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Mechanical performance and water uptake behaviour of treated bamboo fibre-reinforced high-density polyethylene composites

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ABSTRACT

High density polyethylene (HDPE) composites reinforced with short bamboo fibre (BF) were fabricated by compression moulding technique. BF were extracted from bamboo culm and treated with 0.5 M NaOH. The composites were developed by melt-compounding various weight fractions (2, 4, 6, 8 and 10 wt.%) of the treated BF with HDPE with the aid of single screw laboratory extruder at a temperature of 180–220 °C. The extrudates were thereafter moulded into various test specimens with the aid of carver laboratory press at a temperature of 230 °C and applied pressure of 0.2 kPa for 10 min. Effect of the treated BF on the mechanical properties and water uptake behaviour of the composites were studied. The results revealed that there was enhancement in the mechanical properties from 2 – 4 wt.% of BF while the water absorption rate increased with increase in the fibre weight fraction. The morphology of the composites showed that there was a homogenous dispersion of BF at lower weight fraction, although fibre agglomeration was noticed at higher weight fraction. The results of this study revealed that treated bamboo fibres are suitable for reinforcing HDPE.

1. Introduction

Fibre-reinforced polymer composites have been widely used in different industries due to their low density, good mechanical and thermal properties. The properties of the polymer matrix composite depend on the matrix, reinforcement and the interphase, giving many variables to consider when designing a polymer matrix composite (PMC). PMC may incorporate either synthetic or natural fibres as the reinforcement phase. However, natural fibres are increasingly being researched due to their low cost, low density and availability. Natural fibres present a potential substitute in reinforced composites because of rising ecological consciousness and constituted requirements associated with synthetic fibres like carbon and glass [1, 2, 3].

Nevertheless, certain shortcomings, like incompatibility between fibres and polymer matrices, the propensity to form aggregates during processing, weak interfacial adhesion and the meagre resistance to moisture, had discouraged the use of these natural fibres as reinforcements in polymers [1, 2, 3]. To address these limitations, various treatment protocols have been suggested in the literature. These include addition of compatibilizers [4] and coupling agents [5, 6], thermal treatment [3] and alkali/mercerization treatment [1, 2].

Among different natural fibres, bamboo fibres (BF) materials have attracted broad attention as reinforcement in polymer composites due to their environmental sustainability, relatively high mechanical properties, recyclability, and performance comparability with those of glass fibres [7]. Bamboo-derived reinforcement materials have been used in various forms, including strands [8], fibres [9, 10], bamboo charcoal [11] and flour [9]. In a study, processing pressure and temperature are reported to enhance the strength of bamboo strands/epoxy composites [8]. Similarly, short BF have been used to improve the mechanical, dynamic, and thermal properties of high density polyethylene (HDPE) composites [10]. A comparative study on the effect of bamboo flour and BF on the mechanical and thermal properties of HDPE suggests that BF perform better than bamboo flour [9]. Another study reports significant enhancement in the tensile strength of bamboo charcoal polyethylene composites at more than 50 wt.% fraction [11].

However, relevant studies on the effect of treated BF on the properties of HDPE composites are relatively scarce. BF and other natural fibres exhibit poor interfacial adhesion with the polymer matrix, thus negatively impacting strength development [2, 3]. Other than the use of

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compatibilizers [4] and heat treatment [3], various procedures, such as, physical, chemical and biological techniques have been attempted till date to modify the surface of natural fibers, principally to decrease their water retention and improve their grip with polymeric matrices [12]. Normal fibers have likewise been treated with different chemicals, for example, alkaline, silane, peroxides, permanganates, and so forth. It has been seen that a portion of these synthetic treatments for instance, soluble base treatment can fundamentally improve the mechanical properties of natural fibers by changing their crystalline structure, just as by evacuating frail parts like hemicelluloses and lignin from the fiber structure. Also, dampness retention and consequent swelling of natural fibers can be decreased through particular chemical treatment [12].

chemical treatment with appropriate reagents has been reported to ameliorate this problem [13]. Sodium chlorite bleached-BF exhibits enhanced crystallinity than unbleached BF [13]. In addition, the tensile strengths of bleached BF composites are higher than those of unbleached composites [13]. This suggests that the treatment enhances wettability and compatibility with the polymer matrix.

Therefore, the aim of this research is to investigate the effect of BF treatment on the water absorption and mechanical properties of the HDPE/BF composites. Mechanical tests, such as tensile, flexural, impact and hardness, were used to characterize the composites.

2. Materials and methods

2.1. Materials

Bamboo fibres extracted from raw bamboo culms by alkali retting were used in this work. The bamboo culm was collected from Apatapiti Layout, FUTA south-gate, Akure, Ondo State, Nigeria. Sodium hydroxide (NaOH) reagent used for retting was obtained from Pascal Scientific Limited, Akure, Ondo State. High density polyethylene (HDPE) was supplied by DOW Chemicals, RSA. It has a melt flow index (MFI) of 8 g/10min (XZ 89712-00 RD 10140182040), a molecular weight of 168,000 g mol^{-1}, a melting point of 130 °C, and a density of 0.954 g cm^{-3}.

3. Methods

3.1. Bamboo fibre extraction

Raw bamboo culm was split into strips of about 10 cm long. The bark was scraped off and the strips were rinsed with water and dehydrated in an air blast oven at 80 °C for 4 h. The strips were soaked in 0.5 M NaOH in 1 dm^3 of water maintained at room temperature for 3 days. Afterwards, the strips were subjected to a pressure of 2 MPa to loosen the fibres. Fibres were obtained by manually scraping the pressed strips. The extracted fibres were rinsed with water and dried in an oven at 50 °C for 24 h before cutting to shorter lengths of 25mm. Fig. 1 shows the bamboo strips during various stages of extraction and treatment.

3.2. Composite production

The composites were fabricated using compression moulding technique. Samples were produced at 230 °C. The composite samples were developed by compounding 2, 4, 6, 8 and 10 wt. % of the bamboo fibres with HDPE matrix with the aid a single screw laboratory extruder at a temperature of 200–220 °C. The extrudates were pelletized and moulded into various test specimens with the aid of carver laboratory press at a temperature of 230 °C for 10 min under an applied pressure of 0.2 kPa (see Table 1).

3.3. Tensile test

Tensile tests were carried out to evaluate the ultimate tensile strength, young modulus of elasticity and percentage elongation of the developed composite samples utilizing an Instron universal testing machine (Instron Engineering Corporation, USA) with a load cell of 10 kN. Dog-bone-shaped samples prepared by compression moulding were tested in tension mode at a single strain rate of 10 mm/min at room temperature (25 °C) and relative humidity of 40 %. The test piece which is of gauge length 14mm was fixed at the edges of the upper and lower grip of the universal tensile machine. The results presented are the average of three individual test samples.

3.4. Hardness test

Sample hardness was measured with the aid of a micro-hardness tester, model 900–390 in accordance with ISO 868:2008 standards. The test was carried out by indenting the samples for 5 s. Ten indentations were carried out on each sample and the average value of the depth of indentations was taken as the specimen's hardness.

Table 1
Composition and weight of the reinforcement and matrix used to produce composite samples (Tensile, flexural, impact and hardness samples).

Sample Designation	BF Reinforcement (g)	Matrix (g)
HDPE (Control sample)/A	————	147.6
2 wt.% fibres/B	3.0	144.7
4 wt.% fibres/C	5.9	141.7
6 wt.% fibres/D	9.4	138.2
8 wt.% fibres/E	11.2	136.4
10 wt.% fibres/F	14.8	132.8

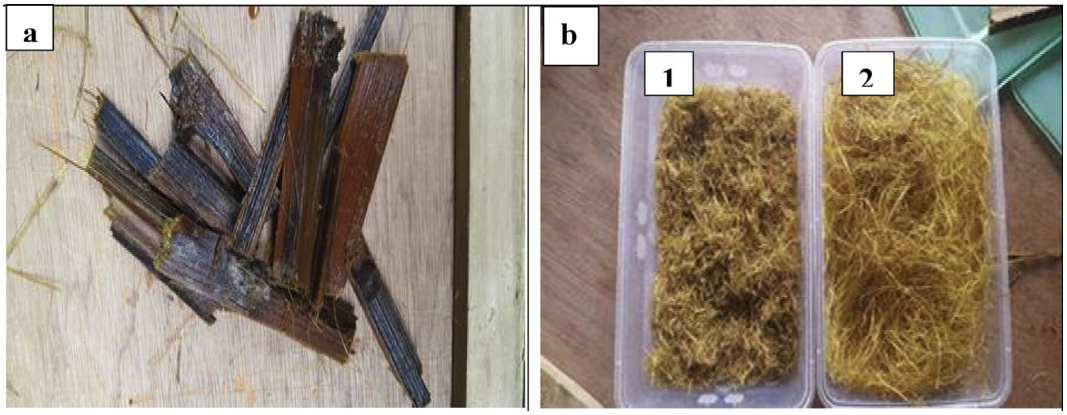

Fig. 1. Bamboo strips: [a] After alkali treatment [b] After extraction (1) After cutting and (2) Before cutting.

3.5. Impact test

The pellets were moulded into rectangular Charpy impact bars of dimension 80 mm × 10 mm × 4 mm. Representative samples of HDPE matrix and HDPE-BF composites were subjected to impact test on a Charpy V- Notch impact testing machine (Instron CEAST 9050) in accordance with ISO 179. The average of 5 samples was reported as the impact strength.

3.6. Water absorption test

Composite samples were weighed and immersed in distilled water at room temperature. The weight of the samples prior to soaking was taken as W_1. The samples were then taken out, washed and weighed again every 3 days interval for 30 days. The weight of the samples after soaking were taken as W_2 Percentage water absorbed was calculated using Eq. (1);

$$W_A(\%) = \frac{(W_2 - W_1)}{W_1} \times 100\% \quad (1)$$

Where;

W_1 = Oven dry weight of specimen in grams (g)
W_2 = Specimen weight after soaking time
W_A = Percentage of water absorbed by the specimens

3.7. Scanning electron microscopic examination

The surface morphology of the treated and untreated fibres was examined with the aid of an AURIGA Scanning Electron Microscope (SEM) (Carl Zeiss, Germany) with an accelerating voltage of 15 kV. The tensile fractured surfaces were also studied to evaluate fibre dispersion and interfacial characteristics.

4. Results and discussion

4.1. Effect of chemical treatment on fibre morphology

A comparison of the surface morphology of treated and untreated BF is shown in Fig. 2. The treated BF in Fig. 2 (a) shows many outgrowths or fibrillation that make the surface appear rough. These outgrowths are, however, less prominent in Fig. 2 (b) of untreated BF. These observations are consistent with some previous studies [14, 15, 16]. In addition to the reduction of lignin, wax, and hemicellulose, the rough surface of treated BF provides numerous sites for mechanically interlocking with the polymer matrix. This enhances interfacial adhesion and strength of the resulting composite.

4.2. Ultimate tensile strength

The variation of tensile strength with percentage weight of fibres is shown in Fig. 3. The tensile strength of the unreinforced HDPE is lower than that of the composites, showing that the addition of fibres has enhanced the tensile strength of the matrix. At 4 wt.% BF, the tensile strength is highest and more than 13 % greater than the control HDPE sample. The next higher strength is exhibited by 6 wt.% composite with a value of ~29.4 MPa. Generally, tensile strength increases with increasing fibre volume fraction up to 4% weight composition after which it drops below the previously seen trend. This is because tensile properties are dependent on the orientation of the fibres and fibre/matrix interfacial adhesion. With increase in fibre weight fraction, there is a higher tendency for agglomeration to occur. This, inadvertently, reduces the fibre/matrix interfacial adhesion and effective stress transfer between the matrix and BF. Similar results have been published in previous studies [9, 10, 16].

4.3. Modulus of elasticity

The modulus of elasticity for each weight percent of the composite

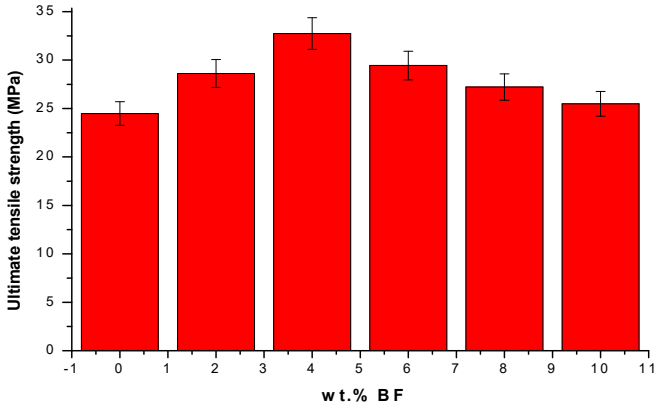

Fig. 3. Tensile strength values of the unreinforced HDPE and the composite samples.

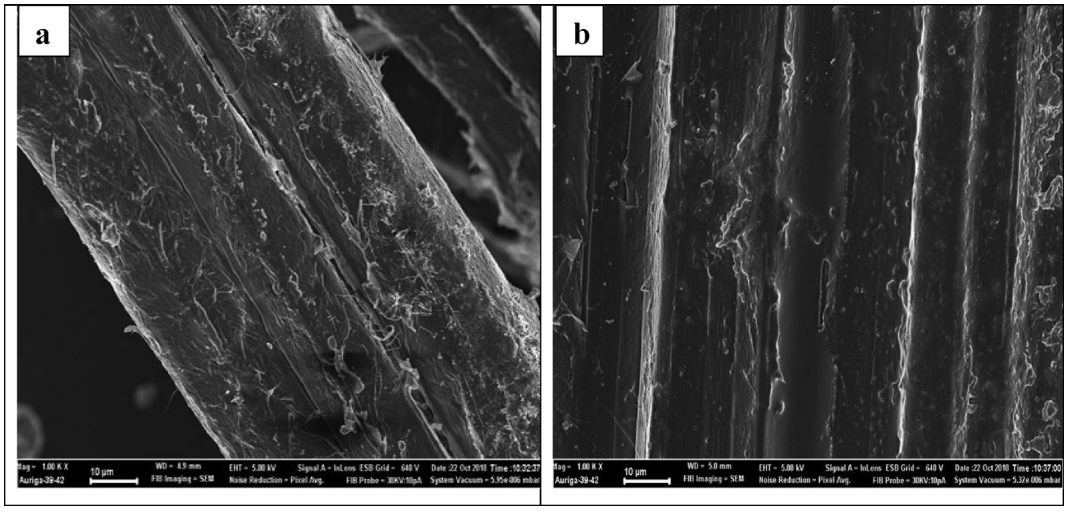

Fig. 2. SEM images of [a] treated bamboo fiber [b] untreated bamboo fibers (1000X).

samples is shown is Fig. 4. The composite samples showed a higher modulus of elasticity than the unreinforced HDPE. The trend here is like that observed for the variation in ultimate tensile strength. However, there is a linear decrease in elastic modulus from 6% to 10% composites. This is due to lowering cross-linking density with increasing fibre volume and agglomeration of BF at higher weight fraction. Also, lower loads were required to fracture the 6%, 8% and 10% composite samples while they showed minimal straining compared with applied load.

This produced a corresponding lower value of elastic modulus for samples in this range. The 2% and 4% samples required higher loads to fracture with strain values in the same range as other composites, causing the stress-strain ratio to yield a higher value. The results presented here are in agreement with results from some earlier studies on BF/polyester [16] and BF/HDPE [9] composites.

4.4. Hardness

Fig. 5 shows the hardness of the different compositions produced as well as the unreinforced HDPE sample. All composites possess higher hardness than the matrix material. This is an indication that the surface of the composite is more rigid and offer higher resistance to penetration than the control HDPE sample. Some authors have attributed this to increase in crystallinity due to the presence of treated natural fibres [17].

4.5. Impact energy

Fig. 6 shows the variation in impact energy of unreinforced HDPE and composite samples.

The composites showed higher impact energy than the unreinforced sample. Composite sample with 2 wt.% BF shows an increment of 39% in impact energy when compared with the control sample. However, as the fibre weight fraction increases beyond 2 wt.%, impact energy reduces. This is ascribed to fibre agglomeration. Generally, all the composite samples exhibit higher impact energy as compared with the unreinforced matrix. A similar work on bagasse fibre/polyester composites reports similar findings [18]. The presence of treated fibres fostered load transfer, enabling the composites to absorb more energy than the unreinforced polymer by undergoing appreciable yielding before fracture.

4.6. SEM images of HDPE matrix and the composites

SEM images of the tensile fractured surfaces of the composites at various fibre contents are shown in Fig. 7 (a-f).

The SEM image of the control sample (HDPE) as shown in Fig. 7 (a) possesses loose, flaky structure with the presence of microvoids, this translates to the facts that its surface is not entirely impervious to moisture and its mechanical integrity is limited in the absence of

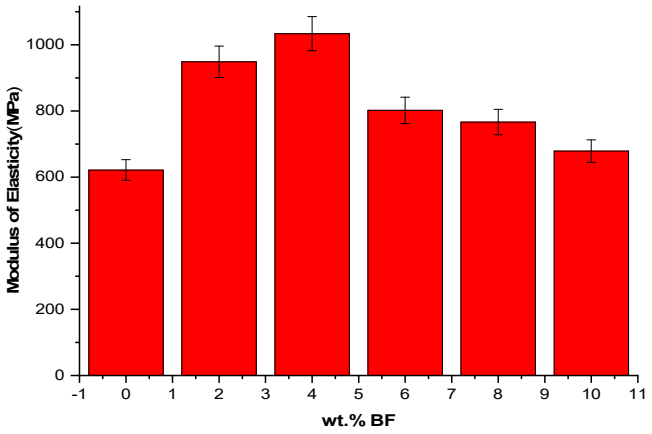

Fig. 4. Variation of Modulus of Elasticity with respect to fibre weight fraction.

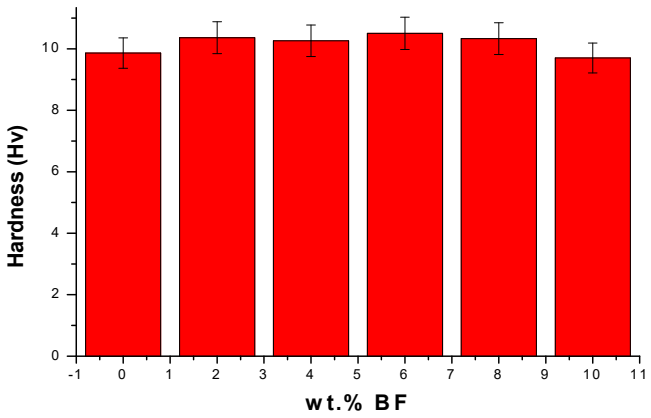

Fig. 5. Hardness values of the unreinforced HDPE and the composite samples.

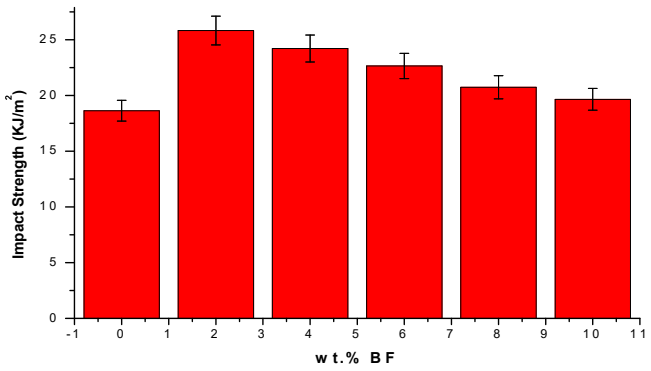

Fig. 6. Impact strength of HDPE and its composites.

reinforcement. Upon introduction of reinforcement, as can be seen in the SEM images in Fig. 7 (b-f), the flaky structure is less pronounced as the fibres take their place within the HDPE matrix, fibre-matrix adhesion then becomes the focal point which is appreciable up to 4 wt% fibre reinforcement, after which congestion is observed for 6 wt.%, 8 wt% and 10 wt% fibre-reinforced composites bringing about eventual debonding and pull out as seen in Fig. 7 (d-f). It is also observed that owing to random orientation, some of the fibres show a degree of elongation at break as seen for the 4 wt% fibre-reinforced composites, justifying the tensile properties conferred on the matrix by the reinforcement, this is in agreement with Daramola *et al.* [19]. Other fibres show a rough and brush-like tip at the point of fracture as seen for the 8 wt % fibre-reinforced composites in Fig. 7 (e) which also indicates appreciable straining before break, the fibre surfaces appear rough indicating one of the effects of alkali treatment as earlier explained to enhance interfacial adhesion between the matrix and fibre. The congestion observed for the 10 wt% fibre-reinforced composites means that more of the loading is absorbed by the fibres which explains the trend in Fig. 7 (f) which was reinforced by 10 wt.%, poor adhesion as observed for the 10 wt% reinforced composites, also provides a free path for ingress of moisture, giving reason for the trend in Fig. 8 where 10 wt% reinforced composites gained the most weight within the same exposure time compared with the other composites during the water absorption study.

4.7. Water absorption behaviour

The water absorption plot for the different samples, showing the weight gained against immersion time is presented in Fig. 8. This test assesses the increase in weight of the composite samples with varying immersion time.

It can be seen from the plot that the water absorption for all the

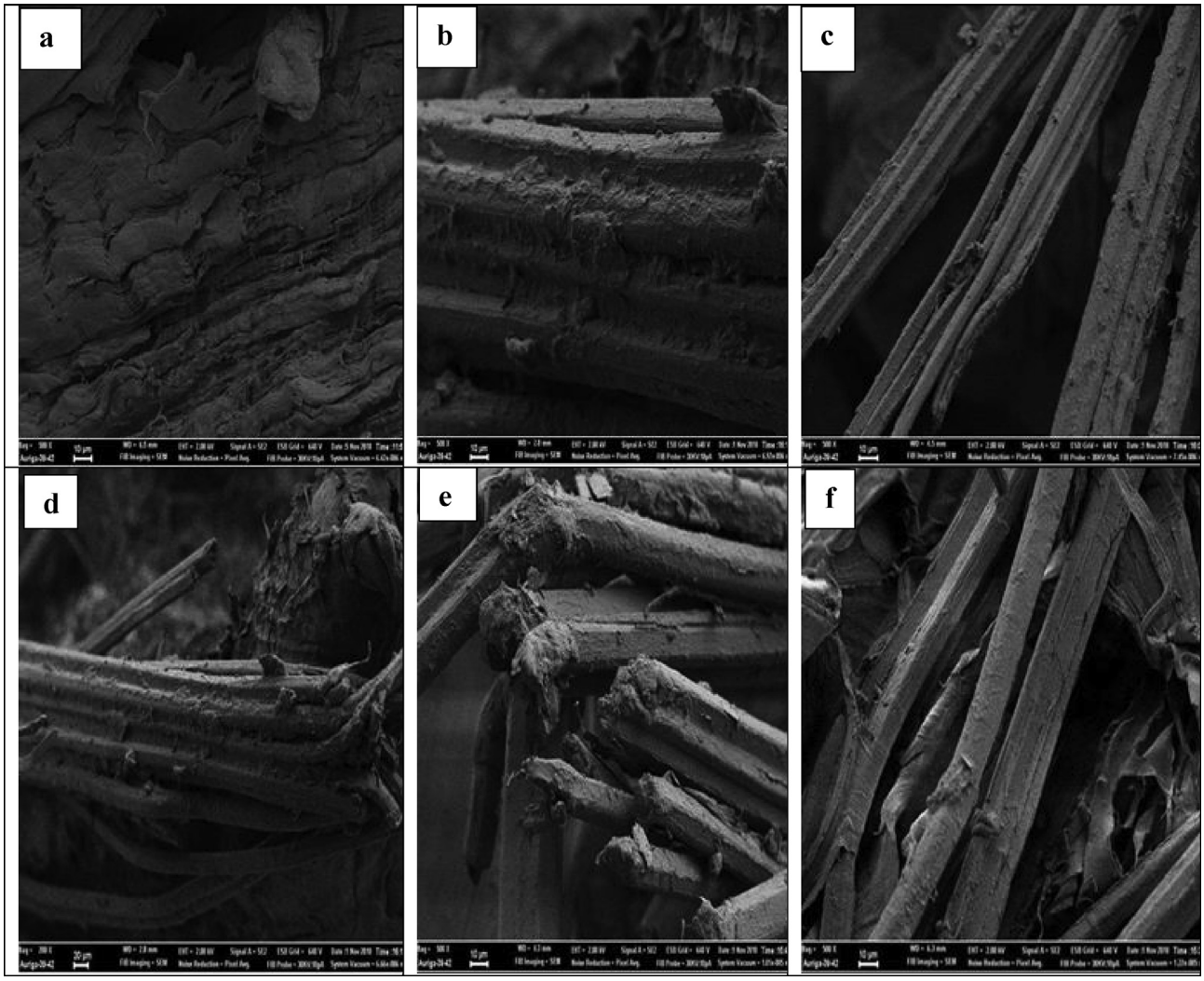

Fig. 7. (a–f): SEM images of (a) HDPE (Control) (b) 2wt.% BF-HDPE (c) 4wt.% BF-HDPE (d) 6wt.% BF-HDPE (e) 8wt.% BF-HDPE (f) 10wt.% BF-HDPE.

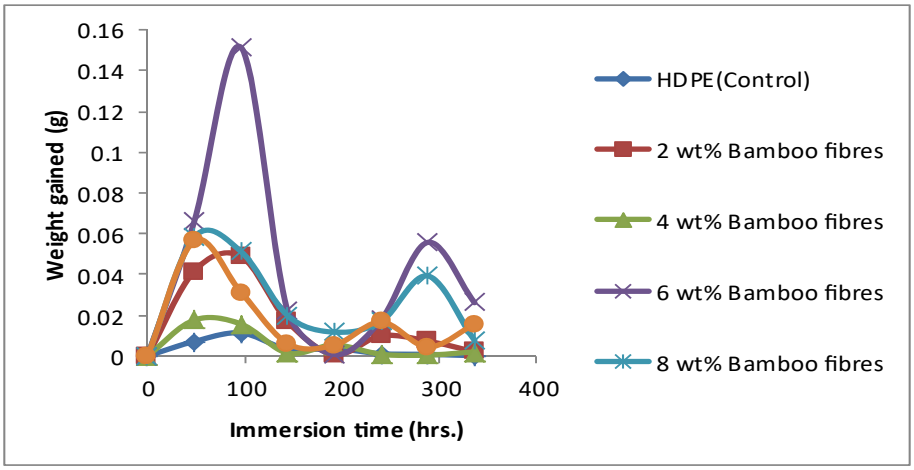

Fig. 8. Plot of weight gained as a function of immersion time for the samples.

samples follow a similar trend. The composite samples undergo rapid water absorption and gain weight within the first 96 h of immersion after which a major drop in weight gained is observed due to slower absorption rates or saturation. Water absorption in all the composite samples exceed that of the control sample. This observation is chiefly attributed to the presence of BF. According to some research studies, the surface of natural fibres contains hydroxyl groups which have high affinity for water molecules [20, 21]. Therefore, the percentage weight gained increases as the weight fraction of BF increases in the composite samples. The control sample exhibits the least weight gained due to the absence of

BF and fewer flaws in the microstructure. Additionally, the absence of fibres is believed to reduce micro-voids and entrained air [2]. These factors are responsible for the reduced water absorption of the control sample. It can also be observed that the water absorption trend alternatingly increases and reduces every four days. Although slower absorption rate is dominant and lesser weight is gained with increasing immersion time, the temperature fluctuation in the environment surrounding the immersion medium partly controls the rate of water penetration into the polymer matrix and brings about the linear fluctuation observed in the plot. Studying the trend, it can be postulated that the peak values for weight gained as seen at 96 h and 288 h will keep reducing with increasing immersion time until saturation point.

5. Conclusions

The mechanical properties (tensile, hardness and impact) and water absorption behaviour of HDPE composites reinforced with treated bamboo fibres have been studied. From the results, the following conclusions can be drawn;

i. Treated BF enhances the tensile, flexural, and hardness properties of the composites. The major enhancement was observed at 2 wt.% BF.
ii. With increasing BF fraction, these properties tend to reduce, apparently due to fibre agglomeration at higher loading fraction. Nevertheless, these properties show significant enhancement when compared with the control sample.
iii. The water absorption test also reveals that weight gained by all the composites increases with immersion time up till four days after which the composites started adding weight rather slowly.

iv. Finally, the results of this study have shown that treated bamboo fibres are suitable for reinforcing HDPE.

Declarations

Author contribution statement

Daramola OO: Conceived and designed the experiments; Analyzed and interpreted the data; Wrote the paper.

Akindote-White O: Performed the experiments.

Akinwekomi AD & Adediran AA: Analyzed and interpreted the data; Wrote the paper.

Sadiku ER: Contributed reagents, materials, analysis tools or data.

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Competing interest statement

The authors declare no conflict of interest.

Additional information

No additional information is available for this paper.

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