MECHANICAL AND BIOLOGICAL PERFORMANCE OF SODIUM METAPERIODATE-IMPREGNATED PLASTICIZED WOOD (PW)

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Malaysia, especially the Borneo Island state of Sarawak, has a large variety of tropical wood species. In this study, selected raw tropical wood species namely *Artocarpus Elasticus, Artocarpus Rigidus*, *Xylopia* spp*., Koompassia Malaccensis*, and *Eugenia* spp*.* were chemically treated with sodium metaperiodate to convert them into plasticized wood (PW). Manufactured plasticized wood samples were characterized using, Fourier transform infrared spectroscopy, scanning electron microscopy, and mechanical testing (modulus of elasticity (*MOE*), modulus of rupture (*MOR*), static Young's modulus (E_s), decay resistance, and water absorption). *MOE* and *MOR* were calculated using a three-point bending test. E_s and decay resistance were calculated using the compression parallel to grain test and the natural laboratory decay test, respectively. The manufactured PW yielded higher *MOE*, *MOR*, and E_s. PW had a lower water content compared to the untreated wood and had high resistance to decay exposure, with *Eugenia* spp. having the highest resistance compared to the others.

Keywords: Mechanical properties; Decay resistance; Chemical treatment; Plasticized wood

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INTRODUCTION

Growing environmental awareness and new rules and regulations are forcing industries to seek more ecological friendly materials for their products (Oksman et al. 2003). Plasticized wood products, which are environmental friendly, have low moisture absorption and high resistance to decay, insects, and ultraviolet ray damage, have become one of the fastest-growing categories of materials in the wood industry (Kim et al. 2008). Plasticized wood has been extensively used for automotive and building products, packing materials, and other applications (Youngquist 1995). Over the years, wood has been treated with a variety of chemicals such as styrene, epoxy resins, urethane, phenol formaldehyde, methyl methacrylate (MMA), and vinyl or acrylic monomers to change its physical and mechanical properties. Modifiers such as solvents, plasticizers, and resins have also been added to the monomer, as well as dyes, antioxidants or salts, to modify the final properties. Such modified wood is not only more resistive against water absorption, but also has much improved mechanical properties, in particular strength. The advantages in using these chemicals include improvements in the physical, mechanical, thermal, and biological properties. By contrast, the disadvantages are relatively minor, such as changes relative to the natural color.

Like wood and other wood composites, PW is subjected to fungal and termite attacks due to wood components being enveloped in the polymeric matrix. Most of the fungi penetrate the material through a check associated with incisions in the wood. Previous studies have shown that 43.6% of wood crossties were removed from railway tracks due to decay (Russel 1986). Recently more efforts have been made to improve the decay resistance of WPC with zinc borate and other chemicals (Verhey et al. 2001). Many studies have been carried out on the decay resistance of wood and WPCs (Khavkine et al. 2000; Mankowshi et al. 2000). In the current work, selected tropical wood species, namely *Eugenia* spp., *Artocarpus rigidus*, *Artocarpus elasticus*, *Koompassia malaccensis*, and *Xylopia* spp., were selected, keeping in mind that they are easily obtainable as waste products and have a minimal effect on the environment due to their biodegradability. The major drawback of using these species is their hydrophilic nature, responsible for water absorption and consequent deformation of the product. In order to overcome this problem, all species were chemically treated with sodium metaperiodate. The objectives of this work were to compare the rate of decay of untreated wood and PW crossties against the brown and white-rot decay fungi and to obtain improved mechanical properties.

MATERIAL AND METHOD

Materials

Five wood species were collected for this study. Among them were the softwoods *Eugenia* spp., *Artocarpus rigidus*, *Artocarpus elasticus*, and *Xylopia* spp., and the hardwood *Koompassia malaccensis*. Chemicals used to treat these wood species were H_2SO_4 and $NaIO_4$ (Marck, Germany). The purity grade of the chemicals was 99%.

Specimen Preparation

Five wood species were felled and each tree was cut into three bolts of 1.2m length. Each bolt was quarter-sawn to produce planks of 4 cm thickness and subsequently conditioned to air-dry in a room with relative humidity of 60% and ambient temperature of around 25^{o}C for one month prior to testing. The planks were ripped and machined to 300 mm (L-longitudinal) x 20 mm (T-tangential) x 20 mm (R-radial), 100 mm (L) x 25 mm(T) x 25 mm (R), and 9 mm (L) x 25 mm (T) x 25 mm (R) specimens for the three-point bending test, compression parallel to grain test, and decay resistance test, respectively.

Manufacturing of Treated Wood Composites

Raw wood specimens were treated with the oxidizing agent 1M sodium metaperiodate solution in present of 0.1M sulfuric acid (as a catalyst) using an autoclave in order to convert them into plasticized wood. The temperature and pressure used were 120°C and 85 kPa, respectively, for 2 hours.

FT-IR Spectroscopic Analysis

The infrared spectra of the raw woods and WPC were recorded on a Shimadzu Fourier Transform Infrared Spectroscopy (FTIR) 81001 Spectrophotometer. The transmittance range of the scan was 370 to 4000 cm^{-1}.

Static Young's Modulus (E_s), Modulus of Elasticity (MOE), and Modulus of Rupture (MOR) Measurements

Determination of E_s, *MOE,* and *MOR* was carried out according to ASTM D-143 (1996). A Shimadzu Universal Testing Machine having a loading capacity of 300kN was used for the test with the cross head speed of 2mm/min. $E_{s,}$ was measured using the uniaxial compression test. The *MOE* and *MOR* were measured using the three-point bending method.

Laboratory Fungal Decay Resistance Test

The decay resistance test was carried out using the Standard Method of Accelerated Laboratory test of natural decay resistance of wood ASTM D2017(2001). Decay resistance was classified using the scale described in ASTM Standard D2017, where highly resistant heartwood experiences (0-10)% weight loss, resistant wood (11-24)% weight loss, moderately resistant wood (25-44)% weight loss, and non-resistant wood experiences weight loss greater than 45%.

The specimens were air dried, and after conditioning to constant weight, they were weighed accurately in the laboratory and transferred into a large totally dark container maintained at 20±1°C and a relative humidity of 65±4%. Two types of fungus, white-rot (*polyporous versicolor* L.ex. Fr.) ATCC No. 12679 and brown-rot (*postia placenta* (Fr). Cke. ATCC No. 11538 were used to study the efficiency of sodium metaperiodate against the decay. Reference blocks were made of sweetgum. There were eight replications for each specimen. The decay test was terminated after 14 weeks when the reference blocks obtained a weight loss of 60%. Mycelium was brushed off and test specimens were air dried and again conditioned to constant weight. The weight was recorded for each specimen. The difference in weights of specimens before and after the decay test gave the rate of decay in test specimen.

Water Uptake

In order to measure the water absorption characteristics of the raw wood and WPC, rectangular specimens were prepared having dimensions of 39 mm (L) x 10 mm (T) x 4 mm (R). The specimens were dried in an oven at 105°C, cooled in a dessicator containing silica gel, and immediately weighed. A Denver Instron balance was used for weight measurement. The dried and weighed specimens were immersed in distilled water according to ASTM D570-99 (2002). Both hot and cold water were used for immersion. A hot water immersion test was conducted only for 2 hours, while the duration of the cold water immersion was 24 hours. After immersion, the excess water on the surface of the specimens was removed using a soft cloth. The final weight of the specimens was then taken. The increase in the weight of the specimens was calculated using the following equation:

$$\text{Water Uptake (\%)} = \frac{\text{Final Weight} - \text{Original Weight}}{\text{Original Weight}} \text{X}\,100 \quad (1)$$

RESULTS AND DISCUSSION

Microstructural Analysis

Raw wood specimens were oxidized with sodium metaperiodate to convert them into PW. The reactions of sodium metaperiodate with cellulose in raw wood fibre at 120°C and 85 KPa pressure yielded the oxidized product. Sodium metaperiodate not only impregnated wood specimens but also reacted with hydroxyl groups of the cellulose and produced 2,3-dialdehyde cellulose. Dialdehyde cellulose filled up the void spaces within the wood structure and produced PW. The FTIR spectroscopic analysis of the raw and PW are shown in Figure 1. The IR spectrum of the PW fibre clearly shows the characteristics band of an aldehyde group in the region of 2906 cm^{-1} and 2850 cm^{-1} due to C-H stretching and in the region of 1734 cm^{-1} due to carbonyl stretching. The IR spectrum of the raw wood fibre shows an absorption band in the region of 1735 cm^{-1}. This absorption band is due to the carbonyl group of the acetyl ester in hemicellulose and carbonyl aldehyde in lignin (Ismail et al. 2002). However, there is also an increased absorption band near 1718 cm^{-1}. This increased absorption band may be due to the carbonyl aldehyde of dialdehyde cellulose, which is formed by the oxidation of wood fibre, as shown in Fig. 2.

The formation of dialdehyde can be explained as being due to the presence of three hydroxyl groups in the cellulose anhydroglucose unit. One is the primary hydroxyl group at C_6, and the other two are secondary hydroxyl groups at C_2 and C_3. The primary hydroxyl group is more reactive than the secondary ones, and the cleavage of the anhydroglucose ring between carbon 2 and carbon 3 results in the formation of dialdehyde.

MOE and *MOR* measurement

The variation of the *MOE* and *MOR* of *Artocarpus elasticus, Artocarpus rigidus*, *Xylopia* spp., *Koompassia malaccensis, and Eugenia* spp. untreated woods and PW are shown in Tables 1 and 2 and Figs. 3 and 4, respectively. The effects of sodium metaperiodate on the *MOE* and *MOR* of the untreated wood and PW were investigated. The increase in *MOE* for *Eugenia* spp. after chemical treatment was highest, followed by *Artocarpus rigidus*, *Artocarpus elesticus*, *Xylopia* spp., *and Koompassia malaccensis*, respectively. *Koompassia malaccensis* (hardwood) showed lowest increment, because of its hardness. PW yielded higher MOE compared to the untreated wood because of the chemical modification, which is in accordance with other researchers (Yildiz et al. 2005; Adams et al. 1970; Ates et al. 2009; Singha et al. 2009; Hamdan et al. 2010).

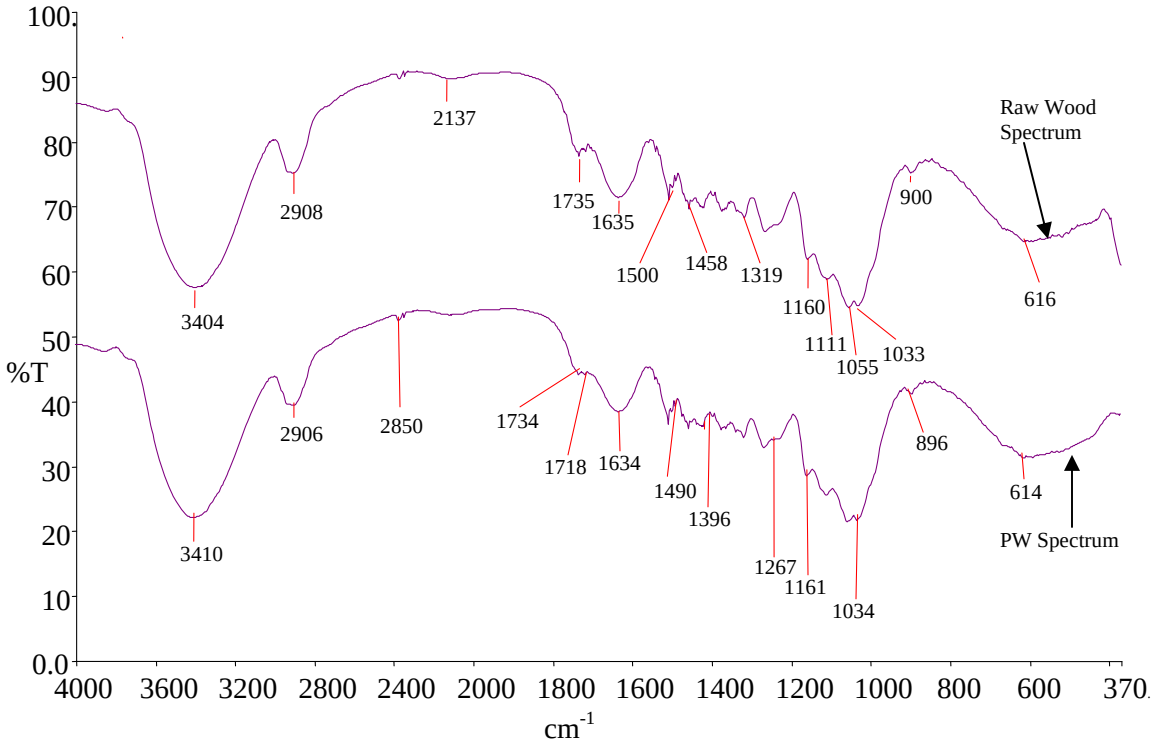

Figure 1. IR spectra of untreated wood and PW

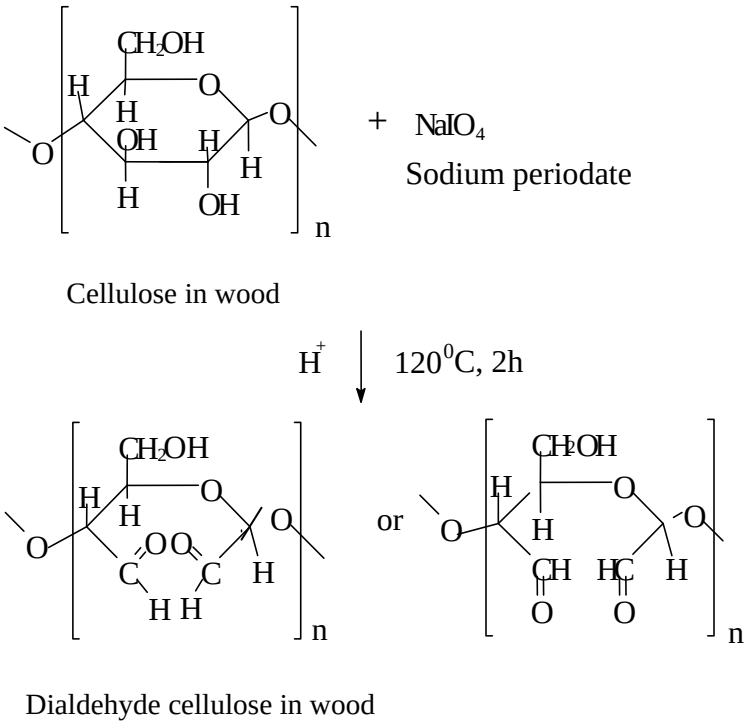

Figure 2. Oxidation of untreated wood fiber specimens with sodium metaperiodate

From Table 1 the *MOE* of the *Eugenia* spp. was significantly different from the untreated sample. In the wood specimens, sodium metaperiodate reacted with the cellulose in wood cells, which converted single bonds into double bonds. Double bonds are stronger than single bonds and change the structure of wood cells. However on *Koompassia malaccensis* (hardwood) there was no significant effect of chemical treatment, because of its hardness.

Table 1. Modulus of Elasticity of Untreated Wood and PW[1]

Treatment	Modulus of elasticity (GPa)	t-test grouping[2]
Untreated (*Artocarpus elesticus*)	6.48±0.52	A
PW (*Artocarpus elesticus*)	7.38±0.55	A
Untreated (*Artocarpus rigidus*)	5.13±0.38	B
PW (*Artocarpus rigidus*)	6.71±0.62	B
Untreated (*Xylopia* spp.)	6.71±1.08	C
PW (*Xylopia* spp.)	7.45± 0.98	C
Untreated (*Koompassia malaccensis*)	15.67± 3.53	D
PW (*Koompassia malaccensis*)	16.10± 2.46	D
Untreated (*Eugenia* spp.)	7.94± 0.72	E
PW (*Eugenia* spp.)	12.92± 1.37	F

[1]Each value is the average of 10 specimens.
[2] The same letters are not significantly different at α =5%

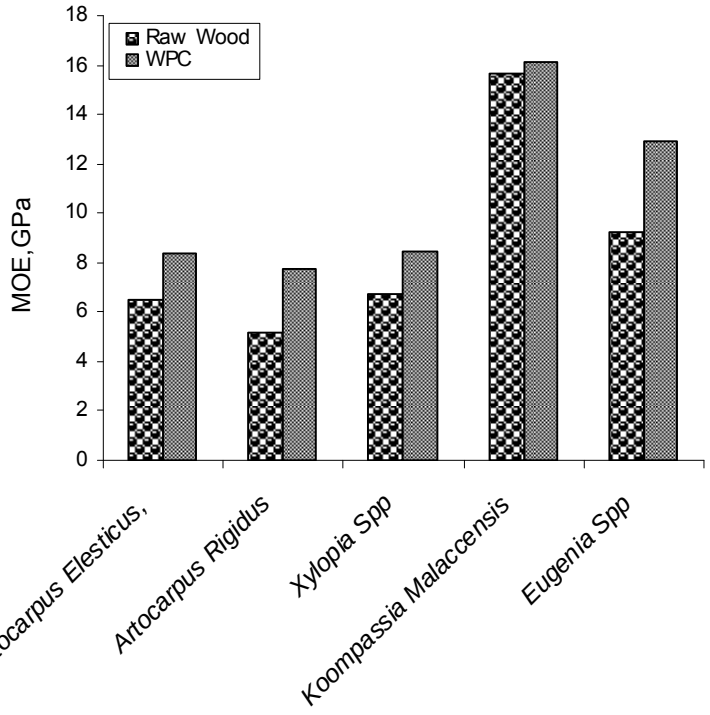

Figure 3. MOE of untreated wood and PW

The MOR also increased after chemical modification, in agreement with previous research (Adams et al. 1970). Table 2 indicates that the modulus of rupture was significantly different between untreated and PW. The increase of MOR after treatment for *Eugenia* spp. plasticized wood was highest, followed by *Artocarpus rigidus*, *Artocarpus elesticus, Xylopia* spp., *and Koompassia malaccensis*, respectively. The plasticized wood of *Koompassia malaccensis* (hardwood) was slightly higher than those of untreated samples, because there was no significant improvement following chemical treatment of the *Koompassia malaccensis.*

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Table 2. Modulus of Rupture of Untreated Wood and PW[1]

Treatment	Modulus of rupture (MPa)	t-test grouping[2]
Untreated (*Artocarpus elesticus*)	59.48± 11.67	A
PW (*Artocarpus elesticus*)	76.17± 9.52	B
Untreated (*Artocarpus rigidus*)	33.02± 11.49	C
PW (*Artocarpus rigidus*)	41.34± 11.78	D
Untreated (*Xylopia* spp.)	45.91± 4.31	E
PW (*Xylopia* spp.)	54.36± 7.02	F
Untreated (*Koompassia malaccensis*)	122.20± 49	G
PW (*Koompassia malaccensis*)	127.14± 55.31	G
Untreated (*Eugenia* spp.)	46.10± 11.47	H
PW (*Eugenia* spp.)	94.40± 18.65	I

[1] Each value is the average of 10 specimens.
[2] The same letters are not significantly different at α =5%.

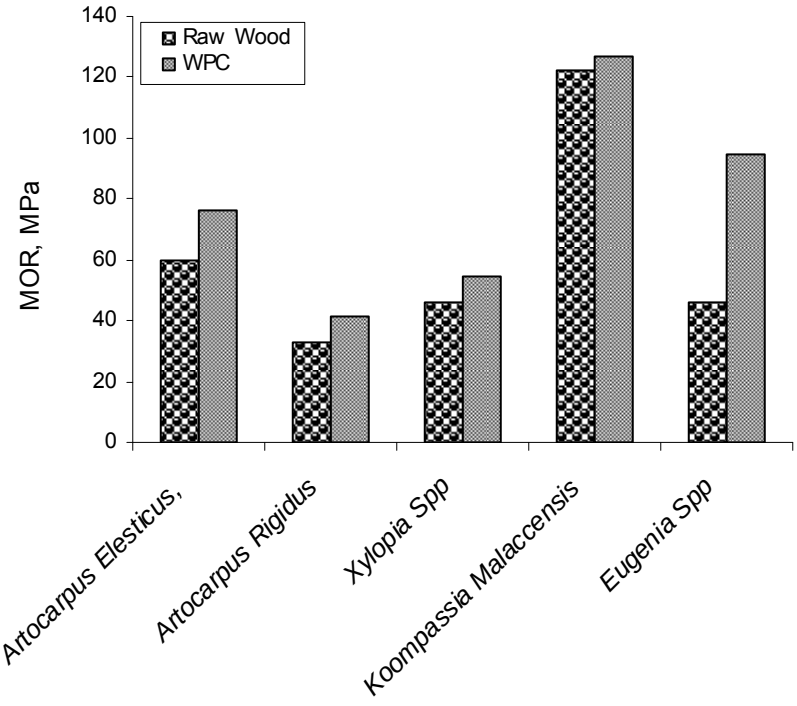

Figure 4. MOR of untreated wood and PW

Static Young's Modulus (*E*) measurement

The compressive strength parallel to the grain was determined from 10 repetitions, as summarized in Fig. 5. The highest value of *E* was observed in *Artocarpus elesticus,* followed by *Artocarpus rigidus, Eugenia* spp., *Xylopia* spp., *and Koompassia malaccensis*, respectively. The figure shows that there was significant difference between untreated wood and PW. After chemical modification, the increment of *E* value was highest in *Artocarpus elesticus,* followed by *Artocarpus rigidus, Eugenia* spp., *Xylopia* spp., *and Koompassia malaccensis*, respectively. The increase of *E* in PW compared to untreated wood was also reported by different researchers (Autio et al. 1970; Ates et al. 2009; Singha et al. 2009; Hamdan et al. 2010). The chemical modification of untreated wood puts a coating on the walls which thickens them, thus greatly increasing their lateral stability.

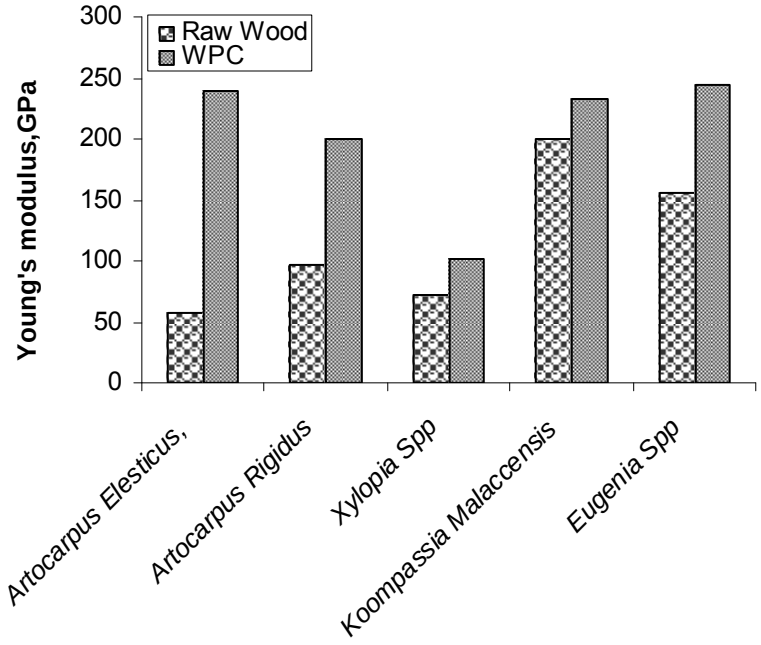

Figure 5. Static Young's modulus of untreated wood and PW

Fungal Decay Resistance Test

Weight loss due to fungal attack for untreated wood and PW are given in Figs. 6 and 7, respectively. The results showed that both the untreated wood and PW were affected by the exposure to the decay fungi *Polyporous versicolor* and *Postia placenta*, respectively. The plasticized wood of *Eugenia* spp. was less affected by *Polyporous versicolor* decay fungi, compared to *Artocarpus elesticus, Koompassia malaccensis, Xylopia* spp., and *Artocarpus rigidus*, *respectively.* The results also showed that generally all raw wood species were non-resistant to decay exposure. However, sodium

metaperiodate enhanced the decay resistance and decreased the weight losses due to both fungi for all wood species. According to the results, the plasticized wood of *Eugenia* spp. was highly resistant to white-rot fungi decay exposure, followed by *Artocarpus elesticus, Koompassia malaccensis, Xylopia* spp., and *Artocarpus rigidus.* On the other hand, the plasticized wood of *Eugenia* spp., *Xylopia* spp., *Artocarpus rigidus, Koompassia malaccensis*, and *Artocarpus elesticus* were moderately resistant to brown-rot fungi decay exposure. It can be concluded that chemical modification was highly effective relative to the decay resistance test, as found by previous researchers (Yalinkilic et al. 1998).

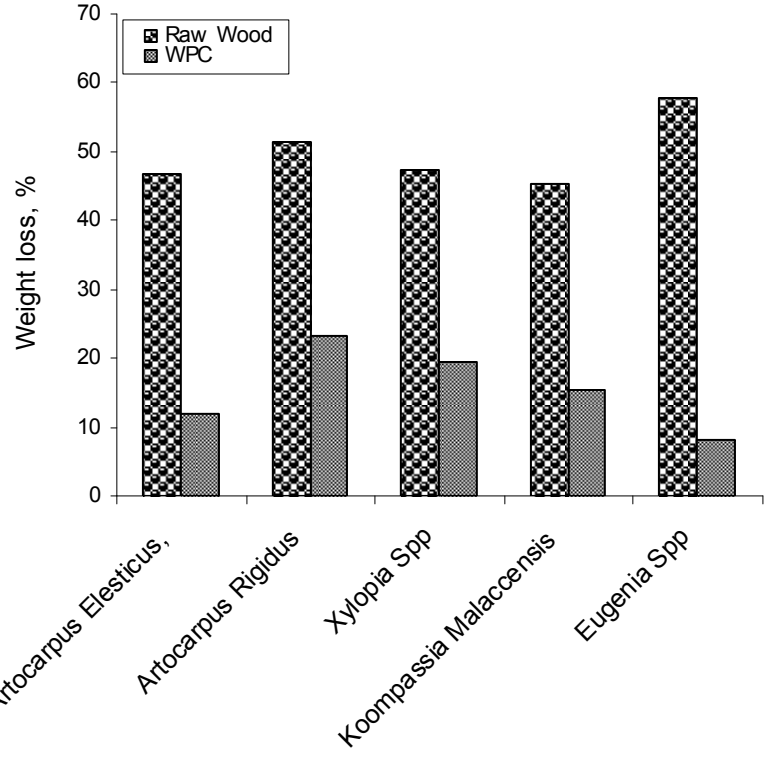

Figure 6. Weight losses of untreated wood and PW after exposure to the decay fungus *polyporous versicolor (White-rot fungus)* for 12 weeks

Water Uptake

Water absorption properties of untreated wood and PW are shown in Table 3 and Figs. 8 and 9 respectively. Figures 8 and 9 show the results for cold and hot water immersion, respectively. From the table, the water uptake of plasticized wood was significantly decreased compared with untreated samples. PW of *Eugenia* spp. had the least water absorption, followed by *Xylopia* spp., *Artocarpus elesticus, Artocarpus rigidus*, and *Koompassia malaccensis*, respectively. PW had lower water content compared to the untreated ones because of chemical treatment. In wood cell, cellulose contains hydroxyl groups. The number of hydroxyl groups in the raw wood increased the water absorption. However, sodium metaperiodate chemical modification reduced the hydroxyl groups in wood specimens and reduced the water absorption (Cai et al. 2008).

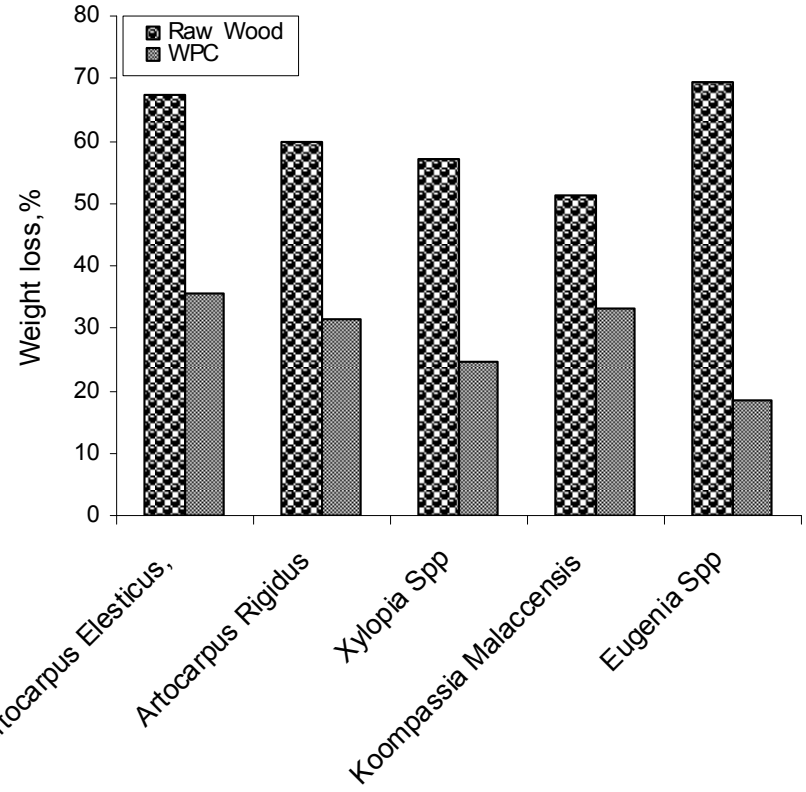

Figure 7. Weight losses of untreated wood and PW after exposure to the decay fungus *Postia placenta* (Brown-rot fungus) for 12 weeks

Table 3. Water Uptake of Untreated Wood and PW[1]

Treatment t-test-grouping[2]	Water Uptake (cold)	t-test grouping[2]	Water Uptake (hot)
Untreated (*Artocarpus Elesticus*)	2.25± 0.51	A	2.40± 0.70
PW (*Artocarpus Elesticus*)	0.27± 0.14	B	0.39± 0.05
Untreated (*Artocarpus Rigidus*)	1.27± 0.41	C	1.40± 0.45
PW (*Artocarpus Rigidus*)	0.25± 0.09	D	0.30± 0.12
Untreated (*Xylopia Spp*)	0.93± 0.31	E	1.27± 0.22
PW (*Xylopia Spp*)	0.05± 0.33	F	0.09± 0.32
Untreated (*Koompassia Malaccensis*)	0.93± 0.85	G	0.96± 0.30
PW (*Koompassia Malaccensis*)	0.16± 0.05	H	0.18± 0.01
Untreated (*Eugenia Spp*)	0.92± 0.23	I	0.98± 0.28
PW (*Eugenia Spp*)	0.11± 0.04	J	0.31± 0.19

[1] Each value is the average of 10 specimens.
[2] The same letters are not significantly different at α =5%

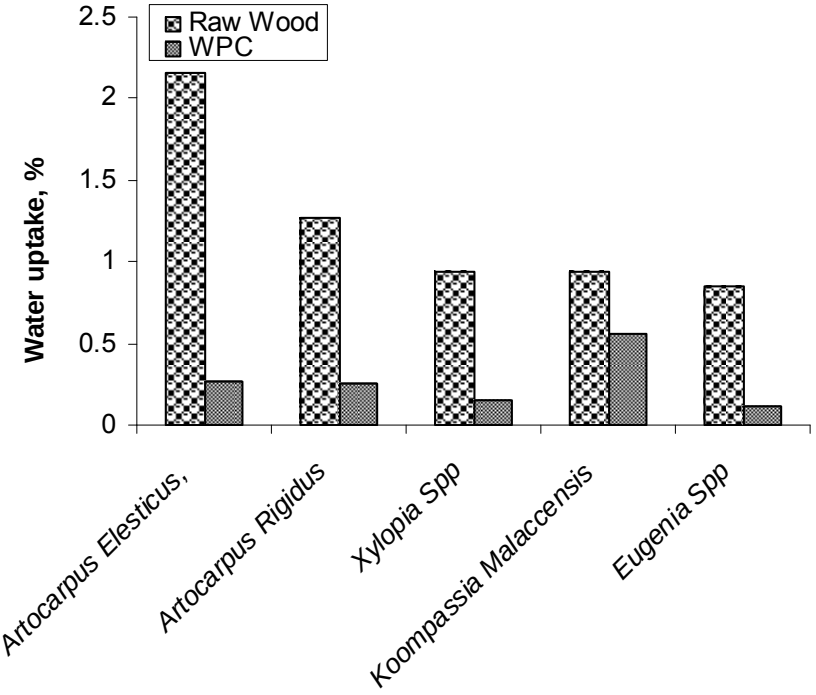

Figure 8. Variation of water uptake for untreated wood and PW immersed in cold water

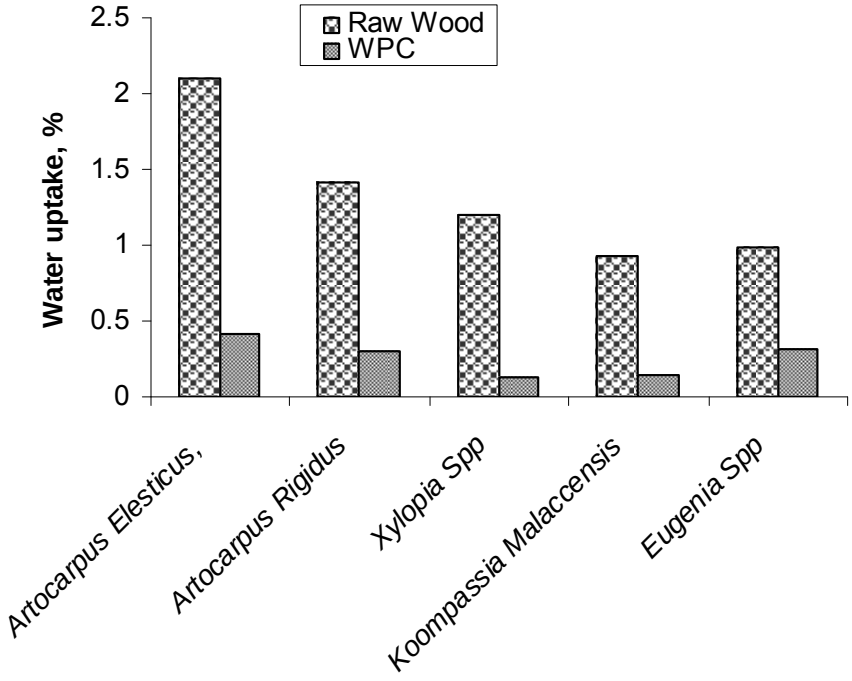

Figure 9. Variation of water uptake for untreated wood and PW immersed in hot water

Scanning Electron Microscopy (SEM)

Scanning electron micrographs (SEM) of untreated wood and plasticized wood are shown in Figs. 10(a) and 10(b), respectively. The SEM micrographs showed that the untreated wood fibers surface were covered with an uneven layer, which is probably waxy substances, and a number of void/hole spaces, as reported previously (Zafeiropoulos et al. 2002).

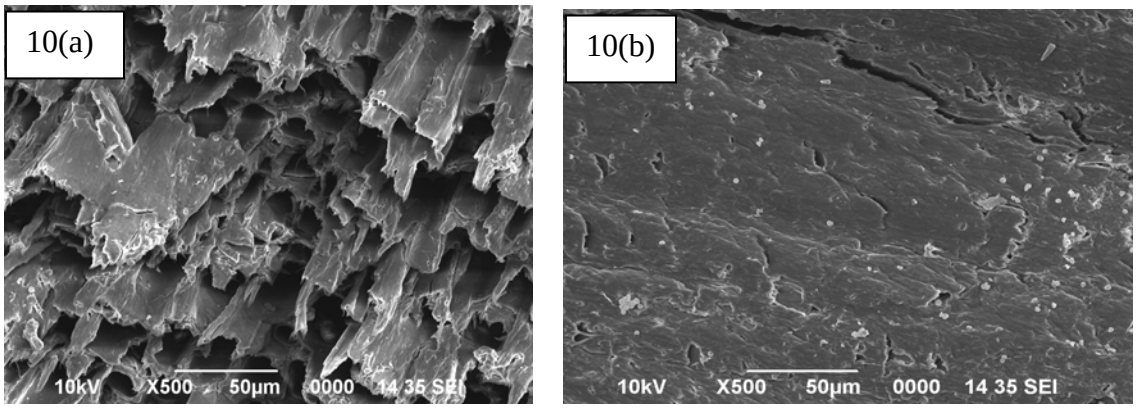

Figure 10. SEM micrographs of 10(a) for Untreated and 10(b) for plasticized wood

The waxy substances of lignocellulosic materials were removable (Zafeiropoulos et al. and Sreekala et al. 2001) and it was possible to fill the void surface by chemical modification. The smooth surface of plasticized wood after sodium metaperiodate modification resulted in good penetration with smoother texture and adhesion of monomer mixture to the cell wall and vessels of the wood.

CONCLUSIONS

In this study it was observed that all plasticized wood (PW) samples had increased mechanical properties and decay resistance. Untreated wood species were chemically treated with sodium metaperiodate, which converted the cellulose into diazo-cellulose. Fabricated PW samples were subsequently characterized using microstructural analysis (Fourier transform infrared spectroscopy, scanning electron microscopy), the three point bending test, the compression parallel to grain test, and the laboratory decay resistance test. The water absorption of PW was less compared to the raw samples. The MOE and MOR of PW were higher than those of untreated wood. The decay exposure of PW was higher than those of untreated wood. The authors propose that after chemical modification the *Eugenia* spp. plasticized wood had the optimum set of decay properties in comparison with other fabricated PW.

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REFERENCES CITED

Adams, D. G., Choong, E.T., and Mcllhenny, R. C. (1970). "Bending strength of radiation-produced southern pine wood-plastic combinations," *Forest Prod. J*. 20(4), 25-28.

ASTM D-143. (2006). "Standard method of testing small clear specimens of timber," American Society for Testing and Materials, USA.

ASTM D 2017. (2001). "Standard method of accelerated laboratory test of natural decay resistance of wood," American Society for Testing and Materials, 4.10, 322-326.

ASTM Standard D 570-99. (2002). "Standard test methods for water absorption of plastics, Annual Book of ASTM Standard, Vol. 08.01.

Ates, S., Akyildiz, M. H., and Ozdemir, H. (2009). "Effects of heat treatment on calabrian pine (*Pinus brutia* ten.) wood," *BioRes*. 4(3), 1032-1043.

Autio, T., and Miettinen, J. K. (1970). "Experiments in Finland on properties of wood-polymer combinations," *Forest Prod. J*. 20(3), 36-42.

Cai, X., Riedl, B., Zhang, S.Y., and Wan, H. (2008). "The impact of the nature of nanofillers on the performance of wood polymer nanocomposites," *Composites Part A*. 39, 727-737.

Hamdan, S., Talib, Z. A., Rahman, M. R., Ahmed, A. S., and Islam, M. S. (2010). "Dynamic Young's modulus measurement of treated and post-treated tropical wood polymer composites (WPC)," *BioRes.* 5(1), 324-342.

Ismail, H., Edyhan, M., and Wirjosentono, B. (2002). "Bamboo fiber filled natural rubber composites: The effects of filler loading and bonding agent," *Poly. Test*. 21(2), 139-144.

Khavkine, M., Kazayawoko, M., Law, S., and Balatinecz, J. J. (2000). "Durability of wood flour-thermoplastic composites under extreme environmental conditions and fungal exposure," *International Journal of. Polymeric Materials* 21(4), 171-177.

Kim, S. S., Yu, H. N., Hwang, I. U,, and Lee D. G. (2008). "Characteristics of wood–polymer composite for journal bearing materials," *Comp. Structures* 86, 279-284.

Mankowshi, M., and Morrell, J. J. (2000). "Patterns of fungal attack in wood plastic composites following exposure in a soil block test," *Wood. Fiber Sci*. 32(3), 340-345.

Oksman, K., Skrifvars, M., and Selin, J. F. (2003). "Natural fibres as reinforcement in polylactic acid (PLA) composites," *Com. Sci. and Tech*. 63, 1317-1324.

Russel, A. (1986). "The decay-underrated factor," *Railway Track Structure* 82(8), 34-37.

Singha, A. S., and Thakur, V. K. (2009). "Study of mechanical properties of urea-formaldehyde thermosets reinforced by pine needle powder," *BioRes*. 4(1), 292-308.

Sreekala, M., Kumaran, M., and Thomas, S. (2001). "Stress relaxation behaviour in oil palm fibres," *Mat. Lett*. 50(4), 263-273.

Yalinkilic, M. K., Tsunoda, K., Takahashi, M., Gezer, E. D., Dwianto, W., and Nemoto, H. (1998). "Enhancement of biological and physical properties of wood by boric acid-vinyl monomer combination treatment," *Holzforshung* 52(6), 667-672.

Yildiz, C. U., Yildiz, S., and Gezer, D. E. (2005). "Mechanical properties and decay resistance of wood polymer composites prepared from fast growing species in Turkey," *Bioresource Tech.* 96, 1003-1011.

Youngquist, J. A. (1995). "Unlikely partners? The marriage of wood and non-wood materals," *Forest Product Journal* 45, 25-30.

Verhey, S., Laks, P., and Richiter, D. (2001). "Laboratory decay resistance of wood-fiber/thermoplastic composites," *Forest Product Journal* 51, 44-49.

Zafeiropoulos, N., Williams, D., Baillie, C., and Matthews, F. (2002). "Engineering and characterisation of the interface in flax fibre/polypropylene composite materials. Part I: Development and investigation of surface treatments," *Composites Part A* 33, 1083-1093.

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