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# EVALUATION OF THE STRENGTH, SORPTION AND THERMAL PROPERTIES OF BAMBOO PLASTIC COMPOSITES

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## ABSTRACT

Natural fiber plastic composites were made from Nigerian grown bamboo (*Bambusa vulgaris*) and high density polyethylene by extrusion and evaluated for strength, sorption and thermal properties. Composites were manufactured using two different screened bamboo particle size fractions (<2 mm and < 0,5 mm). The composites were tested for flexural properties, water sorption, melt flow and thermal properties. The melt viscosities at 190°C were  $22,3 \pm 0,91$  kPa·s (<2 mm) and  $27,4 \pm 1,2$  kPa·s (<0,5 mm). The results obtained indicated that the composites made with the smaller particle size fraction had higher flexural strength ( $37,4 \pm 1,0$  MPa) and modulus of elasticity ( $2,0 \pm 0,2$  GPa) than those made with the larger particle size fraction ( $29,9 \pm 1,1$  MPa and  $1,7 \pm 0,1$  GPa). Dynamic mechanical analysis also showed higher dynamic storage modulus for the <0,5 mm particle-based composites than those made from the <2 mm particle size fraction due to higher density and better interfacial interaction between the fiber and matrix. Also, the composites made with the smaller particles and were more dimensionally stable (water absorption of 5,4% versus 18,5% at 61 d). The bamboo composites had thermal stability range of 265 – 279°C (onset degradation temperature). The composites made with the smaller bamboo particles possessed the better properties in comparison with those made from the <2 mm. Particle size and density significantly affected the mechanical, physical, thermal and rheological properties of the composites evaluated.

**Keywords:** *Bambusa vulgaris*, flexural properties, Natural fiber plastic composites, particle size.

## INTRODUCTION

In view of the attendant shortage of wood flour supply in certain parts of the world, bamboo flour can be considered as a viable substitute (Han *et al.* 2008). This is because bamboo is abundantly available, fast growing and highest yielding renewable material resource with short maturity cycle in the world (Omobowale and Ogedengbe 2008). Bamboo belongs to the subfamily *Bambusoideae* of flowering perennial evergreen plants in the grass family *Poaceae* (Gnanaharan *et al.* 1995). Bamboo has high strength to weight ratio and is widely grown for shade, animal fodder, food and also as a sustainable construction material in Asia, Central and South America and Africa (Omobowale and Ogedengbe 2008). The International Network for Bamboo and Rattan (INBAR 2007) noted bamboo as the single most important organic material used for 70% of rural housing in Asia and has been accepted as a raw material for paper manufacture (Omobowale and Ogedengbe 2008).

There are different bamboo species available in Nigeria. These include *Bambusa vulgaris*,

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*Oxytenanthra abyssinica*, *Guadella macrostachys*, *G. densiflora* and *G. humilis* of which *Bambusa vulgaris* is predominant (Oyeboode and Ogendengbe 2001). It is primarily used as scaffolding materials, fencing, construction, handicraft, basketry works and as fuel (Ogunwusi and Onwualu 2011). Bamboo flour has also been used in plastic composites production attributable to its availability, low cost and recyclability. The incorporation of bamboo flour in HDPE composites has been found to enhance the mechanical and sorption properties. Han *et al.* (2008), Kim *et al.* (2012) and Ren *et al.* (2014) recorded tensile strength and modulus of 11,7 – 29,0 MPa and 0,5 – 3,7 GPa, respectively. While their flexural strength and modulus were 28,9 – 34,6 MPa and 1,9 – 3,1 GPa, respectively. The composites were dimensionally stable having water absorption (WA) of between 1,3 and 8,9% after 70 d immersion. Ajayi and Aina (2008) noted that bamboo plastic composites produced from *Bambusa vulgaris* with low density polyethylene could be used for partitioning, flooring and wall tiles since the composites possessed a flexural strength of 0,7 – 3,7 MPa and flexural modulus of 6,9 – 14,2 GPa.

The literature is however sparse on the effect of particle size and properties of HDPE plastic composites made from *Bambusa vulgaris* with coupling agent (Han *et al.* 2008). This is more so since the incorporation of small sized particles (100 - 200 mesh) was found to increase the melt flow rate (MFR) and flexural strength but resulted in reduction in toughness, stiffness and crystallinity of the composites due attributable to interfacial interaction between the plastic matrix and the lignocellulosics (Lim and Park 2001, Gallagher and McDonald 2013). Also, poor attraction and low interfacial bonding may occur between the hydrophilic bamboo fibers and hydrophobic plastic matrix. Therefore, coupling agents, such as maleated polyethylene (MAPE), may be incorporated in the production process to enhance fiber-matrix compatibility (Kim *et al.* 2006, Gardner *et al.* 2015). This study is therefore aimed at evaluating the use of Nigerian grown *Bambusa vulgaris* in natural fiber plastic composite production using HDPE with MAPE by extrusion. The bamboo particles were partially characterized and the composites strength, thermal, rheological and physical properties were determined.

## MATERIALS AND METHODS

### Production of bamboo plastic composites

Culms of *Bambusa vulgaris* harvested within the premises of University of Ibadan, Oyo state were ground and screened using a Wiley mill to <2 and <0,5 mm particle size fractions. The milled particles were oven dried at 70°C to 0,5% moisture content prior to natural fiber plastic composite production. HDPE (48% w/w) (Equistar Petrothene, LB 0100-00, MFI = 0,3 g/10 min, and density = 0,950 g/cm<sup>3</sup>), bamboo 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<sup>2</sup>) (Wei *et al.* 2013). The barrel and die temperature was between 140 and 160°C.

### Properties characterization of bamboo reinforced plastic composites

#### Bamboo particle characterization

Air dried samples of the bamboo particles (4-5 g) were Soxhlet extracted with dichloromethane (CH<sub>2</sub>Cl<sub>2</sub>, 150 mL) for a period of 20 h according to ASTM D-1108-96 (2006). The CH<sub>2</sub>Cl<sub>2</sub> 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 D-1106-96 (2006). Specifically, the dried extractive free sample (200 mg) was incubated in 72% H<sub>2</sub>SO<sub>4</sub> (2 mL) for 1 h at 30°C, then diluted into 4% H<sub>2</sub>SO<sub>4</sub>, and subjected to secondary hydrolysis in an autoclave (117 kPa and 121°C) for 30 min. The hydrolyzate was filtered to obtain Klason lignin content gravimetrically. The ash content was determined gravimetrically by furnacing the samples at 600°C for 16 h. All analyses were done in triplicate.

Optical microscopy was performed on screened particles on an Olympus BX51 microscope at 40x

magnification equipped with a DP70 digital camera. Particle measurements (length and width) were performed on 140 particles for each sample using the Olympus MicroSuite software (Adefisan and McDonald 2017).

### Sorption, mechanical and melt flow properties of composites

Water absorption (WA) and thickness swell (TS) tests were conducted following a modified ASTM D-570-95 (2008) procedure. Five replicate specimens ( $1,5 \times 20 \times 50 \text{ mm}^3$ ) for each sample were immersed in water at 23°C 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 bamboo composites were calculated using Equation 1 adopted by Fabiyi *et al.* (2011).

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

Where,  $M_{\infty}$  is the maximum moisture content (MC) (%) measured at the end of the test,  $h$  is the sample thickness (m) corresponding to  $M_{\infty}$ ,  $t$  is the time (s) and  $M / \sqrt{t}$  is the initial slope from the graph of MC versus  $\delta\sqrt{t}$  relation.

Three point flexural tests (strength and modulus) were performed on extruded specimens ( $3,56 \times 20,1 \times 110 \text{ mm}^3$ , 5 replicates) according to ASTM D-790-07 (2008) with a crosshead speed of 1,31 mm/min and a span of 57 mm until specimen failure or 5% strain, whichever occurred first on an Instron 5500R-1132 universal test machine. Data were collected and processed using Bluehill v2 software (Instron). Melt flow index (MFI) and melt viscosity of molten plastic composites were measured (3 replicates) using a CEAST Model 7024.000 melt flow indexer according to ASTM D-1238-04C (2008) through a 2,0955 mm  $\varnothing$  x 8 mm die, at 190°C, and load of 15 kg. Dynamic rheological measurements ( $G'$ ,  $G''$ , and  $\eta^*$ ) were performed on a Bohlin CVO 100 rheometer, using serrated parallel plates (25 mm  $\varnothing$ ), in an oscillating mode with an extended temperature control module on disc (3 mm x 25 mm  $\varnothing$ ) samples. Experiments were performed in the linear viscoelastic region. Measurements were carried out at 180 °C in the frequency range of 0,01 to 100 Hz at an applied strain of 0,5% (Luo *et al.* 2016). Data were analyzed using the Bohlin rheology v6.51 software.

### Thermal characterization

#### Thermogravimetric analysis

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

#### Differential scanning calorimetry

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 70°C (3 min) then ramped to 180°C at 10°C/min, held isothermally for 3 min, (ii) cooled to 70°C at 10°C/min and held isothermally for 3 min and the cycles repeated (Wei *et al.* 2013). 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 ( $\Delta H^{\circ}_p$ , 105-145 °C) of the sample to  $\Delta H^{\circ}_f$  of 100% crystalline HDPE 293 J/g (Wunderlich 1973).

#### Dynamic mechanical analysis

Dynamic mechanical analysis (DMA) was performed in 3-point bending mode (15 mm span) on duplicate samples (2 mm x 5,5 mm) using a Perkin Elmer DMA-7 instrument (1 Hz and 0,1%

strain) with refrigerated cooling from -50 to 120°C at a ramp rate of 3°C/min. Interfacial adhesion was evaluated by an adhesion factor ( $A$ ) determined from DMA data at 30 and 40°C according to Kubat *et al.* (1990) as follows Equation 2:

$$A = \left(1 / (1 - V_f)\right) (\tan \delta_c / \tan \delta_m) - 1 \quad (2)$$

where, c and m subscripts represent composites and HDPE matrix, and  $V_f$  is the fiber volume fraction Equation 3:

$$V_f = (W_f \rho_m) / (W_f \rho_m + W_m \rho_f) \quad (3)$$

where  $W_f$  is weight of bamboo,  $W_m$  is the weight of HDPE,  $\rho_f$  is the density of fibers ( $\rho_f = 1,5 \text{ g/cm}^3$ ) (Bowyer *et al.* 2007) and  $\rho_m$  is the density of HDPE ( $0,95 \text{ g/cm}^3$ ).  $V_f$  value of bamboo was 38,8%.

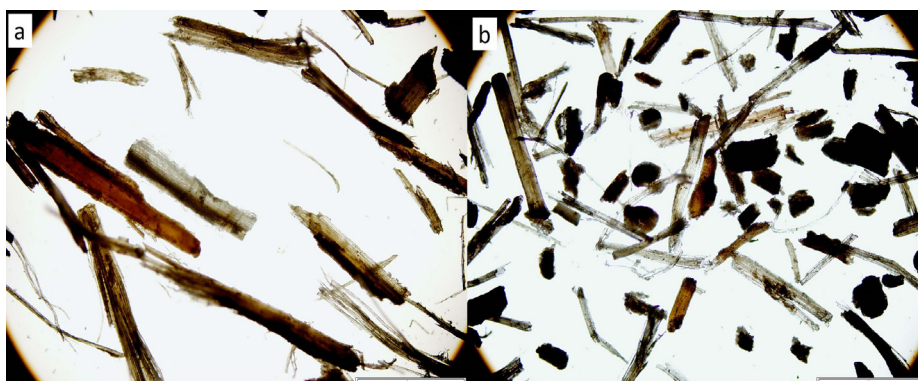
Statistical analysis was performed on data using Microsoft Excel 2016. Means were compared using t-tests to determine whether the results were significant.

## RESULTS AND DISCUSSION

### Properties of bamboo particles

The bamboo samples had  $\text{CH}_2\text{Cl}_2$  extractive content of  $0,5 \pm 0,05\%$ . The obtained bamboo extractive content is low in comparison with 2,6-5,9% obtained by Sadiku and Bada (2017) and Sulaiman *et al.* (2016) which used a polar ethanol-benzene solvent system which extracted both non-polar and polar compounds. The bamboo extractives compared favourably with 0,8% obtained for *E. macrocarpa* and *L. secundiflorum* canes when using  $\text{CH}_2\text{Cl}_2$  (Adefisan *et al.* 2017). However, extractives can act as plasticizing agents and reduce the melt flow index of the plastic composites (Clemons and Stark 2009). The bamboo lignin content was  $31,0 \pm 0,5\%$  while the ash content was  $3,0 \pm 0,2\%$ . The lignin value was higher than those obtained by Sulaiman *et al.* (2016) and Balduino *et al.* (2016) for mature *Bambusa vulgaris* (20-26%). The ash content was comparable (1,2-3,4%) to that obtained by Balduino *et al.* (2016).

The particle lengths of the < 2 mm and <0,5 mm screened bamboo fibers were  $972 \pm 579 \mu\text{m}$  and  $650 \pm 450 \mu\text{m}$ , respectively while the widths were  $116 \pm 83 \mu\text{m}$  and  $83 \pm 55 \mu\text{m}$ , respectively (Figure 1). The calculated aspect ratios for the <0,5 mm and <2 mm fibers were comparable at 8,4 and 7,8 respectively. These values were greater than those reported for wood prepared under similar conditions (Adefisan and McDonald 2017).



**Figure 1:** Optical micrographs of screened (a) <2 mm and (b) <0,5 mm bamboo particles (40x, scale bar 1 mm).



## Density and flexural properties

The density of the composites made from <2 mm particles was 18% lower than that made from <0,5 mm particles (1082 kg/m<sup>3</sup>). A similar decrease in density was observed in wood plastic composites made with <2 mm versus <0,5 mm screened particles (Adefisan and McDonald 2017). The lower density could be attributable to incomplete filling of the voids and/or lumens in the larger screened particles. The results of the flexural tests on the bamboo HDPE composites are shown in Table 1. As shown, the flexural strength and modulus of the composites were between  $29,9 \pm 1,1$  to  $37,4 \pm 1,0$  MPa and  $1,68 \pm 0,1$  to  $2,0 \pm 0,2$  GPa, respectively. The flexural modulus values were comparable those obtained by Han *et al.* (2008) (1,5-1,9 GPa) using bamboo fiber. These values also compared favourably with those reported by San *et al.* (2008), Migneault *et al.* (2008), Fabiyi and McDonald (2010) and Adefisan and McDonald (2017) for wood fiber-HDPE composites. This suggests that there was good interfacial bonding between the bamboo 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 <0,5 mm particles recorded significantly higher flexural strengths and moduli than those made from <2 mm particles. The higher density of the composites made from <0,5 mm particles could have enhanced interfacial bonding between the bamboo particles and the plastic matrix and possibly responsible for its higher flexural properties (Table 1). This is more so since composites made from <0,5 mm particles have larger surface area and low stress concentration and will thus have higher strength properties (Lim and Park 2001, Gallagher and McDonald 2013). The energy at maximum load (EML) of the composites were not significantly different at 0,43-0,46 J (Table 1).

**Table 1:** Flexural properties and density of bamboo plastic composites made with <0,5 mm and <2 mm particles.

| Composites         | Density (kg/m <sup>3</sup> ) | Strength (MPa)          | Modulus (GPa)           | Energy (J)               |
|--------------------|------------------------------|-------------------------|-------------------------|--------------------------|
| < 0,5 mm particles | 1082 <sup>a</sup> (58)       | 37,4 <sup>a</sup> (1,0) | 2,00 <sup>a</sup> (0,2) | 0,432 <sup>a</sup> (0,0) |
| < 2 mm particles   | 882,6 <sup>b</sup> (22,3)    | 29,9 <sup>b</sup> (1,1) | 1,68 <sup>b</sup> (0,1) | 0,456 <sup>a</sup> (0,1) |

\* Means with the same letters and columns are not significantly different.

\* Standard Deviation in parentheses.

## Melt flow and rheological properties

To assess the melt processing behaviour of the composite blends their MFI and melt viscosities were determined using a 15 kg load. The MFI and melt viscosities (Table 2) were between 2,69 to 3,31 g/10 min and 22,3 to 27,4 kPa·s, respectively. These values compared favorably with those reported for wood fiber based composites by Wei *et al.* (2013) (1,53 – 2,19 g/10 min; 25100 – 35200 Pa·s) and Gallagher and McDonald (2013) (0,35 – 2,90 g/10 min; 12700 – 107000 Pa·s). Composites made from <2 mm particles recorded significantly higher MFI and lower viscosity than those from <0,5 mm particles. A similar observation was seen in wood plastic composites made with <2 mm versus <0,5 mm screened particles (Adefisan and McDonald 2017). This phenomenon could be because of the lower density and an increase in the unfilled regions in the composites as observed by Stark and Berger (1997).

**Table 2:** Melt flow index (MFI) and melt viscosities of bamboo plastic composites made with <0,5 mm and <2 mm particles.

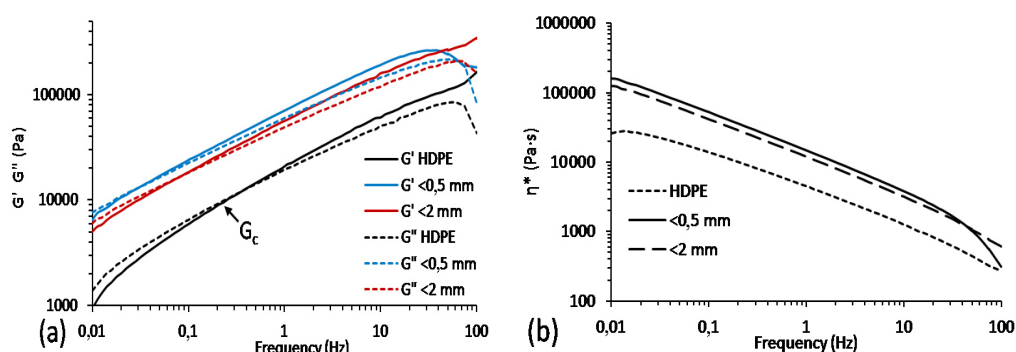
| Composites         | MFI (g/10min)            | Viscosity (kPa·s)        |
|--------------------|--------------------------|--------------------------|
| < 0,5 mm particles | 2,69 <sup>b</sup> (0,10) | 27,4 <sup>a</sup> (1,2)  |
| < 2 mm particles   | 3,31 <sup>a</sup> (0,15) | 22,3 <sup>b</sup> (0,91) |

\* Means with the same letters and columns are not significantly different.

\* Standard Deviation in parentheses.

Dynamic rheological measurements were also obtained on the bamboo composites and HDPE melts. Figure 2 shows the dynamic elastic (G') and viscous (G'') moduli and complex viscosity ( $\eta^*$ ) as a function of frequency for the composites and HDPE at 180°C. For all melt samples G' and G'' were shown to increase with angular frequency. The addition of <0,5 mm bamboo particles to HDPE increased G' 6-fold and G'' 3,5-fold (at 0,1 Hz). At lower angular frequency, the G' was lower than G'',

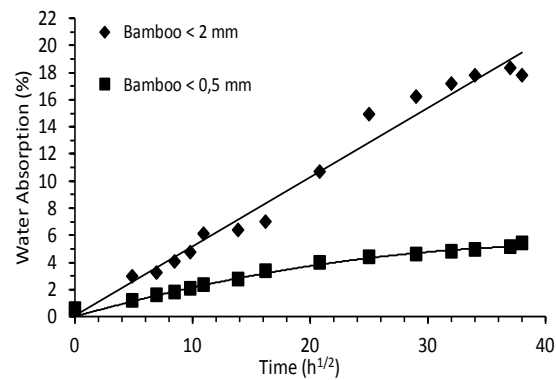
indicating a viscous response and the molten samples were more liquid like. Incorporation of bamboo particles in HDPE increased  $G'$  and  $G''$  and narrowed the gap between them at low frequency, making the resulting melt more solid-like, because of the rigid character of the bamboo particles. Bamboo particle size had a distinct effect on the dynamic rheological behaviour of the composite melts. The cross-over point of  $G'$  and  $G''$  ( $G_c = G' = G''$ ) was shown to occur at a lower frequency for the bamboo composites than for HDPE. The  $G_c$  decreased from 0,2 Hz for HDPE to 0,07 Hz for <2 mm bamboo composites to 0,04 Hz for <0,5 mm bamboo composites (Figure 2), indicating that fiber addition lowered the frequency at which the material transferred from liquid-like to solid-like behaviour. This phenomenon was also observed in rheological measurements on wood-plastic composite (Ou *et al.* 2014), cellulose-plastic composites (Wei *et al.* 2015) and lignin-plastic (Luo *et al.* 2016) melts. The  $\eta^*$  decreased with an increase in frequency, showing a shear thinning behaviour, for HDPE and the composite melts (Figure 2). The  $\eta^*$  (at 1 Hz) was also increased from 4430 Pa·s for HDPE to 11500 Pa·s for the <2 mm particle composites to 15200 Pa·s for the <0,5 mm particle composites. This observation of higher  $\eta^*$  for the <0,5 mm particle melt is consistent with those obtained by MFI. The higher viscosity could be explained by a higher fiber-matrix interaction in the melt attributable to a larger surface area.



**Figure 2:** Dynamic rheology showing (a) elastic ( $G'$ ) and viscous moduli ( $G''$ ) and (b) complex viscosity ( $\eta^*$ ) as a function of frequency for HDPE and bamboo composites at 180°C.

### Water absorption and thickness swelling

The water soak (WA and TS) properties of the composites were measured with time (Table 3, Figure 3). Figure 3 shows the WA of the bamboo composites reaching a pseudo-equilibrium state in accordance with Fickian behavior (Rangaraj and Smith 2000). The respective WA and TS of the plastic composites were between 1,16 to 18,46% and 0,65 to 3,48%. These WA and TS values are similar to 0,14 to 15,9% and 0,16 to 7,6% obtained by Wei *et al.* (2013); 1,9 to 22,4 % and 1,7 to 14,1% recorded by Fabiyi and McDonald (2010) and 1,3 to 28,0% and 0,36 to 4,9% obtained by Adefisan and McDonald (2017), respectively. Bamboo composites made with smaller particle size had the least sorption properties. This may be possibly attributable to the higher density, less voids, and improved interfacial interaction with the plastic matrix which resulted in less moisture ingress. The composites made with the larger particles has an 18% lower density and thus has more voids and thus resulted in higher water uptake (Migneault *et al.* 2009).



**Figure 3:** Water absorption (WA) of bamboo plastic composites with time<sup>1/2</sup>.

**Table 3:** Water soak properties of bamboo plastic composites made with <0,5 mm and <2 mm particles.

| Plastic composites | WA (%)                   |                          | Diffusion coefficient<br>(10 <sup>-10</sup> m <sup>2</sup> /s) | TS (%)                   |                          |
|--------------------|--------------------------|--------------------------|--|--------------------------|--------------------------|
|                    | 1 d                      | 61 d                     |  | 1 d                      | 61 d                     |
| < 0,5 mm particles | 1,16 <sup>c</sup> (0,16) | 5,38 <sup>b</sup> (1,16) | 0,11   | 0,65 <sup>c</sup> (0,55) | 2,59 <sup>b</sup> (0,80) |
| < 2 mm particles   | 2,12 <sup>c</sup> (0,38) | 18,46 <sup>a</sup> (3,3) | 0,29   | 0,68 <sup>c</sup> (0,35) | 3,48 <sup>a</sup> (0,43) |

\* Means with the same letters and columns are not significantly different.  
\* Standard Deviation in parentheses.

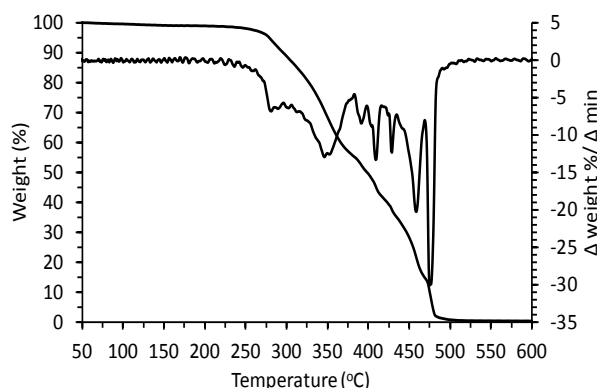
Thermal analysis

The thermal stability of the plastic composites was evaluated by TGA (Table 4 and Figure 4). All thermograms show a small weight loss before 100°C, associated with water loss. The degradation stage <400°C of composites can be mainly attributed to the decomposition of chemical components such as hemicelluloses (150-350°C), lignin (250-490°C), extractives and cellulose (275-350°C) (Kim *et al.* 2006, Wei *et al.* 2013). From the differential thermogravimetric (DTG) thermograms, the decomposition of HDPE occurred at > 470°C. Composites made with larger particle size generally degraded at higher temperatures (279°C) in comparison with those made from smaller sized particle (265°C) indicating higher thermal stability and possibly due to mass transfer effects of the larger particles and this has phenomenon has been observed in pyrolysis kinetic studies (Seebauer *et al.* 1997).

**Table 4:** Thermal degradation behaviour of bamboo plastic composites.

| Plastic composites | onset<br>(°C) | 1st<br>Peak<br>(°C) | 2nd<br>Peak<br>(°C) | 3rd<br>Peak<br>(°C) | 4th<br>Peak<br>(°C) | 5th<br>Peak<br>(°C) | Final<br>Decomposition<br>Temp(°C) |
|--------------------|---------------|---------------------|---------------------|---------------------|---------------------|---------------------|------------------------------------|
| Bamboo (< 0,5 mm)  | 266           | 282                 | 348                 | 406                 | 452                 | 477                 | 483                                |
| Bamboo (< 2 mm)    | 279           | 289                 | 372                 | 421                 | 480                 | 500                 | 510                                |





**Figure 4:** The TGA and DTG graphs of bamboo plastic composites made with <0,5 mm particles.

The degree of HDPE crystallinity and transition temperature in the bamboo plastic composites was determined by DSC and data presented in Table 5. These values were comparable to wood fiber plastic composites (Wei *et al.* 2013, Gallagher and McDonald 2013, Adefisan and McDonald 2017). The HDPE crystallinity in the composites made from <2 mm particles was 8% higher than that made from the <0,5 mm particles (68,6%). This may suggest that the larger particles induced more nucleation of HDPE crystals than the smaller particles. Gallagher and McDonald (2013), observed a similar increase in crystallinity from 35 to 41% for 50% maple-HDPE based composites going from <73  $\mu\text{m}$  to 150-178  $\mu\text{m}$  sized particles. It is postulated that the composites made with <2 mm particles, with a lower packing density than the <0,5 mm fibers, has more room to form spherulites and thus a higher crystallinity (Harper and Wolcott 2004). The melt temperature ( $T_m$ ) for the composites were similar at around 131-132°C. However, there was no significant difference in HDPE crystallization temperature (118-120°C) in composites made from the two different particle sizes.

**Table 5:** Crystallization and melt temperatures and crystallinity of bamboo plastic composites made with <0,5 mm and <2 mm particles.

| Composites | $T_c$ (°C)               | $T_m$ (°C)               | Crystallinity (%)       |
|------------|--------------------------|--------------------------|-------------------------|
| < 0,5 mm   | 117,8 <sup>a</sup> (0,6) | 132,4 <sup>a</sup> (0,4) | 68,6 <sup>b</sup> (0,8) |
| < 2 mm     | 119,7 <sup>a</sup> (2,1) | 131,7 <sup>a</sup> (0,7) | 74,6 <sup>a</sup> (1,1) |

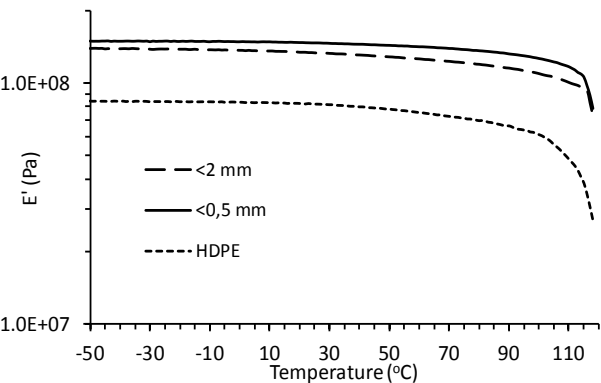
\* Means with the same letters and columns are not significantly different.

\* Standard Deviation in parentheses.

The storage modulus ( $E'$ ) of the composites and HDPE was determined by DMA and values at 30°C are given in Table 6 and the thermograms are shown in Figure 5. The bamboo composites made with <0,5 mm particles had the highest  $E'$  (at 30°C) value at 146 MPa while HDPE had the lowest at 82 MPa. The damping factor ( $\tan \delta$ ) is also measured by DMA on viscoelastic materials and can be used to give information about the interface between different phases (fiber-plastic) in composite materials that affect energy dissipation. The effect of the bamboo particle size on the strength of the fiber-HDPE interface was evaluated using  $A$  and determined from DMA data ( $\tan \delta$ ) according to Kubat *et al.* (1990). The  $A$  values for the bamboo composites particles at 30 and 40°C are given in Table 6. Low  $A$  value is an indicator of good adhesion or high degree of interaction between the two phases (Kubat *et al.* 1990, Wei *et al.* 2013). The bamboo composites made with <0,5 mm particles had the lowest  $A$  (0,27 at 30°C), or strongest interfacial interaction, compared to composite made with < 2 mm particles (0,55 at 30°C). These results are consistent with the flexural properties and storage modulus ( $E'$ ) data. This could be attributed to an increased surface area with the smaller particles and not likely attributable to aspect ratio of the fiber since they were similar (~8). However, these results are in odds with an increase in HDPE crystallinity for the composites made with the larger particles and cannot be explained.

**Table 6:** Adhesion factor (*A*) and storage modulus (*E'*), determined by DMA, of bamboo plastic composites made with <0,5 mm and <2 mm particles.

| Composite | <i>A</i> at 30°C | <i>A</i> at 40°C | <i>E'</i> (Pa) at 30°C |
|-----------|------------------|------------------|------------------------|
| < 0,5 mm  | 0,27             | 0,16             | 1,46 x 10 <sup>8</sup> |
| < 2 mm    | 0,55             | 0,43             | 1,32 x 10 <sup>8</sup> |
| HDPE      |                  |                  | 8,18 x 10 <sup>7</sup> |



**Figure 5:** DMA thermograms of storage modulus (*E'*) of the bamboo composites (made with <0,5 mm and <2mm particles) and HDPE.

CONCLUSIONS

Extruded natural plastic composites were successfully produced from different sized particle fractions of Nigerian grown bamboo. The extruded composites possessed adequate strength properties with low sorption rates and were thermally stable. Differences in the densities of the composites and fiber size appeared to affect the properties of the bamboo plastic composites produced. Composites produced with smaller particle size (<0,5 mm) had superior strength and sorption properties attributable to enhanced interfacial bonding with the plastic matrix. The fabricated plastic composites utilized local bamboo resources which are suitable as building components in Nigeria and the region. For higher performing natural plastic composite materials smaller bamboo particles should be used. Further work will explore the use of waste plastic and bamboo residues for producing sustainable composite materials.

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