STUDIES ON THE DURABILITY AND COLOR OF PLANTATION TEAK (*Tectona grandis* L.f.) WOOD

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بِسْمِ اللَّهِ الرَّحْمَٰنِ الرَّحِيمِ

وَالْعَصْرِ ١ إِنَّ الْإِنسَانَ لَفِي خُسْرٍ ٢
إِلَّا الَّذِينَ آمَنُوا وَعَمِلُوا الصَّالِحَاتِ
وَتَوَاصَوْا بِالْحَقِّ وَتَوَاصَوْا بِالصَّبْرِ ٣

Which means :

In the name of Allah, Most Gracious, Most Merciful. (慈悲あまねく慈愛深きアッラーの御名において)

[1] By (the Token of) Time (through the Ages) (時間にかけて（誓う）,
[2] Verily Man is in loss (本当に人間は，喪失の中にいる),
[3] Except such as have Faith, and do righteous deeds, and (join together) in the mutual teaching of Truth, and of Patience and Constancy (信仰して善行に勤しみ，互いに真理を勧めあい，また忍耐を勧めあう者たちの外は).

The Holy Qur'an (Surah Al Ashr, verse 1-3)

Contents

Chapter 1

General Introduction

1.1. Common Introduction of *Tectona grandis*

Tectona grandis is a species belonging to the family Verbenaceae. Tectona is the only genus of the tribe Tectonae which is classified within subfamily of Viticoideae (Khrisnamurty, 1975). *T. grandis* occurs naturally in peninsular India, Burma, Thailand and Laos (Kaosa-ard, 1981). Teak is suggested not indigenous to Indonesia, since there are indications that it was introduced to Java 400-600 years ago (Van Alphen de Veer, 1957). According to the country of origin, it has been expressed in different common names : jati (Indonesia, Philippines), kyun (Burma), sak (Thailand, Laos), teak (English), teck (French).

Botanical description :

Teak is a medium-sized to large tree up to 50 m tall, bole straight and branchless for up to 20(-25) m, with a diameter up to 150 (-250) cm, sometimes fluted or with low buttresses at base, bark surface with longitudinal cracks, grayish-brown, inner bark with red and sticky sap; leaves broadly ovate, (11-) 20 – 55 cm x (6-) 15- 37 cm (but much larger on suckers), stellate-floccose; inflorescence about 40 cm x 35 cm; flowers 3 – 6 mm long, calyx campanulate, corolla white with pink on the lobes; fruit enclosed by an inflated calyx (Van Alphen de Veer, 1957). Several morphological forms have been distinguished, principally by leaf characters.

Wood description :

The wood of teak is a medium-weight timber which is rather soft and has a very characteristic appearance. The heartwood is often dull yellowish when freshly cut but it turns golden brown or sometimes dark greyish brown after exposure, often streaked grayish or blackish; the sapwood is yellowish white or pale yellowish-brown and up to 50 mm thick. The wood is oily to the touch, and when freshly cut it has smell reminiscent of leather. The density is (480-) 610 – 750 (-850) kg/m^3 at 12 % moisture content (Martawijaya et al. 1986).

The grain of the wood is straight, wavy or slightly interlocked, texture rather coarse and uneven.

Uses

Wood :

Its favourable properties make it suitable for wide variety of purposes. It has already used for ship decking, deck houses, rails, furniture, bridge building, decorative plywood etc.

Bark :

Dyes, astringent

1.2. Background

Teak is one of the most important plantation species due to desirable wood properties, fine grain, durability and amenability for plantation. The species has gained its high reputation from trees grown in natural forest or plantations with long rotation age. Plantation grown teak has been the subject of numerous international markets, the economically important question – how does plantation-grown teak compare to old-growth teak of natural stands - has been repeatedly raised by wood trade and industry, and has been addressed by researchers in some instances.

In Indonesia, teak timber supplies from governmental plantation forest (Perhutani) have decreased during the last 2-3 decades. This led to an increase in investments on raising teak plantations, causing massive demands of superior quality. Private investment on teak plantations has begun as a response to the growing demand for housing and furniture grade timbers. Further, the constant demand and shortfall in its supply has increased the price and made teak as one of the most preferred species among the farming community in Indonesia. This, in turn, has lead to raising teak plantations outside forest areas, particularly in the farmer's field in the recent years. It is estimated that the total area of teak planted in the private land is about 10 % of the Perhutani's teak forest (Sadharjo 2005).

Teak in the community forest is generally grown in mixture with other tree species. Trees were harvested at relatively young ages which based on the assessment of economic and silvicultural considerations. Shortening the rotation to 25 years from 40 years may be considered as the optimum cycle to achieve a viable balance between financial returns and the production of market quality timber. Plantation grown wood may show fairly large tree-to-tree variation in wood durability, and even large differences between wood samples from the same trees (Reichter et al. 2003). Technical information and research data on naturally grown and plantation grown teak are relatively abundant. In contrast, limited information is available on teak managed in short rotation plantations. With teak, the major concerns are with regard to durability and color.

In certain areas, teak stems with an irregular black streak zone occur. This blackening is known to occur in a growing tree and only in the heartwood. The streak generally follows the annual ring and frequently extended from outer to center heartwood. This kind of discoloration is categorized as a defect for some wood industries, thus the wood can suffer a financial loss. It has been observed that the occurrence of black streaked progenies is higher in the black calcareous soil than in the volcanic ash soil (Suhaendi 1998). To date, little information exists concerning the properties and development of black streaked heartwood.

1.3. Thesis objectives

There are no doubts that the most significant factor influencing the durability of wood are extractives. The significance of heartwood extractives for natural durability was demonstrated in various species including teak (Schultz et al. 1995; De Bell et al. 1997; Reyes-Chilpa et al. 1998; Yamamoto et al. 1998; Celimene et al. 1999). Toxic extractive compounds are recognized to be the most important factor (Hillis 1987) and in some durable species even low-toxic extractives may contribute synergistically to high durability (Schults and Nicholas 2000).

Color, along with grain and texture, are regarded as most important for decorative veneer. Color of wood depends on chemical components interacting with light, i.e. the presence or absence of extractives (Hon and Minemura 2001). Therefore, wood color has been linked to the amount of extractives, to wood decay resistance and to wood density (Hiller et al. 1972; Nelson and Heather 1972; Wilcox and Piirto 1976).

There are two main objectives in the present study : 1. to assess the natural termite resistance properties of teak wood from different ages, 2. to characterize the black streak part of teak heartwood. Chapter 2 presents the natural termite resistance, extractive contents and wood color of trees from different ages. The relationships between the natural termite resistance with extractive contents or color were also discussed. In order to find out the role of individual active compounds to relative natural durability, chapter 3 describes the distribution of quinone of trees from different ages as well as radial positions. The relationship between the extractive and component contents was also evaluated. Chapter 4 deals with the color and chemical characteristics of black streak parts in heartwood based on between tree variations.. The relationship between the degree of blackening and some parameters was measured. Chapter 5 deals with the component isolations and their discoloration tests from black streaked heartwood. The chemical structural differences relating to the discoloration was also examined. Finally, chapter 6 summarizes the overall results and conclusions of this study.

Chapter 2

Variation in the natural termite resistance of teak as a function of tree age

2.1. INTRODUCTION

Teak (*Tectona grandis* Linn fil.) is the principal commercial timber in Indonesia, particularly on the island of Java. Despite the existence of teak plantations managed by the state-owned company Perum Perhutani which covers 1.2 million hectares in Java, high demand from the wood industries has created a shortage in the supply of raw material. In order to meet this demand, an increase in the quantity of teak produced in 'hutan rakyat' (hutan = forest, rakyat = community) or farmland has occured. According to the Ministry of Forestry of Indonesia, 'hutan rakyat' is defined as "forest grown on land with ownership or other rights " (Departemen Kehutanan, 1995).

Contrary to the practice adopted by Perhutani which employs a felling cycle of 60 years or more, most the farmland stands are focused on obtaining short- to medium-term return on their efforts by harvesting younger trees. The owners commonly cut their trees when they reach an age of 20 to 30 years. Concerns have been raised over the quality of the wood obtained from such younger trees. Logs from these plantations will have a large proportion of sapwood and immature wood, whose properties may differ from those of older trees. With teak, the major concerns are with regard to durability and color.

In terms of durability, teak is valued for its natural termite resistance properties. Ngee et al. (2004) reported teak as a less preferred species against native pest *Coptotermes, Microcerotermes, Globitermes, Macrotermes* termites in a preference test. It has problems, however, such as its sapwood with reference to the dry wood termite 'inger-inger' (*Neotermes tectonae* Damm) (Subiyanto, 1995). Teak wood was also proved to be naturally resistant against non-native termites (Becker, 1961). There is no doubt that this advantage can be attributed to extractives. Tree age, extractive content and radial position have been reported as affecting the natural termite resistances (Da Costa et al., 1958, 1961; Rudman et al., 1967). The object of this study is to determine the natural termite resistance of heartwood and sapwood of plantation grown teak. Samples have been examined for 8, 30 and 51 years old. A factorial design was used to investigate the effects and interaction of tree age and radial position on termite resistance properties. Analysis of the content of the extractives and the color of the wood were included in the study because these factors are likely to have an effect of the durability of the wood.

2.2. MATERIAL AND METHOD

2.2.1. Tree sampling

Wood samples from sound 8 and 30-year-old trees were obtained randomly from the farmland stands and samples from the 51 year-old trees were obtained from the Perhutani plantation. The condition of the sites and tree characteristics are described in Table 1. Discs 5 cm in thickness from the felled trees were cut at diameter breast height. The test specimens were taken successively from sapwood to heartwood, and divided into five sections diametrically (Fig. 1) :

OS - outer sapwood (*ca.* 0.5 cm from the bark)
IS - inner sapwood (*ca.* 0.5 cm from the heartwood-sapwood boundary)
OH - outer heartwood (*ca.* 0.5 cm from the heartwood-sapwood boundary)
MH - middle heartwood
IH - inner heartwood (*ca.* 2 cm from the pith)

With the limited amount of suitable material available, the MH and IH zones in the 8-year-old discs and the IS zone in the 51-year-old discs were excluded. Each part from two opposing radii was converted into wood meal by drilling. It was then combined to form a single sample in order to minimize variations between radii. The meal samples were then ground to a size of 40 - 60 mesh for determination of extractive content. For the termite resistance test and color properties, blocks *ca.* 5.0 (L) x 0.8 (T) x 0.8 (R) cm matching samples for extractive content determination (Fig. 1), were stripped from each part and radius. The blocks were then dried at 100 ^{0}C for 3 h, after which they were cooled and weighed.

2.2.2. Termite resistance test

2.2.2.1. Termite species.

The subterranean termite *Reticulitermes speratus* Kolbe, one of the most wood damaging species in Japan, was used in this work. Pine (*Pinus densiflora* Sieb et Zucc) logs containing termites were collected in the mountain area near Tsuruoka, Yamagata and maintained in an environmental chamber at 25 ^{0}C, 75 % RH in the laboratory until initiation of the test. Healthy worker termites were taken from these logs and exposed to the wood blocks.

2.2.2.2. No-choice test on wood blocks

For each test, an air-dried wood block (moisture content 10-12 %) was inserted into a plastic cup (5.0 cm x 6.0 cm), and placed on 20 g of sterile sand. The sand was moistened with distilled water regularly to retain a constant relative humidity. Fifty worker termites were added to each cup. Included in the tests for comparative purposes were controls of susceptible pine sapwood blocks and starvation controls containing only sand substrate. Three replicates were measured for each sample, for a total of 171 observations. The cups were placed in the environmental chamber for two weeks. No attempt was made to remove dead termites from the cup during the trial period. To measure the termiticidal activity, surviving termites were counted in first week and at the end of observation. The mass loss was determined to quantify the extent of the termite attack on the wood. A subjective evaluation was performed, whereby all parts tested were classified into the following four classes of resistance according to their mean mass loss values (MML, in mg). Classifications were as follows: highly resistant ($0 < \text{MML} \leq 5$), resistant ($5 < \text{MML} \leq 10$), moderately resistant ($10 < \text{MML} \leq 15$), and non resistant ($15 < \text{MML}$).

2.2.3. Extractive content

The extractive content was determined for 2 grams (based on oven dry weight) wood meal using a Soxhlet apparatus. Extractions were conducted using a 6-hour sequence of *n*-

hexane, ethyl acetate (EtOAc) and methanol (MeOH). The solvents were concentrated in a rotary film evaporator, dried, and weighed to determine the *n*-hexane, EtOAc, and MeOH extractive content based on oven dry wood meal (m/m). The total extractive content was calculated by determining the sum of all extractive contents.

2.2.4. Color measurement

A portable spectrophotometer NF777 (Nippon Denshoku Ind. Co Ltd.) with a diameter opening of 6.0 mm, illuminant A and tungsten halogen light source was used. Percentage of reflectance data was collected at 20 nm intervals over the visible spectrum (400 – 700 nm). Color measurements were taken for air-dried termite wood block test mentioned above. This was performed before initiation of the antitermite test. The color parameters were measured in the middle of the tangential face (adjacent to meal sample) of each sample. Three measurements were made for each sample and the average values of the measurements were calculated as the different color parameters, designated L*, a*, and b*. L* describes brightness (along a brightness axis where 100 = white or total brightness; and 0 = black or darkness) of a color. The value a* describes the redness [along the X axis red (+) to green (-)], and the value b* describes the yellowness [along the Y axis yellow (+) to blue (-)].

2.2.5. Statistical analysis

The effects of tree age and radial position on survival rate and mass loss were calculated by analysis of variance (ANOVA) GLM procedures. The effects were taken into account only when significant at the 95% level using Type III Sums of Squares. The termite survival rates (percentages) were transformed to arc sine for analysis but were presented as untransformed values to facilitate interpretation. Means of extractive content and color measurement were tested by One-way ANOVA. A Duncan test for multiple comparisons was used to show which group means differ. A Pearson correlation analysis was employed for termite resistance parameters, extractive contents and wood color properties. All statistics were performed with SPSS 10.0 software.

2.3. RESULTS AND DISCUSSION

2.3.1. Termite resistance

2.3.1.1. Survival rate

The ANOVA of mean survival rate in the first week indicates that there is no significant tree age and radial position interaction (*p* = 0.08), while the effects of tree age (*p* = 0.011) and radial position (*p* = 0.002) are significant. Comparisons among tree age reveal that the survival rate decreases significantly with tree age (Fig. 2a). Close examination of the mean values within radial position reveals survival rate between the sapwood (69 – 77 %) and heartwood region (50 – 56 %) are significantly different (Fig. 2b). The interaction between tree age and radial position is highly significant (*p* = 0.002) in regards to the mean of survival in the second week. The survival rate means in the second week are shown in Fig. 3a. The highest surviving termite levels are obtained at the OS and IS of 8-year-old trees (47-55 %). No significant differences could be observed between the three tree age groups in the heartwood.

The mean survival rate value of termites under complete starvation control condition is 16 % after the 2-week test period. The survival rate value of the pine control is 88 %. Based on these results, the natural termiticidal activity of teak wood is not thought to be acute. This confirms earlier reports (Da Costa et al., 1958, Rudman et al., 1967), which demonstrated that teak wood is not toxic but merely deters the subterranean *Coptotermes lacteus* Frogg and *Nasutitermes exitiosus* Hill termites. However, the survival rates measured in this work for the termites exposed to teak samples are lower than in those reports. These differences of survival rates may be due to the use of different termite species in this experiment. In a previous study, Becker (1961) observed that the resistance and susceptibility of the wood species varies with every termite tested. Ngee et al. (2004) suggested a differential feeding preference among *Coptotermes* species, as well as towards wood species from different geographical localities. Thus, the use of native pests in a bioassay test, e.g. the most aggressive *Coptotermes curvignathus* Holmgren termites, would provide more information with regard to the natural resistance of teak.

2.3.1.2. Mass loss

The ANOVA of mass loss shows significant tree age and radial position interaction ($p < 0.01$), indicating that the effect of tree age varied with the radial position. Based on MML data (Fig. 3b), heartwood of all ages falls into resistant and highly resistant classes whereas sapwood falls into classes ranging from resistant to non-resistant. The mass loss in the OH tends to decrease with tree age, the relative mass loss in the OH of 51 year-old trees (1.37 mg, highly resistant class) is significantly lower when compared to those of 8 year-old trees (7.45 mg, resistant class). While the IH region is found to be less resistant than the OH or MH region, the ANOVA of mass loss between the radial part in the heartwood of both the 30 and 51-year-old groups does not vary significantly. The mass loss of the OS decreases significantly with tree age. The OS of 8 year-old trees is classified as non-resistant (MML 27.68 mg) while the OS of 51-year-old is classified as resistant (MML 6.30 mg). The level of activity of the OS of 51-year-old trees is even comparable to that of the OH of 8-year-old trees. Compared to the control pine sample (MML 52.41 mg), however, the OS of 8 year-old trees exhibits a higher antifeedant activity. The mass loss in the IS (7.84 mg) are significantly lower than those in the OS (14.52 mg) of 30-year-old trees, but a similar trend is not observed in the sapwood of the 8-year-old groups.

These results seem to be in agreement with previous studies (Da Costa et al., 1958, 1961; Rudman et al., 1967), in that an increase in natural termite resistance with tree age in the heartwood is evidenced. Similar tendencies have also been noted in studies of the decay resistance of teak (Da Costa et al., 1958, 1961; Rudman et al.; 1967, Bhat and Florence, 2003; Haupt et al., 2003). The obtained results show the heartwood of 30-year-old trees achieves similar termite resistance level to 51-year-old trees. This is an encouraging result considering the recent increase of young trees utilization. On the other hand, the termite susceptibility in the sapwood must be taken into consideration, since the percentage of sapwood is relatively high in trees younger than 51 years.

The standard deviation of the mass loss values is large even in the same group. This indicates that wood samples of the same age group and radial part may belong to different classes of antitermitic resistance. A good example of this is the OH of 30-year-old tree no 9. This is classified as resistant while the OH of 30-year-old tree no 7 is classified as moderately resistant (data not shown). With regard to decay resistance, significant variations among tree samples are also found in 5-year-old teak (Bhat and Florence, 2003). Differences in termite survival and mass loss are also found among the control group indicating the possibly that slight differences in test conditions occurred between trials.

2.3.2. Extractive contents

The *n*-hexane extractive content (NHEC) determinations are shown in Fig. 4a. By ANOVA, NHEC levels in the OH of 30 and 51 year-old trees (4.36 and 4.52 % respectively) are significantly higher compared to those of 8-year-old trees (1.74 %). In radial direction, NHEC levels in the IH also differ significantly from those in the OH and MH region. The NHEC levels in the OS region tend to increase with tree age. The maximum levels are obtained in the OS of 51-year-old trees (1.52 %), the difference is significant from the minimum levels in the OS of 8-year-old trees (0.53 %). The NHEC levels between IS and OS does not differ significantly. The EtOAc extractive content (EEC) determinations are presented in Fig. 4b. By ANOVA, the variation among the different tree age in the OS and OH region is not significant. The ANOVA reveals significant differences are found for radial direction of 30-year-old trees, which the EEC levels in the OS and IS (0.36 and 0.41 %, respectively) are lower compared to those in the OH region (1.69 %). The EEC level variation among the different radial direction in the heartwood is not significant.

The MeOH extractive content (MEC) determinations are displayed in Fig. 4c. In the sapwood, the OS of 51-year-old trees shows the highest MEC level (4.41 %), significantly higher in comparison to the lowest levels in the OS and IS of 30 year-old groups (2.16 and 2.09 %). In the heartwood, even though the maximum MEC levels are obtained in the OH of 8 year-old trees (4.07 %), the difference is not statistically significant in comparison to the lower amount in the OH of 30 and 51-year-old groups (2.59 and 2.96 %, respectively). Systematic differences among the different radial direction in the heartwood are not found.

The minimum MEC levels in the heartwood are obtained in the MH and IH of 51-year-old trees (2.19 and 2.05 %).

Within all age groups, total extractive content (TEC) increases from the pith until the OH and then decreases towards the OS (Fig. 4d). The radial distribution pattern of the content of the extractives through sapwood and heartwood corresponds to the schemes generally reported by wood chemists. A comparison between the three tree ages indicates an increase of TEC levels in OS and OH. In the sapwood, the maximum TEC levels are obtained in the OS of 51 year-old trees (6.78 %), which is significantly higher than those of the 8 and 30-year-old groups (4.15 and 3.53 %, respectively). TEC levels in the IS are higher than in the OS of 8 and 30-year-old trees, however, an ANOVA shows that this is not statistically significant. The ANOVA also reveals that TEC levels in the OH of 51 and 30-year-old trees (9.17 and 8.53 %) are statistically different from those in the 8-year old trees (7.15 %). TEC increases significantly from the IH toward OH of 51-year-old trees, but without statistical significance in 30-year-old trees. The pattern of TEC with tree age is in agreement with earlier studies by Da Costa et al., 1958 and Narayanamurti et al., (1962). The corresponding values of TEC in this study are slightly higher than those reported by Da Costa et al., (1958), but lower than those reported by Narayanamurti et al., (1962), and Bhat et al., (2005).

EtOAc, a moderately polar solvent, removed the least extractives while *n*-hexane, the least polar solvent or MeOH, the most polar solvent removed the most extractives in a manner depending upon the part of the wood. Sapwood is generally found to contain more methanol extractives in all age groups. This pattern is also observed in the OH of 8-year-old trees and the IH of 51-year-old trees. This significantly increase of NHEC and TEC levels from IH to OH of 51- year-old trees, as well as, in the OH from 8 to 51-year-old groups indicates the increasing content of TEC in the heartwood is mainly attributed to an increase of HEC level. The tendency of NHEC and MEC in this study is in line with the tendency reported in Narayanamurti et al., (1962), who observed the maximum MEC level is found in the OH of a 10-year-old tree whilst maximum ether extractive content level is found in the OH of a 62-year-old teak tree. These gradients have been interpreted to indicate that conversion of polar compounds to less polar compounds increases with time in the heartwood of growing trees. The data suggest that transformation of juvenile wood into more mature wood is characterized by a significant increase in the amount of less polar extractives. By the time a given tree is 30 years old, a relatively large proportion of less polar extractives is obtained in the extractive content of the heartwood region.

2.3.3. Color properties

For sapwood and heartwood region, the brightness index (L*) ranges from 73 to 77 and 54 to 60, respectively (Fig. 5a). The ANOVA results show that the OS in 51 year-old-trees trees (73.72) give significantly darker color than those in 8 and 30-year-old trees (76.65 and 76.09 respectively). The brightness level tends to decrease from OS to IS, with statistical significance in 30-year-old trees. The OH in 8 and 51-year-old trees (54.39 and 53.06, respectively) gives significantly darker color than those in 30 year-old trees (60.57). Systematic differences among the different radial direction in the heartwood are detected in 51-year-old trees, which the brightness index significantly decreases from IH (58.32) to OH (53.06).

The redness index (a*) of the sapwood and heartwood region ranges from 2 to 3 and 4 to 6, respectively (Fig. 5b). The maximum redness index in the OS (3.94) are measured in 51 year-old trees, the difference is statistically significant in comparison to the lower amount at the OS of 8 and 30-year-old groups (2.97 and 3.50, respectively). The redness index in the OH fluctuates with tree age; the significant mean maximum redness index is detected in the OH of 8-year-old trees (6.66), whereas the minimum index is found in 30-year-old trees (4.69). A radial difference is observed in the heartwood of 51-year-old trees, which redness levels in the MH and IH (6.60 and 6.11, respectively) give significantly higher values than those in the OH region (5.25).

The yellowness index (b*) of the sapwood and heartwood region ranges approximately from 22 to 25 and 24 to 26, respectively (Fig. 5c). The ANOVA reveals no significant difference in the OS between the groups. The highest yellowness level in the sapwood is detected in the IS of 30-year-old trees (25.31). A significantly higher yellowness index is measured in the OH of 30 year-old trees (26.67) as compared to the OH of 8 and 51 year-old trees (25.46 and 24.50, respectively). For both 30 and 51 year-old groups, no significant differences are observed between radial parts in the heartwood.

Kokutse et al. (2006) reported the maximum redness value in the heartwood is detected in the OH area, which differs from the present results, however, the pattern of brightness and yellowness value is in agreement. The corresponding values of brightness and yellowness in the heartwood in this study are slightly higher than previously reported, while the redness values are lower than those of Indian teakwood (Bhat et al., 2005) and Togolese teakwood (Kokutse et al., 2006). The ANOVA reveals that the color index values in the heartwood of 8-year-old trees are almost similar to those of 51-year-old trees. This is an unexpected observation because of the general assumption that the heartwood of younger trees is paler. This position has previously been put forward in a study of oak wood color (Klumpers et al., 1993). The inconsistent results are likely due to variations in silvicultural practice or site condition factors, as suggested by previous reports in teak and other species (Nelson et al., 1969; Wilkins and Stamp 1990; Bhat et al., 2005). The possible effects of those factors are not discussed within the scope of this paper but is worthy of further research.

2.3.4. Relationship between termite resistance and extractive contents

Correlation analysis (Table 2) confirms moderate negative correlation between the mass loss and NHEC (r =-0.58) as well as between the mass loss and TEC (r = -0.51). This outcome is reasonable since teak extractives are recognized to play a significant role in termite resistance. The variations in mass loss with tree age in the OS and OH region are in general accord with the TEC and NHEC distribution trend. Those results confirm that low termite resistance is associated with immature wood. For example, in the 51-year-old group, the trees found to be the most resistant to termites had the highest TEC and NHEC, both in the OS and OH. Da Costa et al (1958) observed the decrease of mass loss with the increase of TEC level in the OH region. However, the relationship between mass loss and TEC or NHEC in the radial position of heartwood is not clear in this study. The IH of 51-year-old trees significantly has lower TEC and NHEC than those of the OH, but without statistical significance in the mass loss. This fact may be due to the differences of the toxic component concentrations which are independent to the pattern of extractive content. In studies of the decay resistance of teak, Haupt et al. (2003), Thulasidas and Bhat (2007) suggest that the presence of individual active compounds, even in minor quantities is more significant than the amount of total extractive content.

With regard to chemical consideration, quinones and their derivatives in teak extractives, particularly tectoquinone, have been shown to be toxic to the termites (Rudman et al., 1958; Rudman and Gay, 1961; Sandermann and Simatupang, 1961). This finding supports this papers preliminary study (Lukmandaru and Ogiyama 2005a, 2005b), which reported that *n*-hexane and less polar fractions of EtOAc soluble extract exhibited antitermitic properties. Furthermore, tectoquinone was identified as being primarily responsible for antitermitic activity. Windeisen et al. (2003) detected tectoquinone and desoxylapachol in petroleum ether soluble extracts. The variations of TEC and NHEC in the same part and group may partly explain the considerable tree-to-tree variation of termite resistance.

Despite the fact that sapwood is known be easily attacked by termites, examination of the termite survival rates and mass loss clearly indicates that teak sapwood exhibits antitermitic activity albeit to a lesser degree than other wood regions. This is more pronounced in the sapwood of 8-year-old trees, which belong to the non-resistant class. This indicates that teak sapwood contains lower levels of compounds that are distasteful, repellent, or toxic to termites. A report by Windeisen et al. (2003) who detected tectoquinone in the sapwood of teak from Panama may support that indication. The high resistance of the sapwood and heartwood in the 51-year-old trees indicates that the aging of toxic constituents is not evident.

2.3.5. Relationship between termite resistance and color properties

The correlation between color and decay resistance in teak heartwood has been investigated. It was found that brightness correlates negatively with mass loss (Kokutse et al., 2006). Bhat et al. (2005) observed a greater content of extractives, more yellow heartwood, and higher decay resistance to brown-rot fungi in teak grown at a dry site home garden and plantation than in teak grown in a wet site home garden. In this study, moderate correlations are observed between mass loss with brightness, as well as between mass loss with redness of the wood (Table 2). Furthermore, correlation analysis also reveals moderate correlation between the survival rate in the first week with brightness or redness. This means the wood is more resistant when it is darker and redder. The brightness and redness appear to be related to termite resistance in the sapwood. As expected, the relatively high termite resistance of the IS of 30-year-old trees and OS of 51-year-old trees correspond to darker and redder sapwood. There is no significant difference in brightness and redness among the radial position in the heartwood of 30-year-old trees, which correspond well with no significant differences in mass loss in those regions. However, a similar trend is not observed between the mass loss and color parameters in the OH regions. Those facts suggest that the relationship between the mass loss and color parameters is complex. As it is known that the color of wood has been related to the quantity and types of wood extractives, this may indicate that the extractives associated with color in the OH might be independent of those that cause termite resistance. In future studies, investigations of more samples and different termite species will be helpful in determining the relationships between termite resistance and color properties of the wood.

Table 1. Description of the sampling and sites

Factor	8 year-old	30 year-old	51 year- old
Origin	farmland stands	farmland stands	Perhutani plantation
Site location (province)	Gunungkidul (Jogja)	Kulonprogo (Jogja)	Randublatung (Central Java)
Number of samples	5 (tree no 1to 5)	4 (tree no 6 to 9)	5 (tree no 10 to 14)
Altitude (m)	450	120	140
East longitude	110^0 30'	110^0 8'	111^0 30'
South latitude	7^0 60'	7^0 44'	7^0 05'
Soil type	black calcareous, loam	alluvial, loamy sand	humous margalitic, loamy sand
Annual rainfall-range (mm)	1400 - 1800	1700-2500	1300 – 2000
Temperature range ^{0} C	22 – 36	18 - 32	20 – 34
Relative humidity	70	76	72
Mean diameter (cm)	10.2	27.1	36.5
Mean heartwood proportion (%)	19.5	60.3	78.7
Mean sapwood thickness (cm)	3.1	3.3	2.1

Table 2. Pearson correlation coefficients (*r*) for the termite resistance parameters, extractive contents and color properties.

Parameters	Survival rate in the first week	Survival rate in the second week	Mass loss
n-hexane extractive content	-0.42**	-0.34*	-0.58**
EtOAc extractive content	-0.49**	-0.34*	-0.49**
MeOH extractive content	0.11	0.08	0.14
Total extractive content	-0.06	-0.30*	- 0.51**
Brightness L*	0.62**	-0.45**	0.62**
Redness a*	-0.68**	-0.45**	-0.64**
Yellowness b*	-0.32*	-0.08	-0.31**

Note ** = significant at 1 % level * = significant at 5 % level

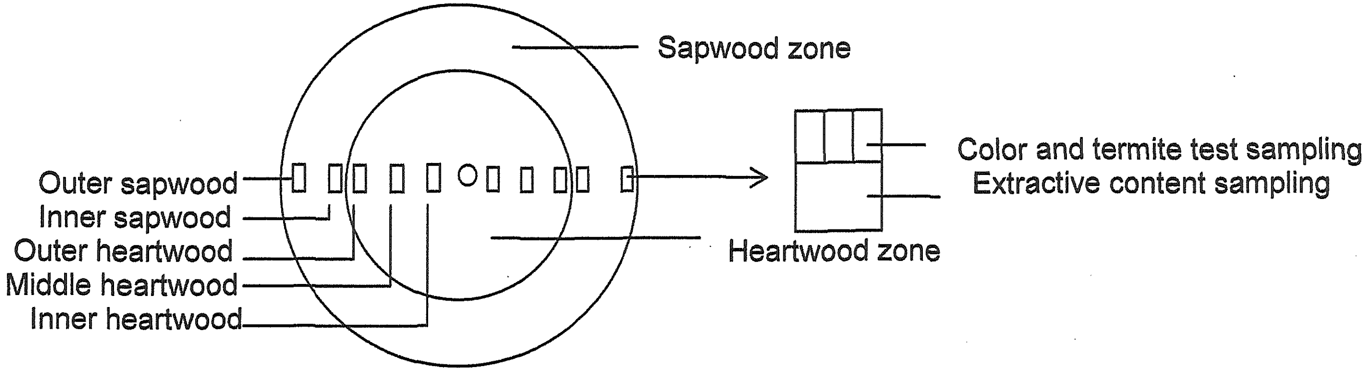
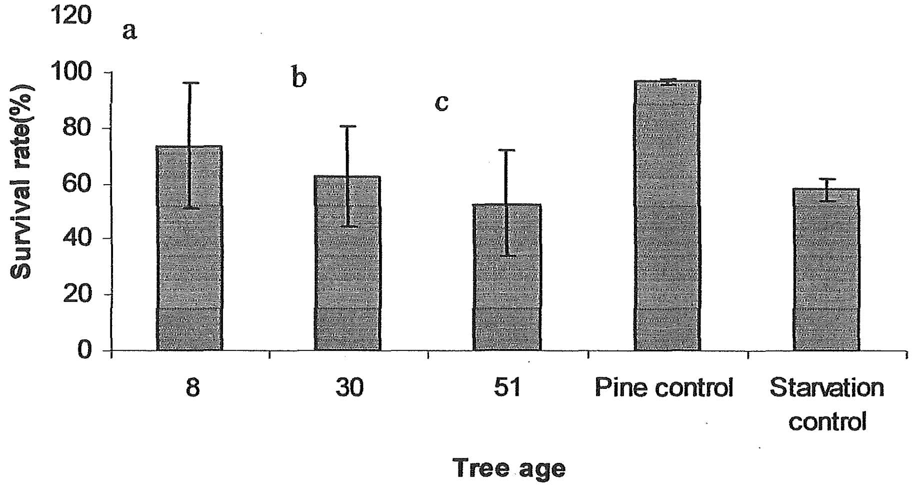
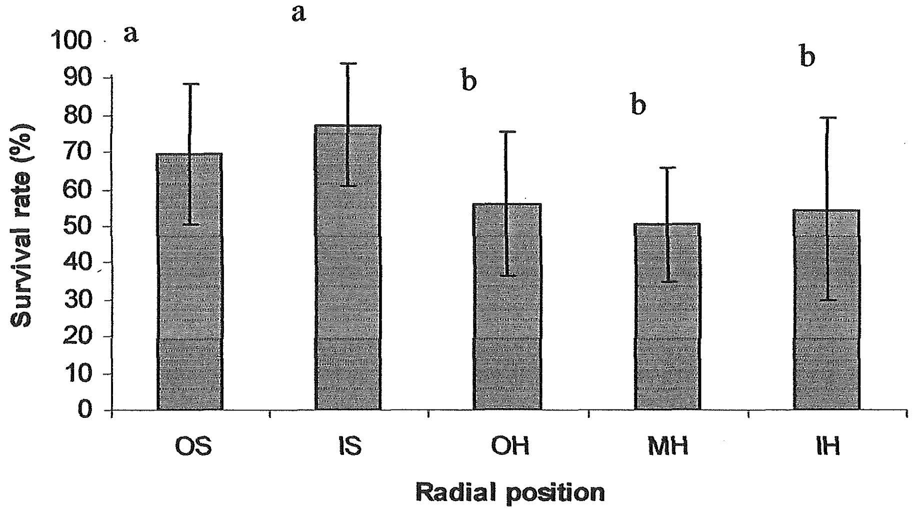


Figure 1. Sampling position on a cross-section of teak trunk

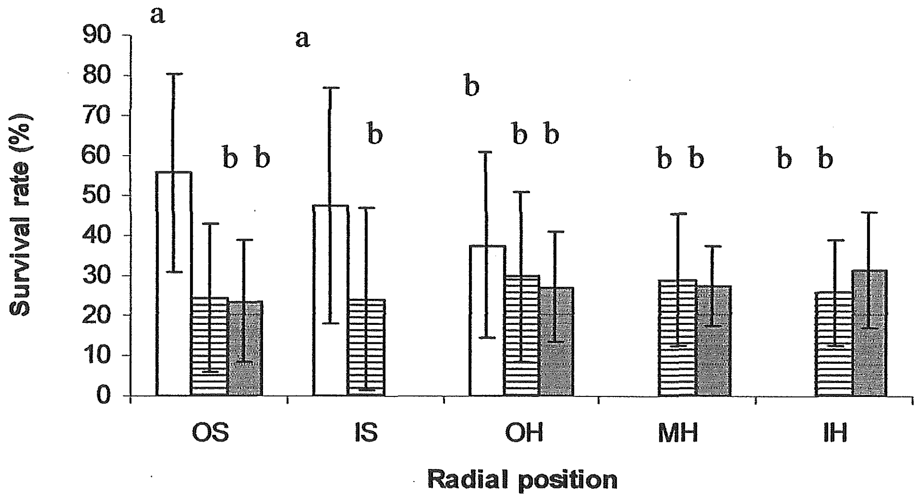


(2a)

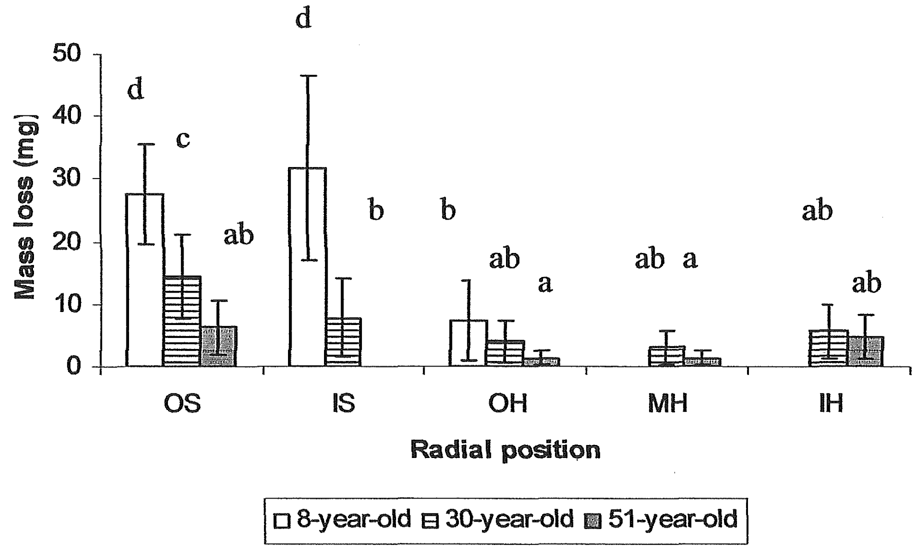


(2b)

Figure 2 a-b. Survival rate against *Reticulitermes speratus* on one-week observation of teakwood by tree age and radial position. Mean of 5 trees (8- and 51 year-old) and 4 trees (30-year-old), with the standard deviation error bar. The same letters on the same graphic are not statistically different at $p < 0.05$ by Duncan's test. Pine and starvation control are included for the purpose of comparison. OS = outer sapwood, IS = inner sapwood, OH = outer heartwood, MH = middle heartwood, IH = inner heartwood.

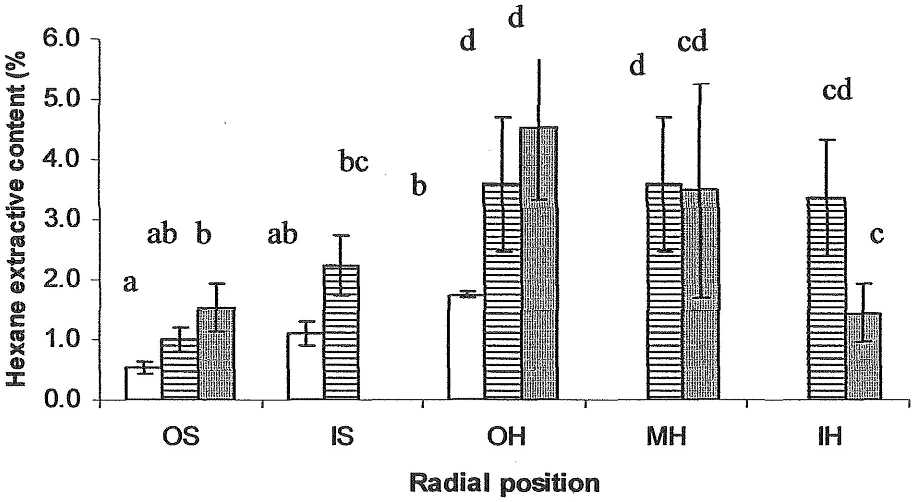


(3a)

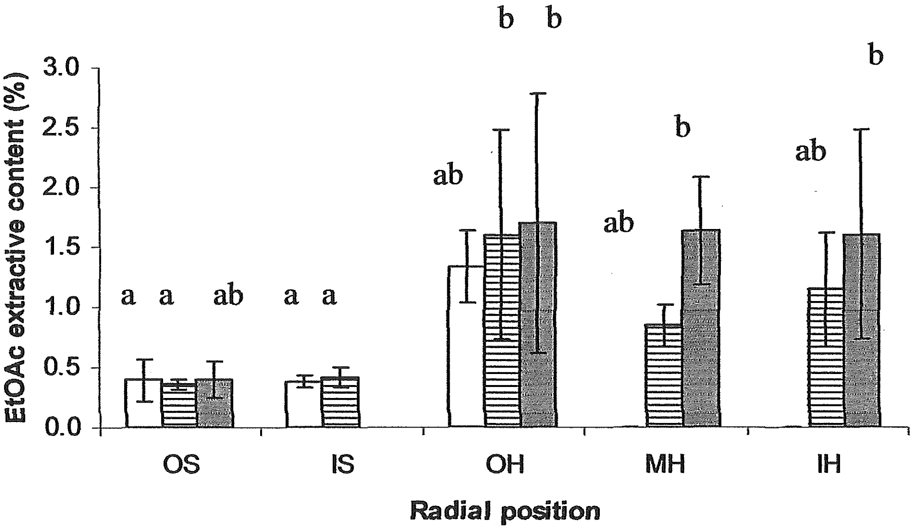


(3b)

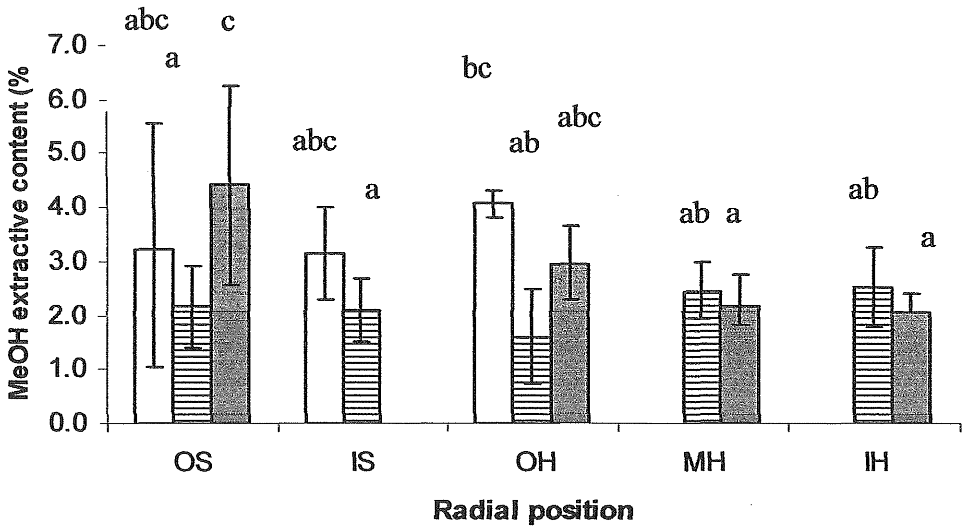
Fig. 3a-b Survival rate and mass loss against *Reticulitermes speratus* on 2-week observation of teakwood by tree age and radial position. Mean of 5 trees (8- and 51 year-old) and 4 trees (30-year-old), with the standard deviation error bar. Means survival rate of pine and starvation control were 88.67 ± 2.30 and 16.6 ± 13.30 %, respectively. Mean mass loss of pine control was 52.41 ± 5.69 mg. The same letters on the same graphic are not statistically different at $p < 0.05$ by Duncan's test. OS = outer sapwood, IS = inner sapwood, OH = outer heartwood, MH = middle heartwood, IH = inner heartwood.


Hexane extractive content (%
6.0
5.0
4.0
3.0
2.0
1.0
0.0
a
ab
b
ab
bc
b
d
d
d
cd
cd
c
OS
IS
OH
MH
IH
Radial position

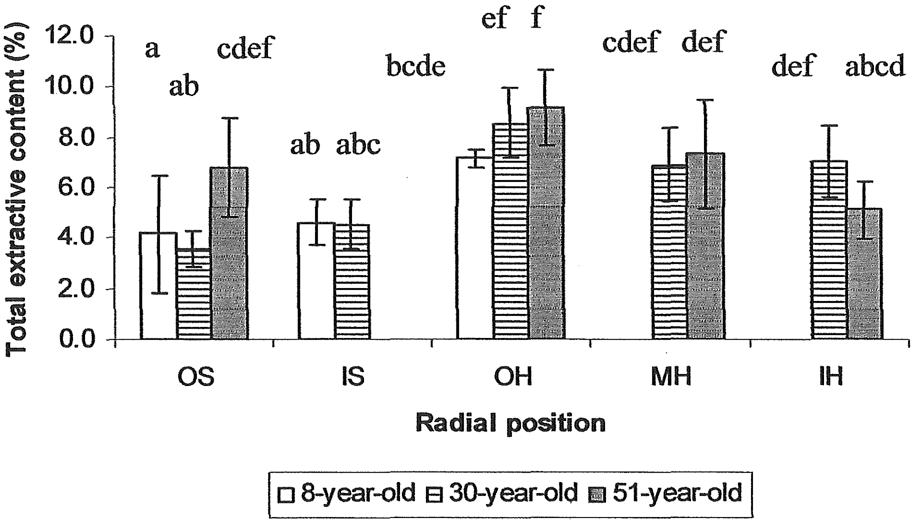
(4a)


EtOAc extractive content (%)
3.0
2.5
2.0
1.5
1.0
0.5
0.0
a
a
ab
a
a
ab
b
b
ab
b
ab
b
OS
IS
OH
MH
IH
Radial position

(4b)

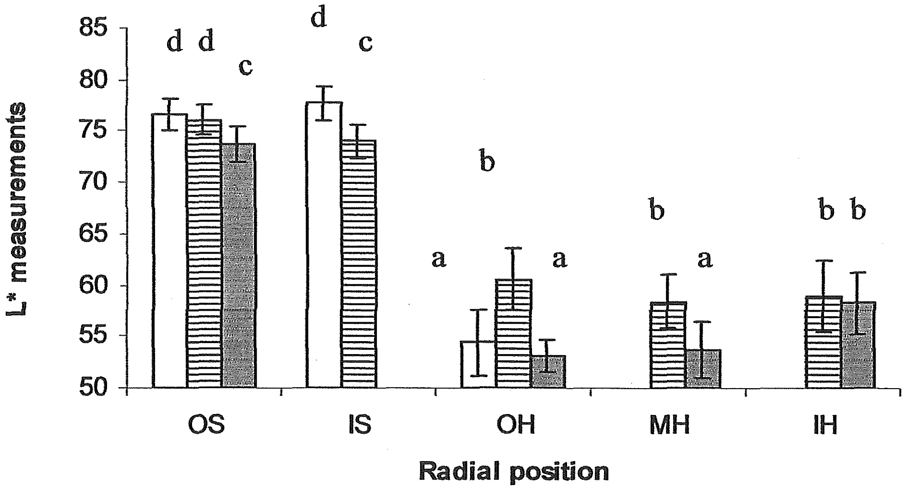


(4c)

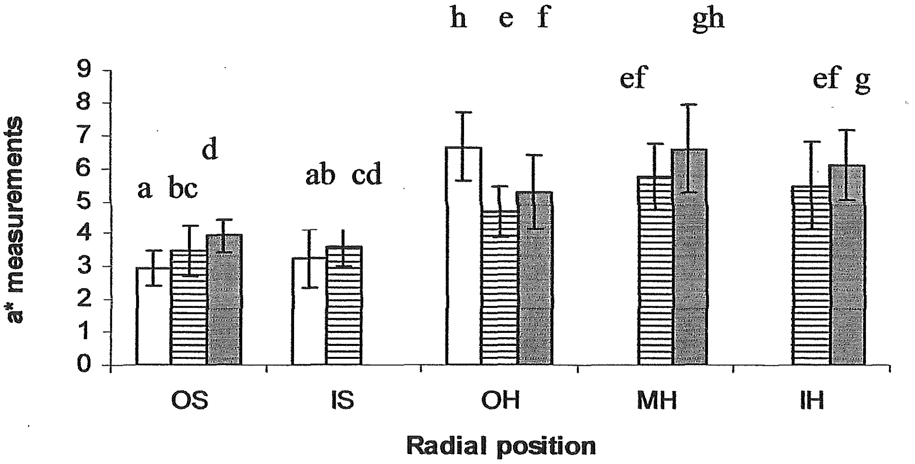


(4d)

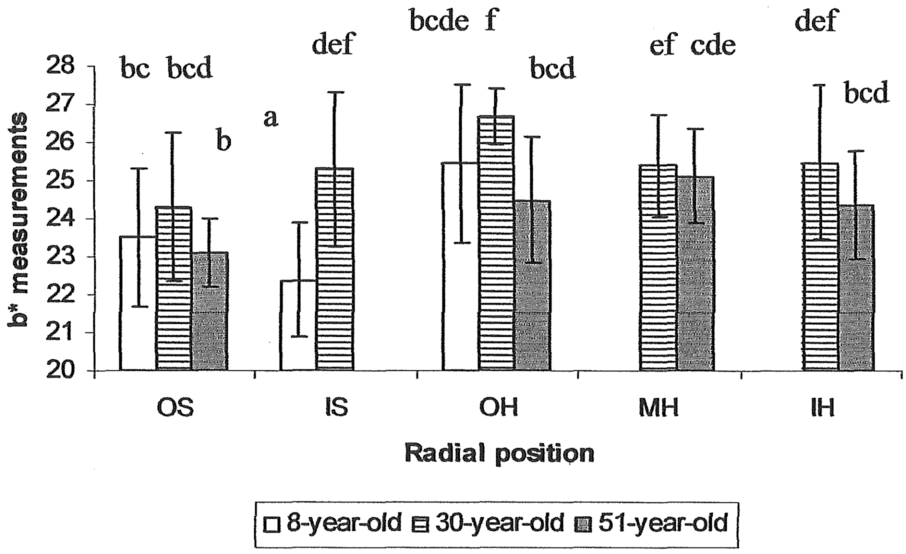
Fig. 4. *n*-hexane (4a)-d, EtOAc (4b), MeOH (4c), and total extractive content (4d) (% oven dried mass m/m) of teakwood by tree age and radial position. Mean of 5 trees (8- and 51 year-old) and 4 trees (30-year-old), with the standard deviation error bar. The same letters on the same graphic are not statistically different at $p < 0.05$ by Duncan's test. OS = outer sapwood, IS = inner sapwood, OH = outer heartwood, MH = middle heartwood, IH = inner heartwood.


85
80
75
70
65
60
55
50
L* measurements
d d
c
d
c
b
a
a
b
a
b b
OS
IS
OH
MH
IH
Radial position

(5a)


9
8
7
6
5
4
3
2
1
0
a* measurements
a bc
d
ab cd
h e f
gh
ef
ef g
OS
IS
OH
MH
IH
Radial position

(5b)



(5c)

Fig. 5. Color properties in brightness L* (5a), redness a* (5b) and yellowness b* (5c) of teakwood by tree age and radial position. Mean of 5 trees (8- and 51 year-old) and 4 trees (30-year-old), with the standard deviation error bar. The same letters on the same graphic are not statistically different at $p < 0.05$ by Duncan's test. OS = outer sapwood, IS = inner sapwood, OH = outer heartwood, MH = middle heartwood, IH = inner heartwood.

Chapter 3

Variation in the quinone content of teak as a function of tree age

3.1. INTRODUCTION

Teak has been valued for its beautiful texture, weather resistance, and natural durability. This advantage has resulted in the use of teak in various applications, from handicrafts to heavy construction. It has been generally assumed that teak wood from natural forests and from plantations with long rotation ages has an established reputation for outstanding quality. In Indonesia, most teak trees are harvested from plantation forests. Recently, industries traditionally reliant on wood have faced a supply shortage, which necessitates the harvesting of younger trees from plantation and farmland stands as a raw material. In order to utilize this younger wood more effectively, basic knowledge is needed on the basic properties that could affect such utilization.

The high natural durability of teak is an important characteristic, which has been undoubtedly attributed to various extractive compounds identified in teak. Yamamoto et al. (1998) has demonstrated the significant influence of teak wood extractives to wood destroying fungi. Quinones and derivatives, thereof have been reported to act against termite and fungal attacks (Rudman and Gay 1961; Sandermann and Simatupang 1966; Haupt et al. 2003; Sumthong et al. 2006; Thulasidas and Bhat 2007). Differences in natural durability may be related to the concentration of toxic extractable substances of wood formed during the formation of heartwood. Unfortunately, little has been reported on the quantity and composition of the active compounds by tree age. It is generally considered that the earliest formed heartwood contains less toxic materials and therefore the wood is less durable than the heartwood when the tree is mature.

Several studies concerning the link between the extractives content, age, radial position and the natural durability of teak have been published (Da Costa et al. 1958, 1961; Rudman et al. 1967). The previous chapter has shown the relationship between the natural termite resistance and the extractive content obtained from successive extraction.

In this work, the radial distribution of quinones of teak was investigated on the same samples (8, 30 and 51 years old) to estimate relative natural durability of the wood. The other purposes of this study were to relate the amount of the major compounds and the extractives content as well as to relate the amount of the active compounds with the previous data on the natural termite resistance properties.

3.2. MATERIALS AND METHODS

3.2.1. Samples preparation

Stand characterization, site localization, climatic condition and sampling method were described in the chapter 2.

3.2.2. Total extractive content determination

Extractives were obtained by extracting one g of wood meal with ethanol/benzene (1/2, v/v) in a Soxhlet for 8 h. After evaporating the solvent under reduced pressure, the extractives were removed, dried and weighed to determine the percentage of total extractive content based on moisture-free sawdust.

3.2.3. Chemical analyses

The extracts (concentration of 100 mg/ml) were analysed by GLC (Hitachi Model G-3500) under the following conditions, detector: FID, column: NB-1 bonded capillary 30 m, column temperature: 120 - 300 ^{0}C (programming 4 ^{0}C/min), held at 300 ^{0}C for 15 min, carrier gas: Helium. The column was injected with 1 micro liter of the solution per sample. For quantification of individual substances, calibrations were made using known amounts of reference samples : tectoquinone (2-methyl anthraquinone, 25753-31 Kanto Chemical), lapachol (142905 Sigma-Aldrich), 2-hydroxymethyl anthraquinone (17241-59-7 Acros Organics), squalene (37309-30 Kanto Chemical), palmitic acid (32016-30 Kanto Chemical) and the response factors were determined for each substance in relation to an internal standard (heneicosane). The amounts of components are expressed as a percentage of oven-dried wood mass. From tectoquinone, lapachol, desoxylapachol and its isomer content, the total quinone content was calculated.

Compounds were identified by comparing their mass spectra with data from the literature and the injection of standards. GC-MS (JEOL XS mass spectrometry at 70eV) was used for gas chromatographic separations.

3.2.4. Statistical analysis

Variation of the total extractive, total quinone, and individual component contents were analyzed (general linear models procedure) by one-way analysis of variance (ANOVA) followed by Duncan's multiple range test ($p = 0.05$). The relationships between the independent variables were studied with a Pearson's correlation analysis. The natural termite resistance data in the correlation analysis were taken from the previous report. The termite survival rates (percentages) were transformed to arc sine for analysis. All statistical calculations were conducted using SPSS-Win 10.0.

3.3. RESULTS AND DISCUSSION

3.3.1. Total extractives content determination

The determination of total extractive content (TEC) is presented in Fig. 6. The tendency in the heartwood region of the total extractive content of all of the tree age groups is in agreement with data from the previous total extractive content obtained by successive extraction, but slight differences were observed in the sapwood region. With the exception of the OH region, significant differences of extractive content levels among the age groups in the same part were not found due to the large variation. The maximum mean values TEC in the OH of 8-, 30 and 51-year-old trees are 5.30, 7.01, and 8.04 %, respectively. The mean values TEC in the OH of control samples were 12.97 %, further confirming that tree age significantly affected the TEC level.

3.3.2. Compound identification

The gas chromatogram of ethanol-benzene extract in the heartwood region is shown in Fig. 7. The major compounds detected in those chromatograms were lapachol, tectoquinone, desoxylapachol and its isomer (isodesoxylapachol), squalene, tectol, palmitic acid (after methylation) and two unidentified compounds. All the major compounds referred to above have been reported as teak components (Sandermann and Simatupang 1966 and literature cited therein). Tectol was identified by comparison of its mass spectra with that of reported by Lemos et. al (1999). Desoxylapachol and its isomer presences referred to a previous report by Perry et al. (1991) and Windeisen et al. (2003). The sequence of both components in the chromatogram was uncertain, owing to almost identical mass spectra of both compounds (Fig. 8). Based on their elution order, the first and second peaks were tentatively assigned as desoxylapachol and isodesoxylapachol, respectively. The molecular masses of unidentified compound 1 (UN1) and 2 (UN2) were found to be *m/e* (base peak) = 244 and 242, respectively. The other minor compounds identified were 2-hydroxymethyl anthraquinone, 5-hydroxylapachol (Khan and Mlungwana 1999), steroids and stearic acid.

3.3.3. Compound quantification

The quantification of major compounds is summarized in Table 3. Within the wood cross section, the amount of most major compounds seems to be related to extractive contents, and follows the same general pattern as it reaches maximum values in the OH. Compared to the literatures (Sandermann & Dietrichs 1959; Windeisen et al. 2003; Thulasidas & Bhat 2007), the values of squalene and tectoquinone content measured in this experiment were generally lower, whereas tectol, lapachol, desoxylapachol and its isomer content values were in the range.

The presence of major compounds in the sapwood was confirmed, although at very low levels. With age, the variation between the sapwood regions in detected compounds contents was small. Desoxylapachol, UN1, and UN2 were not detected in the sapwood and heartwood of 8-year-old groups, while the same compounds along with palmitic acid were absence in the sapwood of 51-year-old trees. In the OH region of 8-year old trees, tectoquinone, followed by lapachol were the most abundant compounds. This composition was different from those in the 30 and 51-year-old trees, where squalene followed by desoxylapachol or tectol were the highest level compounds. While the contents of most compounds were found to increase with age, no significant increase was observed in the contents of lapachol and tectoquinone in that region. In the other parts of the heartwood, only tectoquinone and squalene contents varied significantly with age. The former increased in the MH, while the latter decreased in the IH region.

Among the radial parts in the heartwood of 30-year-old groups, significant differences were observed for desoxylapachol, palmitic acid, and tectol content levels. The significant differences in palmitic acid, isodesoxylapachol, UN2, squalene, and tectol contents in the heartwood of 51-year-old trees were also obtained. The radial variation in the initial amounts of components also can be examined by between-tree comparisons. The OH from 8, IH from 30 and IH from 51-year-old trees were formed in approximately the same growing seasons (juvenile region, 4-6th ring); it reveals the statistical differences of desoxylapachol, UN1, UN2, squalene, and tectol levels between the parts. Sandermann and Dietrichs (1959) observed that the concentration of tectoquinone is highest in the center of heartwood. This finding showed that although the highest level tectoquinone was measured in the IH region of both 30 and 51-year-old trees, the ANOVA revealed there was not a statistically significant difference with those in the OH and MH. Based on the biosynthesis pathway proposed by Sandermann and Simatupang (1966), desoxylapachol is a precursor of both lapachol and tectoquinone. Thus, it might be considered that the conversion rate of desoxylapachol into lapachol or tectoquinone remains relatively steady as a radial position in the heartwood.

The study shows that there are wide variations among trees in regards to the amount of major constituents identified by examining standard deviations, even in trees from the same sites. This means that teak may not always have a high amount of certain compounds. For instance, amounts of tectoquinone identified in five trees of one age (51 years, OH) may vary from 0.11 to 0.59 % (i.e. trees no. 7 and 8). In an earlier report, out of 13 ethanol extracts of teak specimens from various sites, desoxylapachol was detected in only two samples while lapachol only in one sample (Sandermann and Simatupang, 1966). A similar phenomenon was also observed in this study although to a lesser extent which inevitably causes wide variations. This result may support an earlier study by Da Costa et al. (1958), Bhat and Florence (2003), which found significant tree-to-tree variability in teak durability. In order to decrease the variability, tree sampling should be done in larger number in the subsequent investigations.

3.3.4. Relationship between extractive compound and total extractive contents

The Pearsons' correlation between the TEC and various extractive compounds is presented in Table 4. The comparatively high degree correlations were observed between the total extractive content with isodesoxylapachol, squalene and tectol content. The total extractive content seem to be a good indicator for tectol content ($r = 0.84$). Between the quinones, the strongest positive correlation was measured between the content of tectol and isodesoxylapachol ($r = 0.91$). Moderate positive correlations were obtained between the content of naphtaquinones (lapachol, desoxylapachol and its isomer). Between tectoquinone and the napthoquinone compounds, moderate positive relationship was observed in tectoquinone and isodesoxylapachol content ($r = 0.54$).

It was observed in the previous findings that the mass loss due to the termite attacks moderately correlated with *n*-hexane extractive content and total extractive content. As anticipated, correlation analysis revealed significantly positive values between TEC and toxic quinones levels, ranging from 0.45 with lapachol to 0.79 with isodesoxylapachol. These results may partly explain the important of extractives content in relation to the natural durability of teak.

3.3.5. Distribution of extractives as related to natural durability

With regard to termite activity, Rudman and Gay (1959) concluded that all anthraquinones possess termiticidal properties. In a literature review, Sandermann and Simatupang (1966) mentioned that tectoquinone is the principal component, which caused natural durability against termites. Furthermore, desoxylapachol has been mentioned to exhibit strong antitermite activity but lapachol only creates weak antitermite activity. Haupt et al. (2003) reported the quantity of tectoquinone and its ratio to desoxylapachol appears to be a good indicator of antifungal properties, while Thulasidas and Bhat (2007) observed that naphtaquinone is the single major compound, which determines the decay resistance of teak. Sumthong (2006) found both tectoquinone and desoxylapachol are the active compounds against *Aspergillus niger*. Therefore, these findings confirmed the presences of toxic components in the sapwood and heartwood of young trees. In addition these findings confirmed that no ageing or detoxification of teak extractives occurs by the time a given tree is 51 years old. Tectol, palmitic acidid and squalene have never been mentioned with regard to natural durability.

The total quinone content (TQC) of each part obtained in this study was presented in Fig. 9. It has been reported that the wood regions near pith and sapwood were much less resistant to termite and fungal attack than the outer heartwood (Da Costa et al. 1959; Rudman 1967; Narayanamurti et al. 1962; Bhat and Florence 2003; Bhat et al. 2005; Kokutse et al. 2006). The lower natural durability of younger trees has been demonstrated by Da Costa et al. 1958, Narayanamurti et al. 1962, Haupt et al. 2003. As would be expected, the sapwood values were significantly lower than heartwood for TEC, TQC and individual toxic compounds contents. TEC, TQC, desoxylapachol and its isomer amounts in the OH of 51-year-old groups were significantly higher than in the OH of 8-year-old trees. The OH of 30 and 51 year-old trees differed only in desoxylapachol content. The comparison between the OH and IH showed significant differences in isodesoxylapachol levels of 30-year-old trees as well as the TEC and desoxylapachol levels of 51-year-old trees, but there was not significant difference for the TQC levels in both 30 and 51 year old trees. In the case of individual substances, the significant differences of desoxylapachol and/or its isomer content suggest that the wood from younger trees will be less durable due to the lower contents of these compounds such as is the case with teak plantations.

The pattern of TQC levels in the heartwood were corresponded well with the mass loss data due to the termite attacks from the previous results where the mass loss in the OH of 51-year-old groups were significantly lower than in the OH of 8-year-old trees; the mass loss between the OH and IH in both 30 and 51 year old trees was not significantly differed. However, the high natural termite resistance levels in the OS of 51-year old trees which contain low TQC level could not be explained satisfactorily, which indicated the other factors must be contributed. The reasons for the high resistance in that region should be investigated more thoroughly.

3.3.6. Relationship between the natural termite resistance parameters and extractive compound contents

Correlation analysis between the natural termite resistance parameters and quinone compounds is presented in Table 5. There was no significant relationship between lapachol or desoxylapachol and the natural termite resistance parameters. The correlation between survival rate in the first week and the content of compounds was slightly greater than the correlation coefficient between survival rate in the second week and the content of compounds. Survival rate in the first week was correlated best with the content of tectoquinone (*r* = -0.46). The highest correlation coefficient was observed between the mass loss and the content of tectoquinone (*r* = -0.49), followed by the mass loss and the content of isodesoxylapachol (r = -0.47), which means teak is more resistant when the content of those compounds is higher. These findings may support Rudman et al. (1958) who concluded that, although tectoquinone exhibited strong antitermitic properties, this compound is not the sole cause of termite resistance. However, the degree of correlation between the natural termite resistance characteristics and total quinone content was not as strong as might be expected.

The relatively weak correlation degree obtained in this study is interpreted as the complex nature of teak extractives (Sandermann and Simatupang 1966; Yamamoto 1998) as well as the complex interaction between heartwood extractives and its durability. It has been proved that although teak heartwood contains toxic components, it merely deters termites in natural condition (Rudman et. al 1967). Therefore, it is difficult to select one single compound content to correlate directly with the natural termite resistances. Previous studies with other species such as *Larix sibrica* (Venalainen et al. 2006) and *Cinnamomum camphora*. (Hashimoto et al. 1997) showed that variation in fungal and termite resistance could be explained by the concentration of the largely responsible components. In contrast, Taylor et al. (2006) found variations in extractive components could not adequately explain of the variation in fungal and termite resistance of the *Thuja plicata* and *Chamaecyparis nootkanensis* wood.

Table 3. Contents of major components (% of oven-dry wood) in the ethanol-benzene extract of teakwood trees aged 8, 30 and 51 (radial position).

Components	Outer sapwood			Inner sapwood	
	8 years	30 years	51 years	8 years	30 years
Desoxylapachol	nd	tr	nd	tr	nd
Palmitic acid	0.04 (0.01)ab	0.03 (0.007)a	nd	0.04 (0.04)ab	0.03 (0.01)a
Lapachol	tr	tr	tr	0.01 (0.01)a	0.01 (0.002)a
Isodesoxylapachol	tr	0.02 (0.006)a	0.01 (0.004)ab	0.01 (0.01)a	tr
UN1	nd	tr	nd	tr	nd
Tectoquinone	0.02 (0.02)a	0.03 (0.02)a	0.03 (0.004)a	0.03 (0.02)a	0.05 (0.03)a
UN2	nd	tr	nd	tr	nd
Squalene	0.02 (0.02)a	0.07 (0.01)a	0.07 (0.03)a	0.05 (0.02)a	0.15 (0.04)a
Tectol	tr	tr	tr	tr	tr

Note : Mean of 5 trees (8- and 51 year-old) and 4 trees (30-year-old), with the standard deviation in parentheses. The same letters on the same row are not significantly different at p<5% by Duncan's test.

nd = spectroscopically not detected; tr = trace (be detected, the value < 0.01 %)

Table 3. Continued

Components	Outer heartwood			Middle heartwood		Inner heartwood	
	8 years	30 years	51 years	30 years	51 years	30 years	51 years
Desoxylapachol	nd	0.31 (0.48)b	0.19 (0.15)ab	0.02 (0.03)a	0.13 (0.23)ab	0.03 (0.03)a	0.03 (0.05)a
Palmitic acid	0.04 (0.01)ab	0.07 (0.02)b	0.08 (0.02)c	0.03 (0.01)a	0.04 (0.01)ab	0.06 (0.01)abc	0.04 (0.01)ab
Lapachol	0.10 (0.13)ab	0.25 (0.26)b	0.16 (0.32)ab	0.11 (0.07)ab	0.03 (0.06)a	0.10 (0.08)ab	0.03 (0.04)a
Isodesoxylapachol	0.05 (0.04)ab	0.17 (0.10)bc	0.34 (0.23)d	0.12 (0.09)bcd	0.26 (0.11)cd	0.19 (0.16)bc	0.15 (0.06)abc
UN1	nd	0.01 (0.03)a	0.01 (0.02)a	0.03 (0.07)a	0.12 (0.21)a	0.17 (0.30)a	0.19 (0.21)a
Tectoquinone	0.20 (0.06)bc	0.16 (0.06)abc	0.24 (0.22)bc	0.11 (0.08)ab	0.27 (0.07)c	0.19 (0.06)bc	0.30 (0.16)c
UN2	nd	0.06 (0.06)a	0.21 (0.18)b	0.02 (0.02)a	0.09 (0.06)a	0.03 (0.02)a	0.02 (0.02)a
Squalene	0.08 (0.04)a	0.50 (0.22)bc	1.08 (0.39)d	0.42 (0.13)bc	0.50 (0.18)bc	0.56 (0.38)c	0.24 (0.15)ab
Tectol	0.08 (0.04)a	0.26 (0.06)bc	0.47 (0.31)e	0.19 (0.08)abc	0.29 (0.14)cd	0.30 (0.22)cd	0.16 (0.11)abc

Table 4. Pearson's correlation coefficients between total extractive content and extractive component contents.

	TEC	ISO	PAL	LAP	DES	UN1	TEC	UN2	SQU
DES	0.46**								
PAL	0.52**	0.24							
LAP	0.45**	0.61**	0.39**						
ISO	0.79**	0.54**	0.48**	0.64**					
UN1	0.09	-0.01	-0.00	0.06	0.07				
TEC	0.64**	0.12	0.34**	0.27*	0.54**	0.22			
UN2	0.56**	0.55**	0.46**	0.47**	0.73**	-0.05	0.30*		
SQU	0.74**	0.49**	0.60**	0.45**	0.78**	0.12	0.47**	0.72**	
TOL	0.84**	0.46**	0.56**	0.62**	0.91**	0.09	0.61**	0.76**	0.84**

Note ** = significant at 1 % level * = significant at 5 % level

TEC = total extractive content, ISO = desoxylapachol, PAL = palmitic acid, LAP = lapachol, DES = desoxylapachol, UN1 = unidentified compound 1, TEC = tectoquinone, UN2 = unidentified compound 2, SQU = squalene, TOL = tectol

Table 5. Pearson's correlation coefficients between natural termite resistance parameters and extractive component contents.

Extractive content	Natural termite resistance		
	Survival rate in the first week	Survival rate in the second week	Mass loss
Desoxylapachol	-0.19	-0.19	-0.25
Lapachol	-0.18	-0.16	-0.25
Isodesoxylapachol	-0.38**	-0.33*	-0.47**
Tectoquinone	-0.46**	-0.35**	-0.49**
Total quinone	-0.38**	-0.33*	-0.47**

Note ** = significant at 1 % level * = significant at 5 % level

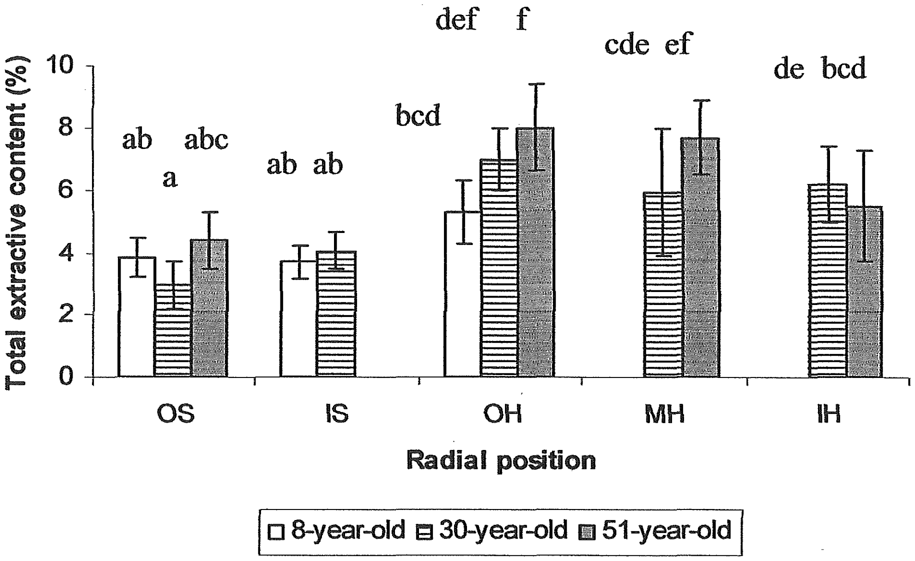


Figure 6. Total extractive content (%) of teakwood by age and radial position. Mean of 5 trees (8- and 51 year-old) and 4 trees (30-year-old), with the standard deviation in error bar. The same letters are not significantly different at $p<5\%$ by Duncan's test. OS = outer sapwood, IS = inner sapwood, OH = outer heartwood, MH = middle heartwood, IH = inner heartwood.

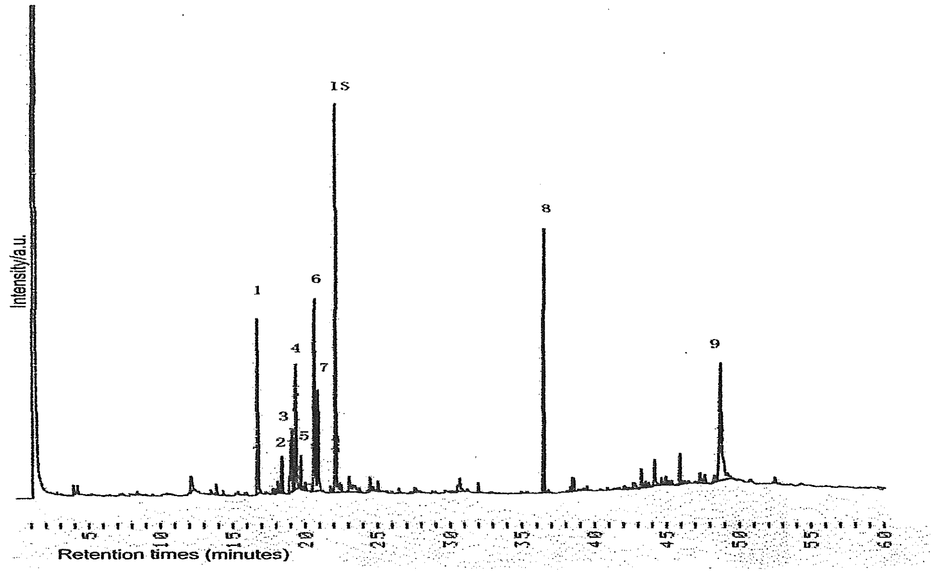
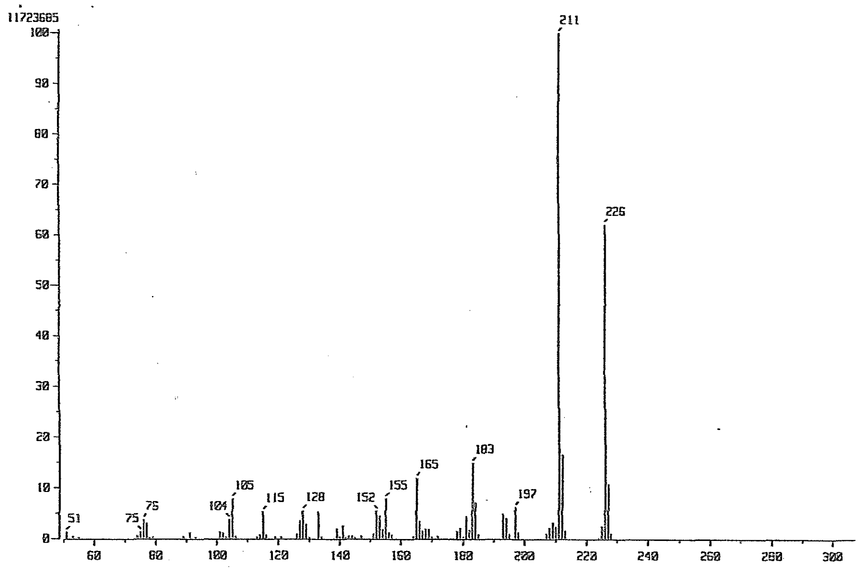
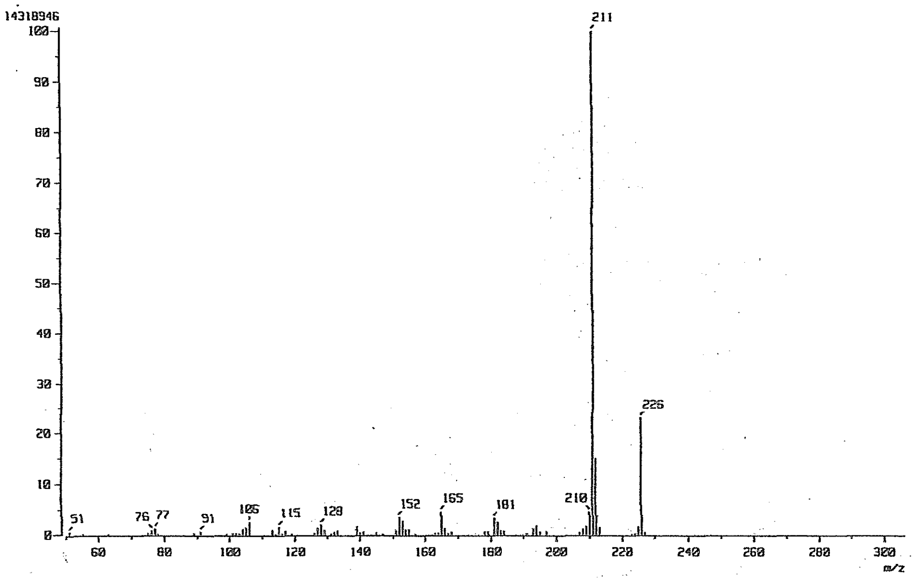


Figure 7. Gas chromatogram from ethanol-benzene extract of teak heartwood. Nine major compounds are indicated : peak 1 (R_t 17.4) & 4 (R_t 20.1) = desoxylapachol and its isomer; peak 2 (R_t 19.0) = palmitic acid; peak 3 (R_t 19.7) = lapachol; and peak 5 (R_t 20.4) = unidentified compound 1, peak 6 (R_t 21.3) = tectoquinone; peak 7 (R_t 21.5) = unidentified compound 2, peak 8 (R_t 36.7) = squalene; and peak 9 (R_t 49.4) = tectol, IS = internal standard (heneicosane).



(8a)



(8b)

Figure 8. Mass spectrum of desoxylapachol (a) and isodesoxylapachol (b)

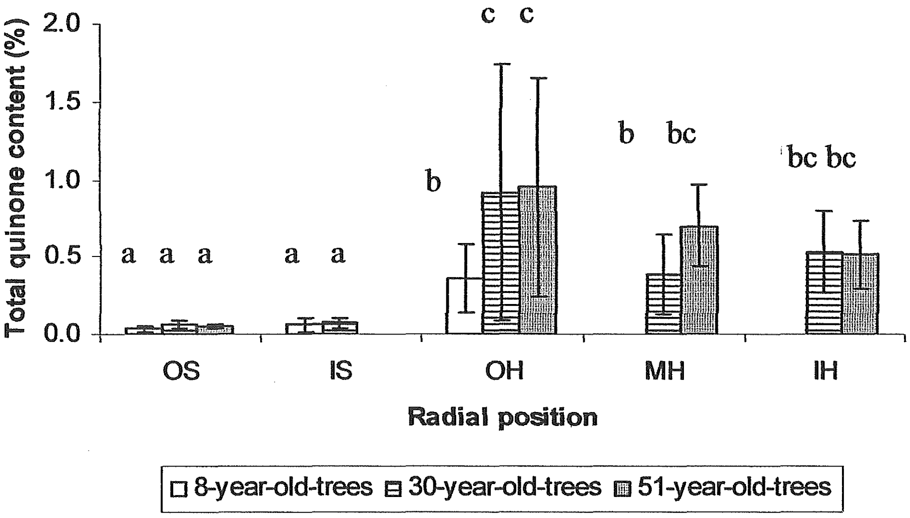


Figure 9. Total quinone content (%) of teakwood by age and radial position. Mean of 5 trees (8- and 51 year-old) and 4 trees (30-year-old), with the standard deviation in error bar. The same letters are not significantly different at p< 5% by Duncan's test. OS = outer sapwood, IS = inner sapwood, OH = outer heartwood, MH = middle heartwood, IH = inner heartwood.