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MECHANICAL PROPERTIES AND WATER ABSORPTION BEHAVIOUR OF POLYESTER/SOIL-RETTED BANANA FIBRE (SRBF) COMPOSITES

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Abstract: The present study developed polyester matrix composites reinforced with banana fibres extracted from banana stem. The banana fibres were extracted by soil retting process. Polyester based composites were prepared by reinforcing the polyester with 10, 20, 30 and 40 wt. % of banana fibres in an open mould using hand lay-up technique. Mechanical (Tensile and Flexural) properties and water absorption behaviour of the developed composites were studied. It was observed that tensile strength increases linearly with increase in fibre content and flexural strength increase up to 20 wt. % before decreasing with further increase in fibre content. Overall, there was improvement in the mechanical properties of the developed composites when compared with the neat polyester. Water absorption test showed that the neat polyester and the composite with 10 and 40 wt. % SRBF exhibit Fickian diffusion mechanism whereas the composites containing 20 and 30 wt. % SRBF deviated from Fickian behaviour.
Keywords: Polyester, Banana fibres, Soil retting, Mechanical properties, Fickian diffusion

INTRODUCTION

Over the past few years, composite materials have been the dominant among all emerging materials. The volume and number of applications of composite materials have grown steadily, penetrating and conquering new markets persistently (Abilashet al., 2013). The intention of producing a composite material is to make a material that combines the best properties of the components whilst eliminating any poor properties. The incorporation of stiff fibers in soft matrices can lead to new materials with outstanding mechanical properties encompassing the advantages ofboth the fiber and matrix (Termonia, 1990). Fiber-reinforced composites are strong stiff and lightweight materials that consist of strong, stiff, but commonly, brittle fibers encapsulated in a softer, more ductile matrix material. The matrix transmits applied loads to the reinforcing fibers within the composite, resulting in a material with improved mechanical properties compared to the un-reinforced matrix material (Beckermann, 2007). Composite mechanical properties are strongly influenced by the mechanical properties and distribution of the fibers and matrix, as well as the efficiency of stress transfer between the two components. Mechanical properties such as strength and stiffness are of great importance when designing composite products. A drawback of natural fibres polymer composites is the incompatibility between the hydrophilic natural fibres and the hydrophobic thermoplastic matrices. This leads to undesirable properties of the composites. It is therefore necessary to modify the fibre surface by employing chemical modifications to improve the adhesion between fibre and matrix (Malkapuram et al., 2008). Banana fibres which are obtained from dried stalk of banana trunk, a waste product of banana cultivation, offers possibilities for engineering applications including automotive. Banana fibre possesses good specific strength properties comparable to those conventional materials like glass (Sapuan et al., 2006). Furthermore, this material has lower density than glass fibre (Mohan et al., 2007). However, banana fibres are associated with some challenges like high moisture uptake, low thermal stability and low bonding with polymers. Previous studies have shown that with appropriate surface treatment, the mechanical properties (such as impact, flexural, tension) can be improved (Bessadok et al., 2008). Alkali treatments have been proven effective in removing impurities from the fibre, decreasing moisture sorption and enabling mechanical bonding and thereby improving matrix-reinforcement interaction (Edeerozey et al., 2007). The performance of natural fibre varies with part of the plant that is used for fibre extraction, age of plant, fibre extraction process, and many more factors (Rowell et al., 2000). Extraction processes of natural fiberscan be performed by different procedures that include mechanical, chemical and biological methods. Each method presents different advantages or drawbacks according to the amount of fiber produced or the quality and properties of fiber bundles obtained (Ganan et al., 2004). Rettingwhich is a fibre extraction method can be achieved mechanically by hammering or chemically by boiling & applying chemicals. The choice depends on the availability of water and the cost of retting process. Dew retting is most popular in Europe, but its quality is not good as much as water retting. Water retting technique is being used in Asian countries (Mwaikambo, 2006).Thermosetting polyester has moderate mechanical properties when compared to other materials such as epoxy and vinylester and this has limited its uses in engineering applications. However these limitations can be improved by adding reinforcements as a means of enhancing the properties of polyester.Oladeleet al.(2013) had shown that soil retting is a promising and low cost process for extracting natural fibres.Hence, utilizing soil retted banana fibres(SRBF) as reinforcement in polyester matrix composites would help to improve its mechanical properties. Upon developing this composite, it would serve a number of interesting engineering applications which would come at a cheap cost and would be environmentally friendly. Nigeria is one of the largest banana producing countries in the world the use of its fiber for material development would be very huge potential in the country's economy. Hence, this work was carried out to ascertain the tensile and flexural properties as well as the water absorption behaviour of polyester composites reinforced with banana fibres extracted by soil retting process.

MATERIALS AND METHODS

Materials

Materials that were used in this work are:Unsaturated polyester resin (with properties such as pink appearance, density of 1.2 g/cm^3 and stability in the dark below 25°C), Accelerator (Methyl Ethyl Ketone Peroxide, MEKP), Catalyst (Cobalt Naphthanate), sodium hydroxide, banana fibres and mould release agent (solid lubricant). The banana stem from which the banana fibre is extracted was obtained from a farmland in Akure, Ondo State, South-West, Nigeria. The polyester resin, catalyst and accelerator were all procured from a chemical store in Ibadan, South-West, Nigeria. Sodium Hydroxide used for chemical treatment of the fibres was procured from Pascal Scientific Ltd. Akure, South-West Nigeria.

Banana Fibre Extraction

Banana fibres were extracted from the banana stem by a process known as soil retting. The banana stem was buried in the ground for 21 days for it to rotten. After the rotting process, it was dug out from the ground to get the banana fibres after which thorough washing in distilled water was done before sun drying.

Chemical Treatment of Soil-Retted Banana Fibre (SRBF)

The extracted banana fibres were immersed in 6% NaOH solution for 2 hours at room temperature. After the sodium hydroxide treatment, the fibres were thoroughly washed by dipping in water containing tanks, followed by running water. The fibres was then filtered and dried in an air blast oven. The banana fibres before and after chemical treatment are shown in Figure 1.

a)

b)

Figure 1: (a) Soil-Retted Banana Fibres (b) Chemically Treated Banana Fibres

Mould Preparation

Tensile mould of gauge length 90 x 10 x 5 mm of a dumb-bell shape and flexural mould of 150 x 50 x 5 mm were used for the production of tensile, flexural and samples from which the samples for the water absorption test were obtained. A solid lubricant was applied on the surface of the aluminium mould to aid easy removal of the cured composite samples.

Composite Fabrication

An open aluminium mould was used to prepare the soil-retted banana fibre reinforced polyester composites using hand lay-up method. The fabrication process started with the determination of the quantities of soil retted banana fibre (SRBF) required in producing 10, 20, 30 and 40 wt. % reinforcement. Measured quantities of polyester resin (which served as matrix for the composites to be fabricated) was mixed with a measured quantities of accelerator (MEKP) and catalyst (Cobalt Naphthanate) then stirred with a rod manually to achieve homogenization. A weighed quantity of banana fibre was placed in the mould after a layer of the mixture (polyester, catalyst and accelerator) had been poured in the mould, and then followed by the final layer of mixture in the mould to seal up the fibres. The total mixture was left in the air for about 30 minutes to cure beforebeing ejected from the mould. Unreinforced polyester functioned as the control sample. The composition and designation of the fabricated composites is presented in Table 1.

Table 1: Composition and Designation of Fabricated Composites

Composition	Designation
100% Polyester	PSRBF0
10 wt. % SBRF/90 wt. % Polyester	PSRBF10
20 wt. % SBRF/80 wt. % Polyester	PSRBF20
30 wt. % SBRF/70 wt. % Polyester	PSRBF30
40 wt. % SBRF/60 wt. % Polyester	PSRBF40

MECHANICAL TESTING

Tensile Test

The tensile test is generally performed on flat specimens. The commonly used specimens for tensile test are the dog-bone type. Tensile tests were performed on INSTRON 1195 at a fixed Crosshead speed of 10 mm/min. Samples were prepared according to ASTM D303-08 standard (2008), and tensile strength of the neat and reinforced composite samples were calculated. The results presented are the average of three individual test samples.

Flexural Test

The flexural strength of the composites was estimated by performing three-point bending tests on the composites. The test was performed at room temperature using a tensiometric universal testing machine operated at a crosshead speed of 0.3 mm/min. The testing procedure and flexural strength determination were performed in accordance with ASTM D7264M-07 standard (2007). The results presented are the average of three individual test samples.

Water Absorption Test

The water absorption tests were carried out following the recommendations specified in ASTM D5229M-12 (ASTM, 2012). Each composite sample was dried in an air blast oven to remove surface moisture and adhering lubricant before weighing. The weight of the oven dried samples was reported as the initial weight of the composites. The samples were then placed in distilled water maintained at room temperature (25°C); and at time intervals of 24 hours, the composite samples were removed from the water, cleaned using a dry cloth and weighed. The weight measurements were taken periodically at time intervals of 24 hours for up to 168 hours. This was after water saturation in all the composite samples had been noticed. The percentage water absorbed by the composites was calculated using the equation (1)

$$W\,(\%) = \frac{W_t - W_0}{W_0} \times 100\% \qquad (1)$$

Where W is percentage water absorption, Wo and Wt are the oven dry weight, and the weight of the sample after time t, respectively. Graphical plot of percentage water absorption for all the composites samples produced was made. The water absorption curve obtained for all the composite samples was used for analysis of the diffusion mechanism. Composites usually conform to Fickian diffusion profiles, but this fact is verified with the experimental data of the different composite compositions. The mechanism of water diffusion into the composites was studied by analysing the slope and intercepts of the water absorption graphs plotted by using the relations in equation (2) and (3) according to Sombastsompop and Chaochanchaikul (2004). The experimental data were fitted to the logarithmic equation (3) whose slope (n) helps determines the diffusion case

$$\frac{M_T}{M_\infty} = kT^n \qquad (2)$$

$$\text{Log}\,\frac{M_T}{M_\infty} = \text{Log}\,(k) + n\,\text{Log}\,(T) \qquad (3)$$

Where M_T is water absorption at interval time T which is the time of immersion, M_∞ is water absorption at saturation point or mass of water absorbed at equilibrium, k is a constant parameter related to the polymer network structure and n is the diffusion exponent value that determined the type of diffusion mechanism.

RESULTS AND DISCUSSION

Mechanical Properties

The tensile properties evaluated from the tensile test are - the ultimate tensile strength, young modulus and elongation at break whereas the flexural properties evaluated from the flexural test are flexural strength and flexural modulus. Table 2 gives a summary of these properties

Table 2: Tensile and Flexural Properties of the Composites

Sample	Tensile strength (MPa)	Tensile modulus (MPa)	Elongation at break (%)	Flexural strength (MPa)	Flexural modulus (MPa)
PSRBF0	10.11	205.45	4.921	16.82	528.24
PSRBF10	11.03	350.94	3.143	18.19	530.65
PSRBF20	11.05	455.81	2.523	26.73	596.90
PSRBF30	12.45	518.97	2.399	25.75	548.75
PSRBF40	17.59	904.84	1.944	25.29	537.32

Figure 2 shows the variation of the ultimate tensile strength for the composites. It was observed that the tensile strength of the composite increases linearly with increase in fibre content. However the best result was obtained in the composite with PSRBF40 with a value of 17.59MPa which represents a 74% increment over the neat polyester. The increase in tensile strength could be attributed to better wettability and interfacial bond between the soil-retted banana fibres and the polyester matrix. The matrix was able to distribute the applied stress evenly among the soil-retted banana fibres, hence improved strength (Malequeet al., 2007). The lower tensile strength value obtained in the samples with 10 and 20 wt. % SRBF was because the amount of fibres incorporated was too small to support the matrix. Nonetheless, they still performed better in tension compared to the neat polyester.

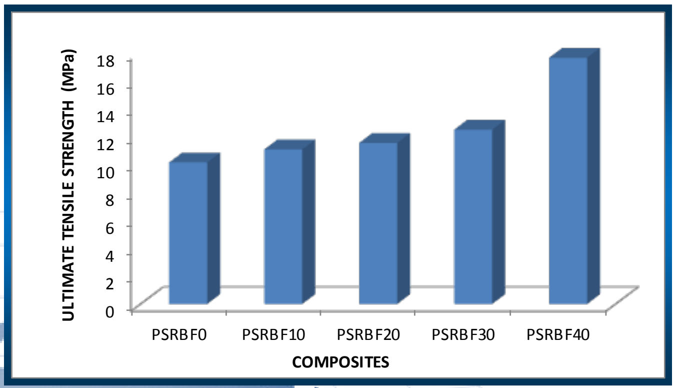

Figure 2: Variation of UTS of the Neat Polyester and Polyester/SBRF Composites

The result of the effect of SBRF content on the tensile modulus is shown in Figure 3, which followed a similar trend as the tensile strength results. It can be observed that the tensile modulus of the composite increases gradually with increasing SRBF loading. The increase in tensile modulus of elasticity is due to the fact that the SBRF provides a stiffening effect in the composites. It has been reported that banana fibres possess higher elastic modulus than polyester, hence the increase in tensile modulus of the composites (Geethamaet al., 1998)

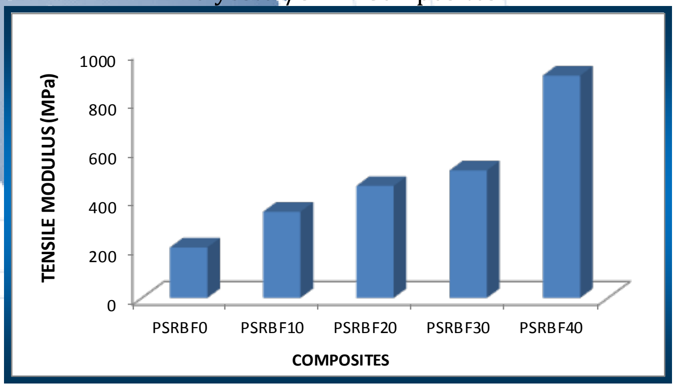

Figure 3: Variation of Tensile Modulus of the Neat Polyester and Polyester/SBRF Composites

Elongation at break is the strain experienced by a sample when it fractures. It is usually expressed in percentage and is a measure of the ductility of the material. From engineering point of view, elongation at break is an important parameter describing the rupture behaviour of composite materials.

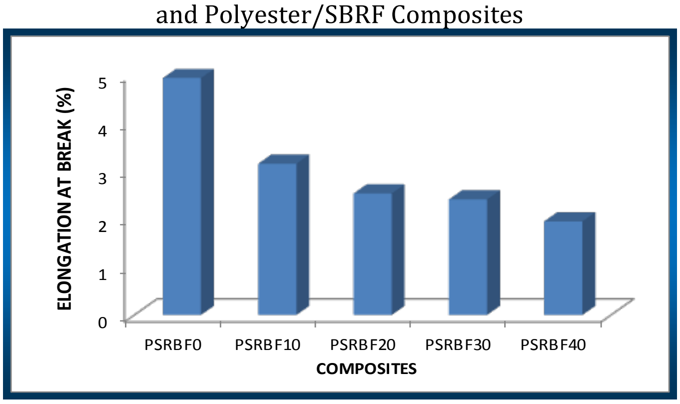

Figure 4: Variation of Percentage Elongation of the Neat Polyester and Polyester/SBRF Composites

Figure 4 reveals the variation of elongation at break of neat polyester and the developed composites. Percentage elongation decreases linearly as the SRBF content increasesfollowing an opposite trend to the tensile strength and stiffness results. The reduced elongation is expected as the SRBF provides a stiffening effect in the composite as seen in Figure 3. The highest ductility was experienced in the neat polyester with a value 4.921 % while the lowest was experienced in the PSRBF40 sample with a value of 1.944 %.

The flexural property is one of the important parameter in composites mainly useful to quantify them in structural applications. Flexural strength denotes the ability of a material to withstand bending or twisting load. The flexural strength of the neat polyester and the developed composites is shown in Figure 5, where it was observed that flexural strength increases with increase in the volume fraction of SBRF up to 20 wt. % before it starts declining. The flexural strength of the developed composite increased from 16.82MPa in the PSRBF0 sample to 26.73MPa in the PSRBF20 sample which represents a 59% increment. This improvement is due to enhanced fibre/matrix adhesion.However, the slight decrease in the bending strength beyond 20 wt. % of SRBF can be related to the decrease in the wettability due to high fibre loading. The inability of the resin to wet the fibres properly leads to the slight decreasestrength under flexural loading. Improper mixing and lay up of fibres could also be a significant cause. When compared to the PSRBF20 composite with the peak flexural strength value (26.73MPa), the PSRBF30 and PSRBF40 samples had flexural strengths 3.8 % and 5.7% less respectively. Generally, all the composite grades had better flexural strength than the neat polyester which implies that soil-retted banana fibres enhances the flexural strength of the composites due to the role they play by supporting stresses that acts transversely to their composite axes.

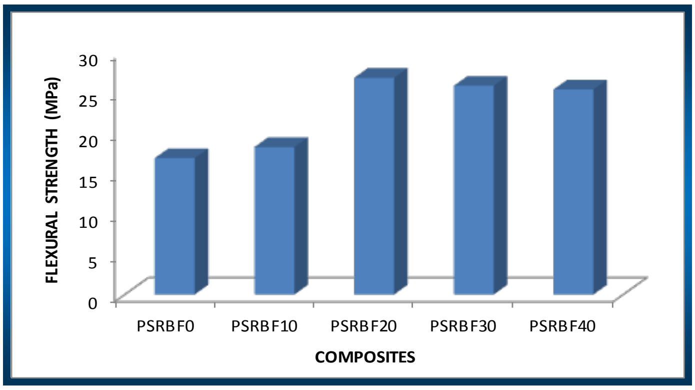

Figure 5: Variation of Flexural Strength of the Neat Polyester and Polyester/SBRFComposites

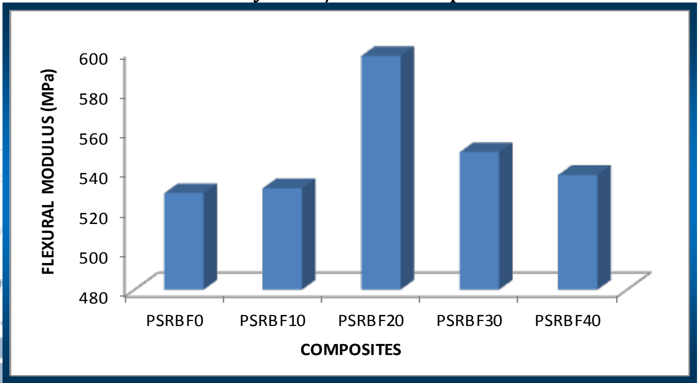

Figure 6: Variation of Flexural Modulus of the Neat Polyester and Polyester/SBRFComposites

The flexural modulus which follows the same trend as the flexural strength is presented in Figure 6. It was observed from the results that the flexural modulus also increases with increase in the volume fraction of SRBF up to 20 wt. % with a flexural modulus of 596.90 MPa before it decreased to a flexural modulus of 537.32 MPa in the composite with 30 wt. % SRBF.The decrease in flexural modulus beyond 20 wt% could be attributed to the poor interaction between the constituents and poor dispersion of the fibre in the polyester matrix (Asri and Abdul Khalil, 2002; Arib,2003). However, all the composite grades had higher flexural stiffness than the neat polyester matrix which implies that the incorporation of SRBF enhances the flexural modulus of the polyester composites.

WATER ABSORPTION PROPERTIES OF THE COMPOSITES

The water absorption curve for the different composite samples is presented in Figure 7. It can be seen from the plot that the water absorption by the composites increases monotonically with immersion time until equilibrium condition is reached after 168 hours at which saturation was experienced in all the samples. For all the samples, the process of water absorption is at the beginning linear type. After it slows and finally after extended immersion time, the samples approaches to the saturation point. Hence, the water absorption behaviour

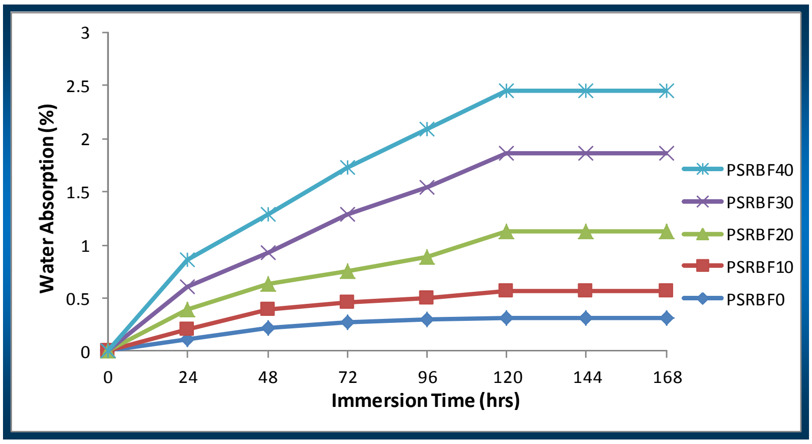

Figure 7: Water Absorption Curves for the Polyester/SRBF Composites

for all the composites can be modelled as Fickian diffusion process. Water absorbed by the neat polyester was insignificantly small. This confirms the hydrophobic nature of polyester. The water uptake for samples with 10, 20, 30 and 40 wt. % SRBF were found to increase monotonically and levelled off at longer immersion time which is an indication of saturation. The saturation moisture content (i.e. levelling off period) increases with the increasing SRBF concentration. The water ingress is also due to the hydrophilic nature of soil-retted banana fibres and also due to the capillary action when fibre ends are exposed to water (Pothanet al., 1997).
Maximum uptake was observed in the PSRBF40 sample. The alkaline surface treatment is used to improve the hydrophobic property of the cellulose allowing increased interfacial strength between the matrix and fibre. Chemical functionalization with hydrophobic constituents improves the adhesion of hydroxyl groups of cellulose; hence the susceptibility to water ingress may be decreased (Shinojet al., 2011; La Mantia and Morealle, 2011). The alkaline treatment produced a fibre with a rough surface thus, making the pore spaces between the matrix and fibre wider. This also contributed to the increasing water absorption with rising SRBF content. It can therefore be stated that the SRBF content in the composites clearly influences the water absorption curves.

Water Diffusion Mechanism

Water diffusion behaviour of polymer matrix composites obeys Fick's diffusion theory and it's reported to be dependent on the relative mobility of water molecules and polymer segments (Dhakalet al., 2007). On account of the transportation of water molecules and polymer segments, when the rate of diffusion of water molecules is much less than that of the polymer composite segment mobility, it is known as Fickian's diffusion mechanism or Case I. For this particular mechanism diffusion exponent value (n) is 0.5 and it's independent of time (Thwe and Liao, 2002). If the rate of penetrant (water molecules) mobility is much greater than other relaxation processes (polymer segment mobility), Case II prevails. The value of n is 1.0 and indicates that diffusion process is more rapid than the relaxation process. $0.5<n<1.0$ indicates Non-Fickian diffusion mechanism (anomalous) which describe cases where the diffusion and relaxation rates are comparable. In this type of diffusion mechanism there is intermediate behaviour between Fickian and non-Fickian diffusion (Cárdenas et al., 2003). When the water penetration rate is much below the polymer chain relaxation rate, it is probable to record the n values below 0.5. This situation, which is classified also as Fickian diffusion, is called as 'Less Fickian' behaviour (Wang et al., 2008; Ganjiet al., 2010).There are cases where $n>1$, such as usually referred to as Super Case II mechanism (Munday and Cox, 2000). These three cases of diffusion can be distinguished theoretically by the shape of the water absorption curve represented by power law expression given by Sombastsompop and Chaochanchikul (2004). Upon fitting the experimental data into equation (3), the diffusion curve fitting was plotted and presented in Figure 8.

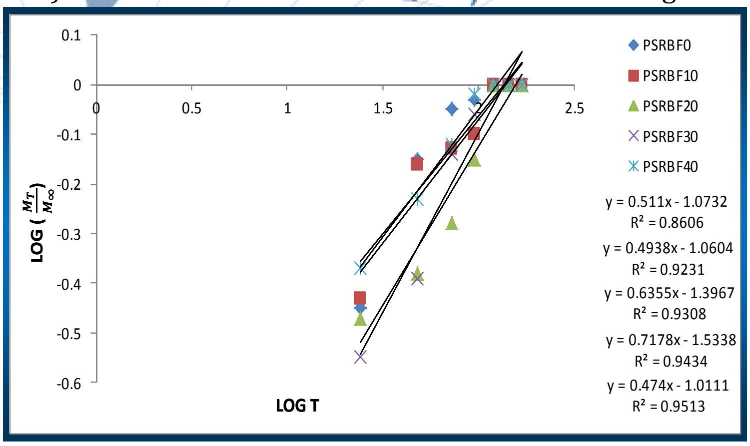

Figure 8: Diffusion Curve Fitting Plot for the Polyester/SRBF Composites

The water sorption constants and water diffusion mechanisms in the polyester/SRBF composites produced are summarized in Tables 3 and 4 respectively.
The water sorption constants n and k calculated from the fitting of the experimental data into equation 2.3 have been presented in Table 3. It can be observed from Table 3 that the diffusion exponent (n) value ranges between 0.474-0.718. The neat polyester and composites with 10 and 40 wt. % SRBF shows a diffusion behaviour approaching Fickian model as seen by their diffusion exponent (n) values being closer to 0.5. This implies that the rate of penetrant (water molecules) diffusion is much less than that of the polymer segment mobility. The PSRBF20 and PSRBF30 composites both exhibited anomalous diffusion mechanism. This irregularity in diffusion

Table 3: Water Sorption Constants of the Polyester/SRBF Composites

Sample	Slope (n)	Intercept (k)	R^2
PSRBF0	0.511	1.0732	0.8606
PSRBF10	0.494	1.0604	0.9231
PSRBF20	0.636	1.3967	0.9308
PSRBF30	0.718	1.5338	0.9434
PSRBF40	0.474	1.0111	0.9513

mechanism of these composites is due to the fact that the penetrant mobility and the polymer segment relaxation are equally corresponding. The composite with 30 wt. % SRBF had the highest diffusion exponent whereas the lowest was experienced in the PSRBF40 composite. The k value gives an indication of the interaction between water and materials (Kittikornet al., 2013). It can be seen from the tablethat the k value increase gradually from the composite containing 10 wt. % SRBF until it peaked at 30 wt. % SRBF. Furthermore, the increasing k value showed that good number composites had greater interaction with the penetrant. Generally, the water diffusion mechanism for the produced composites is presented in Table 4.

Table 4: Water Diffusion Mechanism for the produced Composites

Type of diffusion mechanism	Slope (n)	Time dependence	Composites
Less Fickian	$n < 0.5$	$t^{-1/2}$	_
Fickian Diffusion	$n = 0.5$	$t^{1/2}$	PSRBF0, PSRBF10, PSRBF40
Non-Fickian (Anomalous) Diffusion	$0.5 < n < 1.0$	t^{n-1}	PSRBF20, PSRBF30
Case II Diffusion	$n=1.0$	Time independent	_
Super Case II Diffusion	$n>1.0$	t^{n-1}	_

CONCLUSIONS

The mechanical properties and water absorption characteristics of polyester matrix composites reinforced with varied weight fractions of soil-retted banana fibre (SRBF) have been investigated. From the results obtained, the following conclusions are drawn:

≡ The tensile strength and tensile modulus of the composites increases with increase in the volume fraction of reinforcement (soil-retted banana fibre) due to better wettability, good interfacial bond between the banana fibre and the matrix, high elastic modulus of the reinforcing material. The elongation at break however experienced continuous decrease as fibre content increases.

≡ Flexural modulus and flexural strength of the composites also increases with increase in the volume fraction of reinforcement up to 20 wt. %. Further increase lead to drop in both values. However the flexural strength and stiffness of all the composites were higher than the neat polyester indicating property enhancement.

≡ The degree of water absorption was found to be a function of SRBF content. The diffusion transport mechanism as predicted from the diffusion exponent (n) showed that a large number of composites exhibited Fickian diffusion mechanism.

≡ Summarily, the results showed that soil retting extraction process and subsequent chemical treatment can help produce banana fibres with good reinforcement properties for composite development.The mechanical property enhancement which soil-retted banana fiber imparts alongside their inexpensive and abundant nature makes polyester composites suitable for industrial applications.

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