Evaluation of Wood Plastic Composites Produced from Mahogany and Teak

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Abstract— Wood plastic composites (WPC) were made from Nigerian mahogany (Khaya ivorensis) and teak (Tectona grandis) wood particles and high density polyethylene and evaluated. The WPC were tested for flexural properties, water sorption, melt flow and thermal properties. The results obtained indicated that composites possessed adequate flexural strength (25.6 - 43.0 MPa) and were dimensionally stable (water absorption 1.3 – 28.0%; thickness swell 0.4 -5.0%). Melt flow and viscosities at 190ºC were between 1.31 and 1.6 g/10 min and 46.5 and 57.1 kPa/s, respectively. Particle size (<2 mm versus <0.5 mm) significantly affected the properties of the WPC. Mahogany based composites had higher strength but lower sorption properties in comparison with those of Teak. The densities of the composites seemed to influence properties of the plastic composites.

Keywords— Flexural properties, Khaya ivorensis, Tectona grandis, Water absorption, Wood plastic composites

I. INTRODUCTION

The wood industry in Nigeria generates a significant amount of mill wastes due to old mill equipment, lack of expertise, low capital input and improper processing methods [1]. Low log to lumber recovery factor in most sawmills is estimated to be between 45 and 50% and the remainder is residues [2]. These wastes constitute environmental nuisance and are sources of hazards to the wood, wood products and the wood mill operators. Improper waste disposal oftentimes results in emission of toxic and non-toxic particulates, pollution of inland waters and may also contribute to health hazards [3]. The deleterious effects of wood wastes can be curtailed by incorporating these items in the production of value added composite products. This can be achieved by mixing wood wastes with plastic matrix to form wood plastic composites (WPC) that can be utilized as components in construction for interior and exterior applications. WPCs are perceived to exhibit improved durability with regards to checking, decay, termites, and marine organisms. The presence of wood filler in plastic composites would improve thermal stability compared to other polymer composites [4,5].

However, wood particle geometry has been found to affect the properties of WPCs. Incorporation of wood with small particle size (100 - 200 mesh) was found to increase the melt flow rate (MFR) and flexural strength but resulted in reduction in toughness, stiffness and crystallinity. This is because of the improved interfacial interaction between the plastic matrix and the wood particles and the low stress concentration due to large surface area [6,7]. It is worth noting that Nigerian grown hardwoods such as *Ceiba pentandra*, *Triplochiton scleroxylon*, *Entandrophragma cylindricum*, *Cordia alliodora*, *Funtumia elastica*, *Brachystegia kennedy*, and *Milicia excelsa* have been used to produce WPCs without coupling agents using a single screw extruder and/or compression molded [8-10]. The results obtained revealed that the flexural moduli of rupture (MOR) and modulus of elasticity (MOE) ranged between 1.72 and 24.42 MPa and 0.34 and 15.7 GPa, respectively. Their respective sorption properties (i.e. water absorption (WA) and thickness swelling (TS)) were between 6.4 to 33.2% and 0.6 to 2.7% confirming their suitability for low stress indoor applications.

The properties of WPCs can be enhanced by the addition of coupling agents, such as maleated polyethylene (MAPE) and maleated polypropylene (MAPP) depending on the plastic matrix used. The improved properties are achieved by enhancing the interfacial adhesion between fibers and the matrix [7,11-13]. This study is therefore aimed at evaluating the use of two Nigerian grown wood species i.e. *Khaya ivorensis* (mahogany) and *Tectona grandis* (teak) in WPC production using high density polyethylene (HDPE) and MAPE by extrusion. The wood particles were partially characterized and the composites strength, thermal and physical properties determined.

II. MATERIALS AND METHODS

2.1 Production of wood plastic composites

Particles of mahogany and teak wood were collected from a local sawmill in Ibadan, Oyo state and ground and screened using a Wiley mill to < 2 and < 0.5 mm particle sizes. The milled particles were oven dried at 70ºC to 0.5% moisture content prior to WPC production. HDPE (48% w/w) (Equistar Petrothene, LB 0100-00, MFI = 0.3

g/10 min, and density = 0.950 g/cm^3), wood fiber (50% w/w) and MAPE (Polybond 3029, Crompton) coupling agent (2% w/w) were blended in 500 g batches and then compounded on an 18 mm co-rotating twin-screw extruder (Leistritz, LD ratio of 40, 200 rpm) and extruded into a ribbon (1.5 x 50 mm^2) [14]. The barrel and die temperature was between 140 and 160ºC.

2.2   Properties Characterization of Rattan reinforced Plastic Composites

2.2.1   Wood Particle Characterization

Optical microscopy was performed on < 0.5 mm screened particles on an Olympus BX51 microscope at 100x magnification equipped with a DP70 digital camera. Wood particle measurements (length and width) were performed on 150 particles for each sample. The < 2 mm screened particles were too large to measure in the microscope field of view and not recorded. Air dried samples of the wood particles (4-5 g) were Soxhlet extracted with dichloromethane (CH$_2$Cl$_2$, 150 mL) for a period of 20 h according to ASTM D1108-96 [15]. The CH$_2$Cl$_2$ extract was then evaporated to a constant weight and yield (extractive content) determined gravimetrically. The lignin content was determined on extractive free samples using the Klason lignin method according to ASTM D1106-96 [16]. More specifically, the dried extractive free sample (200 mg) was incubated in 72% H$_2$SO$_4$ (2 mL) for 1 h at 30ºC, then diluted into 4% H$_2$SO$_4$, and subjected to secondary hydrolysis in an autoclave (117 kPa and 121ºC) for 30 min. The hydrolyzate was filtered to obtain Klason lignin content gravimetrically. Wood ash content was determined gravimetrically by furnacing the samples at 600ºC for 16 h. All analyses were done in triplicate.

2.2.3   Sorption, Mechanical and Melt Flow Properties of composites

Water absorption (WA) and thickness swell (TS) tests were conducted following a modified ASTM D570-95 procedure [17]. Five replicate specimens (1.5 × 20 × 50 mm^3) for each WPC sample were immersed in water at 23ºC for 61 days and dimensions periodically measured. Weight gain and thickness swell were measured on a total composite basis for determination of WA and TS respectively. The diffusion coefficients of the wood composites were calculated using equation 1 adopted by Fabiyi et al. [18]:

$$D_{coefficient} = \pi \ (h/4M_\infty)^2 \ (\delta M/\delta\sqrt{t})^2 \quad (1)$$

Where, M_∞ is the maximum moisture content (MC) (%) measured at the end of the test, h is the sample thickness (m) corresponding to M_∞, t is the time (s) and $\delta M/\delta\sqrt{t}$ is the initial slope from the graph of MC versus $\delta\sqrt{t}$ relation. Three point flexural tests (MOR and MOE) were performed on extruded specimens (3.56 x 20.1 x 110 mm^3, 5 replicates) according to ASTM Standard D 790-

07 [19] at a crosshead speed of 1.31 mm/min and a span of 57 mm until specimen failure or 10% strain, whichever occurred first on an Instron 5500R-1132 universal test machine. Data was collected and processed using Bluehill v2 software (Instron). MFR and melt viscosity of molten WPC was measured (3 replicates) using a CEAST Model 7024.000 melt flow indexer according to ASTM D 1238-04C [20] through a 2.0955 mm Ø x 8 mm die, at 190ºC, and load of 15 kg [7].

2.2.4   Thermal characterization

2.2.4.1   Thermal Stability

Thermogravimetric analysis (TGA) was conducted using a Perkin Elmer TGA 7 instrument. Specimens (4-5 mg) were analyzed at a heating rate of 20ºC/min from 50 to 600ºC in a nitrogen atmosphere (30 mL/min) and analyzed using Pyris v8 software (Perkin Elmer).

2.2.4.2   Thermal Analysis

Differential scanning calorimetry (DSC) was performed on samples (4-6 mg, in duplicate) using a TA Instruments model Q200 DSC with refrigerated cooling. The samples were (i) equilibrated at 70ºC (3 min) then ramped to 180ºC at 10ºC/min, held isothermally for 3 min, (ii) cooled to 70ºC at 10ºC/min and held isothermally for 3 min and the cycles repeated. Data were analyzed using TA Universal Analysis v4.4A software. The degree of crystallization of HDPE was calculated from the ratio of the melting enthalpy (ΔH^o_f, 105-145 ºC) of the sample to ΔH^o_f of 100% crystalline HDPE 293 J/g.

III.   RESULTS AND DISCUSSIONS

3.1   Properties of Wood Particles

The particle lengths of teak and mahogany (<0.5 mm screened) were 194 ±143 μm and 217 ±136 μm respectively while the widths were 42 ±29 μm and 56 ±37 μm, respectively (Figure 1a and 1b).
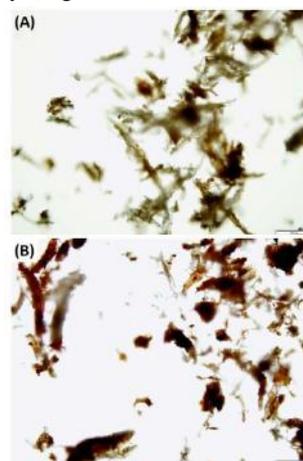

Fig. 1: Optical micrographs of (a) teak and (b) mahogany particles (100x, scale bar 200 μm).

Mahogany and teak wood samples had CH$_2$Cl$_2$ extractives contents of 1.6 and 3.1%, respectively. Extractives can act

as plasticizing agents and reduce WPC MFI [21]. The mahogany and teak lignin contents were 23.0 and 27.8% while the ash contents were 0.9 and 3.4% respectively. These values are similar to 3.8% extractives, 25.3% lignin and 0.5% ash reported for teak by Balogun et al. [22].

3.2   Flexural Properties

The results of the flexural tests are shown in Table 1. As shown, the MOR and MOE of the WPC were between 25.6 to 43.0 MPa and 1.5 to 2.0 GPa, respectively. These values were higher than those of Aina et al. [8,9] and Izekor and Mordi [10] but compared favorably with those reported by San et al. [23], Migneault et al. [24] and Fabiyi and McDonald [5]. This suggests is that there was good interfacial bonding between the wood particles and the plastic matrix by the addition of MAPE coupling agent and high shear mixing using a twin screw compounding extruder. As shown in Table 1, composites made from mahogany particles generally had higher MORs than those made from teak. Furthermore, WPC made from <0.5 mm particles recorded significantly higher MORs and MOEs than those made from <2 mm particles. The higher density and lower extractives content of mahogany WPC in comparison with those of teak are possibly responsible for its higher flexural properties (Table 1). WPCs made from <0.5 mm particles are likely to have an improved interfacial interaction between the plastic matrix and smaller wood particles and the low stress concentration due to a larger surface area thus obtain a higher strength [6,7]. The energy at maximum load (EML), a measure of toughness, of the WPC ranged between 0.3 to 1.38 J (Table 1). Mahogany based WPC generally recorded higher EML than teak. Furthermore, the WPC made from the smaller particles (<0.5 mm) had a higher EML than those made from the larger particles.

Table 1: Flexural properties and density of mahogany and teak WPC

WPC sample	Density (kg/m^3)	MOR (MPa)	MOE (GPa)	EML (J)
Mahogany (<0.5 mm)	1070.0[a] (0.05)	43.0[a] (2.54)	1.93[a] (0.20)	1.38[a] (2.02)
Mahogany (<2 mm)	895.9[b] (39.7)	32.8[b] (3.57)	1.58[b] (0.17)	0.48[a] (0.09)
Teak (<0.5 mm)	1000.0[a] (0.08)	40.1[a] (2.11)	2.0[a] (0.32)	0.52[a] (0.03)
Teak (<2 mm)	864.1[c] (25.7)	25.6[c] (1.33)	1.5[b] (0.09)	0.30[a] (0.08)

Means with the same letter and columns are not significantly different. Standard deviation is given in parentheses.

3.3   Melt Flow Properties

The melt flow rates and melt viscosities of WPC (Table 2) were between 1.31 to 1.60 g/10 min and 46.5 to 57.1 kPa/s, respectively. These values compared favorably for WPC with those reported by Wei et al. [14] (1.53 – 2.19 g/10 min; 25.1 – 35.2 kPa/s) and Gallagher and McDonald [7] (0.35 - 2.90 g/10 min; 12.7 – 107.0 kPa/s). Mahogany based WPC generally recorded higher melt flow rates than those of teak composites possibly due to higher density. However, the particle size did not significantly influence melt viscosities of the WPCs and MFR of mahogany composites.

Table 2: Melt flow rates (MFR) and melt viscosities of WPC

WPC sample	MFR (g/10 min)	Viscosity (kPa/s)
Mahogany (<0.5 mm)	1.55[a] (0.09)	47.8[b] (2.8)
Mahogany (<2 mm)	1.60[a] (0.06)	46.5[b] (2.1)
Teak (<0.5 mm)	1.31[b] (0.13)	57.1[a] (6.0)
Teak (<2 mm)	1.52[a] (0.06)	50.9[ab] (0.9)

Means with the same letters and columns are not significantly different. Standard deviation is given in parentheses.

3.4   Water Absorption and Thickness Swelling

The water soak (TS and WA) properties of the composites were measured with time (Table 3, Figure 2). Figure 2 shows data for WA in the wood composites reaching a pseudo-equilibrium state in accordance with Fickian behavior [25]. The respective WA and TS of the plastic composites were between 1.3 to 28.0% and 0.36 to 4.9%. These values are similar to 0.14 to 15.9% and 0.16 to 7.6% obtained by Wei et al. [14] and 1.9 to 22.4 % and 1.7 to 14.1% recorded by Fabiyi et al. [18] for WA and TS, respectively. Teak composites made with smaller particle size had the least sorption properties. This may be possibly due to the higher contents of hydrophobic compounds i.e. extractive (3.1% vs 1.6%) and lignin (27.8% versus 23.0%). Generally, the WPC densities appear to be a major influence in water soak properties. WPC with high density and made from smaller particle size recorded the least water sorption properties attributed to improved interfacial bonding and less moisture ingress.
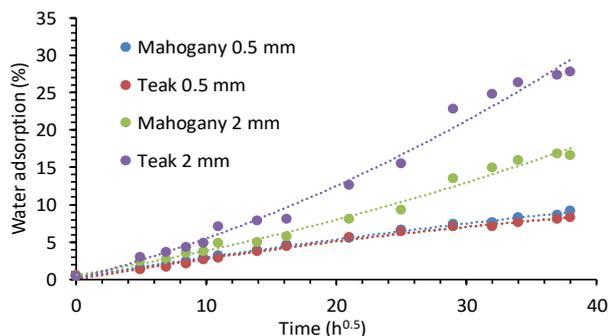
Fig. 2: Water sorption of mahogany and teak WPC with time$^{1/2}$

Table 3: Water soak properties of mahogany and teak WPC

WPC	WA (%)		Diffusion coefficient	TS (%)	
	1 d	61 d	$(10^{-10}$ m^2/s$)$	1 d	61 d
Mahogany (<0.5 mm)	1.51 (0.38)	9.12 (3.00)	6.80	0.84 (0.50)	3.14 (1.47)
Mahogany (<2 mm)	1.86 (0.57)	16.87 (3.91)	0.38	2.32 (3.09)	4.89 (3.42)
Teak (<0.5 mm)	1.28 (0.42)	8.32 (3.21)	7.45	0.36 (0.20)	2.81 (1.00)
Teak (<2 mm)	2.65 (0.34)	27.98 (1.74)	0.31	0.69 (0.29)	3.16 (0.43)

Standard deviation is given in parentheses.

3.5   Thermal Analysis

The thermal stability of the WPC was evaluated by TGA (Table 4 and Figure 3). All thermograms show a small weight loss before 100ºC, associated with water loss. The degradation stage <400ºC of composites can be mainly attributed to the decomposition of chemical components such as hemicelluloses (150-350ºC), lignin (250-490ºC), extractives and cellulose (275-350ºC) [11,14]. From the differential thermogravimetric (DTG) thermograms, the decomposition of HDPE occurred at > 470ºC. Teak based WPC generally degraded at higher temperatures (279 and 294ºC) in comparison with those of mahogany (274 and 290ºC) indicating higher thermal stability. The enhanced thermal stability of teak composites over those of mahogany may be possibly due to higher ash content (3.4% versus 0.9%) [26].

Table 4: Thermal degradation behavior of mahogany and teak WPC by TGA

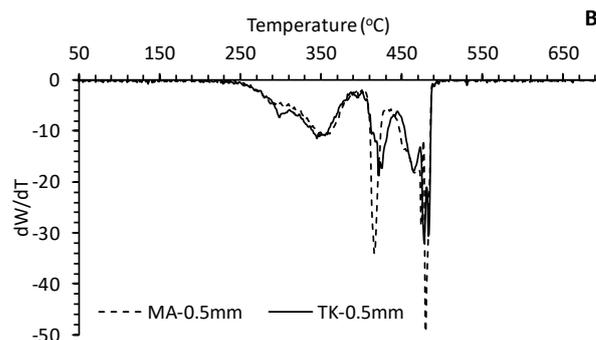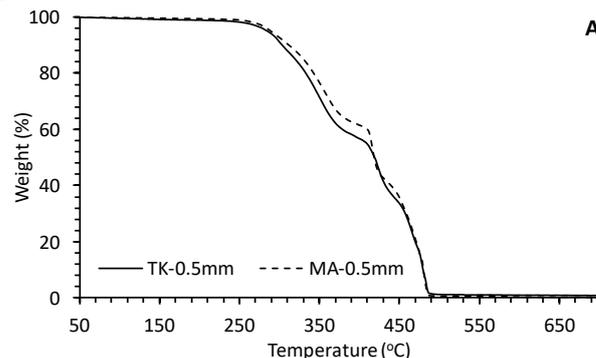| WPC	Onset (ºC)	1st Peak (ºC)	2nd Peak (ºC)	3rd Peak (ºC)	Final Decomposition Temp (ºC)
Mahogany (0.5 mm)	274.9	366.5	437.5	472.6	489.9
Mahogany (2 mm)	290.2	354.4	416.7	481.6	484.3
Teak (0.5 mm)	279.8	367.1	418.6	484.1	496.9
Teak (2 mm)	294.1	346.9	423.2	480.4	484.8

Fig. 3: TGA (a) and DTG (b) thermograms of mahogany and teak WPC

The degree of HDPE crystallinity and transition temperature in the WPC was determined by DSC and data given in Table 5. These values were comparable to those of Wei et al. [14] and Gallagher and McDonald [7]. The crystallization temperatures (T_c) of HDPE in the WPC were similar at 118.3-188.9ºC. The melt temperature (T_m) for the WPC were comparable at around 131-132ºC. However, the reduction in HDPE crystallinity of the mahogany WPC could be responsible lower MOE in line with the reports of Wei et al. [14]. The WPC made with smaller particles had a higher degree of HDPE crystallinity than those made from the larger particles and this could partially explain their higher flexural properties. This could be attributed to the smaller particles creating more nucleation sites due to a higher surface area than the larger particles.

Table 5: Crystallization and melt temperatures and crystallinity of mahogany and teak WPC by DSC

WPC sample	T_c (ºC)	T_m (ºC)	Crystallinity (%)
Mahogany (0.5 mm)	118.6 (0.0)	131.6 (0.0)	69.7 (2.0)
Mahogany (2 mm)	118.9 (0.4)	131.8 (0.4)	68.3 (6.0)
Teak (0.5 mm)	118.6 (0.1)	131.7 (0.1)	73.6 (0.5)
Teak (2 mm)	118.3 (0.0)	132.0 (0.2)	70.7 (1.1)

Standard deviation is given in parentheses.

IV. CONCLUSIONS

Wood plastic composites were successfully produced from different sized particles of Nigerian mahogany and teak woods by extrusion. The fabricated WPC possessed adequate strength properties with low sorption rates and were thermally stable. Differences in the densities of the composites seemed to affect the properties of the plastic composites produced. Composites produced with smaller particle size (<0.5 mm) had superior strength and sorption properties due to enhanced interfacial bonding with the plastic matrix. The fabricated plastic composites are suitable as indoor and outdoor building components in Nigeria and the region.

ACKNOWLEDGEMENTS

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