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Dimensional stability and tensile strength of biopolymer composite reinforced with hardwood fiber at varying proportions

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Abstract. *Bola TS, Oluyege AO, Aina KS. 2020. Dimensional stability and tensile strength of biopolymer composite reinforced with hardwood fiber at varying proportions. Asian J For 4: 1-5.* Wood-plastic composites (WPCs) are emerging materials that have high potentials to be used in many building applications. This study was designed to produce bio-composites made from three different wood species and at three different mixing ratios of plastic to wood on weight to weight basis. The main variables employed in this study were wood species of *Triplochiton scleroxylon*, *Terminalia superba* and *Gmelina arborea*; at three plastic: wood ratios of 40:60, 50:50, and 60:40. The composite samples were made through compounding and extrusion processes. The properties evaluated were carried out in accordance with the American Standard Testing Methods of 570 and 790 to determine the dimensional stability and strength properties of the composites. The values obtained for the wood species ranged from 0.59 g/cm^3 to 0.72 g/cm^3, 0.59% to 0.71%, 0.63% to 0.7%and 1.84 MPa to 2.07 MPa for density, water absorption, thickness swelling and tensile strength, respectively. Meanwhile, the values obtained from the mixing ratio ranged from 0.54 g/cm^3 to 0.79 g/cm^3, 0.53% to 0.79%, 0.42% to 1.00%, and 1.58 MPa to 2.37 MPa for density, water absorption, thickness swelling and tensile strength, respectively. It was observed that mixing ratio and wood species used in this study influenced the dimensional stability and strength properties of the WPCs. This study revealed that as the wood-flour content increased to plastic, the dimensional properties and tensile strength values increases.

Keywords: Absorption composite, ratio, tensile, wood

INTRODUCTION

Wood-plastic composites (WPCs) are any composites that contain wood and non-wood fibers with thermosets or thermoplastics. WPCs are relatively new generation of composite materials made from the combination of two materials, i.e., wood and plastic which are naturally difficult to combine. WPCs are made by combining wood and polymer together to form panel sheets or molded into shapes, with the display of properties of both components (Yang et al. 2007). WPCs are produced as direct replacements or substitute for solid wood due to the need to replace treated solid timbers that are being scarce and limited in supply. In the last decade, WPCs have emerged as an important member of engineering materials that are useful in many building applications, such as decking, docks, landscaping timbers, fencing, etc (Pilarski and Matuana 2005). WPCs have been received some recognition in building sector due to their favorable properties, which include low density, high dimensional stability, improved strength, high resistance to biodeterioration agents, low cost of raw materials, and recyclable (Zhang et al. 2012).

Previous research works on WPCs showed that factors such as the quantity, geometric sizes, and surface characteristics of the wood component and the interfacial properties between the wood and plastic do influence the properties of the products. Many indigenous and exotic wood species have been investigated with results showing that effect of proportional ratio, components of wood species and type of polymer used significantly influenced the properties of WPCs (Ajigbon and Fuwape 2005; Fuwape and Aina 2008; Fuwape et al. 2010). Similarly, other non-wood flour has also been investigated as well as the possibility and potentials of using agro-residues (Ajayi and Aina 2008). These authors found that agro-residues and non-wood flours, like bamboo and corn cob, also performed well in production of WPCs samples. Other agro-residues, such as yam stem, bagasse (sugar cane) coffee waste, and banana stem, also performed well.

Nigeria has over 6000 wood species with the potentials to be developed for WPCs manufacture. Nonetheless, research is required to investigate various indigenous species for possible raw materials of WPCs. Therefore, this study aimed to investigate the suitability of some wood species for the production of WPCs, and to assess the effect of wood to plastic ratio on the strength and dimensional properties of wood-plastic composites.

MATERIALS AND METHODS

Preparation of materials

Three indigenous wood species, namely *Gmelina arborea*, *Triplochiton scleroxylon* (Obeche), and *Terminalia superba* (Afara) were used in this study. The wood particles of each wood species were collected after sawing with CD-6 band saw machine in the Department of Forest Products Development and Utilization, the Forestry Research Institute of Nigeria (FRIN), Ibadan, Oyo State of Nigeria. The wood particles were thoroughly sieved with a wire mesh of size 60 µm to separate the unwanted and to obtain homogenous flour size of particle designed for production. The wood flour was later oven-dried at 103ºC for 24 hrs to attain the 4% moisture content; this was done to avoid unnecessary air bubbles that could be found in the internal structure of the composite. The polymer powder employed in this study was derived from used plastic sachets used for packaging drinking water; these were collected in large quantities from the dumping yards of DFRIN water packaged factory located at FRIN. The plastic has a density of 0.64 g/cm^3 with melt flow index of (0.2 -0.3) 10/min. The used plastic sachets were thoroughly washed, dried, and agglomerated into powder at a temperature of 75 ºC.

Composite preparation and production

An appropriate quantity of wood flour was prepared for each wood species at three mixing ratios of wood/plastic 40/60, 50/50, and 60/40 in a weight-to-weight basis. The mixtures were fed into co-rotating single screw extruders within the temperature range of 80-120°C to produce molten compounded WPCs strands. The molten compounded WPCs extruded strands were allowed to pass through water bath to solidify, and then the solidified WPCs strands were pelletized into grains for molding. The pelletized WPCs were fed into 120-ton polymer injection molding machine at the temperature of 140ºC to 160ºC to mold WPCs samples. The test samples were designed and done in accordance with the American Standard for Testing Materials (ASTM) D 570 and D638 for determination of physical and mechanical properties with five replicates for each testing procedure.

Properties determination and procedures

Dimensional properties test

The tests for water absorption and thickness swelling were conducted in accordance with ASTM D570-98. The test specimens with dimension of 76.2 x 25.4 x 6.4 mm were oven-dried for 24 hrs at 50ºC (122ºF). After conditioning, the width, length, and thickness of each specimen were measured before immersion in water soak test. The specimen was totally submerged in distilled water at room temperature of 26 ± 2 ºC for a period of 24 hrs (1 day) respectively. After water immersion treatment, the specimens were suspended for 10 min to drain off the water and the remaining water was wiped off with dried towel. The specimens were finally weighed and the thickness measured. The water absorption and thickness swelling of the boards were calculated using equation 1 and 2 below;

$$WA\% = \left[(Wt - Wo)/(Wo)x\right]\left[\left[100\right]^{\wedge}\right] \text{ ……….....…. [1]}$$

Where, WA = Water absorption (%), Wo = oven-dry mass (g) and Wt = mass (g) after time t in water immersion

$$TS(\%) = \left[(Tt - To)/(To)\right]\left[\left[100\right]^{\wedge}\right] \text{ ….…………… [2]}$$

Where, TS = Thickness swelling (%), To = panel thickness (mm) before, and Tt = panel thickness after time t in Water immersion

Mechanical tests

Type-I tensile bar of specimens with dimension of 165 x 19 x 6.4 mm were cut from the samples and subjected to Universal Testing Machine of model WDW 5000 (UTM-810 load frame with 50 kN load cell) at a crosshead speed of 2.8 mm/min and lower support of 100 mm. Elongation (strain) of the specimen was measured over 25 mm gauge length using an extensometer. These were done under ambient conditions of 23 ± 2 ºC and 50% relative humidity in accordance with ASTM D638-99. The tensile strength was calculated by dividing the maximum load in Newton by the original minimum cross-sectional area of the specimen in square meters. The young's modulus of elasticity (MOE) was calculated from the load-elongation curves by using the initial linear part. The MOE is equal to the stress increase over this linear period divided by the corresponding increase in the strain.

$$Tensile\ strength = \frac{Maximum\ load(N)}{cross\ sectional\ area(m^2)} \text{ ………. [3]}$$

Experimental design

All measurements of each treatment were done in five replicates; the data collected was analyzed and the statistical method adopted for analysis of variance was 3 x 3 factorial experiments in Completely Randomized Design (CRD) at 5% level of probability using Statistical Package for Social Sciences (SPSS) version 13.0 software. This was carried out to determine significance of the main and interacting effects on the study variables (wood species and mixing ratio). Descriptive analysis of the data was done to determine the mean values with standard deviation while a follow-up test was carried out to determine the differences between the means values and to choose the best level from the factors considered. Duncan Multiple Range Test (DMRT) was adopted for follow-up test. The two main factors considered in this study were the wood species with three treatments (*T. superba*, *T. scleroxylon*, and *G. arborea*) and mixing proportions with three ratios of wood/plastic (40/60, 50/50, and 60/40) on weight-to-weight basis.

RESULTS AND DISCUSSION

Dimensional stability of the WPC boards

The outcome of the results in descriptive statistics and analysis of variance on dimensional properties are presented in Tables 1 and 2, and the graphical presentations are shown in Fig. 1, 2, 3, and 4 respectively. The effect of wood species and plastic/wood ratio on dimensional properties of the resulted in WPCs was also discussed in this study.

The outcome of average values of density, water absorption, and thickness swelling for WPCs as influenced by the wood species and plastic/wood ratio are presented in Table 1. The values ranged from 0.47g/cm^3 to 0.92 g/cm^3, 0.46% to 0.91%, and 3.58% to 6.99% for density, water absorption and thickness swelling, respectively. The densities obtained from the WPCs made from wood species of *T. superba, T. scleroxylon,* and *G. arborea* were 0.59, 0.72 and 0.62 g/cm^3, respectively. The densities obtained from the WPCs at different plastic/wood ratio of 40/60, 50/50 and 60/40 were 0.53, 0.79, and 0.59 g/cm^3 respectively. However, the values obtained in wood species for water absorption and thickness swellings after water immersion period of 24 hours were 5.02% and 0.77%, 5.03% and 0.64%, and; 4.83% and 0.76% for *T. superba*, *T. scleroxylon*, and *G. arborea* respectively. Similarly, the values obtained in WPCs at plastic/wood ratio for water absorption and thickness swelling were 0.53% and 3.98%, 0.79% and 4.23% and; 0.59% and 6.66% for 40/60, 50/50, and 60/40 respectively.

As illustrated in Figures 1, 2, and 3, it was observed that as the content of wood to plastic increases, the percentage of water absorbed increases, and the thickness also swells. The results as presented in Figures 2 and 3 agree with previous findings by Fuwape and Aina (2008) and Zhang et al. (2012). These authors explained the behavior WPCs in water exposure and natural weather. This observation was attributed to the hygroscopic nature of wood; and when the wood is increasing to the proportion of plastic, some wood fiber was not able to be covered or encapsulated with plastic that acted as matrix to protect the wood fiber. Wood fiber has been known to have high affinity to water; it absorbs water and allows poor fiber-plastic interaction to bond, thereby permitting pores or voids for diffusion of moisture across the internal structure of the composite.

It was also observed that variation occurs among the different wood species investigated in this study for dimensional stability (Figures 2 and 3). It was found in this study that WPCs made from *T. scleroxylon* had the highest values in water absorption and thickness swelling more than the others. This implies that *T. scleroxylon* behaves poorly in water retention than others, suggesting low dimensional stability. Cell wall found in wood varies, this is largely made up of cellulose and hemicellulose, and the hydroxyl groups on these chemicals make the cell wall hydroscopic. Lignin, the agent cementing cells together is a comparatively hydrophobic molecule. This implies that the cell walls found in wood have a great affinity for water, but the ability of the walls to take up water is limited in part by the presence of lignin and this also varies in wood species (FPL 2010). The density or specific gravity of wood species does play a major role in dimensional stability of WPCs as well. Klyosov (2007) reported that wood species of higher density have significant influence on density of the WPCs and also lower water absorption. This study also shows that there are variations in dimensional stability of WPCs as influenced by plastic/wood ratio. As observed in Figures 2 and 3, WPCs made from 60:40 had lower dimensional stability than others. This observation agrees with the studies by Ajigbon and Fuwape (2005), Fuwape and Aina (2008), and Chaharmahali et al. (2007; 2008).

The outcome of the result of analysis of variance carried out at 5% level of probability for density, water absorption, and thickness swelling are presented in Table 2. The results showed that there were significant differences in all the factors considered in density, water absorption, and thickness swelling, the outcome values for significance in all the dimensional properties were found to be 0.00* which is lesser than proposed standard of 0.05 level of probability or significance. This implies that both factors (wood species and mixing proportion) used for the production of WPCs have major influence on the dimensional stability of the boards.

Table 1. Mean values of physical and mechanical properties of wood-plastic composites experimented in this study

Variables		**Physical properties**			**Mechanical properties**
Wood species	**Wood/plastic ratio**	**Density (g/cm^3)**	**Thickness swelling (%)**	**Water absorption (%)**	**Tensile strength (MPa)**
Terminalia superba	40:60	0.539 ± 0.004	0.638 ± 0.161	4.378 ± 1.239	1.690 ± 0.183
	50:50	0.665 ± 0.015	0.838 ± 0.277	4.614 ± 0.469	2.067 ± 0.797
	60:40	0.588 ± 0.033	0.845 ± 0.114	6.070 ± 0.957	1.891 ± 0.061
Triplochiton scleroxylon	40:60	0.593 ± 0.004	0.324 ± 0.130	4.006 ± 0.577	1.780 ± 0.361
	50:50	0.911 ± 0.059	0.479 ±0.163	4.160 ± 1.049	2.343 ± 0.247
	60:40	0.619 ± 0.063	1.114 ± 0.480	6.917 ± 2.686	1.933 ± 0.205
Gmelina arborea	40:60	0.459 ± 0.058	0.278 ± 0.117	3.565 ± 0.752	0.695 ± 0.015
	50:50	0.788 ± 0.097	0.931 ± 0.283	3.934 ± 0.464	2.616 ± 0.083
	60:40	0.578 ± 0.034	1.061 ± 0.426	6.992 ± 1.809	2.204 ± 0.188

Note: Each value is the mean and standard deviation of 9 samples of WPCs

Table 2. Result of the analysis of variance for dimensional properties WPCs

Properties	Source	Type III sum of squares	df	Mean square	F	Sig.
Density	Mixing ratio	0.325	2	0.163	1416.13	0.000*
	Wood species	0.079	2	0.040	345.13	0.000*
	Mixing ratio *wood species	0.054	4	0.014	117.66	0.000*
	Error	0.002	18	0.000		
	Total	0.461	26			
Water absorption	Mixing ratio	0.338	2	0.169	1471.484	0.000*
	Wood species	0.062	2	0.031	271.871	0.000*
	Mixing ratio *wood species	0.053	4	0.031	116.258	0.000*
	Error	0.002	18	0.000		
	Total	0.456	26			
Thickness swelling	Mixing ratio	39.347	2	19.674	1066.33	0.000*
	Wood species	0.213	2	0.107	196736.33	0.000*
	Mixing ratio *wood species	3.016	4	0.754	7539.33	0.000*
	Error	0.002	18	1.000E-4		
	Total	42.578	26			

Note: represents significance at ($P \leq 0.05$) probability level

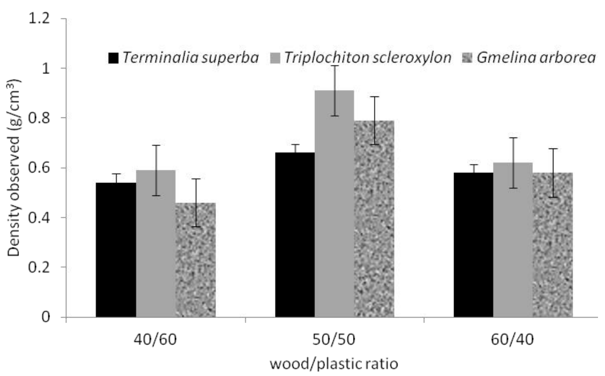

Figure 1. Influence of wood species and mixing ratio on density of the experimented WPCs

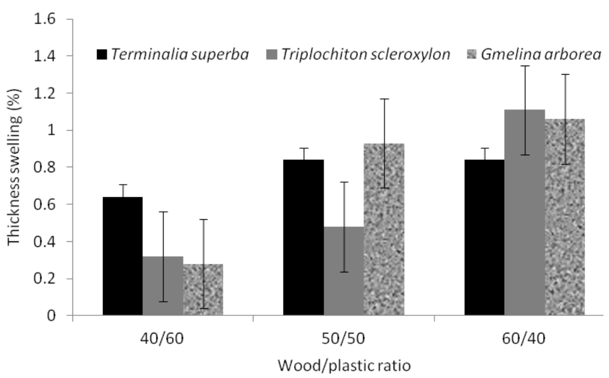

Figure 3. Influence of wood species and mixing ratio on thickness swelling of the experimented WPCs

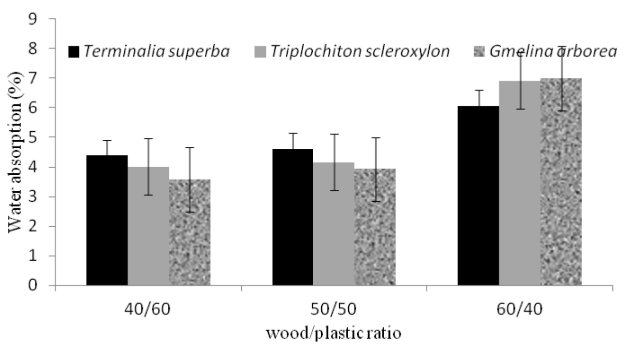

Figure 2. Influence of wood species and mixing ratio on water absorption of the experimented WPCs

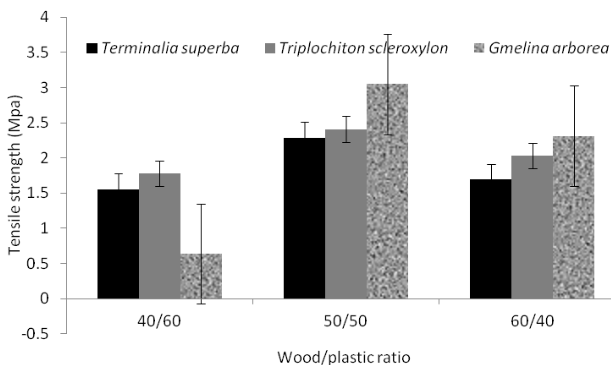

Figure 4. Influence of wood species and mixing ratio on tensile strength of the experimented WPCs

Tensile strength of WPCs

The effects of wood species and mixing proportion on tensile strength of WPCs are also presented in Table 1. The tensile strength values obtained in WPCs made from mixing ratio of 40:60, 50:50, and 60:40 (wood/plastic) ranged from 0.695 to 1.780 MPa, 2.067 to 2.616 MPa, and 1.891 to 2.204 Mpa, respectively. Similarly, in the wood species employed, the tensile strength values obtained from

WPCs made of *T. superba*, *T. scleroxylon*, and *G. arborea* were found to be 5.648 MPa, 6.056 MPa, and 5.515 Mpa, respectively. It was found in this study that the values obtained for tensile strength were low and varied accordingly in wood/plastic mixing ratio and wood species. The tensile values could be attributed to the strength characteristic of individual wood species and it has been noted that wood density has direct influence on the strength properties of WPCs. This agrees with the findings of previous studies (e.g., Stokke and Gardner 2003; Klyosov 2007; Fuwape and Aina 2008; Zhang et al. 2012; Aina et al. 2016). Schoch et al. (2004) further explained that anatomical features of wood species could also contribute to the strength properties of the composite, the intermolecular structure of *G. arborea* and *T. scleroxylon* could have permitted better percolation of molten plastic into the wood cellular network than other *T. superba*. As illustrated in Fig. 4, it was observed that WPCs made from different mixing proportions reacted differently in strength properties. WPC made from equal proportion of wood to plastic (50/50) had the highest tensile values of 7.026 MPa followed by 60/40 and 40/60. This could be attributed to strong fiber interfacial bonds that exist in the structure of the composites with the help of matrix (plastic). The 50% fraction of the fiber gives perfect fiber dispersion and distribution within the 50% of matrix which leads to strong stress transfer in the structure of the composite. But as the fiber fraction is decreasing or increasing (40% and 60%), the fiber interfacial bond got weakened to give gaps that allow weak stress transfer.

The result of the analysis of variance carried out at 0.05 level of probability to test tensile strength of the WPCs made from wood species at different plastic/wood ratio is presented in Table 3. The values obtained for level of significance were higher than 0.05 for wood species while the rest was lesser, this implies that mixing ratio and two-factor interaction were significant except wood species at 0.05 level of probability.

In conclusion, the outcome of this research study revealed that WPCs could be produced from recycled plastic reinforced with wood fiber derived from different wood species. It was also revealed that each wood particle has influence on properties and can play an important role in application. This study demonstrated that some tropical wood species can be suitable for the production of WPCs while some may be less or not suitable. The study also revealed that variations occur in dimensional stability and tensile strength of the WPCs made from different wood species and at mixing proportions. The study found that WPCs made from *G. arborea* at 50/50 gave higher tensile strength than the others. But in dimensional stability, the same WPCs made from *G. arborea* and *T. scleroxylon* performed better at 40/60 and 50/50 (wood/plastic). WPCs investigated in this study, could be of great use if considered for ceiling application as replacement to cement-made ceiling and louvers as replacement for glass.

Table 3. Analysis of variance for tensile strength

Source of variance	Type III sum of squares	df	Mean square	F	Sig.
Mixing ratio	2.841	2	1.421	5.343	0.015*
Wood Species	0.247	2	0.124	0.464	0.636ns
Mixing ratio * Wood species	7.815	4	1.954	7.347	0.001*
Error	4.787	18	0.266		
Total	15.690	26			

Note: represent significant while ns reps not significant at ($P \leq 0.05$) probability level.

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