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(RESEARCH ARTICLE)

Investigation of moisture absorption rate and diffusivity of plant fibre-reinforced composites

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Abstract

This research investigated the moisture absorption rate and diffusivity of plant Fibers-reinforced-composites; using bamboo fiber, raffia and coconut fibers through laboratory experimental investigations. The major limitation of using natural fibers in durable composite applications are their high moisture absorption and poor dimensional stability (swelling); and this swelling of fibers causes micro-cracking and degradation of the composites. In this investigation, the fibers were treated with sodium hydroxide (NaOH) chemical and acetylation to decrease the hydroxyl group in the fibers. Experimental results reveal that the moisture absorption and degree of swelling of the treated bamboo raffia and coconut fiber composites are 25 - 35% lower than those of composites produced with untreated bamboo, raffia and coconut fibers. Experimental results also show that strong intermolecular fiber-matrix bonding decreases the rate of moisture absorption in bio-composites. The diffusivity of the bamboo, raffia and coconut fibers-reinforced-composites for 24hrs at 100^{0}C were experimentally measured to be 4.91, 3.33, and 3.94 mm^2/sec respectively. The results showed that when these fiber plant materials are treated with sodium hydroxide (NaON) the diffusivity rate of the fiber reinforced composite material is brought under considerable control and its dimensional stability immensely enhanced though improved strong intermolecular fiber-matrix bonding and the reduction of swelling.

Keywords: Absorption; Diffusivity; Plant fibers; Swelling; Fiber-matrix

1. Introduction

Natural fibers are hydrophilic in nature, and they absorb or release moisture, depending on the environmental conditions. A major limitation of using natural fibers (bio-fibers) in durable composite applications is their high moisture absorption and poor dimensional stability (swelling) [1]. Swelling of fibers can lead to micro-cracking of the composites, and degradation of their mechanical properties. The target of this research is to estimate the Moisture Absorption and Diffusivity rates of plant fiber-reinforced composites.

The use of composites in place of other engineering materials has been advantageous, but encounters a major problem when used at elevated temperatures, and/or soaked in water for a long time. They have the problems of mechanical strength and stiffness reduction when exposed to environments of water/moisture for long times. Another a major limitation on the use of plant fibers in durable composites applications are their high moisture absorption and poor dimensional stability. However, this problem can be mitigated by proper treatment of the fibers with the desired and required chemical(s) so as to improve their surfaces and surfaces roughness, and decrease the hydroxyl group in the fibers. Furthermore, composites are not successfully used in high temperature environments because their intermolecular bonding and mechanical properties are greatly affected. They (the composites) perform best at room

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temperature. When chemical treatments, such as acetylation and sodium hydroxide (NaOH) are carried out on these plant fibers, it helps to limit the moisture adoption process, chemically modify the plant fibers' surfaces, and increase the surfaces roughness.

Modification of the fibers also improves resistance to moisture-induced degradation of the interface, and the composites' properties [2]. Plasticization of the polymers by absorbed moisture causes a reduction in the glass transition temperature, T_g and a corresponding degradation of composites' properties. See figure 1

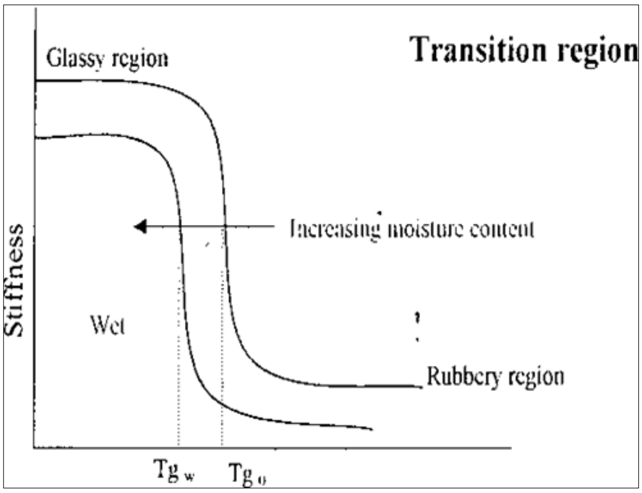

Figure 1 Variation in stiffness of a typical polymer under varying temperature, showing the glass transition temperature, T_g and the effect of absorbed moisture on T_g.

Moisture absorption by composites occurs by diffusion, which is a thermally activated process.

The diffusivity, D is related to temperature by the Arrhenius relationship, (as in Frick's law).

$$D = D_o \exp(-E_a/RT) \qquad 1.1$$

where D_o= material constant

E_a = activation energy for diffusion

R = universal gas constant

T = absolute temperature.

Natural fibers are hydrophilic in nature and they absorb or release moisture, depending on the environmental conditions. Swelling of fibers due to poor dimensional stability can lead to micro-cracking of the composites, and degradation of their mechanical properties. This is because hydrothermal expansion or contraction alters the stress and strain distribution in the composites.Increased temperature and/or moisture content cause swelling of the polymer matrix, whereas reductions in temperature and/or moisture content induce contraction.

$$\text{Increase in mass} = \frac{\text{Conditonal mass} - \text{Dry mass}}{\text{Dry mass}} \text{x } 100\%$$

Let M_C = Conditioned mass

M_d = Dry mass

1.1. Composite naterials

Composite Material is also called composition material with short name to as composite which is its common name. It is a material that is produced from two or more constituent materials. The constituent materials have notably dissimilar chemical or physical properties and they are used to create a material with properties different from the individual elements. Within the finished structures, the individual elements remain separate and distinct. Typical examples of composite materials are reinforced concrete, composite wood (like plywood), reinforced plastics (fibre-reinforced polymer, etc. There are many reasons why composite materials are favoured and mostly used [3]. The reason is that the materials are less expensive and more readily available. Secondly, the materials are lighter or stronger when compared to the single constituent materials. Composite materials are generally used for buildings, bridges and structures such as boat hulls, swimming pool planets, racing car bodies, shower stalls, bath tubes, storage tanks, imitation granite and cultural marble sinks, countertops and robotic materials. The most advanced examples of composite materials perform routinely on space craft and aircraft demanding environments[4].

1.2. Types of composites

The reinforcing materials provide increased strength and stiffiness to the composites. The matrix materials on the other hand, are responsible not only for covering the reinforcement (thereby protecting them from environmental and chemical change) but also for elimination of fiber wearing and crushing that can be caused by deformation, they fix the fibers in position, which is crucial as the reinforcing materials could otherwise easily slip out or become damaged through wear [5]. The matrix material also act as load transferring media; they transfer the load to an orthorgonal direction from fiber axis. It has previously been established that the properties of reinforced composites (such as resistance against loading) vary according to the three dimensions of space. In most construction materials, the stress pattern should be well defined, following force lines; high strength and stiffiness are of primary importance close to force lines, while lower values are suitable away from the point. This accounts for the fact that homogenous material with different reinforcement has a higher modules and strength parallel to loading [6].

The anisotropic nature of composites should facilitate the design of suitable products and structures; however, an adequate knowledge of the strength distribution lines is a prerequisite. The successful application of reinforced composites requires strong adhesion and interfacial forces (both chemical and physical between the matrix and the reinforcements, moreover, this strong interaction must be maintained during all types of loading [7].

Despite such challenges of bio-fibers as their cultivation and continuity of the plants, their usage and application with enhanced features have gained immense importance. L. cylindrica has been recognized as a new biodegradable materials and luffa reinforced composite are being investigated for practical applications. Like other natural fibers, luffa fibers do not create health risk when individuals are exposed to them and they are inexpensive [8].

1.3. Hydrothermal degradation of composites' properties

As reported by Browning *et al.,* (1997), who experimented on graphite/epoxy composites under hydrothermal conditions of various combinations of temperature and absorbed moisture, the imposed hydrothermal conditions cause substantial reductions of both strength and stiffness in both cases, with the 'hot–wet' conditions (combined high temperature and high moisture content) generating the most severe degradation. Based on the data published by Gibson *et al.,* (1982) on the hydrothermal sensitivity of matrix-dominated composites' properties, it was expounded that composites having some continuous fibers and high fiber contents absorb little moisture and show negligible change in modulus with time of soaking. On the other hand, composites with matrix-dominated behaviour (i.e. composites with chopped fibers only, and low fiber contents) exhibit the most moisture "picking" and greatest reduction in modulus.

1.4. Fibre reinforced materials

The plane strain bulk modules and the two shear module of multiphase transversely isotropic fiber reinforced material of arbitrary transverse phase geometry are bounded from above and below in terms of phase module and phase volume fractions. Particular attention is given to the important special case of two-phase fiber reinforced materials.

1.5. Reinforced composites

Reinforced composite is made of high strength addictive which is included in the original resin. The addictive could be glass, carbon, Kevlar fibre, etc. These fibre may be random oriented or inmat format. In some cases, fine metal shavings are used. A common means of achieving the process is through spray up. A catalyst, resin and chopped ravings are all sprayed into mold. For instance in the case of spas, the tub is thermoformed and then spray up is done to strength the part.

Filament winding is another reinforced composite method. In the process, a continuous fibre is wrapped repeatedly into mold to produce directional strength. A large portion of the filament winding done in industry is custom manufacturing.

Pultrusion is a third process by which reinforced composites are made. The process allows composites of a constant profile to continuously produce. The ravings or fibers are pulled through a resin, which impregnates the material. The part strengthens as the resin is allowed to cure,

Composite fabrication is a largely specialized area of study. Thus there are very few companies that focus on composites fabrication to make the bulk of their income and profit. These composites are usually self-managed as opposed to having a corporate office that oversees many smaller plants spread throughout the world.

Reinforced composites are the most widespread type of polymer composite used today. The structural material uses a polymer as the matrix, completely covering the reinforcement, without these reinforcements, the polymer would offer relatively poor mechanical properties. Several studies have investigated the type of reinforcing material used on the properties of the final composite, looking also at related issues such as pre-treatment. There are three principal ways in which the reinforcing material can be incorporated as grainy material (that is as particulates), as fibers (in the form of individual fibers embedded in the matrix) and as layers (fibers woven into mats which are laid on top of one another to create a laminate) [9].

2. Material and methods

2.1. Materials

The basic natural materials used in this research include fibers (coconut, raffia palm, and bamboo fibers), polyester resin, accelerator (cobalt), catalyst (MEKP), binders, formica moulds, gel coat resins, and release agents.

2.1.1 Fibers

The fibers used were extracted from the stem of bamboo plant, raffia plant and coconut husk.

2.1.2 Catalyst

These are chemical compounds used to initiate the chemical reactions of the unsaturated polyester in styrene monomers from liquid to solid states. The catalyst used is Methyl-ethly ketone Peroxide (MEKP).

2.1.3 Accelerator

This compound was used to promote the catalyst at lower temperature. The accelerator used is cobalt.

2.1.4 Polyester resin

The resin used is unsaturated orthostatic polyester. It consists of linear modulus, which is not connected.

2.1.5 Release agents

Polyvinyl Alcohol (PVA) was used.

2.1.6 Binder

This was used during loading of the fibers to hold them together, thereby facilitating effective handling. Polyvinyl acetate was used.

2.1.7 Gel coat resins

This is a protective initial layer of a fiber-reinforced laminate.

2.1.7.1 Tools

The tools used in carrying out the investigations include paint brush, a pair of scissors, rubber hand gloves, rollers, and electric cutting machine.

2.2. Methods

The procedures adopted for the research are:

2.2.1 *Fiber Extraction*

- Fiber extraction from coconut
- Fiber extraction fromraffia palm
- Fiber extraction from bamboo

2.2.2 *Fiber Load Formation*

The fiber loads were formed with regard to chopped strands mat approach. Figure 2.1 exhibits the three samples of the fiber loads formed.

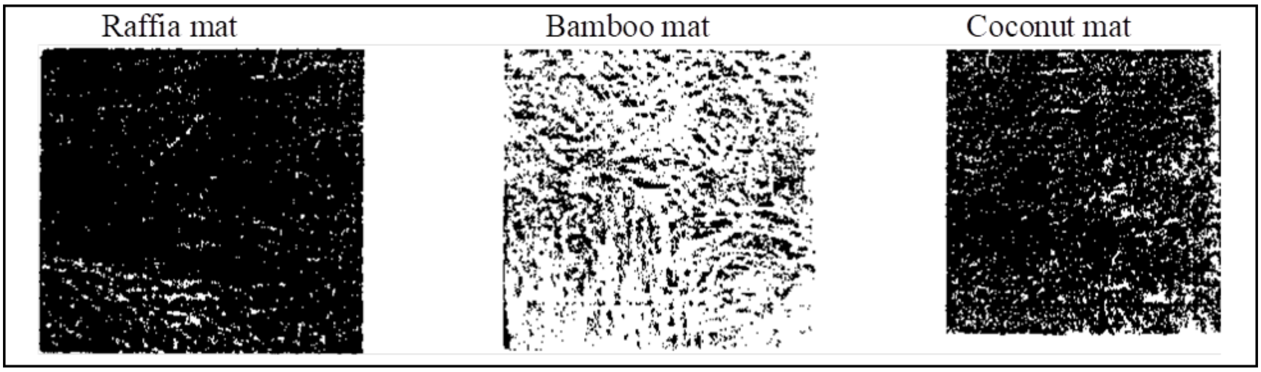

Figure 2 Three samples of formed fiber loads

2.2.3 *Preparation of the Composites for Testing*

The composites were made from the processed and matted fibers. The resin was accelerated with cobalt, then catalyzed with MEKP. The composites were then cut into test specimens of 40 x 20 x 20 mm^3 sizes. The entire specimens were modified (chemically treated with NaOH), and soaked in water for 4hrs, 8hrs, 12hrs, and 24hrs; and heated for 20^{0}C, 40^{0}C, 60^{0}C, and 100^{0}C. These processes were carried out at constant fiber volume fraction, $V_f = 0.35$.

The weight gains of the conditioned specimens were carefully monitored by weighting multiple specimens periodically (4, 8, 12, and 24hrs at 20, 40, 60, and 100^{0}C respectively), with precautions taken to remove the surface moisture by wiping before weighing.

2.2.4 *Volume Fraction Measurement*

Archimedes' principle was applied in the determination of the fibers' volume fractions.

$$\text{Solid volume fraction} = \frac{\text{Volume of solid}}{\text{Volume of fluid}} \qquad 2.1$$

$$\therefore \text{Fiber volume fraction} = \frac{\text{Volume of filter}}{\text{Volume of composite}} = \frac{V_f}{V_c} \qquad 2.2$$

$$= \frac{V_f}{V_f + V_m}$$

where $V_f$is the fiber volume

V_m is the matrix volume, and

V_c is the volume of the composite

3. Results and discussion

The tables and graphs for the moisture absorption of the raffia, bamboo, and coconut fibers-reinforced-polyester composites are given below.

Table 1 Moisture Absorption Results of Raffia, Bamboo and Coconut Fiber-reinforced-Polyester-composites at V_f of 0.35

Types of Composites	**Temperature ^{0}C**	**Soaking time (hours)**	**Mass (g) Before Soaking**	**After**	**Moisture Absorption (%)**
Raffia Fiber Reinforced Composites	20	4	43.0139	43.0390	0.06
		8	43.0138	43.0434	0.07
		12	43.0821	43. 0821	0.16
	40	24	43.0140	43.0920	0.18
		4	43.0137	43.0433	0.07
	60	8	42.9250	43.0000	0.17
		12	44.0100	44.0910	0.18
		24	43.0135	43.1000	0.20
	100	4	43.0000	43.0500	0.12
		8	43.5000	43.6500	0.34
		12	42.9000	44.1500	2.91
		24	44.0000	45.4120	3.21
		4	43.0189	43.1092	0.21
		8	43.0345	44.1835	2.67
		12	43.0400	44.5550	3.52
		24	42.9860	45.0966	4.9
Bamboo Fiber Reinforced Composites	20	4	44.8810	44.8990	0.04
		8	44.8819	44.9090	0.06
		12	44.8825	44.9720	0.19
	40	24	44.7200	44.7905	0.16
		4	44.2000	44.2300	0.06
	60	8	43.0900	43.4175	0.11
		12	42.9900	43.1000	0.17
		24	44.0000	44.0900	0.20
	100	4	43.9200	44.0000	0.18
		8	44.1000	44.1900	0.20
		12	44.2000	44.8100	1.38
		24	44.3010	45.2100	2.05
		4	44.3090	48.7021	0.19
		8	44.2900	44.9145	1.41
		12	43.9980	44.8780	2.01
		24	44.0320	45.7863	3.33

Coconut Fiber Reinforced Composite	20	4	37.6740 37.6902	0.04
		8	37.5220 37.5400	0.05
		12	38.0010 38.0700	0.18
		24	37.3900 37.4510	0.17
	40			
		4	37.5200 37.5460	0.07
		8	37.6750 37.7277	0.14
		12	37.7000 37.7641	0.17
		24	37.3000 37.3895	0.24
	60			
		4	37.6700 37.7077	0.10
		8	37.5900 37.6915	0.27
		12	37.6100 37.3660	2.01
		24	37.8000 37.8773	2.85
	100			
		4	37.9085 37.9847	0.20
		8	38.0000 38.5130	1.35
		12	37.9800 38.8308	2.24
		24	38.1000 39.6011	3.94

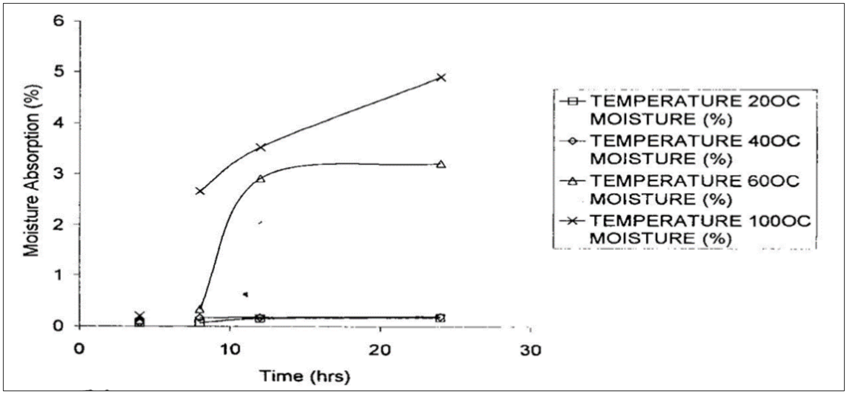

Figure 3 Moisture Absorption Vs Time graphs of raffia fiber-reinforced composites at V_f of 0.35

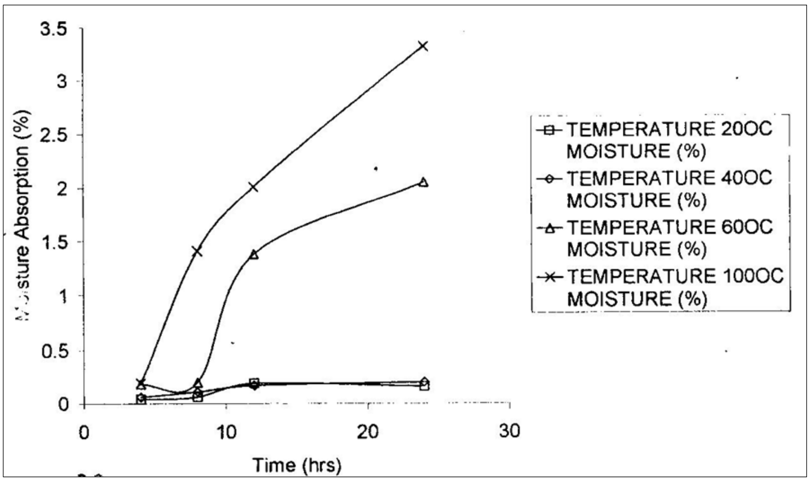

Figure 4 Moisture absorption vs time graphs of bamboo fiber-reinforced-composites atVf of 0.35

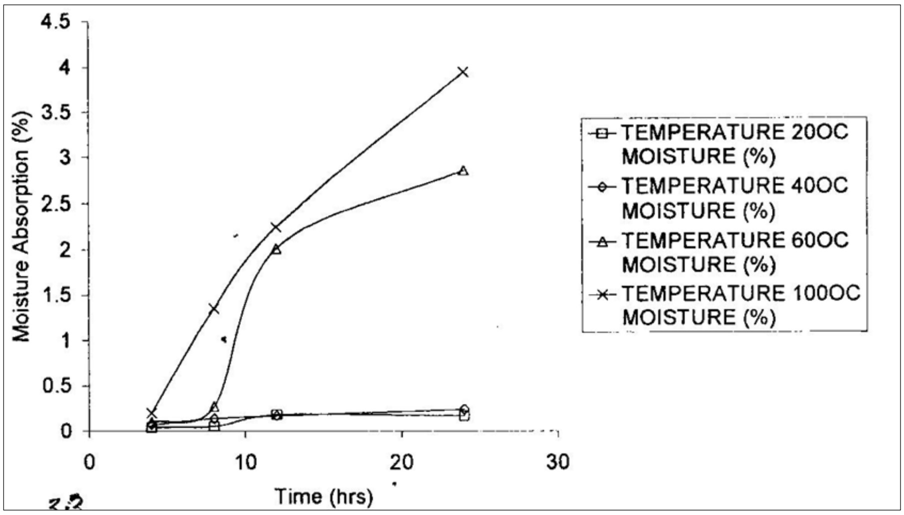

Figure 5 Moisture absorption vs time graphs of coconut fiber-reinforced-composites at Vf of 0.35

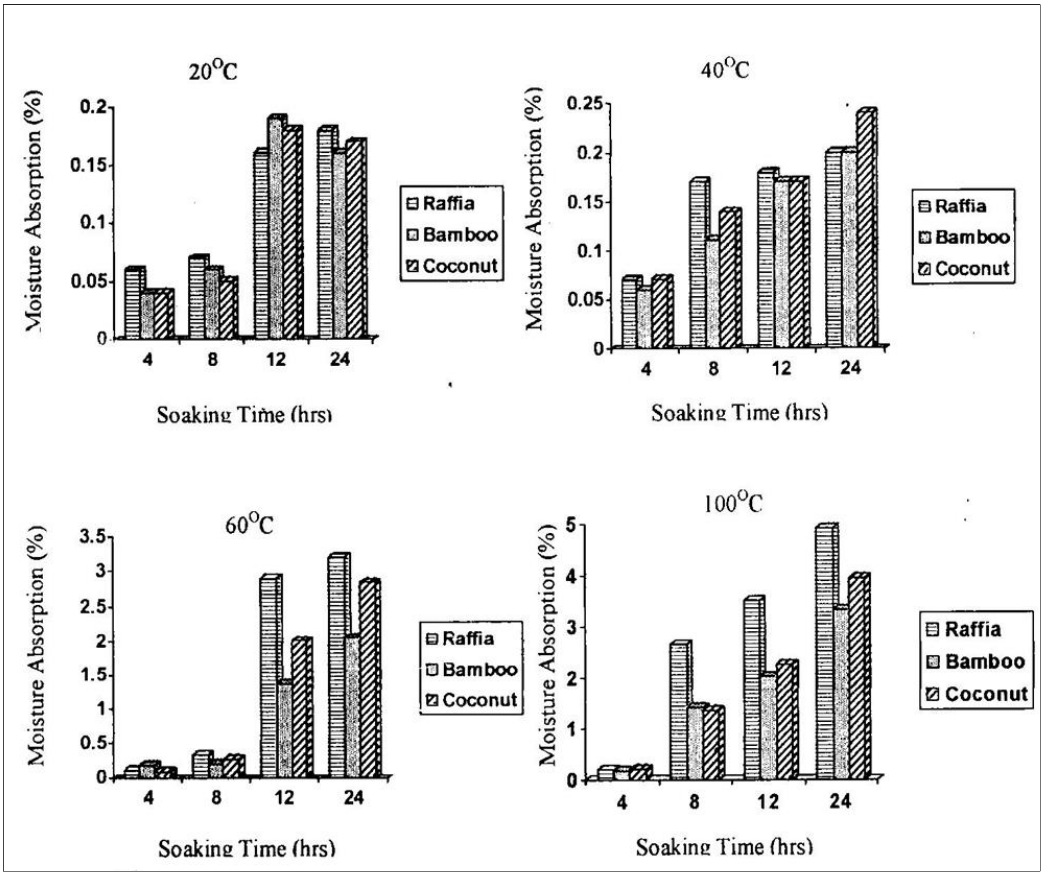

Figure 6 Graphs of Moisture absorption Vs Soaking time

The percentage weight gain was determined as:
Moisture absorbed,

$$M = \frac{\text{Mass after soaking} - \text{Mass before soaking}}{\text{Mass before soaking}} \; x \; 100\% \qquad 3.1$$

As the natural process of moisture absorption by polyester matrices is normally very slow, Frick's second law for concentrated independent moisture diffusion process for long periods of exposure in solution is approximated as:

$$M = [1 - 8/\pi^2 \exp(-\pi^2 Dt/h^2)]M_m \qquad 3.2$$

where M = Moisture absorbed
D = Composite diffusion constant

t = Time at maximum moisture content
h = Specimen thickness
M_m = Maximum moisture content.

Assuming that the moisture absorption process follows Frick's law, the apparent diffusivity, D can be determined as:

$$D = \pi\, [(h/4)M_m]^2[(M_2 - M_1)/(\sqrt{t_2} - \sqrt{t_1})]^2[1+h/L+h/W]^{-2} \qquad 3.3$$

where L = Length of the test specimen
W = Width of the test specimen
M_1, M_2 = Moisture content
t_1,t_2 = Moisture times.

Applying equation 3.3, the diffusivity of raffia, bamboo, and coconut fibers composites at 20°C are evaluated below.

For raffia fiber-reinforced-polyester composite,
h = 5.2 mm, L = 300 mm, W = 21 mm, M_1 = 0.00%, M_2 = 0.18 %, t_1 = 0 hrs, t_2 = 24 hrs. Substituting, we have
$D = 4.12 \times 10^{-8}$ mm²/sec.

For bamboo fiber-reinforced-polyester composite,
h = 5.2 mm, L = 300 mm, W = 21 mm, M_1 = 0.00 %, M_2 = 0.16 %, t_1 = 0 hrs, t_2 = 24 hrs.
Substituting, we have
$D = 2.55 \times 10^{-8}$ mm²/sec.

For coconut fiber-reinforced-polyester composite,
h = 5.2 mm, L = 300 mm, W = 21 mm, M_1 = 0.00 %, M_2 = 0.17 %, t_1 = 0 hrs, t_2 = 24 hrs.
Substituting, we have
$D = 3.27 \times 10^{-8}$ mm²/sec.

Applying equation 3.3, the diffusivity of raffia, bamboo, and coconut fibers composites at 60°C are evaluated below;

For raffia fiber-reinforced-polyester composite,
h = 5.2 mm, L = 300 mm, W = 21 mm, M_1 = 0.00 %, M_2 = 3.21 %, t_1 = 0 hrs, t_2 = 24 hrs. Substituting, we have
$D = 4.16 \times 10^{-3}$ mm²/sec.

For bamboo fiber-reinforced-polyester composite,
h = 5.2 mm, L = 300 mm, W = 21 mm, M_1 = 0.00 %, M_2 = 2.05 %, t_1 = 0 hrs, t_2 = 24 hrs. Substituting, we have
$D = 6.93 \times l0^{-4}$ mm²/sec.

For coconut fiber-reinforced-polyester composite,
h = 5.2 mm, L = 300 mm, W = 21 mm, M_1 = 0.00 %, M_2 = 2.85 %, t_1 = 0 hrs, t_2 = 24 hrs. Substituting, we have
$D = 2.59 \times 10^{-3}$ mm²/sec.

Applying equation 3.3, the diffusivity of raffia, bamboo, and coconut fibers composites at 100°C are evaluated below;

For raffia fiber-reinforced-polyester composite,
h = 5.2 mm, L = 300 mm, W = 21 mm, M_1= 0.00 %, M_2= 4.91 %, t_1= 0 hrs, t_2 = 24 hrs. Substituting, we have
$D = 2.28 \times 10^{-2}$ mm²/sec.

For bamboo fiber-reinforced-polyester composite,
h = 5.2 mm, L = 300 mm, W = 21 mm, M_1 = 0.00 %, M_2 = 3.33 %,t_1 = 0 hrs, t_2 = 24 hrs.
Substituting, we have
$D = 4.825 \times 10^{-3}$ mm²/sec.

For coconut fiber-reinforced-polyester composite,
h = 5.2 mm, L = 300 mm, W = 21 mm, M_1 = 0.00 %, M_2 = 3.93 %, t_1 = 0 hrs, t_2 = 24 hrs. Substituting, we have
$D = 9.35 \times 10^{-3}$ mm²/sec.

From the analysis, raffia composites have a higher diffusion coefficient than bamboo and coconut composites.

3.1. Analysis

Such materials as coconut, raffia and bamboo have immense absorption capacity and can develop immense cracking due to its irregular swelling characteristics. The results shown on Table 3.1 revealed that the moisture absorption rate of the Raffia reinforced composite material was brought under check and reduced. This was as a result of the treatment given to the material. As can be seen from the table the absorption rate of the raffia reinforced composite material was negligible at the various temperatures of the investigation. At the highest temperature of 100°C the moisture absorption rates at a soaking time of 24 hours was found to be 4.91% while at the temperature of 20°C the moisture absorption rates at the soaking durations of 4, 8, 12 and 24 hours were 0.06%, 0.02%, 0.16% and 0.18% respectively. For the bamboo reinforced composites, the moisture absorption rates at the soaking duration of 24 hours at 20°C and 100°C wre found to be 0.16% and 3.33% respectively. Similarly, the absorption rates for coconut reinforced fiber composites at the temperatures of 20°C and 100°C for 24 hours soaking duration were put at 0.5% and 3.94% respectively. It can be observed that there is gradual rise in the moisture absorption rates at higher temperatures. The knowledge of the absorption rates at different temperatures and different moisture exposure conditions will guide engineers in their choice of material for construction purposes.

4. Conclusion

Moisture absorption rates and diffusivities of raffia, bamboo, and coconut fiber-reinforced-polyester composites were investigated under varying conditions of temperature and soaking time. The following conclusions are drawn from the research results:

- De-bonding at the fiber-matrix interface bundle sets in after the amount of absorbed moisture increased with temperature and ‘soaking times’, and this resulted to the decrease of the mechanical properties (ultimate tensile strength and elastic modulus) of the composites.
- The tensile strengths below the composites’ saturated moisture contents decreased as a result of the plasticization of the matrix, thereby de-bonding the interfacial properties of the fiber-matrix interface.

Recommendations

- It is recommended that other types of fibers surface treatments be employed in order to investigate their effects on the chemical and mechanical properties of the plant fibers-reinforced-polyester composites.
- Universal testing machines are recommended for use during laboratory experiments, for accurate results to be achieved.

Compliance with ethical standards

Acknowledgments

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Disclosure of conflict of interest

There was no clash of interest among the authors in the course of doing this research. We worked like a team with a great show of tolerance and understanding.

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