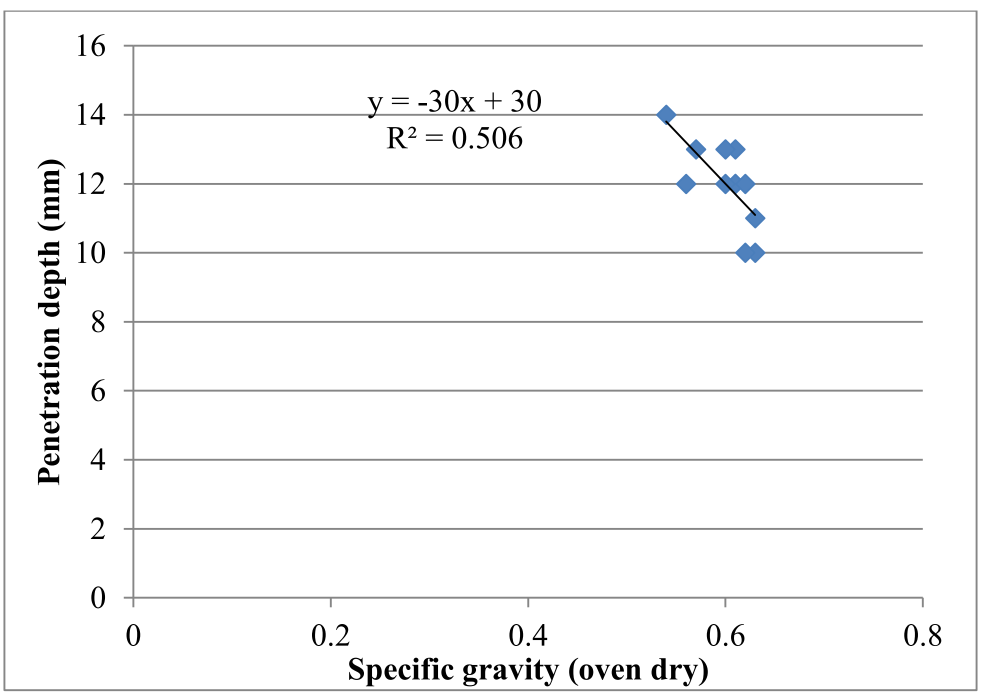

Fig. 8. Relation between specific gravity (oven dry) and penetration depth in *Hevea brasiliensis*

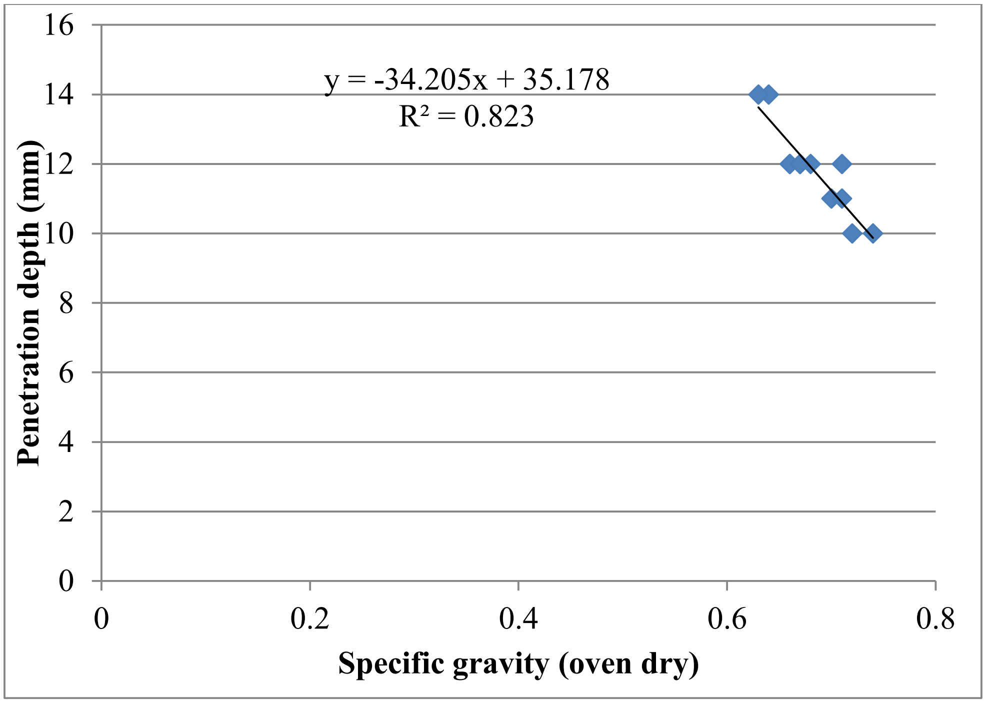

Fig. 9. Relation between specific gravity (oven dry) and penetration depth in *Tectona grandis*

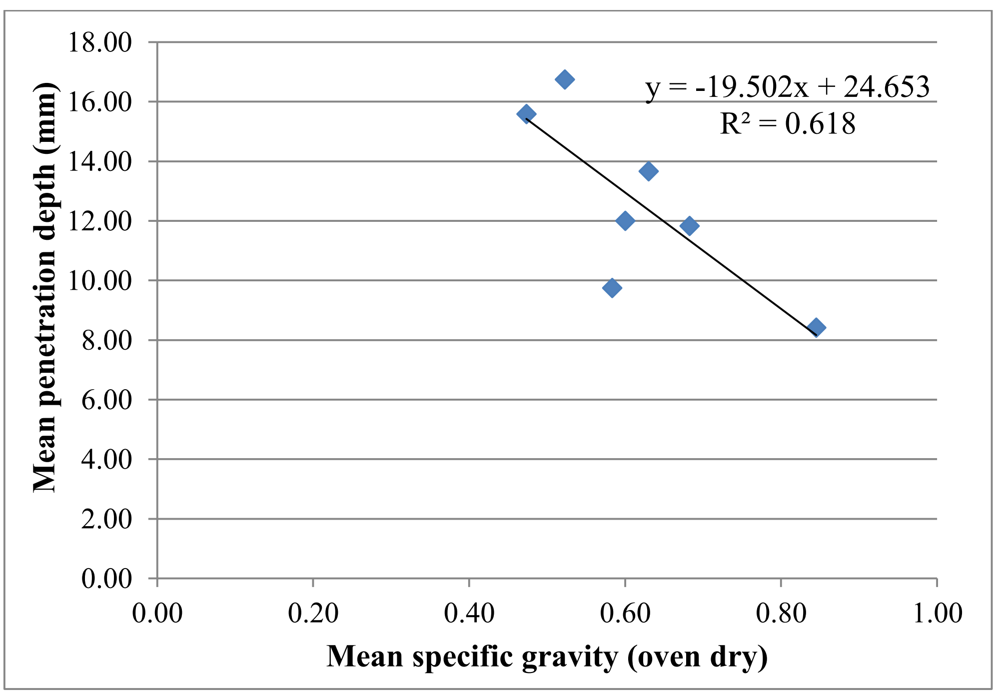

Fig. 10. Relation between average specific gravity (oven dry) and average penetration depth in each of the species

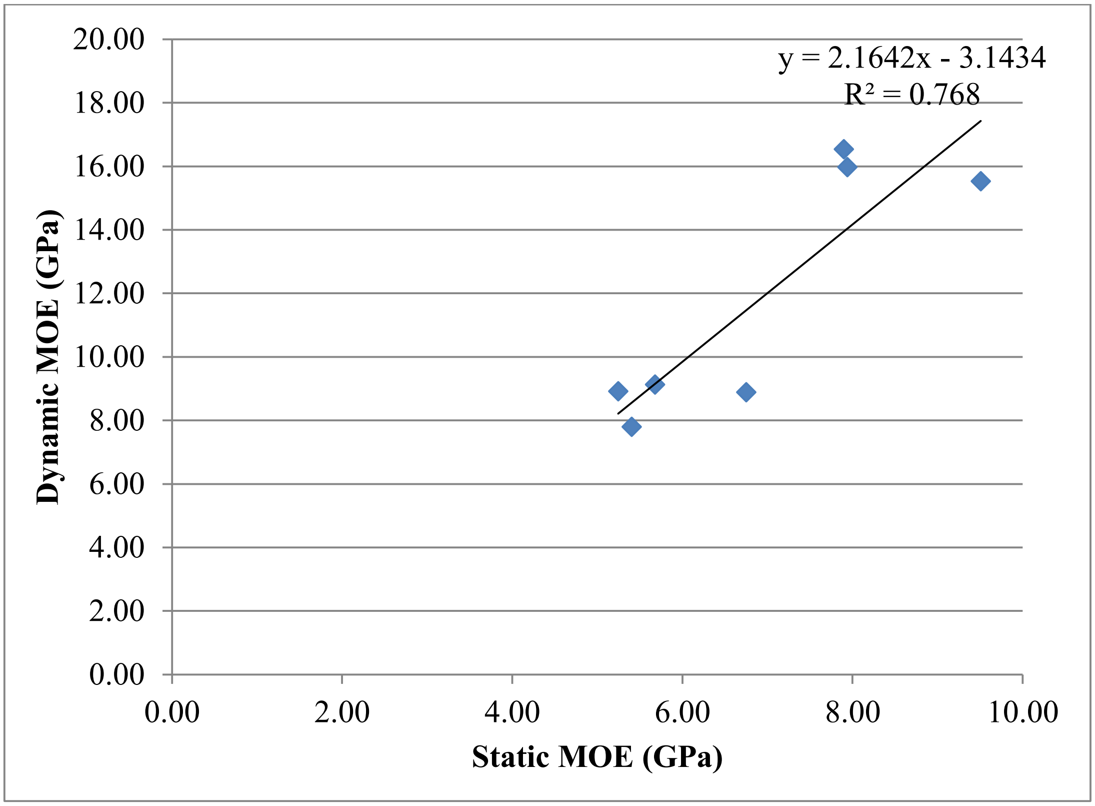

Fig 11. Relation between static MOE and dynamic MOE of each species

Table 28. Results of regression in case of specific gravity (air dry) (X) and penetration depth (Y)

SI No.	Species	Fitted equation	R^2 Square
1	*Acacia auriculiformis*	Y = -14.247 X + 19.105	0.809
2	*Artocarpus hirsutus*	Y = -52.822 X + 52.063	0.687
3	*Artocarpus heterophyllus*	Y = -39.685 X + 42.314	0.744
4	*Swietenia macrophylla*	Y = -66.169 X + 51.149	0.596
5	*Xylia dolabriformis*	Y = -19.355 X + 25.642	0.521
7	*Tectona grandis*	Y = -21.618 X + 28.821	0.891

independent factors and penetration depth as dependent factor. The influence of moisture was found to be non significant (-0.434). Similarly in order to check the influence of moisture content on dynamic MOE, a multilinear regression was done keeping moisture content and static MOE as independent factors and dynamic MOE as dependent factor. It was noticed that the influence of moisture on dynamic MOE was non significant (0.575).

4.6 ASSESSMENT OF HOLLOW PORTION IN TEAK (*Tectona grandis*) LOG

The stress wave velocities obtained when the transducers of the treesonic microsecond timer were inserted from the defective end of the teak log to the other end at 1m interval along the same side was given in Table 29. The velocity obtained range from 4201.68 m/s to 4504.50 m/s. The stress wave velocities obtained when the transducers were inserted on the opposite sides of the log at 1m interval were shown in Table 30. Then the velocity obtained range from 1824.82 m/s to 3225.81 m/s.

Table 29. Measurements obtained when transducers were inserted along the same side of teak log at 1 m interval

Positions	Time (µs)	Velocity (m/s)
AB	222	4504.50
BC	236	4237.29
CD	233	4291.85
DE	246	4065.04
EF	228	4385.96
FG	238	4201.68

Table 30. Measurements obtained when transducers were inserted on the opposite side of teak log at 1 m interval

Positions	Time (µs)	Velocity (m/s)
ai	548	1824.82
bh	533	1876.17
bj	517	1934.24
ci	497	2012.07
ck	364	2747.25
dj	346	2890.17
dl	346	2890.17
ek	334	2994.01
fl	326	3067.48
em	314	3184.71
gm	320	3125.00
fn	310	3225.81

Discussion

DISCUSSION

The present investigation envisages a detailed study of the physical and mechanical properties of wood in timber species such as: acacia (*Acacia auriculiformis* A. Cunn. ex Benth.), anjily (*Artocarpus hirsutus* Lamk.), jack (*Artocarpus heterophyllus* Lamk.), mahogany (*Swietenia macrophylla* King), pyinkado (*Xylia dolabriformis* Benth.), rubber (*Hevea braziliensis* (H.B.K.) M. A.) and teak (*Tectona grandis* L.f.), using destructive and non-destructive methods. The study also aims to evaluate the suitability of non-destructive techniques (NDT) and semi-destructive techniques (SDT) as predictors of timber properties under field conditions.

5.1 PHYSICAL PROPERTIES

5.1.1 Specific Gravity

Wood density or specific gravity is considered the best single index of wood quality because it is the most dependable characteristic for predicting timber strength (Shirin et al., 1998). It correlates with numerous morphological, mechanical, physiological, and ecological properties (Jerome et al., 2006). It is influenced by cell wall thickness, the proportion of different kind of tissues, and the percentage of lignin, cellulose and extractives (Valente et al., 1992).

The present study revealed that wood specific gravity (oven dry) significantly differed between species. *Xylia dolabriformis* was found to have the highest mean specific gravity (0.85) followed by *Tectona grandis* (0.68). It was also observed that *Hevea brasiliensis* (0.60) and *Acacia auriculiformis* (0.58) showed homogeneous values. *Artocarpus heterophyllus* (0.52) and *Swietenia macrophylla* had the lowest specific gravity (0.47). Significant variation in specific gravity (air dry) was also noticed between species. The variation in the specific gravity among the species may be due to difference in the cell wall thickness, the proportion of different kind of tissues and the percentage of lignin, cellulose and extractives.

5.2 MECHANICAL PROPERTIES

The mechanical properties of wood are its fitness and ability to resist applied or external forces. It is largely such properties that determine the use of wood for structural and building purposes and innumerable other uses of which furniture, vehicles, implements, and tool handles are a few examples.

In the present study, the parameters obtained from static bending test viz., modulus of rupture and horizontal shear stress at maximum load and parameters obtained from hardness test like radial, tangential as well as end hardness of pyinkado (*Xylia dolabriformis*) was higher than that of teak (*Tectona grandis*). This might be due to the higher specific gravity (oven dry) of pyinkado (0.85) compared to teak (0.68). The modulus of rupture (MOR) obtained for rubber (*Hevea brasiliensis*) (83.73 N mm^{-2}) in the present study was lower than that obtained by Gnanaharan and Dhamodaran (1992) from a 35-year-old rubber wood plantation in central Kerala (98.4 N mm^{-2}). Also the modulus of elasticity of *Tectona grandis* (96941.41 kg cm^{-2}) was lower than the value reported for teak by Sekhar and Rawat (1966) and modulus of elasticity of *Acacia auriculiformis* (80947.24 kg cm^{-2}) was lower than reported by Shanavas and Kumar (2006). The value obtained for modulus of rupture in *Tectona grandis* was higher than the one reported by Nazma et al. (1981). This variation might be due to difference in environmental, genetic factors and age related factors (Schniewind, 1989). The parameters obtained from compression strength parallel to grain, compression strength perpendicular to grain and hardness test like compressive stress parallel to grain at limit of proportionality, compressive stress parallel to grain at maximum load or maximum crushing strength, modulus of elasticity, compressive stress perpendicular to grain at limit of proportionality, compressive stress at compression of 2.5 mm, radial, tangential and end hardness of pyinkado (*Xylia dolabriformis*) were higher than the values obtained for all the other species. This can again be attributed to the higher specific gravity (oven dry) of pyinkado compared to other species.

The information related to physical property (specific gravity) and the various mechanical properties (static bending, compression strength parallel and perpendicular to grain, hardness, tensile strength and shear) studied also helps to understand the suitability of the seven selected species for various end uses. Incidentally, in the present study pyinkado (*Xylia dolabriformis*) had higher strength values for static bending, compression strength perpendicular to grain and tension parallel to grain compared to all other species. The above tests are useful to assess the utility of a species for making beams. Hence, pyinkado appears to be superior with respect to this use compared to the other species. Pyinkado also had higher values for compression strength parallel to grain and static bending strength which are factors determining the suitability of a species for furniture making.

5.3 CORRELATION BETWEEN NON-DESTRUCTIVE EVALUATION AND DESTRUCTIVE TECHNIQUES OF WOOD

5.3.1 Correlation between Pilodyn Penetration Depth and Density

Strong negative correlations (significant at 1 per cent level) were found between pilodyn penetration depth and specific gravity (oven dry), ranging from -0.712 to -0.907, among the species used for this study. This indicates the potential utility of pilodyn for screening tree species for wood density. The feasibility of pilodyn for screening *Eucalyptus teretocornis* clones for wood basic density has been described by Chauhan and Aggarwal (2011). The highest correlation coefficient was obtained in *Tectona grandis* (-0.91) followed by *Artocarpus heterophyllus* (-0.88), *Swietenia macrophylla (*-0.87), *Acacia auriculiformis* (-0.86), *Xylia dolabriformis* (-0.84), *Artocarpus hirsutus* (-0.82), and lowest in

Hevea brasiliensis (-0.71). The values obtained were lower than previously published value by Cown (1978) in radiata pine (*Pinus radiata*). He correlated the pilodyn readings and outer wood density of radiata pine of different ages and could obtain a correlation coefficient of -0.97. Except the correlation coefficient obtained for *Hevea brasiliensis* (-0.71), correlation coefficients obtained for all other species were higher than those obtained by Taylor (1981) in *Pinus taeda* (-0.81), Yamashita et al. (2007) in *Cryptomeria japonica* (-0.82), Iki et al. (2009) in *Abies sachalinensis* (-0.77) and Chauhan and Aggarwal (2011) in *Eucalyptus tereticornis* (-0.74). All the correlations were higher than that obtained by Hall (1988) in *Picea mariana* (-0.48), *Picea glauca* (-0.62) and *Larix laricina* (-0.48). The higher correlation coefficients may be because pilodyn penetration was done directly into the end cross section of the log along the grain and it was not injected through the bark. Though position wise correlation was done in each species i.e. pith, middle and periphery specific gravity (oven dry) using destructive methods with penetration depth using pilodyn at these corresponding positions, significant correlation was obtained only in certain cases viz., with pith penetration depth and pith specific gravity (oven dry) and that too at 5 per cent level in *Acacia auriculiformis* and *Swietenia macrophylla* only. This might be due to the low number of observations taken from the horizontal positions for the study.

Though the influence of moisture on penetration depth was checked, it was found that the moisture content present has no significant relation with penetration depth in the species. This is contrary to the results obtained by Bonamini et al. (2001) and Gorlacher (1987) who reported that the penetration depth is influenced by the moisture content.

5.3.2 Correlation between Dynamic MOE and Static MOE

Wide range of correlations (0.30 to 0.90) have been obtained between dynamic modulus of elasticity (MOE) derived from time of flight tools (e.g treesonic timer) and static MOE (Halabe et al., 1997; Wang and Ko, 1998; Booker and Sorrenson, 1999; Tsehaye et al., 2000; Wang et al., 2000; Lindstrom et al., 2002). Also, several studies have shown a good relationship (R^2 = 0.44 to 0.89) between stress wave based MOE of logs and static MOE of lumber cut from logs (Arima et al., 1990; Aratake et al., 1992; Aratake and Arima, 1994; Sandoz and Lorin, 1994; Ross et al., 1997). In the present study, dynamic MOE showed significant correlation at 1 per cent level with static MOE (r = 0.876) and R^2 value obtained was 0.76. Dynamic MOE also showed significant correlation with all the other parameters obtained from static bending test like modulus of rupture, horizontal shear stress at limit of proportionality, horizontal shear stress at maximum load and fibre stress at limit of proportionality. Also it showed significant correlation at 5 per cent level with tangential and radial hardness. Both static MOE and dynamic MOE were significantly correlated with modulus of rupture (MOR). MOR is a measure of the breaking strength of a beam. From the study it is evident that using treesonic timer it will help to predict MOR at field condition.

5.3.4 Correlation between Stress Wave Velocity and Mechanical Properties

Significant correlation (at 1 per cent level) was observed between stress wave velocity and the parameters obtained from static bending tests like modulus of rupture, horizontal shear stress at limit of proportionality, horizontal shear stress at maximum load, fibre stress at limit of proportionality and static MOE. Also, significant correlation exists between stress wave velocity and dynamic MOE.

5.4 REGRESSION ANALYSIS

A linear relationship was found between pilodyn penetration depth and specific gravity (oven dry) as explained by various authors (Greaves et al., 1996, 1997b; Raymond and MacDonald, 1998; Muneri and Raymond, 2000). Several researchers (Ross and Pellerin, 1991; Green and Mc Donald, 1993) have developed regression relationships correlating stress wave velocity with the experimental static velocity of wood. The R^2 value of such regressions ranged from 0.61 to 0.9. In the present study, relationship between dynamic MOE and static MOE was also linear and the R^2 value obtained was 0.80.

5.5 ASSESSMENT OF HOLLOW PORTION IN TEAK LOG USING TREESONIC TIMER

Stress waves can be used for detecting decay in trees. Many researchers have conducted study on the use of stress waves in detecting decay or deterioration in wood (Mattheck and Bethge, 1993; Wang et al., 2004). The concept of detecting decay using this method is based on the observation that stress wave propagation is sensitive to the presence of degradation in wood. Stress wave velocity is directly related to the physical and mechanical properties of wood. In general terms, stress waves travel slower in decayed or deteriorated wood than sound wood. They also travel around hollows, increasing the transmission time between two testing points (Wang and Allison, 2008).

In the present study, from the visual inspection itself it can be seen that a hollow is present inside the teak log (6 m length). It was also aimed at finding out the extent of hollow portion inside the log and to check whether the Fakopp treesonic microsecond timer can be used for detecting the hollow portion. For this purpose the transducers of the treesonic microsecond timer was inserted into the teak log at 1 m interval along the same side of the log. The velocity obtained at 1 m intervals ranged from 4065.04 to 4504.50 m/s. (Table 29). Lowest velocity was obtained in the portion 'DE'. This might be due to the presence of knots in the path of stress waves. When a knot is immediately ahead of the wave front, then the local wave front will be delayed by having to sweep round the knots. It is the leading edge of the propagating wave front moving through the outerwood that is picked up by the stop probes resulting in a higher velocity by the Fakopp tool (Chauhan and Walker, 2006). The measurements were also taken by placing the transducers at 1 m interval on the opposite sides of the log. Then there was a wide variation in the values obtained. Mean velocity obtained for the first 2 m of the log starting from the defective end was very high compared to the values obtained for the remaining 4m length of the log. This can be due to the presence of hollow portion inside the log. Later, when the log was sawn into planks, it was found that the hollow portion together with the shake (a defect) present in teak log extend to 130 cm when measurements were taken using the software 'Digimizer'. This suggests that acoustic tools like treesonic timer can be used for estimating the decay or deterioration inside the logs with a high amount of accuracy.

The prediction of parameters obtained from static bending test using the regression equations developed between dynamic MOE or stress wave velocity and static bending parameters like fibre stress at elastic limit, modulus of elasticity (MOE) and modulus of rupture (MOR) will help to assess the strength of the logs at in situ. This implies the possibility of using acoustic tools like treesonic microsecond timer for grading the logs according to dynamic MOE or stress wave velocity obtained. In Kerala currently logs are classified based on (a) dimensions and (b) general appearance of the logs. The actual quality or strength of wood which is dependent on the modulus of elasticity or stiffness of wood is not taken into account. The grading of logs according to stress wave velocities and penetration depth (both being indicators of dynamic MOE and density respectively as is evident from the present study) will help the consumers to buy logs that possess real strength and help avoid purchase of particularly highly priced classes log that are having internal decay. Since fewer numbers of wood samples were assessed in the present study, involving larger number of samples should be conducted before fine recommendations are made.

Summary

SUMMARY

Seven currently used timber species in Kerala such as acacia (*Acacia auriculiformis*), anjily (*Artocarpus hirsutus*), jack (*Artocarpus heterophyllus*), mahogany (*Swietenia macrophylla*), rubber (*Hevea brasiliensis*) and teak (*Tectona grandis*) were tested for physical and mechanical properties using destructive and non-destructive techniques in order to evaluate the suitability of non-destructive techniques in predicting timber properties under field conditions. The logs were collected from the forest depots and retail outlets in Thrissur. The salient findings of the study are as follows:

- Significant difference in specific gravity (oven dry and air dry) was observed among species. *Xylia dolabriformis* had the highest specific gravity in both conditions. *Tectona grandis* had the second highest value. *Swietenia macrophylla* and *Artocarpus heterophyllus* showed the lowest specific gravity.

- Mechanical properties also differed significantly among the species. Modulus of rupture, maximum crushing strength, radial, tangential and end hardness and maximum shearing stress of *Xylia dolabriformis* was the highest. Fibre stress at elastic limit and tensile stress at limit of proportionality modulus of elasticity of *Tectona grandis* was the highest.

- Significant variation was showed between penetration depths of various species. The highest penetration depth was found in *Artocarpus heterophyllus* (16.75 mm). *Xylia dolabriformis* had the lowest penetration depth (8.42 mm).

- Variation was also noticed for stress wave velocity between the species. The highest velocity was obtained for acacia (*Acacia auriculiformis*) (4781.02 m/s) and *Tectona grandis* (4538.59 m/s) and the lowest in *Artocarpus heterophyllus* (2934.93 m/s).

- Significant negative correlation (1% level) was noticed between specific gravity (oven dry) and pilodyn penetration depth between the species. Highest correlation was observed in *Tectona grandis* and the lowest in *Hevea brasiliensis*. Negative correlation was also noticed between specific gravity at pith, middle and periphery regions and penetration depth at these positions

- Specific gravity (air dry) was also found to be significantly correlated with pilodyn penetration depth in all the species except rubberwood (*Hevea brasiliensis*).

- Significant positive correlation was observed between dynamic modulus of elasticity (MOE) and static MOE. Dynamic MOE was found to be significantly correlated with all the parameters obtained from static bending test like modulus of rupture (MOR), modulus of elasticity (MOE), fibre stress at elastic limit, horizontal shear stress at limit of proportionality and horizontal shear stress at maximum load. It was also noticed that dynamic MOE showed significant correlation (5 % level) with radial and tangential hardness.

- Significant positive correlation was found between stress wave velocity with dynamic MOE, all the parameters obtained from static bending test, and tensile strength at maximum load.

- Significant negative correlation was found between penetration depth and MOR, horizontal shear stress at maximum load, dynamic MOE. .Significant correlation (5% level) was found between penetration depth with radial hardness, horizontal shear stress at limit of proportionality and fibre stress at limit of proportionality.

- Regression analysis was done between pilodyn penetration depth and specific gravity (oven dry), revealed that a linear relationship exists between them. R^2 value obtained for the species range from 0.51 to 0.82. The highest R^2 value was obtained in *Tectona grandis* and lowest in *Hevea brasiliensis*. A linear relationship was also noticed between penetration depth and specific gravity (air dry). The R^2 value obtained was highest in *Tectona grandis* and lowest in *Hevea brasiliensis*.

- Regression was also done between dynamic MOE and static MOE among the species. The R^2 value obtained was 0.77.

It can be concluded from the study that both pilodyn and treesonic timer can be used as predictors of timber properties under field conditions. Pilodyn can be used for indirect assessment of density and treesonic timer can be used for predicting wood stiffness of standing trees.

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DESTRUCTIVE AND NON-DESTRUCTIVE EVALUATION OF WOOD PROPERTIES IN SELECTED TIMBERS OF KERALA

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2010-17-102

ABSTRACT OF THESIS

Submitted in partial fulfillment of the requirement for the degree of

MASTER OF SCIENCE IN FORESTRY

Faculty of Agriculture

Kerala Agricultural University

DEPARTMENT OF WOOD SCIENCE
COLLEGE OF FORESTRY
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2012

ABSTRACT

A study entitled "Destructive and non-destructive evaluation of selected timbers of Kerala" was conducted in the College of Forestry, Kerala Agricultural University, Vellanikkara, Thrissur during the period 2010-2012. The objective of the study was to evaluate the physical and mechanical properties of wood in timber species such as: teak (*Tectona grandis* L.f.), mahogany (*Swietenia macrophylla* King), anjily (*Artocarpus hirsutus* Lamk.), jack (*Artocarpus heterophyllus* Lamk.), acacia (*Acacia auriculiformis* A. Cunn. ex Benth.), rubber (*Hevea braziliensis* (H.B.K.) M. A.) and pyinkado (*Xylia dolabriformis* Benth.) using destructive and non-destructive methods. The study also aimed at evaluating the suitability of non-destructive techniques (NDT) and semi-destructive techniques (SDT) as predictors of timber properties under field conditions. Pilodyn 6J ((FUJI TECK, Tokyo, Japan) and treesonic microsecond timer (Fakkopp, Hungary) were the two non destructive equipments used in this study. In the present study, logs of the above species were collected from forest depots and retail outlets in Thrissur. Penetration depth of each species was found out using pilodyn and dynamic modulus of elasticity (MOE) was found out using the treesonic timer.

Discs were taken for analysing specific gravity and the logs were subjected to various mechanical tests. Significant variation in specific gravity, mechanical properties, stress wave velocity and penetration depth were noticed between species. Significant negative correlation (1 per cent level) was noticed between specific gravity and pilodyn penetration depth in each of the species. Also, penetration depth was negatively related to modulus of rupture, dynamic MOE, modulus of rupture (MOR), radial hardness and fibre stress at limit of proportionality. Significant positive correlation was noticed between dynamic modulus of elasticity and all the parameters obtained from static bending tests especially static modulus of elasticity and modulus of rupture. It was also noticed that dynamic MOE showed significant correlation (5 per cent level) with radial and tangential hardness. Significant positive correlation was found

between stress wave velocity and all the parameters obtained from static bending test, and tensile strength at maximum load. When regression was done between pilodyn penetration depth and specific gravity in each of the species, it was noticed that a linear relationship existed between them. A linear relationship was found to exist between dynamic MOE and static MOE among the species. It can be concluded from the study that both pilodyn and treesonic timer can be used as predictors of timber properties under field conditions.