Effect of Layering Pattern on the Water Absorption Behavior of Banana Glass Hybrid Composites

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ABSTRACT: Hybridization of Banana fibers with glass fibers has been found to reduce the water absorption behavior of the composites in an earlier work by us. Banana fibers were hybridized with glass and different layering patterns were followed in the preparation of the composites. The effect of the various layering patterns on the water absorption of the composites was studied. It was found that water diffusion occurs in the composite depending on the layering pattern as well as the temperature. In all the experiments, it has been found that composites with an intimate mixture of glass and banana show the maximum water uptake except for temperature of 90°C. At 90°C the maximum water uptake is found to be for composites where there is one layer of banana and another layer of glass. The water uptake follows the same trend as that in all other temperatures till a time span of 4900 min is reached. The kinetics of diffusion was found to be Fickian in nature. The various thermodynamic parameters like sorption coefficient, diffusion coefficient. Enthalpy change, entropy change, and activation energy of the various composites were calculated. From all the calculations it has been concluded that layering pattern is an important parameter which controls the water absorption of the composites. The layering pattern Cg-*b*-g was found to have the lowest water uptake. © 2007 Wiley Periodicals, Inc. J Appl Polym Sci 105: 2540–2548, 2007

Key words: water absorption; hybrid composites; layering; reinforcement; activation energy; biofibers

INTRODUCTION

The current interest in bio-based materials is taking research in the field of natural fiber composites to a greater heights. Various natural fibers have been found to be effective as potential reinforcement in various matrices. However, the hydrophilic nature of the fibers as well as their incompatibility with polymeric matrices seems to be the important issue that has to be addressed in all cases.

Chemical modification of the fibers as well as hybridization with synthetic fibers has been suggested as the solution in most of the cases to decrease water uptake as well as to increase bonding with polymers. Burgueno et al.[1] has reported on cellular biocomposite cores made from industrial hemp or flax fibers with unsaturated polyester. Mehta et al.[2] reported on the hybridization of various natural fibers for housing applications.

Liu et al.[3] has reported on the effect of water absorption behavior of green composites prepared from soy-based plastic and pineapple leaf fiber. It has been observed that addition of compatibilizer reduces the water absorption of the composites. The diffusion of water and artificial sea water through crosslinked rubber reinforced with coir fibers was studied by Geethamma and Thomas.[4] It was observed that uptake of water and sea water reduced in composites containing treated fibers. Hong and Wool[5] prepared novel bio-based composite materials for electronic application from soybean oil and keratin based fibers. The diffusion coefficient of the composite was found to be dependent on the keratin content. Bledzki et al.[6] prepared microcellular composites based on PP and natural and wood fibers. It was observed that in the foamed specimens the water absorption is at least two times lesser than in the unfoamed specimens. The water absorption was found to be reduced in the case of the treated samples. Mohanty et al.[7] has reported on the water absorption behavior of modified jute fibers and polypropylene. Maleic anhydride modification was found to reduce the water absorption characteristics of the composite. Breno et al.[8] prepared composites based on polyurethane and short sisal fibers. It was found that despite the addition of sisal fibers, the composites showed hydrophobic character. Rodríguez et al.[9] studied the water absorption behavior of composites, based on various natural fibers in polyester and

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TABLE I
Physical and Chemical Characteristics of Polyester

Appearance	A clear pale liquid
Viscosity at 25°C (cps) (Brookfield viscometer)	650
Specific gravity at 25°C	1.11
Typical properties of cured un reinforced resin (Specimens cured for 24 h at room temperature followed by post curing for 4 h at 80°C	
Tensile strength (psi)	9,000
Flexural strength (psi)	16,000
Water absorption at 25°C (%), 28 days	0.65

TABLE III
Physical and Mechanical Properties of Glass Fiber

Density (g/cc)	2.540
Tensile strength (Mpa)	1.7–3.5
Elongation at break (%)	3
Young's modulus (Gpa)	65–72
Diameter (μm)	5–25
Micro fibrillar angle	11°

acrylic matrix. Water absorption studies of the composites were found to depend on the nature of the fiber.

Many techniques have been suggested by other researchers to reduce the water absorption in lignocellulosic materials. Hybridization with synthetic fibers is a novel way of addressing the issue. In an earlier study on the effect hybridization on the water absorption behavior of banana glass hybrid composites,[10] we observed that there is a reduction in the water uptake depending on the amount of glass fiber incorporated.

In the present study, we intend to report the effect of the various layering patterns on the water absorption behavior of the composites to suggest the best layering pattern that can be assumed with natural fibers and synthetic fibers to have minimum water absorption in moist environments. The composites with the fiber volume fraction where there is a balance of properties was chosen to look at the effect of water absorption temperature on the water diffusion.

EXPERIMENTAL

Materials used

Banana fiber obtained from Sheeba Fiber and Handicrafts, Poovancode, Tamil Nadu, was used in this study. Unsaturated polyester HSR 8131 (sp. gravity 1.12, viscosity 65 cps, gel time 25 min) obtained from M/s Bakelite Hylam, Hyderabad, India, was used as matrix. Ceat Ltd., Hyderabad, India, supplied multidirectional glass strand mat used for the study. Methyl ethyl ketone peroxide and cobalt naphthenate were of commercial grade supplied by Sharon enterprises, Cochin. Table I gives the physical and chemical characteristics of the polyester resin used. Tables II and III give the characteristics of the banana fiber and glass fiber used. Figure 1 shows the layering pattern employed in the preparation of the composites.

Preparation of composites

Randomly oriented glass mats and neatly separated banana fiber cut at a uniform length of 3 mm were evenly arranged in a mold measuring 150 × 150 × 3 mm^3 in the required layering pattern for preparing the samples. Composite samples were prepared using banana and glass fiber mats and polyester. The mats were impregnated with the polyester resin to which 0.9 vol % cobalt naphthenate and 1% methyl ethyl ketone peroxide were added. The resin was degassed before addition to the fiber mats. The air bubbles were removed carefully with a roller. The closed mold was kept under pressure for 12 h; and test specimens of the required size were cut out from samples. 0.11 volume fractions of glass were used for the preparation of samples. In all these hybrid (banana/glass) samples, different layering patterns are used. Specimen Cint is the composite in which banana and glass fibers are taken as intimate mixture. Specimen Cg-b is the composite in which one side of the composite is reinforced by glass fiber and the other side by banana fibers. Specimen Cg-b-g is the composite in which banana fiber is sandwiched between two glass fibers and in specimens Cg_3b_2 and Cg_6b_5 the layering pattern of glass and banana fibers is increased (Fig. 1). For example, in

TABLE II
Mechanical Properties of Banana Fiber

Sample no.	Diameter of fiber (μm)	Initial Young's modulus (GPa)	SD* Initial Young's modulus (GPa)	Breaking strength (MPa)	% Strain
1	50	32	8.190	779	2
2	100	30	4	711	2
3	150	29	8	773	3
4	200	27	7	789	3
5	250	29	4	766	3

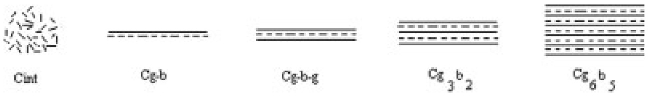


Figure 1 The layering pattern of composite specimen.

Cg_3b_2 composite there are three glass fiber and two banana fiber layers. Similar layering build-up is used for the composite Cg_6b_5.

Testing techniques

Disc specimens having 20 mm diameter and 2.5 mm thickness following the ASTM standard (ASTM D 570) was used for studying the kinetics of water absorption. The water absorption studies were performed following the ASTM standard (ASTM D 570). The specimens were immersed in distilled water at temperatures 30, 50, 70, and 90°C and the percentage weight change was determined until the equilibrium values were reached. After immersion in water, samples were removed at different time periods of 5, 10, 15, and 30 min during the first 400 min and after 48 h after that. The experiment was continued till equilibrium was obtained. Samples were wiped with filter paper to remove surface water and weighed with an analytical balance with 0.1 mg resolution. Water-induced dimensional changes were measured with a micrometer having an accuracy of 0.1 mm.

The molar sorption, Q_t, of water by the composite at time t was calculated from

$$Q_t(\text{mol }\%) = \frac{W_2 - W_1}{18 \times W_1} \times 100 \tag{1}$$

where W_1 is the weight of the dry specimen and W_2 is the weight of the wet specimen. The molar sorption at equilibrium (infinite time) is represented by Q. The weight gains, maximum moisture contents, and diffusivities of such materials during immersion in distilled water were also estimated.

Thermodynamic parameters

The thermodynamic parameters of sorption process can be calculated from diffusion data. The activation energy can be calculated from the eq. (2).[11] Activation energy of water absorption is the amount of energy required for the water molecule to diffuse into the composite.

$$\log\ D = \log\ D_o - E_D/RT \tag{2}$$

where D is the diffusion coefficient; D_o is a constant; E_D is the activation energy.

Plot of log D against $1/T$ gives the value of activation energy from the slope.

Diffusion coefficient

Traditionally, the diffusion theory has been applied to understand the mechanism of moisture absorption in composites. Diffusion coefficient is the rate of transfer of the diffusing substance across unit area of section divided by the space gradient of concentration. Diffusion coefficient characterizes the ability of water molecules to diffuse into the fiber.

The diffusion coefficient can be calculated by the equation[11]

$$D = \pi \left(\frac{h\theta}{4Q_\alpha} \right)^2 \tag{3}$$

where h is the initial thickness or initial average diameter of the sample, and θ is the slope of the initial linear portion of the sorption curve. The slope is calculated from the graph Q_t versus root time.

Sorption coefficient

The sorption coefficient (S) is calculated by the equation

$$S = \frac{M_\alpha}{M_o} \tag{4}$$

where M_α is the mass of the water taken up at equilibrium; M_o is the initial mass of the sample.

Sorption coefficient is a thermodynamic parameter, which depends on the strength of the interaction in the polymer/penetrant mixture. It gives a measure of the extent of sorption.

Permeability coefficient

Permeability coefficient gives an idea about the amount of water permeated through uniform area of the sample per second. The permeability coefficient is given by equation:

$$P = DS \tag{5}$$

Permeability therefore talks about the net effect of sorption and diffusion. A schematic representation of a typical diffusion path in permeable (A) and impermeable (B) fiber composites were shown in Figure 2.

Entropy change, enthalpy change, and free energy change

Thermodynamic functions ΔS and ΔH were calculated by linear-regression analysis using the Vant Hoff equation.[12]

$$\ln K_s = \Delta S/R - \Delta H/RT \tag{6}$$

$$\Delta G = \Delta H - T\Delta S \tag{7}$$

where, K_s (No. of moles of solvent sorbed at equilibrium)/(Mass of the polymer); ΔS the entropy change; ΔH the enthalpy change; ΔG is the free energy change.

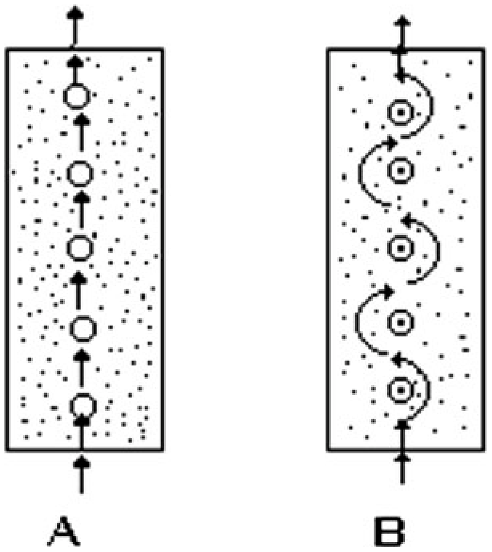


Figure 2 Typical diffusion path in permeable (A) and impermeable (B) fiber composites.

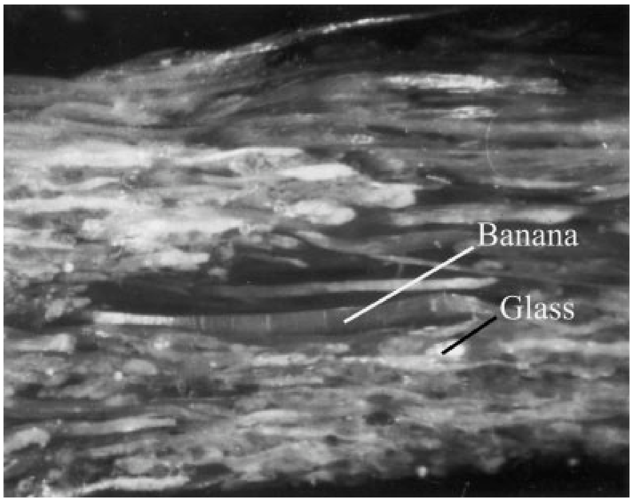


Figure 3 Optical photograph of hybrid composite containing intimate mixture of glass and banana fibers.

RESULTS AND DISCUSSION

Water absorption in natural fiber composites have been studied by many researchers and it has been found in all cases that water absorption is dependent on the nature and amount of fiber used. In an earlier publication, we have reported on the effect of hybridization on the water absorption behavior of banana fiber/polyester composites.[10] In the present communication, the effect of layering pattern on the water absorption behavior of the composites is reported. Composites of banana/glass with glass fiber volume fraction 0.11 and banana fiber fraction (0.4–0.11) 0.29 were prepared.

Optical and scanning electron micrographs

Figure 3 shows the optical photograph of hybrid composite containing intimate mixture of glass and banana fibers. The gray portion in the figure represents the banana fibers and water can be absorbed easily through this region. Figure 4 shows the scanning electron micrograph showing the fiber end regions of glass and banana fiber of intimate hybrid composites. The dark regions in the figure shows the presence of banana fibers and through this region water can be absorbed and thus coinciding with the theoretical observation that composite made of intimate mixture of glass and banana has the maximum water uptake.

Hygrothermal behaviors and the effect of the immersion temperature on the thermodynamic parameters of different composites

Effect of layering pattern on water absorption behavior

The amount of water absorbed by composites with different layering patterns was calculated by the weight difference between the samples and the dry sample. In Figure 5, percentage of moisture content were plotted against square root of time for samples with different layering pattern of glass and banana with a glass fiber volume fraction 0.11. In this figure, the maximum water uptake is found in composites where there is an intimate mixture of banana and glass (Cint) and the minimum in composites where glass forms the skin and banana the core (Cg-*b*-g). This is due to the fact that in Cint there is a continuous path for the entrance of water molecules through the composite and thus promote the greater tendency of water absorption. But in Cg-b-g the continuous path for the solvent to pass through the composite is hindered and thus shows only minimal absorption.

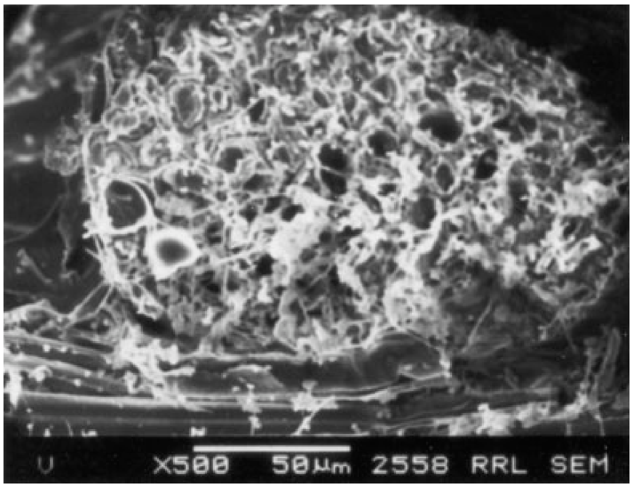


Figure 4 Scanning electron micrograph showing the fiber end regions of glass and banana fiber of intimate hybrid composites.

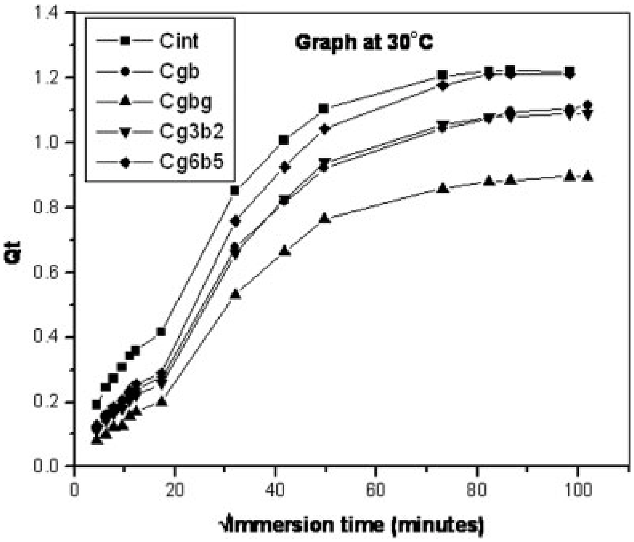


Figure 5 Effect of layering pattern on the water absorption of the composite at room temperature.

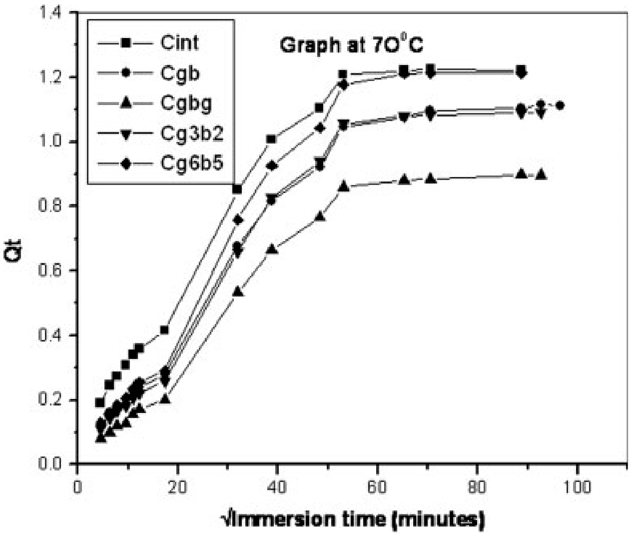


Figure 7 Effect of layering pattern on the water absorption of the composite at 70°C.

In Figure 6, percentage of moisture content were plotted against square root of time for samples with different layering pattern of glass and banana with a glass fiber volume fraction 0.11. In this case also the maximum water uptake is found in composite Cint where glass and banana fibers are mixed intimately, and thus promoting water absorption and minimum for Cg-b-g, where there is a discontinuity in the path due to the presence of glass fibers on both sides of the hydrophilic banana fibers and thus resist the water absorption through the considered sample.

In Figure 7, percentage of moisture content were plotted against square root of time for samples with different layering pattern of glass and banana with a glass fiber volume fraction 0.11 as in the above cases. From the figure, we can observe that there is an increase in water uptake for samples Cg_3b_2 and Cg_6b_5 where there is an increase in fiber layering. The water uptake for these composites reaches some what near Cint even though there are glass layers in between the banana layers. In the case of composites where the banana fibers are sandwiched between glass fibers, more microchannels are there. The difference in properties and hence the incompatibility between the fibers causes the formation of microchannels, which contribute to the higher water uptake in the samples. In addition this paves way to the absorption of water through the pores on the surface of the fibers as well. Through this path, water can penetrate more easily into the composite and this water is absorbed by the polar —OH group of the banana fiber and thus absorption increases. For this case also Cint has maximum water absorption and Cg-b-g has the minimal water uptake.

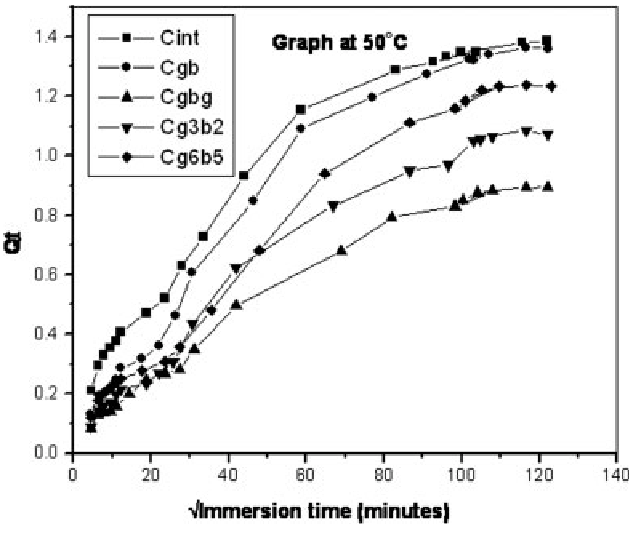


Figure 6 Effect of layering pattern on the water absorption of the composite at 50°C.

In Figure 8 also percentage of moisture content were plotted against square root of time for samples with different layering pattern of glass and banana with a glass fiber volume fraction 0.11.The maximum water uptake is found to be for composites where there is one layer of banana and another layer of glass (Cg-b). The water uptake follows the same trend as that in all other temperatures till a time span of 4900 min is reached. After the time span, the water absorption is found to be higher for composites where a single layer of glass and banana are used. This peculiarity in behavior is expected due to the reason that when temperature is increased, it results in the swelling of the fibers and development of microcracks in the bulk of the material, which

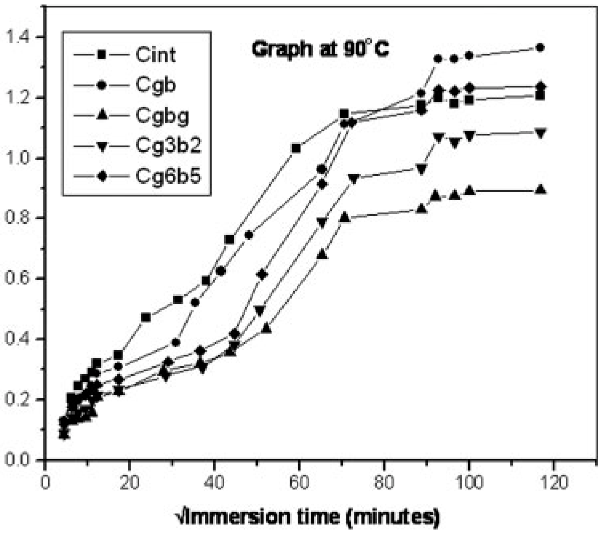


Figure 8 Effect of layering pattern on the water absorption of the composite at 90°C.

increases the water absorption. In all the samples, the total fiber volume fraction was kept constant.

As has been found by MRI studies reported by other researchers,[13] water absorption takes place through the cut edges because more fiber ends are likely to be there at the cut edges. However, in this particular study, the fibers exposed at the cut surface remaining the same, the water absorption seems to be the lowest in all cases where the glass fibers form the skin and banana fibers the core. This is unlike the observations made by Couturier et al. in their water absorption studies of flax composites. If water diffusion takes place only through the fiber ends near the cut edge of the samples, keeping more hydrophobic glass fibers at the outer edges should not have any effect. However, it has been found that when glass fibers form the skin, the water diffusion is lowered.

The nature of the curves is also found to be different from composites where there are only natural fibers present. In composites where the glass and synthetic fibers have been used, water absorption has been found to take a two step mechanism. Water absorption occurs mainly through the fibers by capillary action.

Another interesting observation is that when the temperature is increased to 90°C, the maximum water uptake is found to be for composites where there is one layer of banana and another layer of glass. The water uptake follows the same trend as that in all other temperatures till a time span of 4900 min is reached. After the time span, the water absorption is found to be higher for composites where a single layer of glass and banana are used. The reason for this is that when temperature is increased, it results in the swelling of the fibers and development of microcracks in the bulk of the material, which increases the water absorption.

The initial water uptake and equilibrium water uptake decreases in the same order. This can be explained by considering the permeability of the fibers. In all the samples, the glass volume fraction is 0.11. In g-b layering pattern, the arrangement is such that on one side there is banana and the other side there is glass. Water enters directly into the banana fiber from one side where its path is continuous and then it passes to the glass fiber, which impedes the flow. Considering the sample with layering pattern g-*b*-g, on the sides of the banana fiber there is glass fiber. So its water uptake is lower than that of g-b layering.

But in the sample Cg_3b_2 where the layering pattern is g-b-g-b-g where banana layers are sandwiched between glass layers, the water absorption is more than in Cg-b-g. The increased water uptake in the case of composites with an intimate mixture of glass and banana can be attributed to the availability of more fiber ends at the cut regions which contribute to free water diffusion through the fiber ends by capillary action. In the case of composites where the banana fibers are sandwiched between glass fibers, more microchannels are there. The difference in properties and hence the incompatibility between the fibers causes the formation of microchannels, which contribute to the higher water uptake in the samples. In addition, this paves way to the absorption of water through the pores on the surface of the fibers as well. Through this path, water can penetrate more easily into the composite and this water is absorbed by the polar —OH group of the banana fiber and thus absorption increases. Thus, more dispersion of banana layers causes water absorption to increase.

Table IV gives the values of the permeation coefficient, sorption coefficient, and diffusion coefficient of various samples under study.

From the values, it is seen that diffusion coefficient is maximum for sample which contains polyester reinforced with banana fiber only (Cint) where there is continuous path for water entrance and minimum for sample Cg-b-g where the continuous path for the flow of water is hindered. Higher diffusion coefficient of sample, which contains only polyester reinforced with banana fiber (Cint), leads to the conclusion that a large amount of moisture is absorbed by the sample. Diffusion coefficient increases with increase in temperature. The permeability coefficient is also high for Cint and low for Cg-b-g since permeability is the net effect of sorption and diffusion. Permeability coefficient also increases with increase in temperature.

The activation energy of the samples is given in Table V. From the values, we can see that activation

TABLE IV
Values of Diffusion Coefficient, Sorption Coefficient, and Permeability Coefficient for Various Samples

Sample	Temperature (°C)	Diffusion coefficient (*D*) (m^2/min)	Sorption coefficient (g/g)	Permeability coefficient (*P*) ($P = D \times S$) (m^2/min)
Cint	30	1.96×10^{-8}	0.2182	4.27×10^{-9}
	50	2.55×10^{-8}	0.2217	5.66×10^{-9}
	70	2.59×10^{-8}	0.2247	5.81×10^{-9}
	90	2.92×10^{-8}	0.2523	7.37×10^{-9}
Cg-b	30	5.58×10^{-9}	0.1804	1.01×10^{-9}
	50	6.02×10^{-9}	0.1926	1.16×10^{-9}
	70	6.42×10^{-9}	0.1949	1.25×10^{-9}
	90	7.39×10^{-9}	0.2025	1.49×10^{-9}
Cg-b-g	30	3.03×10^{-9}	0.1544	4.68×10^{-10}
	50	3.57×10^{-9}	0.1610	5.74×10^{-10}
	70	3.72×10^{-9}	0.1636	6.08×10^{-10}
	90	5.17×10^{-9}	0.1658	8.56×10^{-10}
Cg_3b_2	30	5.19×10^{-9}	0.1728	8.96×10^{-10}
	50	5.41×10^{-9}	0.1780	9.62×10^{-10}
	70	5.82×10^{-9}	0.1837	1.07×10^{-9}
	90	6.68×10^{-9}	0.1884	1.26×10^{-9}
Cg_4b_3	30	5.82×10^{-9}	0.2156	1.25×10^{-9}
	50	5.92×10^{-9}	0.2193	1.29×10^{-9}
	70	6.37×10^{-9}	0.2212	1.41×10^{-9}
	90	6.77×10^{-9}	0.2457	1.66×10^{-9}

energy is minimum for Cint because the fiber can easily form bond with the water molecule due to the free entrance of water and so the energy needed for the process is comparatively less. But in the case of the sample Cg-b-g the continuous path for the entrance of water is blocked so the energy needed for the fiber to form bond with the water molecule is comparatively higher than sample Cint.

The thermodynamic parameters are presented in Tables VI–VIII. From Table VI, we can observe that the change in enthalpy is a positive value indicating that the process is endothermic. That is, during water absorption, the composite receives heat energy from surroundings and this energy is utilized for water absorption.[14] It can be seen that the value of enthalpy change of minimum for sample Cint contains banana and glass mixed intimately. Cg-b-g where continuous path is hindered by the presence of glass fiber on both sides of banana fiber, and so the enthalpy change is found to be maximum. From Table VII, entropy change also shows a similar pattern as that of enthalpy change. From Table VIII, we can observe that the free energy change values are found to be positive for all the systems indicating that the diffusion process is not spontaneous. In Cg-b, the ΔG value is lower than Cint confirms the presence of continuous path for water flow. ΔG value is found to be highest for Cg-b-g as expected and these in perfect agreement with the kinetic observation.

In Cg_3b_2 and Cg_4b_3, free energy change is lower than that of Cint and Cg-b-g. An increase in the extent of water absorption is observed with increase in the number of banana fiber layers in kinetic study. The free energy change values for these composites also agree with the kinetic observation.

Interpretation of the obtained results

In all the cases, the water absorption seems to take a two step mechanism. In all the samples, up to a time span of 400 min, the diffusion of water takes place by more or less the same mechanism. From the graphs after the initial slow absorption of water there seems to be a steep rise and the diffusion mechanism is found to be Fickian. The maximum water absorption is always found to take place in the case of composites where there is an intimate mixture

TABLE V
Values of Activation Energy of the Samples Under Study

Samples	Activation energy (E_D) (kJ/mol)
Cint	2.38×10^2
Cg-b	4.10×10^2
Cg-b-g	7.38×10^2
Cg_3b_2	5.61×10^2
Cg_4b_3	3.74×10^2

TABLE VI
Values of Enthalpy Change of the Sample Under Study

Samples	ΔH_S (kJ/mol)
Cint	7.95×10^2
Cg-b	11.58×10^2
Cg-b-g	17.63×10^2
Cg_3b_2	13.32×10^2
Cg_4b_3	8.83×10^2

TABLE VII
Values of Entropy Change of the Sample Under Study

Samples	ΔS (J/mol/K)
Cint	1.01
Cg-b	2.70
Cg-b-g	3.97
Cg_3b_2	2.81
Cg_4b_3	1.52

of glass and banana and minimum for composites Cg-b-g where the banana fiber layer is present in between two glass fiber layers. At the initial part of the diffusion curves, water absorption occurs only slowly, obviously due to particles, which hinder a fast absorption. After the initial time span, the particles, which hinder the absorption, are either pushed away due to capillary pressure or dissolved out partially. The lumen becomes more prone to water uptake on prolonged exposure. But increase of temperature is found to make the curves steeper after the initial slow absorption of water, or in other words, the rise in temperature augments the water diffusion as has been observed by other researchers. From Figure 8, it is also clear that the equilibrium water uptake of sample Cg-b becomes higher than that of sample where there is an intimate mixture of glass and banana due to the reason that when temperature is increased, it results in the swelling of the fibers and development of microcracks in the bulk of the material, which increases the water absorption.

The thermodynamic parameter diffusion coefficient and permeability coefficient is high for composites made of lignocellulosic fibers. Both diffusion and permeability coefficient increases with increase in temperature. The activation energy values show a reciprocal behavior from diffusion and permeability coefficient values. The activation energy is low sample Cint and high for Cg-b-g. The positive value of enthalpy shows that the process is endothermic. The enthalpy change is also minimum for Cint sample and maximum for Cg-b-g sample. The diffusion processes are nonspontaneous for all the system due to the positive free energy change. The change in entropy and free energy are minimum for Cint and maximum for Cg-b-g.

TABLE VIII
Values of Free Energy Change of the Sample Under Study

Samples	ΔG (kJ/mol)
Cint	488.09
Cg-b	339.43
Cg-b-g	560.06
Cg_3b_2	479.86
Cg_4b_3	422.59

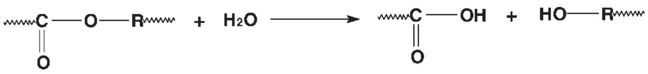
TABLE IX
pH Measurements of Samples at Different Temperature

Sample name	Temperature	pH
Pure distilled water	30	7.76
Banana/polyester composite	30	7.35
	50	6.82
	70	4.65
g-b hybrid (0.03 glass)	30	6.94
	50	5.23
	70	4.48
g-b-g (0.03 glass)	30	6.85
	50	5.08
	70	4.33
g-b-g-b-g (0.03 glass)	30	6.84
	50	6.08
	70	4.49
g-b (0.11 glass)	30	7.18
	50	6.31
	70	5.00

pH measurements

The chemical interaction of water with the composite can be studied by measuring the pH of water at different stages. From Table IX, it is found that pH of water decreased with time. Also as the temperature is increased from 30 to 70°C, the pH is very much decreased. This is due to the fact that the polyester group is susceptible to hydrolysis. As the temperature increases, rate of hydrolysis increases, and pH is found to be decreased due to the formation of free acid. It is found that pH is unaffected by change in volume fraction or change in layering pattern.

Hydrolysis of polyester resin can be schematically shown as



$$\sim\!\sim\underset{\underset{\mathrm{O}}{\|}}{\mathrm{C}}-\mathrm{O}-\mathrm{R}\sim\!\sim \;+\; \mathrm{H_2O} \longrightarrow \sim\!\sim\underset{\underset{\mathrm{O}}{\|}}{\mathrm{C}}-\mathrm{OH} \;+\; \mathrm{HO}-\mathrm{R}\sim\!\sim$$

CONCLUSIONS

An investigation into the water sorption characteristics of banana and glass hybrid fiber reinforced polyester composites was attempted. It was found that water uptake was mainly dependent on the properties of the lignocellulosic fibers. The mechanism of diffusion was found to be Fickian: the curves of water absorption had an initial steep rise followed by a leveling off. From sorption curves of the composites it was found that the water uptake is maximum for sample which contains polyester reinforced with banana and glass as intimate mixture (Cint) due to continuous path in the composite and minimum for sample which contains banana fiber sandwiched between two glass fibers (Cg-b-g) due to discontinuity in the flow of solvent. The rate of diffusion was seen to increase with temperature due to the weakening of fiber–matrix adhesion and formation of microcracks confirmed from the optical micrographs. From the kinetic parameters, we can conclude that diffusion coefficient is minimum for Cg-b-g sample and maximum for Cint. Activation energy was found to be maximum for the Cg-b-g composite and minimum for the composite containing polyester reinforced with banana and glass as intimate mixture (Cint).The enthalpy change is found to be maximum for Cint sample where there is an intimate mixture of glass and banana since in this case more water is absorbed and the total heat change associated with the absorption of water by the composite is high and minimum for sample Cg-b-g where continuous path is hindered. The enthalpy and entropy change was found to be positive indicating the process to be endothermic. The free energy of the composites was found to be negative indicating that the diffusion process is a feasible reaction. The pH measurement shows that there is some interaction between water and composite. pH was found to be decreased with increase in temperature.

Finally, it is important to add that water transport studies could be used as a probe to evaluate the effect of layering pattern on banana glass hybrid composites.

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