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Studies of Water Absorption Behavior of Plant Fibers at Different Temperatures

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Abstract Moisture absorption of natural fiber plastic composites is one major concern in their outdoor applications. The absorbed moisture has many detrimental effects on the mechanical performance of these composites. A knowledge of the moisture diffusivity, permeability, and solubility is very much essential for the application of natural fibers as an excellent reinforcement in polymers. An effort has been made to study the water absorption behavior of some natural fibers such as bowstring hemp, okra, and betel nut at different temperatures to improve the long-term performance of composites reinforced with these fibers. The gain in moisture content in the fibers due to water absorption was measured as a function of exposure time at temperatures ranging from 300 K to 340 K. The thermodynamic parameters of the sorption process, such as diffusion coefficients and corresponding activation energies, were estimated.

Keywords Activation energy · Diffusion coefficient · Hygroscopicity

1 Introduction

Natural fibers have shown great promise in a variety of applications that were previously dominated by synthetic fibers due to their important aspects of biocompatibility, possible biodegradation, non-toxicity, and abundance. Currently, automotive and construction industries have been interested in composites reinforced with natural plant fibers as alternative materials for glass-fiber reinforced composites in structural applications with modest demands on strength reliability [1,2]. It has been known that the high level of moisture absorption by natural fibers, the poor wettability, and the insufficient adhesion between the untreated fibers and the polymeric

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matrix lead to bonding failure with age [3]. Moreover, the absorbed moisture has many detrimental effects on the mechanical performance of these fibers. Therefore, an understanding of the hygroscopic properties of natural fibers is very important to improve the long-term performance of composites reinforced with these fibers [4].

It is well accepted in the literature that moisture absorption in fibers occurs by means of a solution diffusion process [5]. The experimental data of moisture absorption of natural fibers have been generally described using Fick's law of diffusion but some deviations have been reported and described through non-Fickian mechanics the sigmoidal sorption and two step-mode [6]. Classical sorption experiments involve the monitoring of mass gain by the sample as a function of time but alternative methodologies have also been proposed [7]. Absorption of water molecules takes place below a critical temperature due to Van der Waal's forces between the vapor molecules and the solid surface of the structure [8]. The amount of water vapor that can be absorbed by the materials is dependent on the fiber regain and the humidity of the atmosphere. In case of absorbent fibers, e.g., cotton and rayon, the moisture sorption is not only dependent on regain and humidity but also on phenomena associated with sorption hysteresis the effect of heat dimensional changes and elastic recovery effects due to the reduced swelling of the fibers. In this article an effort has been made to study the water absorption behavior at different temperatures of some plant fibers such as bowstring hemp, okra, and betel nut, which are available in North-East India using an ordinary gravimetric absorption method.

2 Experimental

2.1 Materials

Plant fibers such as the leaf fiber of bowstring hemp, bark fiber of okra, and seed fiber of betel nut were collected from different localities of North-East India. They were processed, and various samples needed for the present investigation were prepared by the methods described elsewhere [9]. The average cross-sectional area and diameter of the samples were determined using an optical microscope (Fig. 1). Compositions and structural parameters of samples studied in this work are listed in Table 1.

2.2 Gravimetric Moisture Absorption

In the case of the gravimetric moisture absorption method, each sample having a mass of 0.1 g was washed thoroughly with distilled water and dried in an oven at 373 K for 2 h. The dried samples were immersed fully in distilled water kept at different constant temperatures (300 K, 310 K, 320 K, 330 K, and 340 K). The immersed samples were removed at different intervals of time and immediately weighed on a Mettler AE 200 analytical balance (uncertainty = 0.0001 g). The water content absorbed by the sample at time 't' was calculated using:

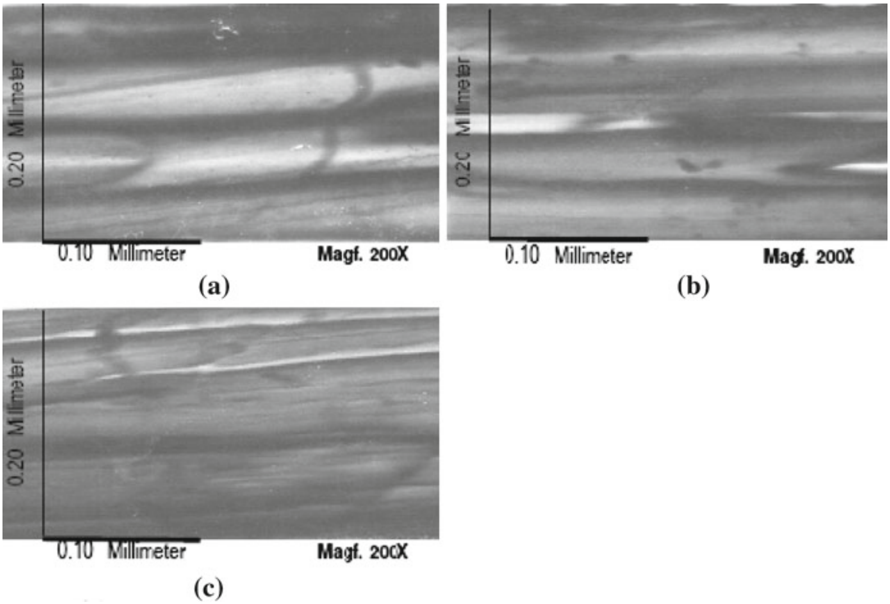

Fig. 1 Photomicrographs of (a) bowstring hemp, (b) okra, and (c) betel nut

Table 1 Composition and structural parameters of samples

Sample	Diameter (mm)	Density ($g \cdot cm^{-3}$)	Cellulose content (%)	Lignin content (%)
Bowstring hemp	0.19	1.52	70–73	5–7
Okra	0.16	1.45	72–76	8–10
Betel nut	0.20	1.20	40–44	38–42

$$M_t = \left[\frac{M_w - M_d}{M_d} \times 100 \right] \% \tag{1}$$

In Eq. 1, M_d is the mass of the dried sample (in g) and M_w is the mass of the wet sample after time t (in g). In all cases, the mean ± standard deviation data from three repeated experiments were taken to ensure reliability of the results. Following the analysis by Carter–Kibler [10] and Gurtin–Yatomi [11], the kinetics of water absorption of the fibers at specific temperatures had been analyzed on the basis of

$$M_t = M_m \left[1 - \frac{8}{\pi^2} \sum_{n=0}^{\alpha} \frac{1}{(2n+1)^2} \exp \left\{ -\frac{D(t)}{h^2} \pi^2 (2n+1)^2 \right\} \right] \tag{2}$$

In Eq. 2, M_m is the maximum water content absorbed at equilibrium, h is the initial diameter, and n is the summation index. By considering the slope of the linear part of the mass gain curve versus the square root of time, the diffusion coefficient D of the sample for a given temperature was determined using

$$D = \pi \left(\frac{h}{4M_{\mathrm{m}}}\right)^2 (\mathrm{slope})^2 \tag{3}$$

Applying the Arrhenius equation to the experimental data, the activation energy of diffusion, E_{D}, can be calculated using

$$D = D_0 \exp\left(\frac{-E_{\mathrm{D}}}{RT}\right) \tag{4}$$

In Eq. 4, D_0 is the pre-exponential factor of the diffusion, R is the universal gas constant, and T is the absolute temperature. By plotting log D versus $1/T$, E_{D} can be determined from the slope of the linear fit.

3 Results and Discussion

Figure 2a–c shows experimental data and the amount of water absorbed by the samples as a function of the square root of time, obtained from absorption gravimetric

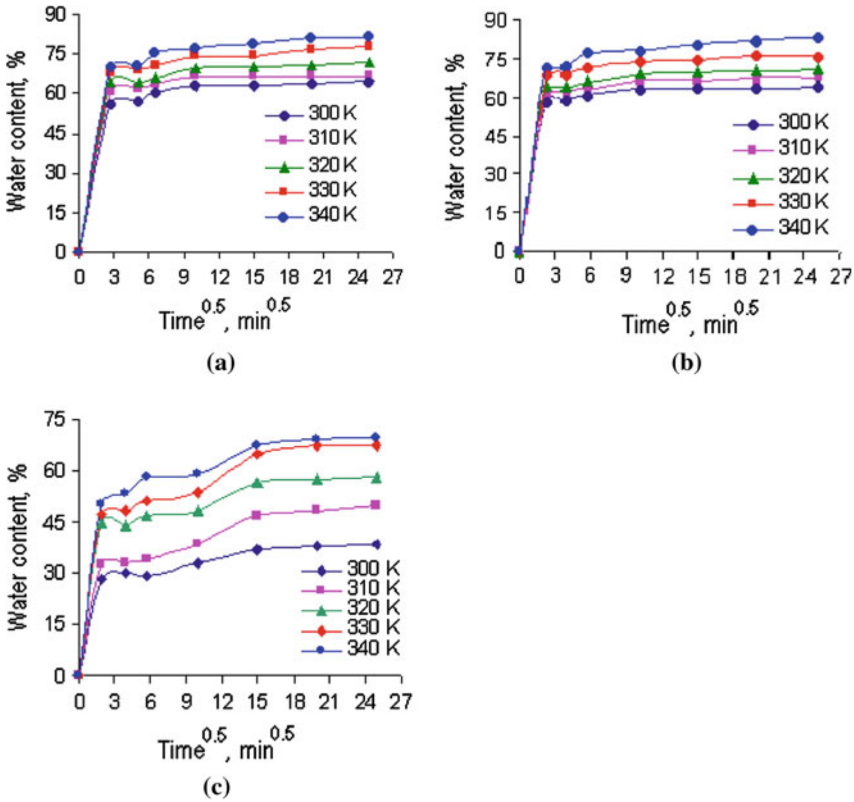

Fig. 2 Water content absorbed by (a) bowstring hemp, (b) okra, and (c) betel nut fibers as a function of the square root of time at different temperatures

studies. The general shape of the water absorption curves for bowstring hemp, okra, and betel nut is similar to those of cellulose and other natural fibers [12–14]. These results exhibit the two-stage absorption behavior of the fibers. The first stage occurred very rapidly (at a rate approximately proportional to the square root of time) having a linear uptake to above 60 % of sorption, which might be due to the presence of hydroxyl groups and amorphous areas in the cellulosic structure of the samples as well as the occurrence of capillary action following Fick's law of diffusion [15,16]. The percentages of water absorbed after the first 5 min duration for bowstring hemp, okra, and betel nut were 45 %, 60 %, and 30 %, respectively. The rate of water sorption for okra fibers was found to be more than the other sample, and this might be due to the presence of more cellulose content (76 %) in its fiber structure. The maximum water intake of fiber depends on the fiber volume fraction [17,18]. The second stage of absorption began very slowly and proceeded up to complete saturation. This non-linear uptake behavior exhibited by each sample represents a non-Fickian diffusion ($0.031 < n < 0.249$) [19]. The calculated diffusion parameters, i.e., maximum water content absorbed and diffusion coefficient for bowstring hemp, okra, and betel nut fibers at different temperature are shown in Table 2. The diffusion coefficient was found to increase with temperature for all samples.

Arrehenius plots obtained from the dependence of the logarithm of the diffusion coefficient on the reciprocal of the constant absolute temperature of water absorption studied in this work are shown in Fig. 3. The activation energy of diffusion calculated from the slope of the linear Arrehenius plots is shown in Table 3. Results revealed that the activation energy of water diffusion for each fiber was positive in nature, and it was

Table 2 Maximum water content absorbed and diffusion coefficient for bowstring hemp, okra, and betel nut fibers at different temperatures

Sample	Temperature (K)	Maximum water content absorbed (%)	Diffusion coefficient ($10^{-5}\,cm^2 \cdot s^{-1}$)
Bowstring hemp	300	62	0.52
	310	64	1.11
	320	67	1.28
	330	76	1.32
	340	80	1.36
Okra	300	64	0.54
	310	66	1.14
	320	69	1.30
	330	78	1.34
	340	81	1.38
Betel nut	300	38	0.28
	310	51	0.68
	320	58	1.04
	330	66	1.15
	340	70	1.19

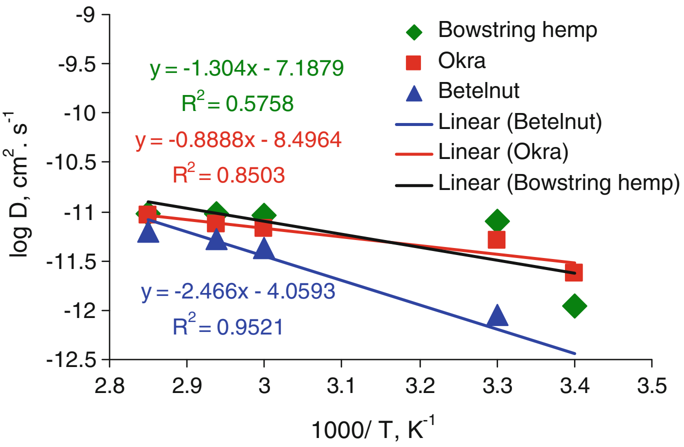

Fig. 3 Linear fit of logarithm of diffusion-coefficient (D) versus reciprocal of absolute temperature (T)

Table 3 Thermodynamic parameters of water absorption for bowstring hemp, okra, and betel nut fibers

Sample	Pre-exp. factor of diffusion ($cm^2 \cdot s^{-1}$)	Activation energy of diffusion ($kJ \cdot mol^{-1}$)
Bowstring hemp	0.001	11.781
Okra	0.001	12.116
Betel nut	0.039	27.436

found to be higher in the case of betel nut fibers, which indicates that the penetration of water into the betel nut is more difficult.

4 Conclusion

Bowstring hemp, okra, and betel nut fibers exhibited similar two-stage absorption behaviors. The first stage occurred very rapidly and obeys Fick's law of diffusion. The second stage of absorption represents non-Fickian diffusion. Water diffusion in the fibers is a thermally activated process due to the temperature dependence of the maximum water uptake and the diffusion coefficient.

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