VARIATION OF HEARTWOOD PROPORTION AND LEACHABILITY IN PLANTATION GROWN TECTONA GRANDIS L. f.

BY

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To my parents and the toiling peasants of Tanzania.

DECLARATION

I, Kiko Francis Silas Hamza, do hereby declare to the Senate of Sokoine University of Agriculture that this thesis is my own original work and that it has not been submitted for a degree award in any other University.

Signed : ....

Date : 22 SEPT. 1987

ABSTRACT

The age at which heartwood starts to form in Tectona grandis L.f., the relationship between some stem parameters and heartwood proportion, heartwood anatomy and chemical aspects were studied. Sample trees for determination of age at which heartwood starts to form were obtained from 5, 6, 7, 8, 9 and 10 year old stands. For the determination of heartwood proportion and its variation with age, dbh, total tree height and height in the stem, heartwood acidity and leachability, sample trees from 7, 11, 16, 21 and 25 year old stands and from 32 and 50 year old trial plots were used. It was found that heartwood started to form when the trees are between 7 to 9 years old. It was also observed that :

- heartwood proportion increased asymptotically with increase in age;
- heartwood proportion increased asymptotically with increase in dbh;
- heartwood proportion increased asymptotically with increase in total tree height for 11, 21 and 25 year old trees;
- heartwood proportion increased with increase in dbh and total tree height considered together;
- heartwood proportion decreased with increase in height in the stem;

An average heartwood pH of 5.5 was obtained from 25 year old trees. Within a period of 30, 60, 90 and 120 days heartwood sample pieces soaked in cold water lost 0.05%, 0.11%, 0.19% and 0.21% by weight respectively. A loss of 0.07%, 0.16%, 0.27% and 0.5% by weight occurred for hot water leaching for 24, 48, 72 and 96 hours respectively. These losses were not significant at 95% confidence level.

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TABLE OF CONTENTS

Page

Page

LIST OF TABLES

LIST OF ILLUSTRATIONS

LIST OF APPENDICES

1. INTRODUCTION

Tectona grandis L.f. (Teak) is indigenous to India, Burma, Western parts of Thailand and Indo China. It occurs from about 12^o to 25^oN latitude and from 73^o to 104^oE longitude. The species is also found just on the South of the Equator in Java and some of smaller islands of the Indonesian Archipelago. The species occurs from sea level for example in Java to 1,200 metres above sea level in central India. Climate in these countries ranges from very moist to rather dry tropical, with rainfall ranging from 620 mm to 5,000 mm a year and temperature ranging from 2^oC to 48^oC (Gupta and Kumar, 1979). In Java, the suggested financial rotation age of teak is 50 years, 55 - 60 years and about 80 years for site qualities I, II and III respectively. However based on technical and market considerations the suggested rotation is 70 - 90 years or an average of 80 years for all three site classes (Beekman, 1918). The species has been introduced in several regions outside South East Asia, namely, East, Central and West Africa, Latin America and the Caribbean (FAO, 1957; Keogh, 1979). Rotation age in these countries is about 60 to 80 years. (FAO, 1967).

In the countries where Tectona grandis L.f. is indigenous its wood is used mainly for general construction, including construction of wharfs, bridges and ship decking and for furniture. In countries where the species is exotic its wood is used for ship building, joinery, fine finish furniture, flooring, carving, cabinet work, paneling turnery tanks and vats, fixtures requiring high resistance to acids and as poles for building and communication purposes (Wangaard and Muschler, 1952; Thomas, 1964; Anon, 1973; Chudnoff, 1979; Abdelkariem, 1980; Ngok, 1980).

Teak was introduced in Tanzania in the late 19th century. However it was between 1906 and 1936 that scientific trial plots were established in different parts of the country (Wood, 1967). The species good performance in these trial plots led to the establishment of Mtibwa plantation in 1936, Rondo plantation in 1955 and Longuza plantation in 1959 in mainland Tanzania (Wood, 1967). These plantations have trees old enough to produce thinnings suitable for sawlogs and saleable poles for building and communication purposes (Abdelkariem, 1980).

Compared to most indigenous hardwoods of similar properties, teak can be raised more easily in plantations (Wood, 1967) and the wood volume that can be harvested is in most cases higher (Abdelkariem, 1980). It is known that the heartwood of this species is naturally durable while its sapwood is perishable. The higher durability of the heartwood in comparison to sapwood is attributed largely to the presence of extractives in the heartwood that are toxic to the wood deteriorating organisms.

The toxic extractives include tectol, anthraquinones and anthrones (Rudman and Gay, 1961). Also the presence of extractives in the heartwood reduce its permeability (Prasad et al., 1964). Generally the reduction in permeability makes heartwood more resistant to impregnation with preservatives and fire - retardant chemicals and causes difficulties in drying and pulping (Panshin and de Zeeuw, 1970).

The heartwood of the species has better strength properties (Rajiput *et al*., 1983), higher calorific value (Krishna and Ramaswamy, 1931) and is dimensionally more stable than the sapwood (Schwarb, 1978).

Knowledge on the age at which heartwood starts to form, heartwood relative proportion in different parts of the stem, its pH and leachability are important for improved utilization of the species. The age at which heartwood starts to form indicates when durable wood starts to form in the tree. In those tree species where heartwood is known to be resistant to attack by biological wood deteriorating agents, the proportion of heartwood relative to sapwood is an important factor that can be used to determine the value of wood from a given tree or stand. Heartwood pH is important for low pH may result in corrosion of metal fasteners and processing machinery and that acidic extractives in the wood interfere with setting of paints and varnishes and may have an adverse effect on the formation of strong glue bonds (Panshin and de Zeeuw, 1970). Processes leading to the removal of the extractives from heartwood may reduce its natural durability, higher calofic value and resistance to treatment with preservatives and fire retardant chemicals. Leaching is one of the processes which removes heartwood extractives. Leaching may take place during log storage, floating and steaming prior to peeling or slicing. Little information exists about the age at which heartwood starts to form in *Tectona grandis* L.f. grown in Tanzania. Heartwood proportion, pH and leachability of the species are also little known.

Using Tectona grandis L.f. grown at Mtibwa forest project this study had the following objectives :-

- to determine the age at which heartwood starts to form.
- to determine the proportion of heartwood and its variation with age, dbh, total tree height and height in the stem.
- to determine the pH of heartwood.
- to determine the leachability of heartwood.
- to compare results from this study with results from similar investigations on the same species.

2. LITERATURE REVIEW

This chapter is divided into nine subchapters. Suchapter one outlines the classification of trees and compares various definitions of heartwood by different authors. A definition which fits *Tectona grandis* L.f. is adopted and discussed in detail. Site, season and causes of heartwood formation and age at which it starts to form in different trees species are reviewed in subchapter two. Subchapter three reviews heartwood natural durability, factors influencing it and its variation between species and within a tree. The functions which heartwood serves in a tree are discussed in subchapter four. In subchapter five methods of determining heartwood are reviewed while in subchapter six the variation of heartwood proportion within a tree, between trees and between species are discussed. Variation of heartwood proportion and its qualities in teak are discussed in subchapter seven. Heartwood acidity and its effects on wood utilisation are dealt with in subchapter eight. In the last subchapter heartwood leachability and its consequences on wood utilisation are discussed.

2.1 Classification of trees and heartwood definition

2.1.1 Classification of trees

In order to define heartwood in a given tree species it is necessary to first identify the class into which it falls. Trees are grouped into four classes according to heartwood formation as indicated in Table 1. In the table old and new terminologies, description of each class and some examples are given. It is important to note that the classification of trees according to heartwood formation in Table 1 was accepted by a group of scientists at an international symposium on wood quality in Melbourne, 1965 (Bosshard, 1968). It is also important to note that Tectona grandis L.f. belongs to the groups of tree species with obligatory coloured heartwood.

2.1.2 Heartwood definition

The definitions that follow are applicable to obligatory coloured heartwood. Most definitions define heartwood in terms of colour, its location and physiological role in the stem. The definitions aim among other reasons at distinguishing heartwood from sapwood. Some definitions however, in addition to distinguishing heartwood from sapwood differentiate various types of heartwood formed in tree species.

Jane (1970) and Haygreen and Bowyer (1982) define heartwood as the dead inner core of a woody stem generally distinguished from the outer portion sapwood by its dark colour. This definition is valid where the wood species under consideration form distinct colour difference between sapwood and heartwood. Examples of these include Dalbergia melanoxylon, Erythrophleum guineense, Grevillea robusta, Isoberlinia scheffleri, Maesopsis eminii and

Table 1 : Classification of trees according to heartwood formation (from : Panshin and de Zeeuw, 1970)+

Old terminology	New terminology	Description	Example
Sapwood trees	Trees with retarded formation of heartwood	Wood containing some living cells is found in the vicinity of the pith. Changes characteristic of heartwood formation are considerably delayed and hence are evident only in trees of advanced age.	Alnus spp
Ripewood trees	Trees with light heartwood	Heartwood remains light-coloured, because extraneous materials remain unpigmented but all the parenchyma cells are dead	Abies spp
Trees with regularly formed heartwood	Trees with obligatory coloured heartwood	Pigmented heartwood materials are always formed in the parenchyma cells. Pigmented materials are found not only in the cell cavities but in the cell walls as well	Quercus spp
Trees with irregular heartwood formation	Trees with facultatively coloured heartwood	Coloured heartwood may be present in all specimen or may be formed only on one side of the stem. Pigmented substances are retained as inclusions in parenchyma cells, while cell walls of these and other xylary cells remain unpigmented	Fraxinus spp

+ The table is slightly modified.

Sterculia quinqueloba (Bryce, 1967), Pterocarpus angolensis D.C. (Bryant, 1968) and Tectona grandis L.f. (Chudnoff, 1979). Using this definition it is difficult to distinguish between sapwood and heartwood of species such as Antiaris toxicaria, Acacia albida, Cephalosphaera usambarensis, Entandrophragma stolzii, Mitragyna rubrostipulata, Strombosia scheffleri and Syzygium guineense (Bryce, 1967) whose heartwood and sapwood do not differ in colour. In addition this definition does not take into consideration the occurrence of heartwood - sapwood transition zone in certain tree species in which colour changes gradually from sapwood to heartwood, for example Pygeum africanum and Trachylogium verrucosum (Bryce, 1967).Shigo and Hillis (1973) have pointed out that when colour alone is the basis for distinguishing the type of tissue under consideration confusion may arise. This is because change of colour in wood of trees can be the result of processes associated with aging resulting into normal heartwood or injury resulting into discoloured wood.

Anon. (1957), Anon. (1964), Ford-Robertson (1971) and Kubler (1980) define heartwood as the inner layer of wood which in the growing tree has ceased to contain living cells and in which reserve materials such as starch have been removed or converted into heartwood substances and it is generally dark in colour than sapwood though not always differentiated. This definition is an improvement on that by Jane (1970) and Haygreen and Bowyer (1982) by including an additional characteristic, such as starch in the heartwood. The presence or absence of reserve materials as a criterion for distinguishing sapwood from heartwood has however been disputed by other workers. Reviews by Chattaway (1952) and Hills (1968) for example infer that though starch is never found in heartwood tissue, its absence can not be taken as evidence that a transition has occurred. The reason advanced for this is that starch occurs seasonally in the tree depending on the tree's need for energy and that starch is locally distributed in the tree, sometimes being present on one side of a tree and absent from the other (Chattaway, 1952).

Corkhill (1979) defines heartwood as the inner part of exogeneous trees that normally does not contain living cells and that it is usually harder, heavier, less permeable and more durable than sapwood. This definition is similar to that of Jane (1970) and Haygreen and Bowyer (1982) and that by Anon. (1957), Anon. (1964), Ford-Robertson (1971) and Kubler (1980) in that death of the parenchyma cells is a phenomenon mentioned in all the three definitions. It differs from that by Jane (1970) and Haygreen and Bowyer (1982) and by Anon. (1957), Anon. (1964), Ford-Robertson (1971) and Kubler (1980) in that colour is not used, instead other characteristics such as hardness, density permeability and durability were included. Hardness is influenced by a number of factors, density being the most important (Panshin and de Zeeuw, 1970). Since density itself is influenced by a number of factors including presence of extractives, it would be expected that both hardness and density would not change abruptly at the sapwood - heartwood boundary. This is because the amount of extractives in most species for example Quercus spp and Tectona grandis does not change abruptly at the sapwood - heartwood boundary (Hillis. 1968). The decrease in permeability from sapwood to heartwood may be caused mainly by deposition of extractives during heartwood formation (Prasad et al., 1964) and/or due to pit aspiration (Panshin and de Zeeuw, 1970). The decrease in permeability may not be abrupt at the sapwood - heartwood boundary due to the same reason given for hardness and density. Durability is not necessarily different between heartwood and sapwood, it is there only if the wood contains toxic extractives (Panshin and de Zeeuw, 1970). Therefore using Corkhills' definition one can not accurately distinguish heartwood from sapwood in certain species.

Panshin and de Zeeuw (1970) differentiated the various type of heartwood as indicated in Table 1. In considering obligatory coloured heartwood the authors stated further that, in addition to colouring of the heartwood the polyphenolic infiltrations penetrate the cell wall and coat the cellulosic and hemicellulosic materials present in them causing a decrease in shrinking and swelling capacity of the wood progressively from cambium to the pith. These polyphenolic infiltrations also reduce the permeability of the heartwood. The reduction in permeability makes heartwood more resistant to impregnation with preservatives and fire retardant chemicals and causes difficulties in drying and pulping. Table 2 shows differences in chemical composition between sapwood and heartwood of some species.

Table 2 : Differences in chemical composition between sapwood and heartwood of some wood species. (from : Rydholm, 1965)

Species name	Common name		Ash %	Ether extract %	Lignin %	Pentosans
Betula	paper	sapwood	0.3	0.5	24.7	21.4
papyrifera	birch	heartwood	0.4	0.8	24.6	20.4
Liriodendoron	yellow	sapwood	0.5	0.3	23.1	18.4
tulipifera	poplar	heartwood	0.4	0.4	22.2	18.5
Pinus	white	sapwood	0.2	5.5	26.5	9.3
strobus	pine	heartwood	0.4	3.6	26.1	8.6

2.2 Heartwood formation

2.2.1 Site and season of heartwood formation

Higuchi *et al.*, (1967) suggested that the precursors and heartwood compounds are mostly synthesized in sapwood and transition wood. A review by Hillis (1968) on site of formation of heartwood extractives indicates that extractives arise in situ from translocated or stored carbohydrates. The formation of heartwood substances by ray parenchyma cells in the transition wood has been proved by Nobuchi *et al.* (1982) and Yamamoto (1982).

On the basis of cytological observations (Nobushi *et al.*, 1982), respiratory activity (Shain and Mackay, 1973) and ethylene production (Shain and Hillis, 1973; Nelson, 1978) heartwood formation has been thought to occur mainly during the dormant season in warm temperate zones. Yamamoto (1982) reported that heartwood formation occurs during July to September in the cold temperate zone. In their review on season of heartwood formation, Bamber and Fukazawa (1985) concluded that lignification and the final death of parenchyma cells occur during the late growth season because the newly formed parenchyma cells mature and begin to function as food reservoirs taking over the role from the inner and more inaccessible parenchyma cells.

2.2.2 Causes of heartwood formation

Several hypotheses on the cause of heartwood formation in trees have been put forward. At present there seems to be no definite agreement among scientists on the cause of heartwood formation.

Frey-Wyssling and Bosshard (1959) postulated that heartwood formation is caused by aging and loss of vitality of the ray parenchyma cells in the older part of sapwood. Other scientists are not in agreement with this proposed theory. Bamber and Fukazawa (1985) for example argue that if heartwood forms simply because the cells become old and lose vitality then they can not be expected to die in such a regular pattern observed by Bamber (1976a), but rather in an irregular pattern. It has also been reported that in some tree species for example *Acer saccharum* parenchyma cells have the capacity to retain their vitality for more than a hundred years (Hillis, 1977) and to accelarate respiration rate (Shain and Mackay, 1973). Death of parenchyma cells is considered to be the result and not the cause of heartwood formation (Bamber, 1976a).

Hillis (1962), Bosshard (1966), Higuchi *et al.* (1967) and Bosshard (1968) hypothesized that polyphenolic materials formed in the parenchyma cells at the sapwood-heartwood boundary accumulate to lethal quantities causing the death of parenchyma cells and formation of heartwood. Bamber (1976b) argued that polyphenolic materials are ubiquitous in plant cells and, even though they are found in the cytoplasm in living cells do not seem to be associated in normal cells with any loss of vitality. The author further points out that polyphenols are mostly membrane bound, occurring as discrete particles in the cytoplasm.

Some workers, for example Good et al. (1955), Jorgensen (1962), Rudman (1966) and Stewart (1966) postulated that withdrawal of water from the middle of the stem induces heartwood formation. A review by Hillis (1968) on the initiation of heartwood formation infers that moisture distribution in most living trees varies with species, between parts of the tree, between seasons of the year and conditions of the site. Skaar (1972) reported that sapwood generally contains more moisture than heartwood in the case of softwoods, while there appears to be no consistent difference in the case of hardwoods. Contrary to the theory by Good et al. (1955), Jorgensen (1962), Rudman (1966) and Stewart (1966), Hillis and Inoue (1966) reported that withdrawing water from the stems of Rhus sp. did not cause heartwood formation. However, moisture stresses may be important for the stimulation of ethylene production (McMichael et al., 1972) which plays a key role in the formation of some extractives (Shigo and Hillis, 1973).

Carrodus (1971) and Carrodus and Triffett (1975) hypothesized that higher carbon dioxide levels in Acacia mearnsii contributed to heartwood formation.

Another hypothesis which is less disputed at the moment is that advocated by Ziegler (1967), Shain and Hillis (1973), Bamber (1976a) and Nelson et al. (1981). These authors suggested that heartwood formation is induced by hormone(s). Bamber (1976a) made more suggestions concerning the origin, mode of movement and when the hormone(s) reach the threshold value for heartwood formation to commence. He suggested that the hormone(s) originate(s) in the younger sapwood or cortical tissue and diffuse(s) centripetally along the rays and reach(es) a threshold value for heartwood formation in the cells adjacent to the pith or heartwood core where further radial movement is blocked thus causing the concentration to increase in these cells.

2.2.3 Age at which heartwood starts to form

It was reported that heartwood starts to form in *Tectona grandis* L.f. (Ferguson 1934), *Eucalyptus* spp (Dadswell and Hillis, 1962) and in *Pterocarpus angolensis* (Bryant, 1968) at about 1 - 10 years, 15 years and 2 to 6 years respectively. Bauch (1980) suggested that the difference between species in the age at which heartwood starts to form is controlled mainly by genetical factors. According to Rydholm (1965) within species difference in the age at which heartwood starts to form in conifers may be controlled by environmental factors.

2.3 Heartwood durability

In the broader sense natural durability of wood is defined as its degree of resitance to deterioration by biological, chemical, mechanical and physical agents. In the narrow sense natural durability of wood refers only to its degree of resistance to attack by biological agents (Fortin and Poliquin, 1976). The main biological wood deteriorating agents include fungi, wood - boring insects and marine borers (Kollmann and Cote, 1968). Natural durability in the narrow sense is adopted in this text. The rating of tree species according to natural durability is based on the average life of all sample blocks at test site (Bryce, 1967; Fortin and Poliquin, 1976). Table 3 shows the rating of some Tanzanian timbers according to natural durability.

2.3.1 Causes of natural durability

Basically wood is composed of cellulose, hemicellulose lignin and extractives. Hemicelluloses, followed by cellulose are more susceptible to attack by biological agents than lignin. Although wood structure, lignification of the cell walls and crystallinity of cellulose contribute to the natural durability of a tree species it is the toxic extractives deposited during heartwood formation that are the principal source of natural durability (Scheffer and Cowling, 1966). In the case of resistance to termites, it is the repellency of extractives rather than the toxicity which explains the natural durability of many tropical woods (Carter *et al.*,1975). Table 4 shows heartwood extractives known to cause resistance to attack by wood destroying agents in softwoods.

Table 3 : Rating of some Tanzanian timbers according to natural durability. (from : Bryce, 1967)

Rating	Average life	Example
Very durable	Over 10 years	Olea africana Albizia antunesiana
Durable	5 - 10 years	Chrolophora excelsa Pterocarpus angolensis
Moderately durable	2 - 5 years	Tectona grandis L. f. Khaya nyasica
Non-durable	1 - 2 years	Ocotea usambarensis Albizia gummifera
Perishable	Less than 1 year	Celtis africana

Table 4 : Heartwood extractives indicated to be decay retardant (from : Scheffer and Cowling, 1966)

Tropolones	Terpenoids
α - Thujaplicin	Carvacrol
β - Thujaplicin	p - Methoxycarvacrol
γ - Thujaplicin	p - Methoxythymol
α - Thujaplicinol	Thymoquinone
β - Thujaplicinol	Sugiol
Pygmaein	Totarol
β - Dolabrin	Ferruginol
Nootkatin	Chamic acid (non-phenolic)
	Chaminic acid (non-phenolic)
	l-Citronellic acid (n.p. aliphatic)

Stilbenes	Flavonoids
Pinosylvin	Quercetin
Pinosylvin monomethylether	Robinetin
Pinosylvin dimethylether	Taxifolin (trans-dihydroquercetin)
3,5,4' - Trihydroxystilbene	Dihydrorobinetin (taxifolin isomer)
2,3,4,5,' Tetrahydroxystilbene	Homoferreirin
3,4,5,3'5' - Pentahydroxystilbene	Ougenin
4 - Hydroxystilbene	Lapachonon (non phenolic)
3,4,3', 5', - Tetrahydroxystilbene	Metairesionol
Pterostilbene	

According to Scheffer and Cowling (1966) thujaplicins are the most potent group of extractives; their effectiveness is comparable to pentachlorophenol.

The relationship between resistance to attack by wood destroying agents and chemical structure of extractives has been established for only a few species in hardwoods (Carter et al., 1975). These include Tectona grandis L.f. (Rudman and Gay, 1961), Dalbergia spp. (Diestrichs and Hausen,1971; Bultman and Parrish, 1979), Paratecoma peroba and Tabebuia flavescens (Rudman, 1963), Maclura pomifera (Barnes and Gerber, 1955), Acacia georginae and Ougeinea dalbergiodes (Rowe, 1962).

It is reported that anthraquinones and anthrones are responsible for the resistance to termites of Tectona grandis L.f. heartwood (Rudman and Gay, 1961). It is further reported that quinonemethide and obtusaquinone in Dalbergia retusa (Bultman and Parrish, 1979), lapachonon in Paratecoma peroba and Tabebui flavescens (Rudman, 1963), 2, 3,', 4, 5 tetrahydroxystilbene in Maclura pomifera (Barnes and Gerber, 1955), fluoracetate in Acacia georginae and homoferreirinougenin in Ougeinia dalbergioides (Rowe, 1962) are the extractives responsible for the resistance to fungi.

2.3.2 Variation of natural durability

2.3.2.1 Variation between tree species

Natural durability varies between tree species a phenomenon that can be attributed to a large extent on the differences in the type and amount of extractives formed in various trees species. In tropical wood species the amount of extractives varies from 3 to 17% with those having large amounts of extractives being more durable (Wangaard and Granados, 1967).

2.3.2.2 Between tree variation

The natural durability of wood from different trees of the same species may vary considerably. Variation has been reported to occur between trees of *Tectona grandis* L. f. (da Costa *et al.*, 1958), and *Thuja plicata* (Scheffer, 1957). This variation is mainly controlled genetically, although superimposed on genetic variability are moderate variations from tree size and age (Scheffer and Cowling, 1966).

2.3.2.3 Variation within trees

The natural durability of wood originating from different parts of the same stem varies considerably. Scheffer and Cowling (1966) have made the following general observations on decay resistance for a number of tree species:

- decay resistance decreases progressively from the outer heartwood to the pith.

- decay resistance of the outer heartwood decreases progressively from the base of the tree upward, whereas the opposite is true for the inner heartwood.

- outer heartwood at the base of the tree is most resistant and inner heartwood at the base is least resistant, heartwood in the upper bole being intermediate between these extremes.

- the larger the tree, the more resistant is the outer heartwood at the base and the less resistant is the inner heartwood.

Within tree variation in natural durability may be explained by the differences in the type and amount of extractives in the different parts of the tree.

2.4 Functions of heartwood

Review of literature indicates that there is disagreement among scientists on the actual function of heartwood. Mechanical and physiological roles are the two main functions suggested. Bamber (1976b), working with 40 year old plantation grown *Pinus radiata* reported that a tree 30 m in height contains about 15% heartwood. It is suggested that the contribution of the heartwood to the support of the tree is minimal, but its essential role is in some way physiological (Bamber and Fukazawa, 1985).

Stewart (1966) suggested that heartwood serves as a repository for the toxic excretory products of metabolism namely polyphenols. This concept requires that the concentration of polyphenols increases towards the heartwood boundary. A review by Bamber and Fukazawa (1985) however indicates that the concept is at variance with the macro and microscopic pattern of polyphenol deposition in which polyphenols appear to be substantially laid down during heartwood formation.

Bamber (1976a) argued that heartwood formation is a phase of growth, serving to control or regulate the amount of sapwood; it being advantageous to the tree to keep the amount of sapwood at an optimal level. The same author (Bamber, 1976c) postulates that the principal factor determining the amount of sapwood is provision for the storage of food reserves such as starch.

2.5 Determination of heartwood

Heartwood and sapwood are usually separated on the basis of colour in trees with obligatory coloured heartwood. In other classes, that is trees with retarded formation of heartwood, trees with light heartwood and trees with facultatively coloured heartwood, however, use must be made of other characteristics that may include chemical or anatomical features for example tyloses where these are known to be reliable (Bamber and Fukazawa, 1985).

2.5.1 Determination by natural colour

In tree species with obligatory coloured heartwood, heartwood can be distinguished from sapwood by its darker colour. Separation of heartwood from sapwood using colour can be carried out in the genera *Lovoa*, *Albizia*, *Entandrophragma* and the species *Morus lactae* (Dawkins, 1958), *Pterocarpus angolensis* D.C. (Bryant, 1968), *Tectona grandis* L.f. (Anon. 1973; Mnangwone, 1977; Chudnoff, 1979). *Eucalyptus tereticornis* sm.(Purkayastha *et al*., 1980. The use of colour is however not applicable to certain tree species including *Antiaris toxicarya*, *Acacia albida*, *Entandrophragma stolzii*, *Mitragyna rubrostipulata* and *Strombosia scheffleri* (Bryce, 1967) as these species belong to the group of trees with light heartwood. Use of colour can also lead to wrong interpretation when distinguishing sapwood from heartwood in species with colour difference between the two when the colour change is a result of processes associated with injury(ies) which produce(s) discoloured wood. When colour is used in such species it is important to exclude defected trees.

In addition if colour changes gradually from sapwood to heartwood, it will be difficulty to demarcate the two. In such species chemical determination or other methods may be used.

2.5.2 Determination by chemical methods

Chemical methods used to distinguish heartwood from sapwood are based on the differences in chemical composition of the two zones and their reactions with certain compounds.

Sapwood and heartwood differ in starch, sugar, polysaccharides, fat, nitrogen, vitamins, resins, polyphenolic compounds and in acidity (Hillis, 1968). As a result of these differences sapwood and heartwood of certain species produce different colours when certain chemical compounds are applied on the wood (Kutscha and Sachs, 1962; Bamber and Fukazawa, 1985). Tests for carbohydrates, polyphenols and heartwood acidity are the more common chemical tests applied.

2.5.2.1 Test for carbohydrates

Starch is a carbohydrate which is usually found in the sapwood. The amount of starch varies greatly between genera, for example in the genus Eucalyptus starch levels in the sapwood have been found to range from less than one per cent in E. pibularis to nearly eight per cent in E. fastigata (Lambert, 1983). Generally starch disappears at the heartwood - sapwood boundary although small amounts of free sugars may be found in the heartwood (Hillis, 1962). Starch test using Alizarine - red 75 per cent or Alizarine - Iodine can be a reliable method of differentiating heartwood from sapwood in softwoods which have no colour differences between the two and those in which colour changes gradually from heartwood to sapwood. The two compounds produce different colours when applied on a wood sample. Alizarine - red produce red colour in sapwood and yellow to orange colour in heartwood while Alizarine - Iodine produces green to yellow colour in sapwood and brown colour in heartwood (Kutscha and Sachs, 1962). However it is important to note that a negative test may not confirm heartwood. This is because starch occurs seasonally in the tree depending on the tree's need for energy and that starch is locally distributed in the tree, sometimes being present on one side of a tree and absent from the other (Chattawy, 1952).

2.5.2.2 Test for polyphenols

Marked qualitative differences have been observed between the phenolic compounds present in heartwood and those in sapwood (Hillis, 1968). Phenolic compounds found in heartwood include terpenoids, tropolone, flavonoids and stilbenes and those found in sapwood include diterpenes, steroids and terpenoid glucoside (Kramer and Kozlowski, 1979). A number of chemical tests for polyphenols have been described for softwoods. The test are mostly based on the reactivity of wood polyphenols, for example pinosylvin with diazo compounds (Kutscha and Sachs, 1962; Santos, 1963). The first of the diazo compounds to be used was based on benzidine. When benzidine is applied to a conifer wood, a red colour is produced if pinosylvin phenols are present in the heartwood and a yellow to brown colour is produced in the sapwood (Kutscha and Sachs, 1962). Since benzidine is a carcinogen, a number of other similar non - carcinogenic compounds have been described, for example 0 - anisidine (Stalker, 1971), para - amino - NN - dimethylaniline (Cummins, 1972; Beszterda and Raczowski, 1976). The latter compound has been found to be a reliable heartwood indicator when applied on wood of Pinus spp. (Bamber and Fukazawa, 1985).

2.5.2.3 Heartwood acidity

The pH difference between sapwood and heartwood can be used to determine heartwood in wood of certain tree species using the hydrogen - ion activity. The various chemicals used include bromocresol green, bromophenol blue and methyl orange (Kutscha and Sachs, 1962).

2.5.3 Determination by histochemical methods

One of the histochemical tests used for distinguishing heartwood from sapwood is that described by Bamber and Colley (1983). Working with Pines the authors showed that if sections, preferebly tangential longitudinal, were stained with double stain safranin and alcian blue, the cell walls of the radial resin canals stained blue green in the sapwood and red in the heartwood. The differential staining reaction is due to the lignification of the resin canal tissue in the genus Pinus which occurs during heartwood formation (Bamber, 1976d).

2.5.4 Determination by differences in anatomical features

In hardwoods, one of the common anatomical features used to indicate presence of heartwood is occurrence of tyloses. The presence of tyloses is a realiable indicator in members of the genera Eucalyptus and Shorea but in some genera for example Quarcus, Leucobalamus, Fraxinus, Ulmus, Juglans and Maclura tylosis formation is not associated with heartwood formation (Gerry, 1914). In softwoods pit aspiration can be used to separate heartwood from sapwood since more than 90% of pits in the heartwood are aspirated (Kramer and Kozlowski, 1979).

It would appear that heartwood and sapwood can be more accurately separated by using a combination of a number of the aforementioned methods.

2.6 Variation of heartwood proportion

The amount of heartwood and sapwood in a tree varies with species, age, position in a tree, rate of growth and site (Hillis, 1977). Bamber (1976c) considered the principal factor determining the amount of sapwood to be provision for the storage of food reserves such as starch which have been shown to be required for re-establishment of the tree crown (Bamber and Humphreys, 1965). This may be the reason for some trees such as apple and pome to have small proportion of or lack heartwood because of their large starch requirement (Kile and Wade, 1975).

2.6.1 Variation between species

Existing literature indicates that between species variation in heartwood proportion is mainly genetical. It has been reported that heartwood proportion is mainly genetically controlled in the genera Lovoa, Entandrophragma and Albizia (Dawkins, 1958) and Eucalyptus (Dadswell and Hillis, 1962). In other tree species for example Callitris columellaris (Hillis, 1974) heartwood propotion is not strongly related to genetical constituents.

2.6.2 Variation within species

It has been established that heartwood proportion varies within species and depends on age, growth rate, crown size and environmental factors.

It has been reported that heartwood proportion varies with age in *Tectona grandis* L.f. (Ferguson, 1934; Mnangwone, 1977), *Pterocarpus angolensis* D.C. (Bryant, 1968) and *Pseudotsuga taxifolia* (Brix and Mitchel, 1983). Bryant (1968) observed that once initiated, the production of heartwood proceeds at a rate greater than that of diameter growth. The author further reported that the situation later stabilizes and the volume of heartwood formed each year becomes roughly equal to the volume added by new growth.

Existing literature indicates that heartwood proportion may or may not be related to growth rate as expressed by total tree height and/or dbh. Purkayastha *et al*. (1980) working with *Eucalyptus tereticornis* sm. found that heartwood proportion increases with increase in total tree height and dbh. Nair and Chavan (1985) reported that trunk circumference shows strong positive correlation with the ratio of heartwood area to sapwood area for *Acacia catechu* Willd., *Albizia lebbek* (L) Bth., *Albizia procera* (Roxb) Bth. *Bridelia retusa* (L) spreng, Dalbergia latifolia (Roxb) Grewia tiliifolia Vahl, Kydia calycina Roxb, Melia dubia cav., Ougeinia oojeinensis (Roxb) Hochreut, Tectona grandis L.f. and Terminalia crenulata Roth. In other tree species for example Pseudotsuga menziesii (Lassen and Okkonen, 1969), Quercus suber and Eucalyptus camaldulensis (Hillis, 1974) heartwood proportion decreases with increase in growth rate. Tectona grandis L.f. (Ferguson, 1934; Soonyakhanit, 1963), Pseudotsuga taxifolia (Smith et al., 1966) Acacia catechu Willd., Albizia lebbek (L) Bth., Albizia procera (Roxb.) Bth., Bridelia retusa (L) spreng., Dalbergia latilifolia Vahl., Kydia calycina Roxb., Melia dubiaccav. Ougeinia oojeinensis (Roxb) Hochreut. and Terminalia crenulata Roth. (Nair and Chavan, 1985) showed no relationship between trunk length and heartwood proportion. Nair and Chavan (1985) however reported that the increment in length of the trunk results in the increment of heartwood independent of the sapwood both at the base and apex for Acacia catechu Willd., Albizia lebbek (L) Bth., Albizia procera (Roxb) Bth., Bridelia retusa (L) spreng., Dalbergia latiifolia (Roxb) Grewia tiliifolia Vahl., Kydia calycina Roxb., Melia dubia cav. Ougeinia oojeinensis (Roxb) Hochreut., Tectona grandis L.f. and Terminalia crenulata Roth.

Since environmental factors influence the rate of growth they are expected to have an indirect influence on heartwood proportion. Lassen and Okkonen (1969) reported that heartwood proportion of Pseudotsuga menziesii grown in the United States increases from interior to the coast and it decreases with increasing altitude. This may be caused by changes in soils, rainfall and temperature.

2.6.3 Variation within a tree

Heartwood proportion decreases with increasing height in the stem in certain tree species. These species include Tectona grandis L.f. (Ferguson, 1934; Mnangwone, 1977) Eucalyptus tereticornis sm. (Purkayastha et al., 1980) and Pseudotsuga taxifolia (Smith et al., 1966; Brix and Mitchel, 1983). The decrease in heartwood proportion with increasing height can be explained by the manner in which tree stems increase in diameter and in height through the addition of growth increments as indicated in Figure 1. This results in a decrease in the number of growth rings with increasing height in the stem hence a decrease in heartwood proportion as for these species the number of growth rings with sapwood remains almost constant throughout the stem.

2.7 Heartwood in teak

2.7.1 Qualities of heartwood

Teak has a yellow - brown, green - brown, golden brown or dark golden yellow heartwood turning dark brown on exposure and a pale yellow sharply demarcated sapwood (Anon., 1973; Chudnoff, 1979; Donaldson, 1984). The wood is medium to coarse in texture,hard, dense and has straight to wavy grain. It has conspicuous growth rings and distinctive odour (Donaldson, 1984).

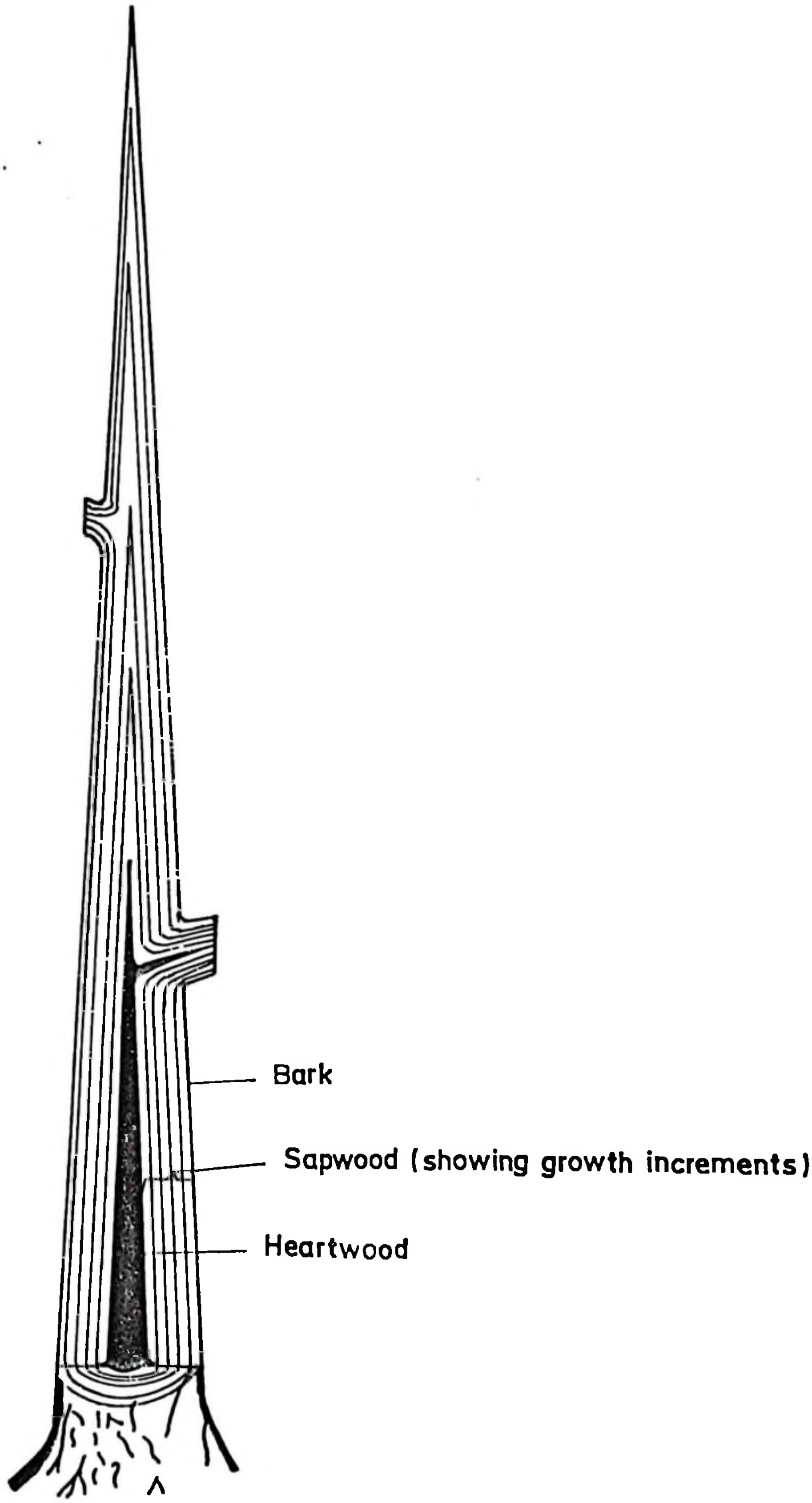

Fig.1. The manner in which tree stem(s) increase(s) in diameter and in height through the addition of growth increments for a 7 year old stem.

one of the qualities which places teak wood among the most valued world timbers is the reputed high resistance of the heartwood to attack by wood destroying fungi, termites and other biological agents (Rudman and da Costa 1959; Anon., 1961; Prasad et al., 1964; Abdurachim, 1965; Bryce, 1967; Hillis, 1968). The higher durability of the heartwood in comparison to sapwood is attributed largely to the presence of extractives in the heartwood that are toxic to the wood deteriorating organisms. The toxic extractives include quinones, naphthalene compounds, fatty acids, oils, caoutchoue, anthroquinones, anthrones, lapachol, desoxylapachol and 2 - hydroxymethyl - anthroquinone (Pavanaram and Row, 1957; Rudman, 1961; Rudman and Gay, 1961; Narayanamurti et al., 1962; Anon., 1967; Hillis, 1968). Anthraquinones and anthrones (Rudman and Gay, 1961), Lapachol and desoxylapachol (Anon., 1967) are the main extractives responsible for the resistance of the heartwood to termites. Decay resistance is associated with a neutral extractive which has properties similar to tectol and in a minor degree with 2 - hydroxymethyl - anthraquinone (Rudman, 1961). Also the higher durability of heartwood is caused by reduction in the amount of air and moisture available for fungal growth which is due to reduced heartwood permeability. The reduced heartwood permeability is partly due to presence of extractives (Prasad et al., 1964) and cell wall structure (Rudman and da Costa, 1959). The resistance of heartwood to attack by wood destroying fungi, termites and other biological agents increases witha age of tree (Rudman and da Costa, 1959; Narayanamurti et al., 1962; Abdurachim, 1965). The resistance also increases from inner to outer heartwood (Rudman and da Costa, 1959; Narayanamurti et al., 1962).

This is because the earliest formed heartwood is poorer in the toxic materials such as anthrones, lapachol, anthraquinones, desoxylapachol, caoutchoue and naphthaquinones and therefore less durable than heartwood laid down when the tree is mature (da Costa et al., 1961)

Generally the reduction in permeability due to presence of extractives and/or cell wall structure makes heartwood more resistant to impregnation with preservatives and fire - retardant chemicals andccauses difficulties in drying (Panshin and de Zeeuw, 1970).

The presence of extractives also increases the calorific value of the heartwood (Krishna and Ramaswamy, 1931).

The heartwood of teak has better strength properties (Rajiput et al., 1983) and is dimensionally more stable than its sapwood (Schwarb, 1978).

2.7.2 Variation of heartwood proportion in teak

In *Tectona grandis* L.f. heartwood proportion varies both between and within trees. It is reported that heartwood proportion increases with increase tree age and that increase in growth rate in dbh or height has no effect on the heartwood proportion (Ferguson, 1934; Soonyakhanit, 1963). Nair and Chavan (1985) reported that trunk circumference of the same species shows strong positive correlation with the ratio of heartwood area to sapwood area. The authors further reported that the species showed no relationship between trunk length and heartwood proportion but the increment in length of the trunk results in the increment of heartwood independent of the sapwood both at the tree base and apex. Ferguson (1934) concluded that heartwood proportion in Tectona grandis L.f. may be genetically controlled.

Within the tree heartwood proportion decreases with increase in the stem (Ferguson, 1934; Mnangwone, 1977). A similar observation was made in the report by Nair and Chavan (1985) on the same species. The authors found that the base of the tree trunk has a large amount of heartwood than the apex. The decrease in heartwood proportion with increase in height in the stem is to be expected in Tectona grandis L.f. because the number of growth rings with sapwood remains almost constant throughout the stem (Ferguson, 1934).

2.8 Heartwood pH

The pH of heartwood is in most cases lower than that of sapwood (Hillis, 1968; Bamber and Fukazawa, 1985). Table 5 shows pH values for heartwood and sapwood in some hardwoods. (Gray, (1958) reported a pH of 4.8 and Sandermann and Rothkamm (1959) reported a pH of 5.4 for heartwood of Tectona grandis L.f.

Acidity in wood is caused by the presence of formic acid, acetic acid and carbonic acid resulting from decomposition of sugars, starches and other carbohydrates. Other acids include those commonly found in plants such as malic, citric, pyruvic and oxalic acids (Gray, 1958). Often the acidity of wood increases

Table 5 : pH values for heartwood and sapwood in some hardwoods.

(from : Sandermann and Rothkamm, 1959)

Species name	pH values	
	Heartwood	Sapwood
Diospyros sp.	5.4	5.8
Dalbergia melanoxylon	8.0	5.8
Tectona grandis L.	5.4	5.8
Liriodendron tulipiferum L.	5.4	5.5
Mansonia altissima chev.	4.2	4.5
Schinopsis balansae Engl.	4.3	4.7

towards the centre of the tree because of a gradual hydrolysis of acetyl group resulting in the formation of acetic acid (Stewart et al., 1961).

When acidic in nature extractives in wood may corrode metallic components or affect machinery and instruments in manufacturing processes, may interfere with setting of paints and varnishes and have an adverse effect on the adhesion of surface films and on the formation of strong glue joints (Panshin and de Zeeuw,1970; Guevara and Johns, 1981).

Heartwood pH is reported to vary between tree species and may also vary within tree species due to change in geographical location (Gray, 1958). This variation may be caused by differences in growth conditions.

Guevara and Johns (1981) reported the following variations in pH for Pinus oocarpa S.

- heartwood pH increases with tree height
- heartwood pH varies between geographical location
- trees with slower rates of growth had higher heartwood pH values
- wood specific gravity was positively correlated with heartwood pH among trees, but negatively correlated within a tree.

2.9 Heartwood leachability

Extractives are synthesized in mature parenchyma cells in the sapwood - heartwood transition zone (Hillis, 1962). They then diffuse into adjacent wood fiber cells and are deposited largely in the cell walls of these cells. Deposition within cell walls makes wood more resistant to leaching than if it occurred in the cell lumens as in the case of wood artificially impregnated with oil borne preservatives (Scheffer and Cowling, 1966). Preventing logs from deterioration during storage by soaking in water and pretreating them by steaming or boiling in water for subsequent processing are important undertakings of the high quality veneer producing industries (FAO, 1966; Kollmann *et al.*, 1975). These processes result into leaching of the water soluble extractives such as gallotannins, ellagotannins, phlobatannins, flavonones, sugars, acids and phenols (Rydholm, 1965). Leaching of the water soluble extractives may be an advantage or a disadvantage depending on the use for which the timber is intended. Evidence exists that the natural durability of wood may be seriously affected by the treatment to which the wood is subjected. It is reported that drying of *Sequoia sempervirens* which involves pre-steaming may lower the decay resistance of the species sufficiently to force its reclassification from highly resistant to resistant class (Panshin and de Zeeuw, 1970). Yoshimura (1962) found that *Tectona grandis* L.f. wood samples extracted with hot water and other solvents were easily attacked by *Poria monticola* than unextracted ones. Gupta and Jain (1980) found that removal of hot water extractives from Tectona grandis wood samples decreased the failing load and also affects the bond quality by slight reduction in joint strength. For species such as Thuja plicata which have a high cold water soluble extractive content up to 10%, when used for lining wells or for roofs where drinking water can be collected, it is important that the wood be leached first. This is because the water frequently assumes a characteristic colour and odour which may cause adverse reaction to humans (Maclean, 1970).

Prolonged soaking in cold water or steaming changes the natural colour of wood which is one of the most important appearance characteristic of decorative veneer or panels (FAO, 1966). This may be caused by loss of cold water soluble extractives which may be the colouring material. Colour change may also be caused by hydrolysis of chemicals in the wood (Rydholm, 1965).

The amount of hot and cold water extractives differ between species. Table 6 shows hot and cold water extractives of some hardwood. It is evident from the table that Acer rubrum has the higher percentage of hot water extractives. It can also be noted from the table that hot water extractives values are higher than cold water values for Betula papyrifera and Populus tremuloids.

Table 6 : Hot water and cold water extractives of some hardwoods. (unextracted, dry wood basis) (from: Rydholm, 1965).

Species name	Common name	Extractives %	
		Hot water	Cold water
Acer rubrum	red maple	4.4	-
Betula papyrifera	paper birch	2.7	2.0
Fagus grandifolia	American beech	1.5	-
Populus tremuloides	quaking aspen	2.8	1.5
Ulmus americana	American elm	1.6	-

3. MATERIALS AND METHODS

3.1 Source of materials

The samples used in this investigation were obtained from Mtibwa Forest Project. The area lies between latitude $6^{o}00'$ to 6^{o} $10'$ south and longitude 37^{o} $40'$ to 37^{o} $45'$ east on the northern side of Morogoro Rural district. It is located on the Morogoro - Korogwe road approximately 100 km from Morogoro town. Figure 2 shows the location of the plantation. The plantation is composed of two blocks namely Mtibwa and Lusunguru with areas of 868 and 1230 hectares respectively. Based on a study by Abdulkariem (1980) in which the author determined site classes in each block, the whole forest project can be considered to belong to one site class. Mtibwa block is flat while Lusunguru is characterized by a number of low lying hills scattered over the entire block.

The location has two rain seasons, the long rains from March to May and short rains in November and December with a mean annual rainfall of approximately 1020 mm. The site is about 460 metres above sea level and has a mean temperature of $22^{o}C$.

The first trial plots were established at Mtibwa in 1936 while large scale stand establishment started in 1961. The original vegetation was a mixed natural forest with several tree species

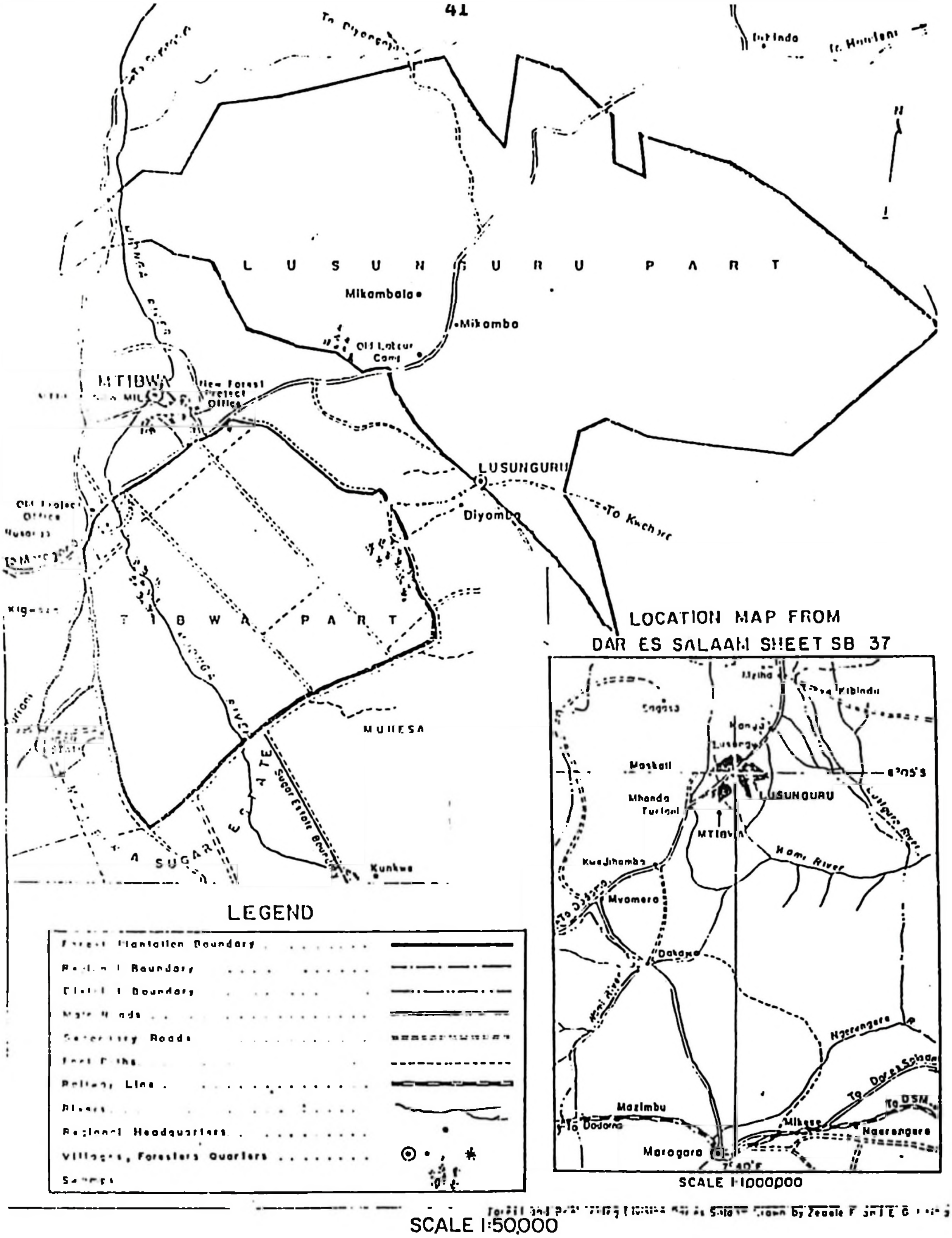

Fig.2. Map of Mtibwa forest project, Morogoro rural district

that include Acacia albida Del., Brachystegia benthamii T., Brachystegia microphylla, Isoberlinia globiflora, Dalbergia melanoxylom, Chlorophora excelsa Benth. and Hook F., Khaya nyasica Staff ex Baker and Pterocarpus angolensis D.C. In addition to Tectona grandis L.f. Cedrela mexicana is also planted.

The oldest stand planted in 1961 has an espacement of 2.5 m x 2.5 m while younger stands up to 16 years have an espacement of 1.8 m x 1.8 m. Three thinnings have been carried out in stands above 16 years old. No thinning has been done in stands aged 16 years and below. It was reported that some parts of 10 and 11 year old stands were damaged by fire and that planting stopped in 1981 (Kiyogwe, 1985).

3.2 Sampling procedures

3.2.1 Tree sampling procedure for determination of age at which heartwood starts to form

Sample trees for determination of age at which heartwood starts to form were obtained from 5, 6, 7, 8, 9 and 10 year old stands. Before the sample tree were identified in each selected stand, a survey of diameter distribution was carried out to ensure that the entire diameter range would be represented in the sample. Sampling started in the youngest stands followed by older ones until it was established that all trees in a given age had formed heartwood.

A 2.0 cm diameter class width was adopted for each of the 6 ages. For each diameter class in each age, three trees representing the smallest, medium and largest trees were selected. Table 7 shows the mean dbh, standard deviation and range for the stands.

Before felling, dbh for each sample tree was measured. After felling the butt end was examined for the existence of heartwood.

3.2.2 Tree sampling procedure for determination of heartwood proportion acidity and leachability

In order to establish a sample size for the study a preliminary investigation was carried out to determine heartwood proportion and its variation. A standard deviation of 9 was obtained for 10 trees. The following formular was used to calculate sample size :

$$n = \frac{4S^2}{E^2}$$

where n = estimated sample size at 95% confidence level

S = standard deviation (based on 10 trees from 25 year old stands)

E = allowable error, (in this case 4 per cent).

The above values gave a sample size of twenty trees. This sample size was adopted for 7, 11, 16, 21 and 25 year old stands. Three trees representing the smallest, medium and largest trees were selected from each of the 32 and 50 year old trial plots as data on other research was still being collected on the trees. Trees bordering stand edge were excluded while potential sample trees with

Table 7: Mean dbh, standard deviation and range for sample trees

Age years	No. of trees	Mean dbh	Std. dev.	Range
5	18	8.0	3.69	2.0 - 13.1
6	18	8.3	3.67	2.2 - 13.8
7	18	8.5	3.64	2.4 - 14.0
8	18	19.1	3.65	4.0 - 15.3
9	18	10.3	3.62	4.4 - 16.0
10	18	10.4	3.61	5.2 - 16.5

defects for example poor form or degradation were rejected and replaced with neighbouring defect free trees.

Dbh for each sample tree was measured on standing trees to a precision of 0.1 cm while total tree height was measured after felling also to a precision of 0.1 cm. Four disks each 6 cm thickness were cut from each sample tree at butt end, 20 per cent, 40 per cent and 60 per cent of total tree height. The diameter of each disk was measured using a diameter tape. Each disk was labelled to show the stand, tree number and height at which it was cut.

3.3 Laboratory measurements

3.3.1 Heartwood proportion

In order to determine heartwood proportion a map of the total disk area under bark and the heartwood area were traced for each disk on a tracing paper. The stand, tree number, disk diameter and the height at which the disk was cut were recorded on the tracing paper. For each disk map, total disk area and heartwood area were determined using a planimeter. Heartwood proportion (Hp) in per cent was computed as follows:

$$Hp = \frac{\text{disk heartwood area}}{\text{total disk area under bark}} \times 100$$

3.3.2 Heartwood pH

For the determination of heartwood pH, dried wood samples from the heartwood portion were taken at a distance of 3 cm from the pith in each disk. The different wood samples were milled separately after which 20 gm of each were boiled in 200 mls of distilled water for 30 minutes. The mixture was then left to cool and sediment followed by decanting extract. pH of the extract was measured to 0.01 precision using a pH metre.

3.3.3 Heartwood leachability

Sample pieces for leachability studies were extracted from 21, 25, 32 and 50 years old trees. For 21 and 25 year old trees, 4 wood pieces from heartwood portion extracted 3 cm from the pith in each of the four cardinal directions in each disk were used. Altogether there were 720 heartwood pieces of 2 cm x 2 cm x 10 cm dimensions originating from 24 trees.

3.3.3.1 Moisture content estimation

Eighty heartwood pieces, twenty from each age were used for moisture content estimation. The pieces were weighed and dried in an oven kept at $103^o - 105^oC$ until they attained constant weight. Moisture content in per cent was determined as follows :

$$Mc\ (\%) = \frac{Wu - Wo}{Wo} \times 100$$

where Mc (%) = moisture content of sample piece, per cent

Wu = original weight of sample piece, g.

Wo = oven dry weight of sample piece, g.

3.3.3.2 Cold water leaching

A complete randomised block design which had 4 blocks representing age group 21, 25, 32 and 50 years and 4 treatments representing soaking time for 30, 60, 90 and 120 days was used. Each experiment contained 20 experimental units. A total of 320 heartwood pieces, 80 from each age were leached. After weighing the heartwood pieces were soaked in cold water at room temperature (22 - 25°C) for 30, 60, 90 and 120 days for the first, second, third and fourth treatment respectively.

After the respective periods the pieces were removed from water and dried in an oven kept at 103 - 105°C until they attained constant weight. The amount of extractives leached out expressed in per cent was determined using the following formular:

$$L\ (\%) = \frac{Wu - Wo_2 - Mc}{Wo_1} \times 100$$

where L (%) = amount of extractives leached out, per cent

Wu = original weight, g

Wo_1 = estimated oven dry weight of unleached piece, g.

Wo_2 = oven dry weight of leached piece, g

Mc = estimated moisture content, g

3.3.3.3 Hot water leaching

A complete randomised block design which had 4 blocks representing age group 21, 25, 32 and 50 years and 4 treatments representing soaking time for 24, 48, 72 and 96 hours was used. Each experiment contained 20 experimental units. A total of 320 heartwood pieces 80 from each age were leached. After weighing the pieces were soaked in hot water at 80°C for 24, 48, 72 and 96 hours for the first, second, third and fourth treatment repestively. After the respective period the pieces were removed from water and in an oven kept at 103 - 105°C until they attained constant weight. The amount of extractives leached out expressed in per cent was determined using the following formular:

$$L\ (\%) = \frac{Wu - Wo_2 - Mc}{Wo_1} \times 100$$

where L (%) = amount of extractives leached out, per cent

Wu = original weight, g

Wo_1 = estimated oven dry weight of unleached pieces, g.

Wo_2 = oven dry weight of leached piece, g

Mc = estimated moisture content, g.

3.4 Data analysis

3.4.1 Heartwood proportion

Stand mean heartwood proportion was estimated as the mean of stand sample tree means.

3.4.1.1 Relationship between heartwood proportion and age, dbh, total tree height and height in the stem

The relationship between mean heartwood proportion and stand age dbh, total tree height and height in the stem were established by regression analysis. Models commonly used by other scientists were tried to find which one fits the data well. The models tried were :

- Logarithmic model specified by the equation :

$$Y = \alpha + \beta \log X + \varepsilon$$

- asymptotic model specified by the equation :

$$Y = \alpha + \beta / X + \varepsilon$$

- second degree polynomial specified by the equation :

$$Y = \alpha + \beta_1 X_1 + \beta_2 X_1^2 + \varepsilon$$

3.4.1.2 Relationship between heartwood proportion and dbh and total tree height

The relationship between heartwood proportion and dbh and total tree height considered together was established by regression analysis to find which model fits the data well. Models which are commonly used were tried. The models were :

- linear model, specified by the equation.

$$Y = \alpha + \beta_1 X_1 + \beta_2 X_2 + \varepsilon$$

- asymptotic model, specified by the equation

$$Y = \alpha + \beta / X + \varepsilon$$

- second degree polynomial models specified by the equation:

$$Y = \alpha + \beta_1 X_1 + \beta_2 X_1^2 + \beta_3 X_2 + \beta_4 X_2^2 + \mathcal{E}$$

3.4.2 Heartwood pH

Heartwood mean pH was established as the mean of sample tree means. Sample tree mean pH was estimated as mean of the pH value at butt end, 20 per cent, 40 per cent and 60 per cent of total tree height. Analysis of variance was used to establish the relationship between pH and height in the stem.

3.4.3 Heartwood leachability

3.4.3.1 Cold water leaching

Analysis of variance was carried out to test the hypothesis that cold water leaching has effect on weight of the sample pieces. The following model was used.

$$Y_{ij} = \mu + \alpha_j + \bar{\Pi}_i + \mathcal{E}_{ij}$$

where Y_{ij} = observed dependent variable

α_j = treatment effect

$\bar{\Pi}_i$ = mean of dependent variable

$\mathcal{E}_{ij}$ = residual error

3.4.3.2 Hot water leaching

Analysis of variance was carried out to test the hypothesis that hot water leaching has effect on weight of the sample pieces. The same model used in 3.4.3.1 was adopted.

4. RESULTS

4.1 Age at which heartwood starts to form

The proportions of sample trees that had formed heartwood in each of the 5, 6, 7, 8, 9 and 10 year old stands were computed and the results are presented in table 8. The table shows that at age 5 and 6 years none of the trees had formed heartwood while at age 7 and 8 years about 83 and 94 per cent respectively of the sample trees had formed heartwood.
It is also apparent that all the 18 sample trees from each of the 9 and 10 year old stands had formed heartwood.
These results indicate that heartwood starts to form in *Tectona grandis* L.f. grown at Mtibwa forest project when the trees are between 7 and 9 years old.

4.2 Heartwood proportion

The arithmetic mean of heartwood proportion for each age was computed from twenty individual tree values. The results are presented in table 9 while appendices 1 to 7 present heartwood proportion values for the individual trees. It is observed in table 9 that heartwood proportion ranged from 3.2 per cent to 64.7 per cent in 7 and 50 year old trees respectively and that there was a wide range within each age except the 7 year old stand. It is also observed that the standard deviation values for trees from 16, 21 and 25 year old stands are above 10 while those from 7 and 11 year old stands are below 6. Standard deviation for 32 and 50 year old stands

Table 8 : Proportions of sample trees with heartwood in each of the 5, 6, 7, 8, 9, and 10 year old stands

Age , years	No. of trees	Mean dbh, cm	Proportion of sample trees with heartwood, per cent
5	18	8.0	0
6	18	8.3	0
7	18	8.5	83
8	18	10.1	94
9	18	10.3	100
10	18	10.4	100

were not computed because the number of sample trees was too low to justify statistical analysis.

4.2.1 Relationship between heartwood proportion and stand age

The stand mean heartwood proportion values and stand age shown in Table 9 were subjected to regression analysis in order to establish the relationship between heartwood proportion and stand age. Among the 3 models tried as presented in 3.4.1 the asymptotic model more accurately and logically describes the relationship between the two variables. Appendix 8 shows the equations and correlation coefficients obtained for the other two models. The following equation was obtained :

$$Hp = 69.569 - \frac{518.416}{A} \quad \text{with r value of 0.93}$$

where Hp = heartwood proportion, per cent

A = age, (between 7 and 50 years)

The relationship is significant at 99 per cent confidence level. Table 10 shows values estimated from the equation and the actual mean values.

The differences between the actual heartwood proportion and the estimated values expressed as per cent of actual values were found to be highest for 11 and 16 years old trees. These differences were 72 and 29 per cent for 11 and 16 years old trees respectively. Comparable values for 21, 25, 32 and 50 year old trees lay between 10 to 17 per cent. Figure 3 illustrates the trend of heartwood proportion with tree age based on the model.

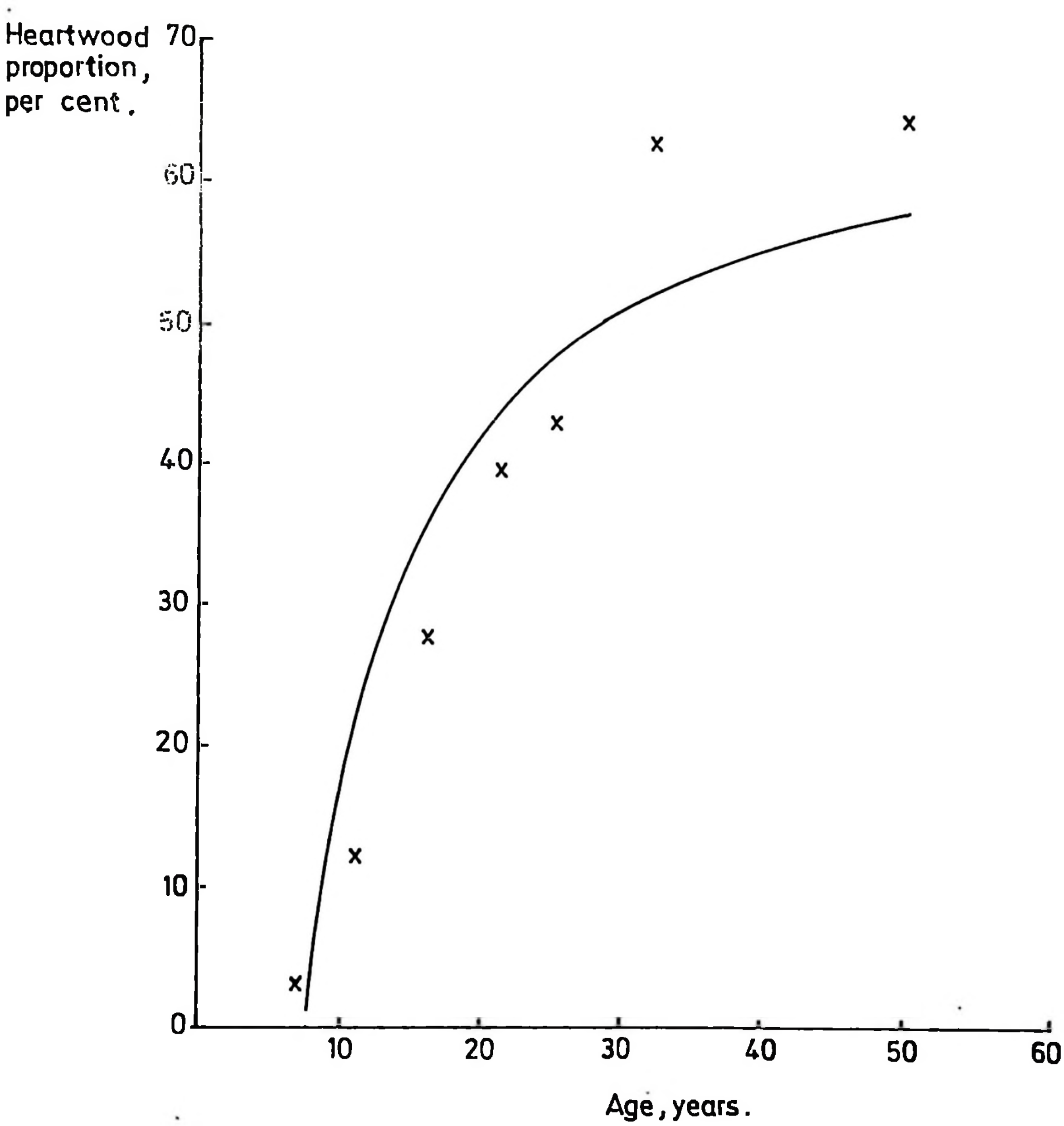

Fig. 3. Relationship between heartwood proportion and age.

Table 9 : Mean dbh, total tree height and heartwood proportion for the seven stands

	Arithmetic Mean		Heartwood proportion per cent		
Age years	dbh cm	Total tree height (m)	Arithmetic mean	Sd.	Range
7	9.7	12.7	3.2	1.12	1.9 - 5.0
11	10.3	12.0	12.5	5.54	1.0 - 23.7
16	14.2	18.5	28.0	11.33	23.0 - 51.7
21	17.7	20.8	39.8	10.44	15.1 - 63.2
25	20.4	22.0	43.1	10.85	20.3 - 63.2
32	23.3	24.9	63.1	-	56.5 - 70.9
50	33.1	25.0	64.7	-	63.6 - 66.4

Table 10 : Actual heartwood proportion values, estimated heartwood proportion values and their differences for the six ages

Stand age	Heartwood proportion per cent		Differences between actual and estimated values, per cent
	Actual	Estimated from equation	
11	12.5	21.4	72
16	28.0	36.2	29
21	39.8	43.9	10
25	43.1	47.8	11
32	63.1	52.4	17
50	64.7	58.2	10

Heartwood proportion increases from 21.4% at age 11 to 47.8 per cent at age 25 and 52.4 per cent at age 32 to 58.2 per cent at age 50 years.

4.2.2 Relationship between heartwood proportion and dbh

The individual tree heartwood proportion values and tree dbh were subjected to regression analysis. It was found that among the three models tried, the asymptotic model ($Hp = \alpha + \beta/D + \varepsilon$ fits the data with the highest correlation coefficient except for 11 and 16 year old stands which have highest correlation coefficients when logarithmic model is used. See appendix 9 and table 11. Table 11 shows the regression equations relating heartwood proportion and dbh for 7, 11, 16, 21 and 25 year old trees. It is evident in this table that with exception of age 16 there was significant correlation at 99 per cent confidence level between heartwood proportion and dbh for all ages. Figure 4 shows curves relating heartwood proportion and dbh for all five stands. It can be noted in Figure 4 that for the same dbh, heartwood proportion increase with increase in age. For example for a dbh of 10 cm, heartwood proportion is about 25, 14 24, 27,5 and 34 per cent for 7, 11, 16, 25 and 21 year old stand respectively. It can also be noted that the rate of increase in heartwood proportion is higher for smaller dbh values and that the rate decreases with increase in dbh. The rate stabilizes at high dbh values.

Table 11 : Regression equations and correlation coefficients for the relationship between heartwood proportion and dbh for 7, 11, 16, 21 and 25 year old trees

Age years	Regression equation	Correlation coefficient
7	$Hp = 5.226 - \frac{17.820}{D}$	0.57**
11	$Hp = 25.35 - \frac{119.34}{D}$	0.65**
16	$Hp = 43.219 - \frac{204.769}{D}$	0.33 NS
21	$Hp = 53.92 - \frac{221.077}{D}$	0.63**
25	$Hp = 63.245 - \frac{376.202}{D}$	0.63**

Where Hp = heartwood proportion, per cent

D = dbh, cm

NS = not significant at 95% confidence level

** = significant at 99% confidence level

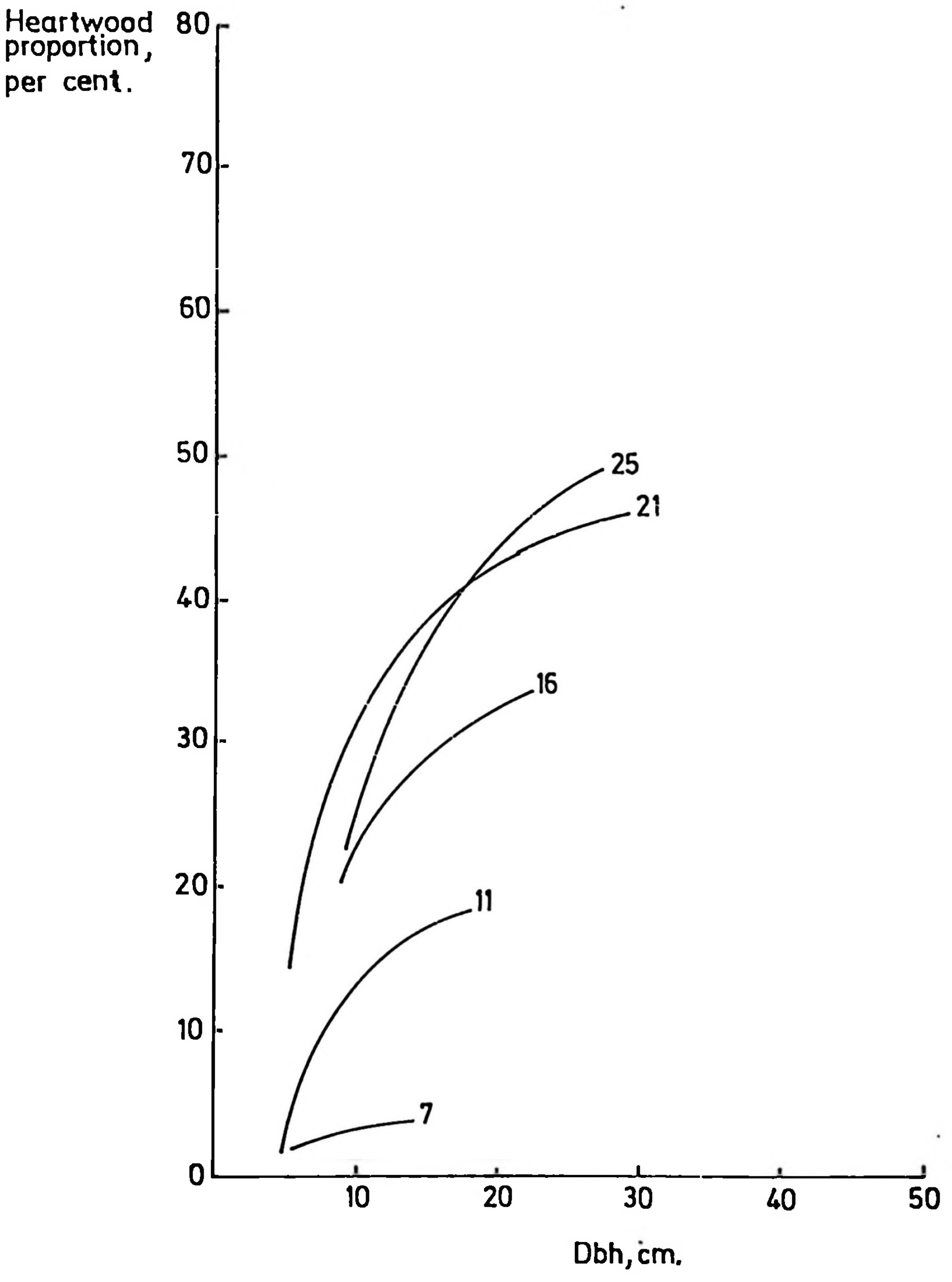

Fig.4. Relationship between heartwood proportion and dbh for 7,11,16,21 and 25 year old trees.

4.2.3 Relationship between heartwood proportion and total tree height

The individual tree heartwood proportion and total tree height values were subjected to regression analysis and found that among the 3 models tried, the asymptotic model ($Hp = \alpha + \beta/h + \mathcal{E}$) describes the relationship between heartwood proportion and total tree height more accurately. See Appendix 10. Table 12 shows the regression equations relating heartwood proportion and total tree height for 7, 11, 16, 21 and 25 year old trees. It is apparent from the table that the relationship between the two variables is significant at 99%. confidence level for 25 year old trees, significant at 95% confidence level for 11 and 21 year old trees and not significant at 95% confidence level for 7 and 16 year old trees. Figure 5 illustrates the relationship between heartwood proportion and total tree height based on values estimated by the equations in Table 12.

4.2.4 Relationship between heartwood proportion and dbh and total tree height

The individual tree heartwood proportion values, tree dbh and total tree height were subjected to regression analysis. It was established that the second degree polynomial model fits the data with the highest overall correlation coefficient.

Table 12 : Regression equations and correlation coefficients for the relationship between heartwood proportion and total tree height for 7, 11, 16, 21 and 25 year old trees

Age years	Regression equation	Correlation coefficient
7	$Hp = 9.135 - \frac{75.082}{T}$	0.28 NS
11	$Hp = 33.792 - \frac{249.869}{T}$	0.47^{*}
16	$Hp = 80.989 - \frac{973.169}{T}$	0.39 NS
21	$Hp = 81.169 - \frac{845.794}{T}$	0.53^{*}
25	$Hp = 58.107 - \frac{323.927}{T}$	0.75^{**}

Where Hp = heartwood proportion, per cent

T = total tree height, m.

NS = not significant at 95% confidence level

* = significant at 95% confidence level

** = significant at 99% confidence level

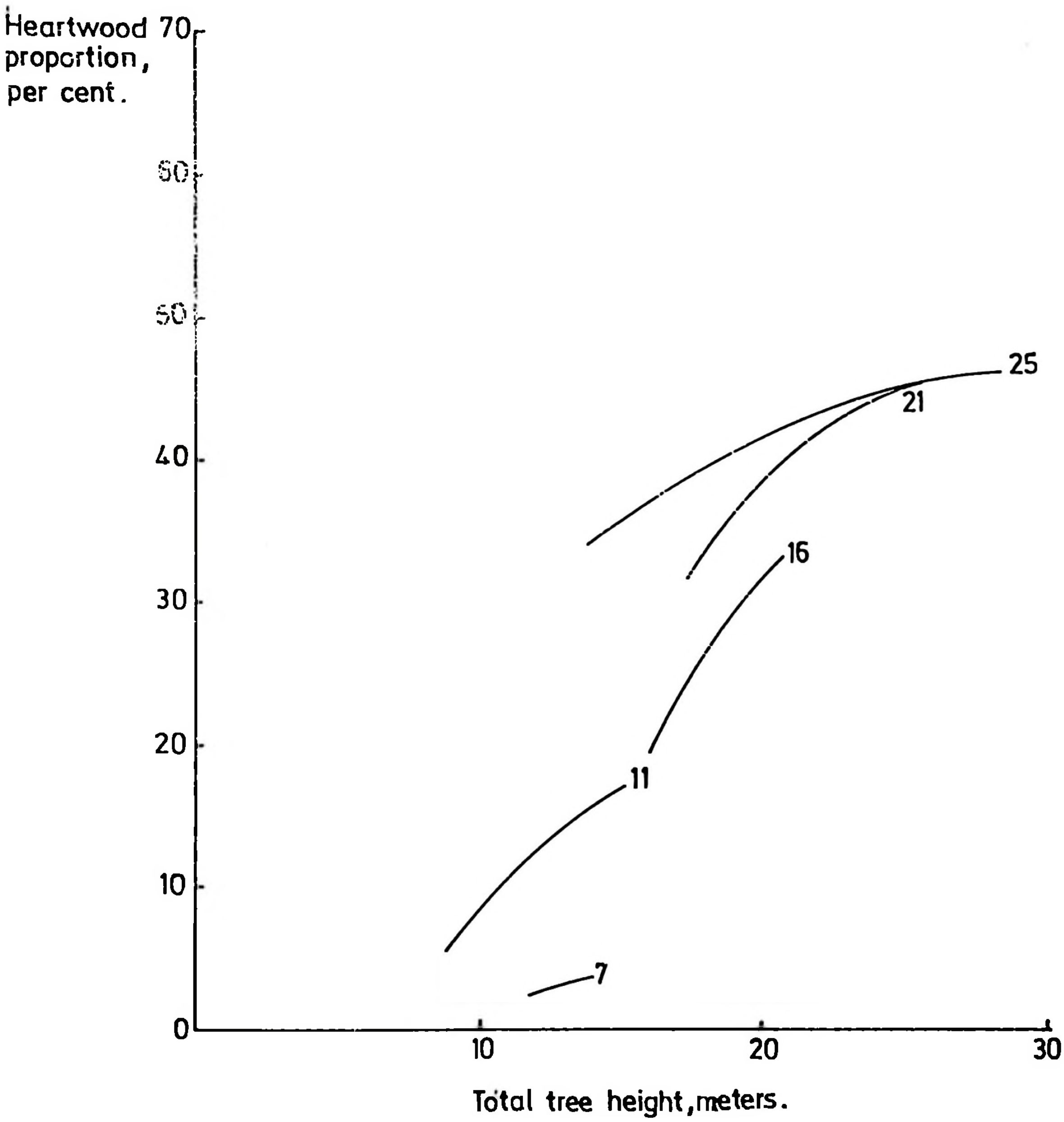

Fig.5. Relationship between heartwood proportion and total tree height for 7, 11, 16, 21 and 25 year old trees.

It was also observed that the asymptotic model describes the relationship equally well in some of the stands as indicated in Appendix 11. Table 13 and Appendix 11 show the regression equations relating heartwood proportion and dbh and total tree height considered together. It can be inferred from the results in both Table 13 and Appendix 11 that the relationship between heartwood proportion and dbh and total tree height considered together is significant at 99 per cent confidence level for 7, 11, 21 and 25 year old trees and significant at 95 per cent confidence level for 16 year of trees.

4.2.5 Relationship between heartwood proportion and height in the stem

Mean heartwood proportion values for each of four positions in the tree and heartwood proportion were subjected to regression analysis. Among the three models tried as presented in 3.4.1.1 the second degree polynomial model ($Hp = \alpha + \beta_1 H_1 + \beta_2 H_1^2 + \beta_3 H_2$) was found to fit the data with the highest correlation coefficient See Appendix 12. Table 14 shows the regression equations relating heartwood proportion and height in the stem. It can be noted from the table that the relationship between heartwood proportion and height in the stem is significant at 99% confidence level for all stands. Figure 6 illustrates the relationship between the two variables based on the equations in Table 14. A fast rate of decrease in heartwood proportion is noted between butt

Table 13 : Regression equations and correlation coefficients for the relationship between heartwood proportion and dbh and total tree height

Age years	Regression equation	Correlation coefficients
7	$Hp = 3.850 + 1.625D - 0.054D^2 - 0.067^2$	0.78^{**}
Std. Error	0.631 0.029 0.019	
11	$Hp = 52.603 - 0.576D - 0.105D^2 + 10.134T - 0.427T^2$	0.84^{**}
Std. Error	1.628 0.072 7.532 0.31	
16	$Hp = 97.822 + 8.182D - 0.24D^2 + 3.345T$	0.54^{*}
Std. Error	5.387 0.178 1.643	
21	$Hp = 36.516 + 2.658D - 0.048D^2 + 3.886T - 0.08T^2$	0.64^{**}
Std. Error	2.685 0.072 13.602 0.34	
25	$Hp = 16.877 + 3.601D - 0.068D^2 + 1.098T - 0.015T^2$	0.63^{**}
Std. Error	4.042 0.084 8.471 0.182	

Where Hp = heartwood proportion, per cent
D = dbh, cm
T = total tree height, m
* = significant at 95% confidence level
** = significant at 99% confidence level

Table 14 : Regression equations and correlation coefficients for the relationship between heartwood proportion and height in the stem for 7, 11, 16, 21, 25, 32 and 50 year old trees.

Age years	Regression equation	Correlation coefficient
7	$Hp = 10.497 - 0.45\ Hs + 0.005\ Hs^2$	1**
11	$Hp = 26.433 - 0.643\ Hs + 0.004\ Hs^2$	0.99**
16	$Hp = 46.887 - 0.387\ Hs - 0.005\ Hs^2$	1**
21	$Hp = 57.901 - 0.472\ Hs - 0.003\ Hs^2$	1**
25	$Hp = 58.587 - 0.207\ Hs - 0.007\ Hs^2$	1**
32	$Hp = 73.935 - 0.048\ Hs - 0.007\ Hs^2$	1**
50	$Hp = 78.757 - 2.88\ Hs - 0.004\ Hs^2$	1**

Where Hp = heartwood proportion, per cent

Hs = height in the stem, per cent

** = significant at 99% confidence level.

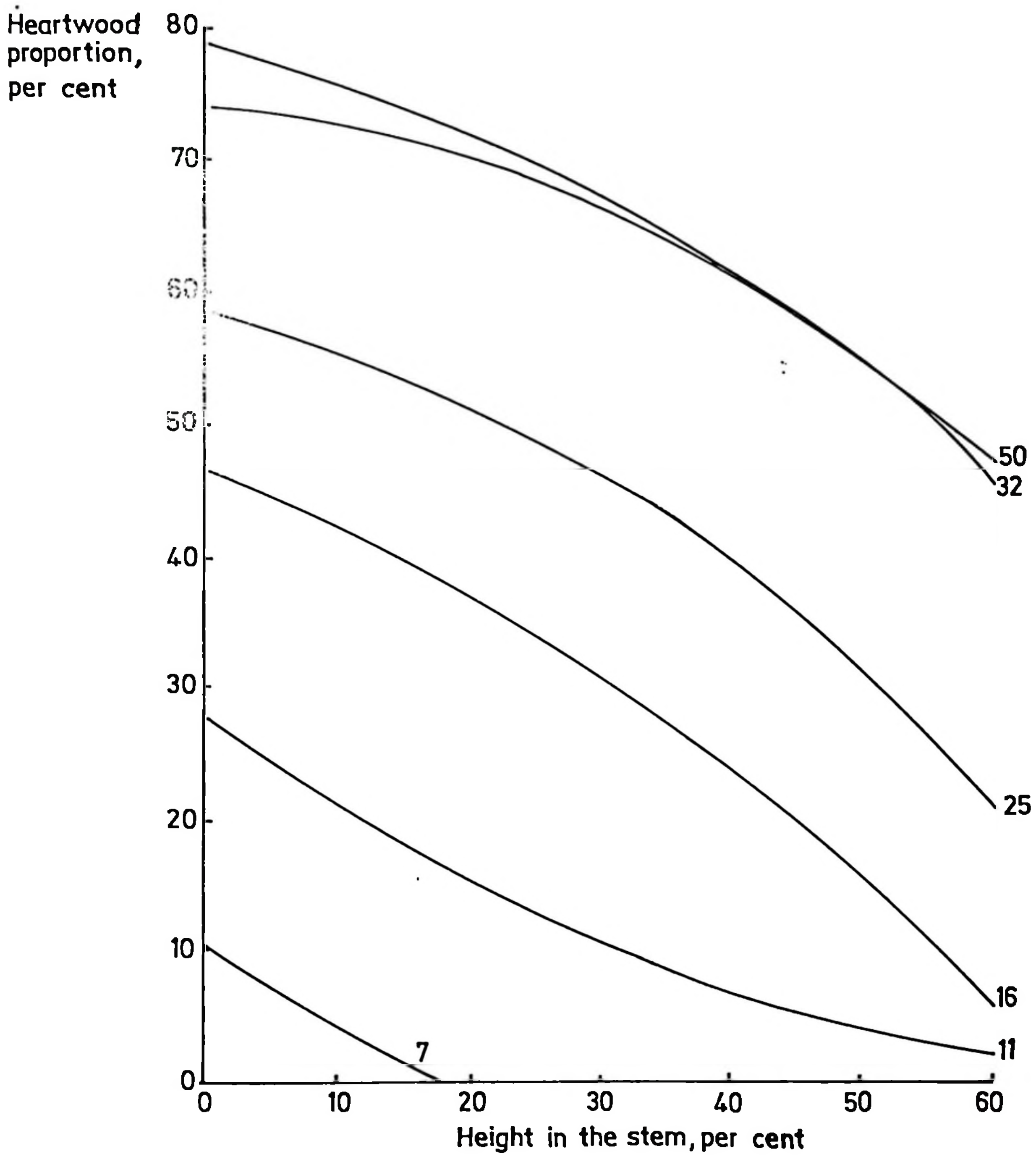

Figure 6. Relationship between heartwood proportion and height in the stem.

end and 20 per cent of total tree height for 7 and 11 year old stands.

4.3 Heartwood pH

The arithmetic mean of heartwood pH was computed based on the 80 values obtained for the extracts. The mean heartwood pH was found to be 5.5 ranging from 5.2 to 5.9.

4.4 Heartwood leachability

4.4.1 Cold water leaching

The arithmetic mean of the loss in weight for each treatment and block was computed. Table 15 shows the mean losses in weight due to cold water leaching. It was observed that the loss in weight was not significant for the respective periods.

4.4.2 Hot water leaching

The arithmetic mean of the loss in weight for each treatment and block was computed. Table 16 shows the mean losses in weight due to hot water leaching. It was found that the loss in weight was not significant in each duration.

Table 15 : Loss in weight for heartwood soaked in cold water for 30, 60, 90 and 120 days

Duration, days	30	60	90	120
No. of samples	80	80	80	80
Mean loss in weight due to leaching per cent	0.05	0.11	0.19	0.21
Std. deviation	1.3	0.4	1.8	1.1

Table 16 : Loss in weight for heartwood soaked in hot water for 24, 48, 72 and 96 hours

Duration, hours	24	40	72	96
No. of samples	80	80	80	80
Mean loss in weight due to leaching, per cent	0.07	0.16	0.27	0.56
Std. deviation	1.7	1.4	2.2	1.4

5. DISCUSSION

5.1 Age at which heartwood starts to form

The results obtained in this study indicate that heartwood formation starts in *Tectona grandis* L.f. when the trees are between 7 to 9 years old. These results fall within the age range of 1 - 10 years reported by Ferguson (1934) for the same species. The age is higher than the upper age limit for heartwood formation in *Eucalyptus* spp. that has been reported to be between 2 and 6 years old (Dadswell and Hillis, 1962). It was also observed that the age is different from that reported by Bryant (1968) for *Pterocarpus angolensis* D.C. in which heartwood formation starts when the trees are about 15 years old. Based on this study it is not possible to say what exactly trigers heartwood formation and what causes variations between trees grown in the same site class in Mtibwa. This could be a result of differences in genetical factors (Bauch, 1980) and or environmental factors (Rydholm, 1965).

5.2 Heartwood proportion

The mean heartwood proportion of 3.2 to 64.1 per cent obtained in this study indicated in Table 9 are about the same as those reported by Mnangwoue (1977) for the same species for 9 to 30 year old stands. The proportions are similar to those reported by Bryant (1968) for *Pterocarpus angolensis*

D.C. The author reported a mean heartwood proportion of about 2 per cent to 70 per cent for 11 - 15 and 45 - 50 years age classes respectively.

5.2.1 Relationship between heartwood proportion and age

The results obtained in this study indicate a significant positive relationship between heartwood proportion and tree age at 99 per cent confidence level.

Figure 3 shows that for young stands up to 18 years the trend conforms to that reported by Mnangwone (1977) that heartwood proportion increases linearly from 5 to 39 per cent between 9 and 18 year old stands. However it is observed in this study that an asymptotic model best describes the relationship when stands of older ages are included. The observed trend in heartwood proportion is in agreement with results reported by Ferguson (1934) for the same species. The same trend is reported for other hardwood species including Pterocarpus angolensis D.C. (Bryant, 1968) and Pseudotsuga taxifolia (Brix and Mitchel, 1983).

5.2.2 Relationship between heartwood proportion and dbh

The results obtained in this study indicate that there is a significant positive relationship between heartwood proportion and dbh at 99 per cent confidence level for 7,11, 21 and 25 year old trees. These results are in agreement with those reported by Nair and Chavan (1985) for the same species. Similar findings are reported for Acacia catechu willd., Albizia lebbek (L) Bth., Albizia procera (Roxb.) Bth., Bridelia retusa (L) spreng, Dalbergia latifolia (Roxb.), Grewia tiliifolia Vahl, Kydia calycina Roxb., Hochreut and Terminalia crenulata Roth. (Nair and Chavan, 1985), However, the results indicate that there is no significant relationship between heartwood proportion and dbh for the 16 year old stand. Based on this study it is not clear why the results are different from the rest of the stands.

5.2.3 Relationship between heartwood proportion and total tree height

The results obtained in this study show that there is a significant positive relationship between heartwood and total tree height at 99 per cent confidence level for the 25 year old stand and at 95 per cent confidence level for the 11 and 21 year old stands. This relationship is best described by the asymptotic model, see Table 12 and Appendix 19. These results are in agreement with those reported by Nair and Chavan (1985) for the same species and other ten-: hardwood species. The authors reported that the increment in length of the trunk results in the increment of heartwood independent of the sapwood both at the base and apex for Tectona grandis L.f. Acacia catechu Willd.

Albizia lebbek (L) Bth., *Albizia procera* (Roxb.) *Grewia tillifolia* Vahl., *Kydia calycina* Roxb, *Melia dubia* cav., *Ougeinia oojeinensis* (Roxb.) Hochreut and *Terminalia crenulata* Roth. The results also show that there is no significant relationship between heartwood proportion and total tree height for 7 and 16 year old stands. Differences in genetical constitutents, age and environmental factors might be the possible reasons explaining the variations observed in this study (Ferguson, 1934).

5.2.4 Relationship between heartwood proportion and dbh and total tree height

The combined effect of dbh and total tree height improved the correlation coefficient for each stand. For example correlation coefficient ranged from 0.33 to 0.65 for dbh and 0.28 to 0.75 for total tree height compared to 0.54 to 0.84 when the two factors are combined. It can be noted in Table 13 and Appendix 11 that the asymptotic and the second degree polynomial models can be used interchangebly for estimating heartwood proportion for 7, 21 and 25 year old stands since both have the same correlation coefficients. It can also be noted that the second degree polynomial model is more reliable in estimating heartwood proportion for 11 and 16 year old stands.

5.2.5 Relationship between heartwood proportion andh height in the stem

The results show that there is a significant negative relationship between heartwood proportion and height in the stem at 99 per cent confidence level. The decrease in heartwood proportion with increase in height in the stem observed in this study is in agreement with results reported by Ferguson (1934) and Khangwone (1977) for the same species. The results are also in agreement with the results for Pseudotsuga taxifolia (Smith et al., 1966; Brix and Mitchel, 1983) and on Eucalyptus tereticornis Sm. (Purkayastha et al., 1980).

5.3 Heartwood pH

The results obtained in this study indicate that heartwood pH in Tectona grandis does not vary significantly with height in the stem. The mean heartwood pH of 5.5 obtained in this study with a range of 5.1 to 5.9 is about the same as the mean pH of 5.4 reported by Sandermann and Rothkamm (1959) for the species. However the value differs from that of 4.8 reported by Gray (1958) for the same species. The differences in heartwood pH between that obtained in this study and the pH reported by Gray (1958) may be caused by differences in age, genetical and environment factor (Gray, 1958). The pH is about the same to that reported for other hardwoods for example in Diospyros sp. and Liriodendron tulipiferum L. (Sandermann and Rothkamm, 1959). The pH however differs from that reported for other hardwoods for example Dalbergia melanoxylon with a pH of 8, Mansonia altissima chev. with a pH of 4.2 and Schinopsis balansae Engl. with a pH of 4.3 (Sandermann and Rothkamm, 1959).

5.4 Heartwood Leachability

The results obtained in this study indicate that the loss of weight of 0.05, 0.11, 0.19 and 0.21 per cent when the heartwood samples were soaked in cold water for 30, 60, 90 and 120 days respectively are not significant. The loss in weight is very low when compared to total amount of cold water extractives for example in Betula papyrifera and Populus tremuloides which were 2 and 1.5 per cent respectively (Rydholm, 1965).

The results also point out that the loss of weight of 0.07, 0.16, 0.27 and 0.56 per cent when the heartwood samples were soaked in hot water for 24, 48, 72 and 96 hours respectively are not significant. It is difficult to compare these results with those reported by Yoshimura (1962) and by Gupta and Jain (1980) for the same species since the authors did not show the amount of loss of weight. However it is important to qualitatively analyse the nature of the compounds that are leached out since the composition is more important than the amount of extractives in determining the durability of wood, see Scheffer and Cowling (1966). The loss in weight is smaller when compared to the total amount of hot water extractives in Acer rubrum, Betula papyrifera and *Populus tremuloides* which were 4.4, 2.7 and 2.8 per cent respectively (Rydholm, 1965).

6. PRACTICAL SIGNIFICANCE OF THE RESULTS

6.1 Age at which heartwood starts to form

The results obtained in this study may be used in allocating the use to which the wood from thinnings can be put to. The first thinning at age 4 years will have no heartwood and the second thinning at age 8 years will have low heartwood proportions. This means that :

- without treatment, poles from the two thinnings will be unsuitable for use in construction of rural houses i.e. mud and pole houses, both for wall and roofs due to attack by insects and fungus.

- the wood may be used mainly as wood fuel for the local population in and around the project. The bulk may be sold to the Mtibwa sugar factory nearby for use in generation of energy.

6.2 Variation of heartwood proportion

6.2.1 Variation of heartwood proportion with age and growth rate as measured by dbh and total tree height

Heartwood proportion increased with age and growth rate as measured by dbh and total tree height. This means that :

- logs from older stands and those from fast growing trees will have higher heartwood proportion. This points to the fact that longer rotations will products logs which have higher heartwood proportions and hence more durable timber. The present rotation of 60 years will give log with more than 63 per cent heartwood;

- since heartwood proportion increases with growth rate, it may be preferable to select trees with high growth rate. It is also pertinent to select stand management practices that results into fast growth.

6.2.2 Variation of heartwood proportion in the stem

Butt logs contain higher proportion of heartwood than top logs. Therefore the former are expected to be more valuable than the latter. Top logs contain low proportion of heartwood and thus low volume of durable wood. This situation will require treatment of the sapwood in order to increase the service life of the products manufactured from it.

6.3 Heartwood acidity

pH is important in designing and fabricating wood structures using metal fasteners. pH of 5.5 obtained in this study may not cause corrosion of metal fasteners (Gray, 1958).

6.4 Heartwood leachability

The results obtained in this study indicate that soaking logs in cold water for up to 120 days or in hot water for up to 96 hours result into insignificant loss in weight. Therefore logs can be stored in cold water to soften and prevent them from deterioration and may be soaked in hot water as a pre-treatment in veneer production. However it is important to qualitatively analyse the nature of the compounds that are leached out as it is the composition of the extractives rather than the amount which is more important in determining the durability of a tree species.

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Appendix 1 : Dbh, total tree height and heartwood proportion for 7 year old trees

Tree No.	Dbh, cm.	Total tree height m	Disk heartwood proportion per cent at: Butt end	20%	40%	60%	Mean heartwood proportion, per cent
1	5.5	11.8	8.453	0	0	0	2.113
2	5.7	11.6	8.378	1.318	0	0	2.424
3	5.9	11.9	7.848	0	0	0	1.962
4	6.6	12.2	5.557	2.104	0	0	1.915
5	6.9	11.8	9.367	1.886	0	0	2.813
6	7.4	12.4	9.487	0	0	0	2.372
7	8.0	12.0	17.096	1.402	0	0	4.624
8	8.6	12.1	15.103	0	0	0	3.776
9	8.9	13.3	5.992	1.817	0	0	1.952
10	9.5	13.1	7.237	1.212	0	0	2.112
11	9.9	12.9	13.929	3.452	0	0	4.345
12	10.3	13.3	7.213	2.118	0	0	2.333
13	10.7	12.8	14.061	2.655	0	0	4.179
14	11.4	13.2	14.095	3.217	0	0	4.328
15	11.8	13.4	9.898	4.150	0	0	3.512
16	12.6	13.5	7.662	3.744	0	0	2.851
17	12.9	12.9	15.609	4.443	0	0	5.013
18	13.3	13.2	4.878	4.102	0	0	2.245
19	13.8	13.4	13.276	3.981	0	0	4.314
20	14.0	13.5	15.632	4.377	0	0	5.002
Mean	9.7	12.7	10.5	2.3	0	0	3.2

Appendix 2 : Dbh, total tree height and heartwood proportion for 11 year old tree

Tree No.	Dbh, cm.	Total tree height, m.	Disk heartwood proportion per cent				Mean heartwood proportion percent
			Butt end	20%	40%	60%	
1	14.5	15.1	38.374	25.255	11.349	6.266	20.286
2	15.8	14.6	39.136	25.746	5.0	1.494	17.844
3	6.9	13.4	8.195	2.778	3.571	0	3.636
4	12.5	14.8	27.166	16.178	5.511	0	12.214
5	11.5	13.8	27.678	14.502	2.281	0	11.115
6	5.0	9.7	22.281	10.334	5.217	0	9.458
7	5.6	12.2	21.677	10.128	0	0	7.951
8	6.4	10.3	13.357	7.298	4.121	0	6.194
9	7.0	9.7	13.192	7.362	0	0	5.138
10	10.4	12.2	27.797	15.405	5.108	0	12.078
11	10.0	13.2	31.291	18.707	9.325	0	14.831
12	18.0	13.2	40.146	38.261	21.477	16.947	29.208
13	11.0	12.4	37.511	21.687	8.76	0	16.989
14	9.8	11.6	30.215	20.290	6.048	0	14.138
15	9.4	11.2	20.131	9.956	0	0	7.521
16	11.1	9.9	17.678	8.794	0	0	6.618
17	8.4	8.9	26.334	18.814	0	0	11.287
18	9.0	10.0	8.247	2.450	0	0	2.674
19	11.0	11.7	30.163	16.716	6.831	0	13.427
20	13.0	11.8	40.318	33.016	18.555	14.159	26.512
Mean	10.3	12.0	26.0	16.2	5.7	1.9	12.5

Appendix 3 : Dbh, total tree height, and heartwood proportion for 16 year old trees

Tree No.	Dbh, cm.	Total tree height, m.	Disk heartwood proportion, per cent at				Mean heartwood proportion, per cent
			Butt end	20%	40%	60%	
1	8.8	19.0	31.338	16.321	0	0	11.915
2	9.5	18.9	34.618	6.28	4.097	0	11.259
3	10.5	19.5	57.745	56.606	45.911	0	39.316
4	10.8	16.1	53.913	25.706	4.888	0	21.127
5	11.2	19.1	54.608	37.486	31.386	38.29	40.417
6	12.0	16.5	40.618	14.392	0	0	13.753
7	12.4	20.1	29.268	23.895	0	0	13.291
8	13.0	19.8	48.013	35.300	22.08	0	26.348
9	13.5	19.3	59.436	54.620	58.685	34.03	51.693
10	13.8	18.1	46.288	52.973	59.659	2.739	40.415
11	13.8	17.3	45.065	44.692	40.956	0.0	32.678
12	14.0	19.9	56.385	40.979	32.262	20.548	37.544
13	14.2	16.2	39.168	23.139	20.578	4.217	21.776
14	15.5	17.9	40.307	37.467	13.509	0	22.821
15	16.0	20.2	55.374	47.515	21.782	0	31.168
16	16.8	17.4	53.967	53.478	19.447	0	31.721
17	18.0	19.4	59.276	41.920	18.609	5.771	31.394
18	18.9	18.3	39.629	45.718	29.297	3.25	30.474
19	19.2	15.9	31.678	39.412	0	0	17.773
20	22.0	20.6	57.063	48.267	40.664	7.899	38.473
Mean	14.2	18.5	46.7	37.3	22.2	5.8	28.3

Appendix 4 : Dbh, total tree height and heartwood proportion for 21 year old trees

Tree No.	Dbh, cm.	Total tree height, m.	Disk heartwood proportion, per cent at				Mean heartwood proportion, per cent
			Butt end	20%	40%	60%	
1	16.0	21.1	54.329	54.937	34.413	13.481	39.290
2	29.0	22.4	56.196	54.213	48.626	22.984	45.505
3	20.5	22.3	68.628	58.382	46.215	31.858	51.271
4	17.2	21.5	63.584	41.921	43.642	22.142	42.822
5	22.5	21.3	60.545	58.707	55.493	33.227	51.993
6	18.5	20.6	36.425	28.244	10.678	15.222	22.642
7	17.8	17.1	61.452	47.527	27.536	22.156	39.668
8	16.4	19.9	52.133	39.098	30.372	11.231	33.208
9	21.0	18.2	51.036	51.884	40.682	28.038	42.910
10	17.5	19.0	70.462	50.251	34.777	18.212	43.426
11	13.5	21.0	55.210	37.306	10.737	1.033	26.071
12	20.5	22.9	66.780	59.435	41.631	38.294	51.535
13	5.6	14.2	44.310	11.326	4.757	0	15.098
14	14.4	21.2	59.678	38.136	26.841	2.771	31.857
15	23.5	23.4	56.506	54.686	38.841	21.321	42.838
16	24.4	24.7	57.897	52.311	36.498	32.685	44.847
17	12.8	19.8	58.409	56.633	50.284	25.781	47.776
18	14.0	21.8	47.133	37.202	19.783	10.672	28.697
19	16.0	21.8	67.628	66.048	46.697	29.281	52.413
20	12.0	20.9	65.070	58.905	34.235	13.208	42.854
Mean	17.7	20.8	57.7	47.9	34.1	19.7	39.8

Appendix 5 : Dbh, total tree height and heartwood proportion for 25 year old trees

Tree No.	Dbh, cm.	Total tree height, m.	Disk heartwood proportion per cent at				Mean heartwood proportion, per cent
			Butt end	20%	40%	60%	
1	11.5	16.3	40.222	31.144	5.124	4.698	20.297
2	25.7	21.4	71.142	58.483	45.671	16.772	48.017
3	33.2	24.7	62.629	59.637	48.674	28.894	49.958
4	23.3	24.0	51.263	49.155	40.489	26.542	41.862
5	18.0	21.0	66.686	52.877	26.446	16.870	40.720
6	16.0	18.5	70.353	56.814	65.382	48.518	60.266
7	16.0	22.1	59.688	58.261	46.266	13.910	44.531
8	27.0	28.3	60.925	63.823	51.368	26.301	50.604
9	20.0	23.0	77.476	69.597	55.966	49.917	63.239
10	18.0	20.8	63.345	44.958	38.455	15.211	40.492
11	19.5	21.6	62.888	55.291	39.478	3.308	40.241
12	16.3	22.0	48.805	41.127	29.794	4.545	31.068
13	22.9	23.4	56.480	42.667	44.082	30.144	43.343
14	24.8	24.2	52.456	46.437	36.769	12.301	36.991
15	9.2	13.6	35.802	20.439	21.200	11.792	22.308
16	24.6	21.4	57.581	51.465	47.967	14.304	42.829
17	19.0	22.3	47.590	39.278	31.635	27.426	36.482
18	23.5	25.0	67.396	60.775	55.504	36.882	55.139
19	15.5	21.0	65.301	47.868	41.602	15.530	42.575
20	23.0	25.3	64.109	53.598	54.363	31.707	50.944
Mean	20.4	22.0	59.1	50.2	41.3	21.8	43.1

Appendix 6 : Dbh, total tree height, and heartwood proportion, for 32 year old trees

Tree No.	Dbh, cm.	Total tree height, m.	Disk heartwood proportion, per cent at				Mean heartwood proportion, per cent
			Butt end	20%	40%	60%	
1	35.0	26.1	86.076	74.661	69.936	52.950	70.906
2	13.0	19.0	68.261	62.293	59.376	36.043	56.493
3	22.0	29.5	70.367	65.142	63.232	48.961	61.926
Mean	23.3	24.9	74.9	67.4	46.2	64.0	63.1

Appendix 7 : Dbh, total tree height and heartwood proportion for 50 year old trees

Tree No.	Dbh, cm.	Total tree height, m.	Disk heartwood proportion, per cent at				Mean heartwood proportion, per cent
			Butt end	20%	40%	60%	
1	49.2	28.0	77.528	72.723	64.533	51.004	66.447
2	20.0	18.0	81.385	79.428	51.353	42.224	63.598
3	30.0	28.7	74.862	69.678	59.788	51.493	63.955
Mean	33.1	24.9	77.9	73.9	58.6	48.2	64.7

Appendix 8 : Regression equations and correlation coefficients for heartwood proportion and age for the logarithmic and second degree polynomial models

Model	Regression equations	Correlation coefficients
a	$Hp = -67.017 + 80.252 \log A$	0.91^{**}
b	$Hp = -24.19 + 3.955A - 0.043A^2$	0.98^{**}

When a = logarithmic model

b = second degree polynomial model

Hp = heartwood proportion, per cent

A = age, years

** = significant at 99% confidence level

Appendix 9 : Regression equations and correlation coefficients for heartwood proportion and dbh for the logarithmic and second degree polynomial models

Age years	Model	Regression equations	Correlation coefficients
7	a	$Hp = -1.442 + 4.812 \log D$	0.57^{**}
	b	$Hp = 0.212 + 0.408D - 0.009 D^2$	0.33 NS
11	a	$Hp = -22.555 + 35.342 \log D$	0.77^{**}
	b	$Hp = 5.908 + 0.446D + 0.095D^2$	0.66^{**}
16	a	$Hp = -8.224 + 31.757 \log D$	0.51^{*}
	b	$Hp = -20.103 + 5.902D - 0.168D^2$	0.11 NS
21	a	$Hp = -13.515 - 43.535 \log D$	0.57^{**}
	b	$Hp = -0.337 + 3.601D - 0.069D^2$	0.40 NS
25	a	$Hp = -20.311 + 49.107 \log$	0.53
	b	$Hp = -10.748 + 4.471D - 0.084 D^2$	0.39 NS

Where a = logarithmic model

b = second degree polynomial model

Hp = heartwood proportion; per cent

D = dbh, cm.

NS = not significant

* = significant at 95% confidence level

** = significant at 99% confidence level

Appendix 10 : Regression equations and correlation coefficients for heartwood proportion and total tree height for the logarithmic and second degree polynomial models

Age years	Model	Regression equations	Correlation coefficients
7	a	$Hp = -\ 0,495 + 3.350 \log H$	0.01 NS
	b	$Hp = -\ 97.397 + 15.535\ H - 0.598\ H^2$	0.01 NS
11	a	$Hp = -\ 40.667 + 49.480 \log H$	0.47^{*}
	b	$Hp = -\ 40.845 + 7.195\ H - 0.224\ H^2$	0.23 NS
16	a	$Hp = 22.513 + 3.585 \log H$	0.0 NS
	b	$Hp = -280.154 + 31.067\ H - 0.774\ H^2$	0.16 NS
21	a	$Hp = -\ 94.398 + 102.138 \log H$	0.52^{*}
	b	$Hp = -\ 85.20 + 10.41 - 0.209\ H^2$	0.28 NS
25	a	$Hp = -\ 78.807 + 91.155 \log H$	0.59^{**}
	b	$Hp = -\ 47.932 + 6.742\ H - 0.116\ H^2$	0.35 NS

Where a = logarithmic model

b = second degree polynomial model

Hp = heartwood proportion, per cent

H = total tree height, m.

NS = not significant

* = significant at 95% confidence level

** = significant at 99% confidence level

Appendix 11 : Regression equations and correlation coefficients for the relationship between heartwood proportion and dbh and total tree height

Age years	Regression equation	Correlation coefficients
7	$Hp = -13.984 - \frac{48.593}{D} + \frac{288.384}{T}$	0.78^{**}
Std. Error	9.699 79.368	
11	$Hp = 31.643 - \frac{101.44}{D} - \frac{96.345}{T}$	0.67^{**}
Std. Error	39.388 112.411	
16	$Hp = 98.452 - \frac{213.838}{D} + \frac{1001.233}{T}$	0.52^{*}
Std. Error	129.467 515.626	
21	$Hp = 62.91 - \frac{180.813}{D} - \frac{236.502}{T}$	0.64^{**}
Std. Error	104.530 482.15	
25	$Hp = 66.437 - \frac{319.691}{D} - \frac{133.438}{T}$	0.63^{**}
Std. Error	283.562 615.725	

Where Hp = heartwood proportion, per cent

D = dbh, cm.

T = total tree height, m.

* = significant at 95% confidence level

** = significant at 99% confidence level

Appendix 12 : Regression equations and correlation coefficients for heartwood proportion and height in the stem for the logarithmic and asymptotic models

Age years	Model	Regression equation	Correlation coefficient
7	a	$Hp = 10.388 - 6.150 \log Hs$	-0.99^{**}
	b		
11	a	$Hp = 27.361 - 12.736 \log Hs$	-0.91^{**}
	b	$Hp = 1.816 + \frac{7.869}{Hs}$	-0.83^{**}
16	a	$Hp = 50.161 - 18.681 \log Hs$	-0.85^{**}
	b	$Hp = 2.481 + \frac{22.040}{Hs}$	-0.69^{**}
21	a	$Hp = 60.642 - 17.778 \log Hs$	-0.86^{**}
	b	$Hp = 2.397 + \frac{33.778}{Hs}$	-0.72^{**}
25	a	$Hp = 62.146 - 17.341 \log Hs$	-0.86^{**}
	b	$Hp = 2.146 + \frac{37.686}{Hs}$	-0.67^{**}
32	a	$Hp = 77.079 - 12.026 \log Hs$	-0.78^{**}
	b	$Hp = 1.579 + \frac{59.141}{Hs}$	-0.64^{**}
50	a	$Hp = 80.888 - 13.966 \log Hs$	-0.81^{**}
	b	$Hp = 1.778 + \frac{60.164}{Hs}$	-0.64^{**}

Where a = logarithmic model
b = asymptotic model
Hp = heartwood proportion, per cent
Hs = height in the stem, m.
** = significant at 99% confidence level

Appendix 13 : Variation of heartwood pH with height in the stem for 25 year old trees

Tree No.	Heartwood pH at :				Mean
	Butt end	20%	40%	60%	
1	5.30	5.20	5.50	5.20	5.30
2	5.20	5.30	5.10	5.30	5.20
3	5.40	5.15	5.30	5.20	5.26
4	5.10	5.25	5.40	5.35	5.28
5	5.55	5.80	5.65	5.65	5.66
6	5.60	5.75	5.60	5.65	5.65
7	5.60	5.80	5.65	5.70	5.69
8	5.40	5.35	5.45	5.50	5.43
9	5.80	5.70	5.45	5.25	5.55
10	5.00	5.40	5.20	5.20	5.20
11	5.20	5.45	5.60	5.50	5.44
12	5.70	5.90	5.70	5.50	5.70
13	5.75	5.90	5.70	5.55	5.73
14	5.65	5.80	5.70	5.85	5.75
15	5.55	5.35	5.30	5.30	5.38
Mean	5.45	5.54	5.49	5.45	5.5