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Physico-Mechanical Properties and Durability of Thermally Modified Malapapaya [*Polyscias nodosa* (Blume) Seem.] Wood

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The study investigated the use of thermal modification to improve physico-mechanical properties and decay resistance of Malapapaya [*Polyscias nodosa* (Blume) Seem.] wood. Results showed that wood properties were altered with exposure to high temperature and long treatment duration. Wood color changed from light yellowish brown to very dark brown with increasing treatment temperature. No defects due to heat treatments were observed. Treatments resulted in improved dimensional stability as indicated by the reduction in water absorption and thickness swelling of treated materials. Decay resistance against white rot [*Fomes lividus* (Kalchbr.) Sacc] and brown rot [*Lenzites striata* (Swartz ex Fries)] fungi improved significantly at the highest treatment combination of 220º C-120 minutes. Mechanical properties as measured by modulus of rupture and toughness were significantly reduced.

Key Words: decay fungi, dimensional stability, durability, Malapapaya, physico-mechanical properties, thermally modified wood

INTRODUCTION

In civil construction or in downstream processing such as wood joinery/moldings, furniture and handicraft making, wood is used with limited modifications in terms of properties. Being a hygroscopic and biodegradable material, wood in service shrinks and swells due to varying humidity (Simpson 1999) and its service life can be shortened due to decay fungi when exposed to humid or wet conditions, and insects such as powder post beetles and termites (Highley 1999).

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Chemical impregnation with toxic biocides is the traditional method of prolonging the life span of wood. However, some wood preservatives (i.e., creosote, chromated copper arsenate and organo-chlorine based compounds like aldrin, dieldrin, chlordane, heptachlor, and pentachlorophenol), have been banned due to their harmful and adverse effects to humans and the environment (US EPA 2009; Beyond Pesticides 2002). An alternative way of protecting wood from decay and insects without the use of toxic preservatives and improving its dimensional stability is through thermal modification (Rapp 2001; Homan and Jorissen 2004; Sundqvist 2004).

Thermal modification is the process of subjecting solid wood to temperatures close to or above 200º C for several hours in an atmosphere with low oxygen content (Rapp 2001). This process results to the modification of cell wall components. Portions of hemicelluloses are hydrolyzed into their monosaccharide components such as glucose, galactose, mannose, arabinose, and xylose, while the amorphous regions of cellulose are hydrolyzed, breaking cellulose into shorter chains. The degradation of these two major components of the cell wall lead to a reduction of free hydroxyl groups in their chemical structures. In contrast, lignin's cross-linking is believed to increase (Nuopponen 2005; Sundqvist 2004; Sundholm 2001).

These modifications in the cell wall result in several changes in wood properties. Regardless of the process used, common results are color change from white or yellowish into brown or dark brown; decreased shrinking and swelling by 50 – 90% due to reduced equilibrium moisture content of the wood; improvement of biological durability; decreased mechanical strength by up to 30%; decreased heat conductivity by 10–30%; reduction in weight by 5–15%; and extractives migration onto the wood surface (Rapp 2001; Homan and Jorissen 2004; Jamsa and Viitaniemi 2001).

Wood properties can be tailored to specific end uses, depending on the process conditions employed (treatment time and temperature). Increased resistance against decay and insects and improved dimensional stability are among the desired properties. Although the process of thermal modification of wood is already commercialized (i.e., Finnish ThermoWood, Dutch PlatoWood, French Retification and Perdure, and German Oil Heat Treatment [Rapp 2001]), only few and mostly temperate wood species had been tested. Response to thermal modification varies widely among wood species due to their differences in physical, anatomical, and chemical properties. Thus, all untested wood species needs to be evaluated. Parameters used such as treatment time and temperature must be optimized separately for different wood species to attain the desired properties (Ranin 2004).

In tropical countries like the Philippines, the cutting of trees from natural forests stand is now prohibited and a limited number of species are available for study. Therefore, the thrust of wood utilization is now on plantation forests and a potential plantation species that shows promise is malapapaya [*Polyscias nodosa* (Blume) Seem.]. The Department of Environment and Natural Resources (DENR) and local communities in the provinces of Pangasinan, Laguna, and Quezon intensified the propagation and planting program for this species (PCARRD 2007). Dwindling wood supply from the natural forests resulted to its utilization as an alternative to some traditional wood species.

Malapapaya wood belongs to moderately low strength group. It has good machining properties (Estudillo and Revilleza 2003), easy to dry, and can tolerate high temperature during the initial stages of drying up to the final stages without major drying defects (Jimenez 2004). Its common uses are limited to veneered products (matchsticks, chopsticks, popsicle sticks and food containers), crates, and pallets. The main drawback, however, of using malapapaya wood is to add value by reducing its susceptibility to attack of decay fungi and wood boring insects (Roxas 2003).

The aim of this study is to modify the properties of malapapaya wood to expand its uses in high value products like architectural wood moldings, external claddings and wall partitions, floor tiles, and light outdoor furniture, and handicrafts. This study investigated the effects of thermal modification on the physico-mechanical properties and durability of thermally modified malapapaya wood.

MATERIALS AND METHODS

Collection of Malapapaya Trees

Seven malapapaya trees were collected in Atimonan, Quezon from a private coconut plantation farm where malapapaya trees were growing. Each tree had a minimum average diameter of 30 cm at breast height. The height of the trees ranged from 19.8 to 24.4 m. To minimize variation, only the butt log of the seven trees were used for the experiment. The butt log measured 4.57 m and cut into three 1.52 m sections.

Preparation of Samples

The logs were immediately sawmilled into lumber and only the center planks for each log were used in the preparation of samples. These samples had the perfect tangential and radial sections on its sides. The sawn planks were air-dried to approximately 20% moisture content and then machined to the required specimen sizes for thermal modification.

Thermal Modification Process

A steaming cylinder at Forest Products Research and Development Institute (FPRDI) was used as the treating chamber for thermal modification. The cylinder was fitted with three 4-kW electric heater tubes with temperature control.

The thermal modifications were performed in several batches using 160, 180, 200, or 220º C at 30, 60, or 120 minutes. Treatment time was recorded once the inside temperature of the cylinder reached target treatment temperature.

The malapapaya wood samples had a moisture content ranging from 20–22%. For each treatment combination, a total of ten replicates of 25mm x 25mm x 600mm

(static bending samples) and twenty replicates of 20mm x 20mm x 381mm (toughness samples) were used. During the thermal modification process, water vapor or steam was continuously injected in the treatment cylinder to shield the wood from burning. The steam pressure inside the treatment cylinder was maintained at 105 kPa by releasing the excess pressure using a manual pressure release valve. After the treatment and prior to physico-mechanical properties testing, the thermally modified samples together with the control (untreated air-dried samples) were conditioned for one month in a humidity controlled air-conditioned room at temperature of 23 ± 2º C and relative humidity of 65 ± 5%.

Physical Properties Tests

General Appearance

After thermal treatment, the treated samples were characterized and compared with untreated control specimens based on color, texture, and odor. The presence of any defects due to treatments was also noted.

Hygroscopicity and Dimensional Stability

The hygroscopicity (measured by water absorption) and dimensional stability (measured by tangential and radial thickness swelling) were determined following ASTM D 1037-99 (ASTM 2000c) with some modifications. Sample specimens measuring 2.54 cm x 2.54 cm x 10.16 cm were cut from tested static bending samples. Four replicates per treatment were prepared. Prior and after submersion in water, the dimensions and weight were measured using a Mitutoyo digimatic indicator and digital balance, respectively. The samples were submerged horizontally in 400 mL distilled water maintained at 26º C. After 24 hours, the samples were removed and suspended vertically in air to drain for 10 min then the excess surface water was wiped off with dry cloth. The amount of water absorbed and thickness swelling were calculated by using the difference of the weight and dimensions before and after submersion expressed as percentage of the initial weight or dimensions.

Mechanical Properties

Static Bending

Stiffness and flexural strength of thermally modified malapapaya were determined in accordance with ASTM D143-94 (ASTM 2000b). A total of four replicates of 25 mm × 25 mm × 410 mm for each treatment combinations were tested using a Shimadzu universal testing machine (UTM). The actual width and thickness of each sample were measured prior to testing. Center loading of the 356 mm span of the sample was used. The load was applied through the bearing block to the tangential surface nearest the pith. Speed of test was 1.3mm/min.

Toughness

Toughness was determined according to ASTM D 143-94 (ASTM 2000b) using a Baldwin Toughness Test Machine. A total of five replicates (20 mm × 20 mm × 280 mm) were tested for each treatment. Center loading and span length of 240 mm were used. The load was applied to a radial or tangential surface on alternate specimens.

Durability Properties

Resistance Against Decay Fungi

Test for the decay resistance was performed using an accelerated laboratory test of natural decay resistance of woods following ASTM D 2017-94 (ASTM 2000a).

Preparation of the test fungi. Two species of decay fungi, Fomes lividus (Kalchbr.) Sacc (white rot) and Lenzites striata (Swartz ex Fries) Fries (brown rot) were used. These fungi were obtained from the stock culture of the FPRDI Entomology-Pathology Laboratory. Reisolation was done on test tube containing 10 mL of Malt-Agar substrate. A ten-day old culture was prepared in Petri dishes as the source of inoculi in the bioassay. Four 1 cm by 1 cm cultures were placed in the Petri dishes. They were allowed to grow for five days prior to inoculation.

Preparation of test specimens. Specimens for the test were cut from the tested static bending samples. A total of five replicates (25 mm x 25 mm x 9 mm) for each treatment were used. The blocks were conditioned in an oven set at 40° C for one week to bring them to equilibrium and the initial weight (Wi) recorded.

Preparation of feeder blocks. Mollucan sau [*Albizia falcataria* (L.) Fosb.] (0.5 cm × 2.5 cm × 3.5 cm) was used as feeder blocks. The total number of feeder blocks was equal to the total number of test blocks for all the treatments. The blocks were soaked in distilled water prior to placement in the culture bottles.

Preparation of culture media. Malt agar substrate was used as the nutrient medium for the stock test tube cultures and for Petri dish cultures of the test fungi. It was prepared by mixing of 12.5 g of Bacto malt extract and 10 g of Prodinisa plant culture (E-406), then dissolved in 500 mL of distilled water. The medium was sterilized for 20 minutes at 121° C (105 kPa). Ten (10) mL of medium was poured into the test tube prior to sterilization to serve as tubing. The medium was sterilized in an Erlenmeyer flask. Thirty (30) mL of medium was poured to sterile Petri dishes for plating.

Preparation of soil substrate. The soil was obtained from the vicinity of the FPRDI Entomology-Pathology Laboratory. It was sieved using a wire mesh of 5 mm and placed in round 50 mm diameter culture bottles. The soil surface was leveled prior to addition of approximately

20 mL of water. The feeder block was introduced at the center of the substrate with a slight push to establish a better contact with the soil. The bottles with caps loosened were sterilized in an autoclave at 121° C (105 kPa) for 30 min then cooled prior to inoculation.

Inoculation of bottles. The fungus inoculum, approximately 5 mm disc, was cut from the petri dish culture using a cork borer. Three inoculi was placed on the sides of the feeder block. The inoculated bottles with lid slightly turn from the tightened position was incubated at 26.7 ± 1° C and RH of 70 ± 4% for two weeks or until the feeder blocks were completely covered by mycelium. The bottles were then ready to receive the test blocks.

Exposure of test blocks. The conditioned test blocks were placed in tightly closed glass bottles similar to the culture bottles used. They were sterilized at 100° C for 20 min at atmospheric pressure. The test blocks were allowed to cool and were introduced to the inoculated bottles (1 per bottle) with the cross section face down on the feeder block. The culture bottles were incubated for 16 weeks in storage shelves. At the end of incubation period, the blocks were removed and the mycelia carefully scraped off using a scalpel and cotton. The blocks were exposed to air for two days and were placed in the oven set at 40° C to condition the blocks to constant weight. The weights were recorded as the final weight (Wf). The percent weight loss were calculated as follows:

$$\%\text{Weight Loss} = \left(\frac{Wi - Wf}{Wi}\right) \times 100$$

The percent weight losses in the test blocks provided a measure of the relative decay susceptibility or, inversely, of decay resistance of the thermally modified wood.

Statistical Analysis

Data obtained in the study were analyzed using analysis of variance (ANOVA). Test of significance of the different treatment variables was estimated using a 3 x 4 factorial in a Completely Randomized Design (CRD). Treatment means were separated using the Least Significant Difference (LSD) Test at $\alpha = 0.05$.

RESULTS AND DISCUSSION

Physical Characteristics

General Appearance

The color of thermally treated malapapaya wood varied from pale yellowish brown at 160º C–30 min to very dark brown at the 220ºC–120 min. The color of untreated control samples were pale white to yellowish brown (Figure 1).

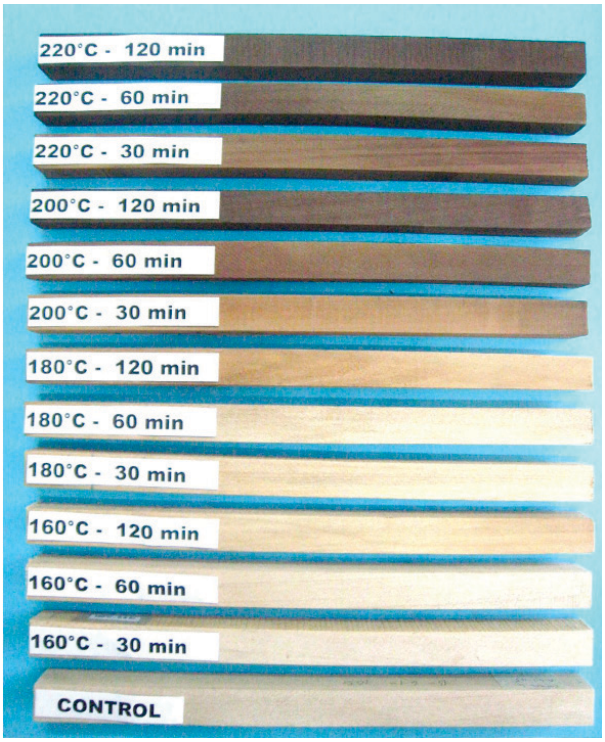

Figure 1. Comparison of the color of untreated and thermally modified malapapaya wood at different temperature and duration.

It was evident that as the treatment temperature and duration was increased from 160º C–30 min to 220º C–120 min, the color change intensified from yellowish brown to chocolate brown. Color change of wood during heating can be attributed to many complex chemical reactions. When wood is heated, aldehydes and phenols are formed from degraded carbohydrates, which may result in the formation of colored compounds after chemical reactions (McDonald et al. 2000). Sundqvist (2004) proposed that in the color formation of wood, oxidative changes rather than hydrolysis predominate. Oxidation of polysaccharides and lignin may produce phenolic compounds that can induce color change (Fengel and Wegener 1989). Bekhta and Niemz (2003) attributed the reduced lightness and increased color intensity to the decrease in the hemicellulose content. In steaming of walnut, Burtin et al. (1998) suggested that color formation is the result of both hydrolytic and oxidative mechanisms. A study by Sundqvist (2004) on the effect of extractives in the color of heat-treated wood showed that unextracted and acetone extracted samples had color differences. He concluded that both extractives and structural components (hemicelluloses and/or lignin) took part in color change of heat-treated wood.

A typical smoky smell was observed from the thermally modified malapapaya wood. Like the change in color, intensity of the smell increased from the samples treated at

lower temperature and duration to the highest temperature and duration. The smoky smell maybe attributed to the degradation products of cell wall components during thermal treatment such as pyrolysis products. Some of the samples had unpleasant and strong smell similar to organic acids and aldehydes (Sundqvist 2004; Manninen et al. 2002; McDonald et al. 2002; and Finnish Thermowood Association 2003). The smell, however, disappeared after two to three months. Visual inspection of the thermally treated woods showed no signs of defects after exposure to high temperature. In addition, fine dust loosely adhering on the surface of the wood was observed. The fine dust might be the result of pyrolysis of loose fibers present on the surface of the sample.

Hygroscopicity and Dimensional Stability

Water absorption. Thermally treated samples showed water absorption ranging from 21.93 (200° C–120 min) to 37.75% (160° C– 120 min). Relative to the control, which absorbed 39.33%, the thermally treated samples' water absorption capacity was reduced by 4.02–44.24%. This showed a substantial reduction in hygroscopicity of the treated materials after a 24-hour period. ANOVA shows that the water absorption of the control is significantly different from the treated samples. Comparison of the means showed that generally the amount of water absorbed by the control was significantly different from the treated samples (Table 1). The decrease in the water absorption may be attributed to the reduction of available bonding sites of hydroxyl groups in the hemicelluloses and cellulose. Thermal degradation and the increased cross-linking of lignin could also limit sorption sites for water (Jimenez and Razal 2004; Sundqvist 2004; Wikberg 2004; and Nuopponen 2005).

Tangential thickness swelling. Compared to the treated samples, which swelled by 3.14–0.59% , the mean tangential thickness swelling of the control, which had a value of 4.41%, was greater by 28.83–86.6%. ANOVA shows that the treatment significantly reduced the mean tangential thickness swelling of the treated samples compared to control. For the treated samples, the highest tangential swelling occurred at 160° C -120 min with value of 3.14% and the lowest was at 220° C -120 min with value of 0.59% (Table 1). In general, it showed that as the treatment temperature and duration was increased, the percent tangential swelling decreased.

Radial thickness swelling. The control swelled by 2.96% while the treated samples by 0.45% (220° C–120 min) to 2.47% (160° C–120 min). This showed a reduction in radial swelling of the treated samples by 84.8%–16.6%, respectively. ANOVA and mean comparison shows that the control was significantly different compared to the treated samples (Table 1). In general, it can be said that the radial thickness swelling of all treated samples was similar in trend/behavior to that of tangential thickness swelling except that it was lower in percentage value due to its different cell arrangement (Maruzzo et al. 2003).

Table 1. Physical properties of thermally modified malapapaya (*Polyscias nodosa* [Blume] Seem) wood.

Treatment (°C-min)	Water Absorption (%)	Tengential Swelling (%)	Radial Swelling (%)
Control	39.33 *(0.34)* a	4.41 *(0.17)* a	2.96 *(0.15)* a
160 – 30	31.00 *(0.32)* bc	2.67 *(0.23)* b	2.34 *(0.15)* b
160 – 60	36.16 *(0.73)* ab	3.00 *(0.26)* b	2.13 *(0.31)* bc
160 – 120	37.75 *(0.88)* a	3.14 *(0.14)* b	2.47 *(0.23)* b
180 – 30	28.70 *(1.07)* cde	2.71 *(0.19)* b	2.04 *(0.24)* bcd
180 – 60	29.92 *(0.43)* c	2.68 *(0.29)* b	2.09 *(0.09)* bc
180 – 120	23.55 *(0.52)* def	1.97 *(0.31)* c	1.74 *(0.09)* cd
200 – 30	29.87 *(2.79)* cd	1.83 *(0.15)* c	1.61 *(0.17)* d
200 – 60	23.40 *(3.89)* ef	0.83 *(0.08)* d	0.67 *(0.06)* e
200 – 120	21.93 *(2.52)* f	0.74 *(0.11)* d	0.62 *(0.04)* e
220 – 30	28.06 *(3.92)* cde	0.91 *(0.04)* d	0.75 *(0.07)* e
220 – 60	26.67 *(3.70)* cdef	0.77 *(0.04)* d	0.68 *(0.05)* e
220 – 120	28.04 *(0.55)* cdef	0.59 *(0.06)* d	0.45 *(0.08)* e
ANOVA	F_{com} = 6.22	F_{com} = 43.89	F_{com} = 26.69
	df = 12	df = 12	df = 12
	P< 0.001	P< 0.001	P< 0.001

Each mean is the average of four replicates; means followed by the same letter are not significantly different with each other using LSD at $\alpha = 0.05$. Italicized value in parenthesis is the standard error. Fcom = F computed; df = degrees of freedom

Mechanical Properties

Static Bending

Modulus of elasticity. Thermally treated samples' Modulus of Elasticity (MOE) varies from 6.03 GPa (220º C–120 min) to 8.69 MPa (200º C–120 min) (Table 2). Relative to control (7.81 GPa), treatments resulted to a negative change in MOE by 22.79% to positive change in MOE by 11.27%, respectively. However, ANOVA shows that the change in MOE of the treated samples was not significantly different to the control. The variation in the MOE, although not significant, might be attributed to inherent variability within the seven trees – this could be due to the anatomical structure of the wood or to the density variation of the samples.

For the treated samples, it was found out through ANOVA that temperature factor contributes to the variation in MOE. Among the four temperature levels, the highest temperature setting of 220º C significantly varies with 160, 180, and 200º C (Table 3). In the works of Finnish ThermoWood Association (2003) with pine wood treated at temperatures of 100, 120, 140, 160, 180, 200, 220, and 240º C, they reported that heat treatment did not significantly changed the MOE. Similar result was found by Rapp and Sailer (2001) with the oil heat treatment and dry-air heat treatment of pine (*Pinus sylvestris* L.) treated at 180, 200, and 220º C. The heat-treated pine's MOE was not significantly different with the control although at 200º C the highest MOE of 11,000 N/mm^2 was achieved.

Modulus of rupture. The variation of the thermally treated samples' MOR ranged from 25.16 MPa (220º C–120 min) to 64.28 MPa (180º C–60 min) (Table 2). Relative to control (58.58 MPa), treatments resulted to a negative change of 57.1% to positive change of 9.7%. ANOVA shows that the treatments used in the study had significant effects on the modulus of rupture (MOR) of the treated samples in comparison to the control. The general trend shows that as the treatment temperature increases, the MOR of thermally treated samples decreases (Table 3).

The significant reduction in the MOR, which occurred from the treatment combination of 200º C–60 min up to 220º C–120 min, ranged from 37.6 to as high as 57.1%. This range was higher compared with the reduction in the MOR reported by Vernois (2001). In Plato-treatment, Beech wood's MOR was reduced by only 5 to 18% (Militz and Tjeerdsma 2001). In ThermoWood, MOR was reduced from 10–30% for the Finnish pine, spruce and birch. The different MOR values obtained can be attributed to various parameters such as atmosphere, temperature, duration, rate of heating, species, weight and dimensions of the pieces treated and original MC (Vernois 2001; Kocaefe et al. 2008).

Toughness

Toughness values of treated samples were significantly different in various conditions used in this study. As the temperature and duration were increased, toughness

Table 2. Mechanical properties of thermally modified malapapaya (*Polyscias nodosa* [Blume] Seem) wood.

Treatment (°C-min)	Modulus of Elasticity (GPa)	Modulus of Rupture (MPa)	Toughness (J)
Control	7.81 *(0.28)* a	58.58 *(2.88)* a	19.18 *(1.53)* a
160 – 30	7.40 *(0.26)* a	62.60 *(1.97)* a	16.27 *(0.86)* ab
160 – 60	8.35 *(1.11)* a	63.26 *(6.93)* a	14.17 *(1.49)* b
160 – 120	7.91 *(0.80)* a	62.00 *(3.62)* a	14.04 *(1.46)* b
180 – 30	7.27 *(0.49)* a	57.73 *(3.71)* a	16.66 *(2.02)* ab
180 – 60	7.98 *(0.24)* a	64.28 *(4.36)* a	13.78 *(1.43)* b
180 – 120	8.48 *(0.35)* a	53.53 *(6.34)* a	9.13 *(0.66)* c
200 – 30	8.67 *(0.89)* a	55.02 *(11.38)* a	10.01 *(1.38)* c
200 – 60	8.19 *(0.89)* a	34.84 *(4.24)* b	8.17 *(1.68)* cd
200 – 120	8.69 *(0.65)* a	36.58 *(7.88)* b	7.15 *(0.81)* cd
220 – 30	6.55 *(0.34)* a	28.96 *(1.06)* b	7.75 *(0.40)* cd
220 – 60	7.28 *(0.51)* a	27.13 *(2.08)* b	5.71 *(0.36)* d
220 – 120	6.03 *(0.31)* a	25.16 *(4.22)* b	4.88 *(0.23)* d
ANOVA	F_{com} = 1.74	F_{com} = 8.04	F_{com} = 14.05
	df = 12	df = 12	df = 12
	P = 0.096	P< 0.001	P< 0.001

Each mean is the average of four replicates; means followed by the same letter are not significantly different with each other using LSD at $\alpha = 0.05$. Italicized value in parenthesis is the standard error. Fcom = F computed; df = degrees of freedom

Table 3. Comparison of the treatment means for the MOE and MOR at different temperature settings.

Temperature (°C)	Modulus of Elasticity (GPa)	Modulus of Rupture (MPa)
160	7.88 *(0.44)* a	62.62 *(4.22)* a
180	7.91 *(0.25)* a	58.51 *(5.02)* a
200	8.52 *(0.43)* a	42.14 *(8.94)* b
220	6.62 *(0.26)* b	27.08 *(2.65)* c
ANOVA	F_{com} = 4.74	F_{com} = 35.74
	df = 3	df = 3
	P = 0.007	P< 0.001

Each mean is the average of 12 replicates; means followed by the same letter are not significantly different with each other using LSD at $\alpha = 0.05$
Italicized value in parenthesis is the standard error
Fcom = F computed; df = degrees of freedom

decreased. Relative to control, which had a toughness value of 19.18 J, the toughness of the treated samples decreased from 16.66 J (13.13%) to as low as 4.88 J (74.57%). Comparison of the means showed that the control was not significantly different from 160-30 and 180-30 although toughness decreased by 15.18 and 13.13%, respectively. For the rest of the treatment combinations, the control was significantly different (Table 2).

The reduction in toughness value, as the temperature and duration of treatment was increased, indicated increasing brittleness of the thermally treated malapapaya wood. Assessment of the crack failures produced by impact showed that at lower treatment combinations, the cracks showed pulled out fibers similar to the fibrous failure in static bending. Whereas at higher temperature starting at 200-60 combinations, the crack failures produced were similar to the brash failure in static bending in which the fibers delaminated into layers without splinters. The type of failure that occurred in the thermally treated wood and the reduced strength was probably due to the degradation of the hemicelluloses, which no longer fortified the cellulose microfibrils (Wikberg 2004). As the treatment temperature and duration increased, degradation of hemicelluloses and amorphous cellulose aggravated these effects (Bekhta and Niemz 2003; Sundqvist 2004).

Resistance to Decay Fungi

The resistance of the thermally modified malapapaya wood against the white rot fungi (*F. lividus*) and brown rot fungi (*L. striata*) varied widely with the heat treatment conditions. For these two fungi, the control is classified as non-resistant or highly perishable having a weight loss of more than 45% (Table 4). Improvement of thermally modified malapapaya wood against decay started at treatment combination of 200º C–60 min where weight losses recorded were only 43.88% (for the white rot fungi) and 28.97% (for the brown rot fungi). At this percent weight loss, the treated wood became moderately resistant as per classification in ASTM D 2017-81. Further, at 200º C–120 min, the treated wood became resistant (with 21.97% weight loss) against *F. lividus* and highly resistant (with less than 10% weight loss) against *L. striata*. It was only at the highest treatment combination of 220º C–120 min that the treated wood became highly resistant against the white rot fungi (*F. lividus*) with 8.86% weight loss.

This study showed that to protect the treated wood against the brown rot fungi, the treatment combination needed is only 200º C–120 min but the protection against white rot is not yet at maximum. Apparently, to completely protect the treated malapapaya wood against the two decay fungi, the highest treatment combination of 220º C–120 min is needed. The reason behind is because white rot fungi can attack both lignin and cell wall polysaccharides (hemicelluloses and cellulose) while brown rot attacks only the hemicelluloses and cellulose and does little damage on the lignin (Kirk and Highley 1973; Highley 1973; Highley 1999). Similar findings of Banatin (1972) and Mailum and Arenas (1974) on the effect of heat on the natural decay resistance of some Philippine hardwoods showed that the white rot (*F. lividus*) caused more damage than brown rot (*L. striata*).

Table 4. Durability of thermally modified malapapaya wood (*Polyscias nodosa* [Blume] Seem) against decay fungi.

Treatment (°C-min)	Weight Loss (%) due to *Fomes lividus*	Weight Loss (%) due to *Lenzites striata*
Control	86.62 *(1.24)* a	72.24 *(1.07)* a
160-30	83.92 *(1.26)* a	68.77 *(1.61)* ab
160-60	83.55 *(0.85)* a	65.66 *(3.26)* b
160-120	82.55 *(0.79)* a	65.04 *(3.07)* b
180-30	82.98 *(0.78)* a	64.51 *(1.12)* bc
180-60	75.41 *(2.49)* b	62.31 *(1.53)* bc
180-120	72.19 *(1.79)* bc	57.70 *(4.91)* cd
200-30	69.68 *(1.88)* c	52.98 *(3.66)* d
200-60	43.88 *(2.53)* d	28.97 *(2.98)* e
200-120	21.97 *(1.89)* e	3.12 *(0.31)* f
220-30	24.09 *(2.10)* e	5.47 *(1.09)* f
220-60	16.57 *(2.62)* f	2.81 *(1.43)* f
220-120	8.86 *(1.34)* g	0.70 *(0.17)* f
ANOVA	F_{com} = 284.95	F_{com} = 144.54
	df = 12	df = 12
	P = 0.001	P< 0.001

Each mean is the average of five replicates; means followed by the same letter are not significantly different with each other using LSD at $\alpha = 0.05$
Italicized value in parenthesis is the standard error
Fcom = F computed; df = degrees of freedom

Pictorial comparisons of the control against the various treatment combinations were shown in Figures 2 to 5.

The improved decay resistance of the thermally modified malapapaya wood can be attributed to the modification of its chemical components. Reduced hemicelluloses contents of the thermally treated wood have a significant impact on the biological resistance since it is the primary carbon source of decay fungi (Nuopponen 2005). The reduction in the amount of free hydroxyl groups in the hemicellulose and cellulose and the increased cross linking of lignin lower the equilibrium moisture, which also enhances biological resistance of thermally treated wood (Bourgois et al. 1989; Nuopponen 2005; Wikberg 2004). In a study by Kamdem et al. 2000, they detected polyaromatic compounds (toxic degradation products of wood polysaccharides) in the extracts of heat-treated wood that they presumed to add biological resistance. Moreover, prolonged heat treatment time and increased temperature have been reported to enhance fungal resistance of wood (Viitaniemi et al. 1997; Mohamara et al. 2003; Banatin 1972; Mailum and Arenas 1974).

SUMMARY AND CONCLUSION

The thermal modification of malapapaya wood affected both its physical and mechanical properties. The degree of modification varied with temperature and duration of treatment. The color of the wood changed from light yellowish brown to very dark brown with increasing treatment temperature and duration. The modified wood had a smoky smell, which disappeared after two to three months. No defects due to treatments were observed. The hygroscopicity and dimensional stability improved as measured by reduced water absorption and thickness swelling. The resistance against *Fomes lividus* and

Figure 2. Comparison of the damaged sustained by the treated and control samples after exposure to *Fomes lividus* (left) and *Lenzites striata* (right) at 160º C for 30 to 120 min.

Figure 3. Comparison of the damaged sustained by the treated and control samples after exposure to *Fomes lividus* (left) and *Lenzites striata* (right) at 180º C for 30 to 120 min.

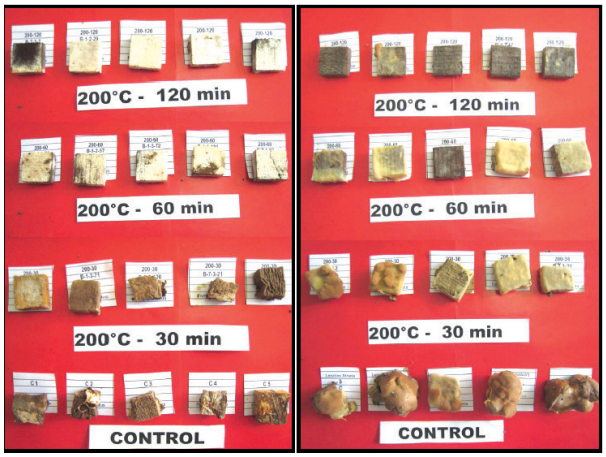

Figure 4. Comparison of the damaged sustained by the treated and control samples after exposure to *Fomes lividus* (left) and *Lenzites striata* (right) at 200º C for 30 to 120 min.

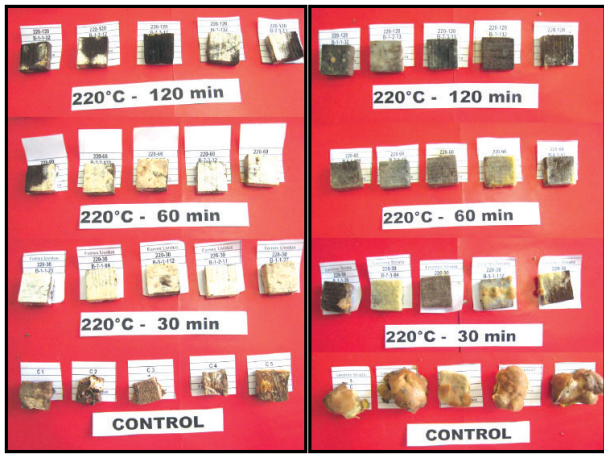

Figure 5. Comparison of the damaged sustained by the treated and control samples after exposure to *Fomes lividus* (left) and *Lenzites striata* (right) at 220º C for 30 to 120 min.

Lenzites striata was greatly improved that the treated wood at the highest temperature and duration (220º C-120 min) became highly resistant to both fungi with less than 10% weight loss. The major disadvantage of thermal modification, however, is the significant reduction in the mechanical properties especially the bending strength and toughness. The MOE was not significantly affected but the MOR was reduced by as much as 57% while toughness was reduced by as much as 75%. The upper limit for process temperature and duration after which the losses in strength increased significantly was found to be at either 180º C for 120 minutes or 200º C for 30 minutes. Beyond these treatment combinations, severe loss of strength but further increase in dimensional stability, and complete fungal resistance were observed.

RECOMMENDATIONS

From the study conducted, it can be suggested that desired wood properties can be delineated from the various treatment combinations employed. For instance, if only improvement of dimensional stability and wood color change are desired with no change in wood strength, the 180º C–120 minutes treatment combination would suffice since it would result in 50% improvement. However, if the desired properties are dimensional stability with some degree of protection against decay and with acceptable reduction in wood strength, the optimum treatment combination of 200º C–120 minutes is recommended. The highest treatment combination of 220º C–120 minutes would produce wood that has 85% improvement in dimensional stability and highly resistant to both decay fungi but this would severely reduce the strength property. The type of use for the thermally modified Malapapaya wood can be based on the desired properties. If use will be for indoor light furniture and molded products such as decorative cornice in which dimensional stability is the most sought property, the treatment combination of 180º C–120 minutes is adequate. If there would be outdoor exposure of the products but with no ground contact, the optimum treatment combination of 200º C–120 minutes is required.

As regards to the efficacy of thermally modifying wood using heat and steam, it is recommended to test other plantation species as their response to thermal treatment may vary. Moreover, resistance tests against other agents of wood deterioration such as other species of fungi, termites, powder post beetles, and graveyard test of the thermally modified wood may need to be carried out to determine full potential of the treatment on improving the durability. Also, working properties such as machining, gluing, finishing and weathering test need investigation.

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