# Chapter 6
# Conclusions

This book is entirely dedicated to diffusion processes in polymer composites, with particular reference to moisture absorption in vegetable fiber-reinforced polymer composites. An overview of basic issues related to this class of physical problem including fundamentals, experiments, advanced mathematical modeling, and engineering applications are shown in detail. Special attention is given to unsaturated polyester composites reinforced by caroá and macambira vegetable fibers.

Composite is a multiphase material consisting of a continuous phase (matrix) and one or more dispersed phases (reinforcement). The majority of the composites use thermoset matrices, with particular attention to epoxies and polyesters. Vegetable fibers may be used reinforment in polymer composites.

The use of raw materials from renewable sources, such as, vegetable fibers have been the subject of several sudies for many years due to different reasons such as high potential for diverse industrial and technological applications especially those related to socio-economic and environmental benefits.

Despite of their importance, environmental factors such as, moisture and temperature, strongly affect the durability, mechanical properties and many other characteristics of vegetable fiber-reinforced polymer composites. The hydrophilic nature of the vegetable fibers leads to weak interfacial adhesion which causes a reduction in the mechanical properties of the composite. Thus, it can be stated that these materials are very sensitive to water and heat and, to address new researches related to water absorption process in vegetable fiber-reinforced polymer composites, it is crucial to control the process in order to obtain good quality composites when in operation.

The contents of this book evince that the mechanisms governing water absorption in polymer composite are very different from those which are encountered in traditional materials, and requires a full understanding of their constituents (reinforcing and matrix) and their interaction at the fiber-matrix interface (adhesion) or interphase. The adhesion quality is vital to obtain high mechanical performance of the composite, avoiding failure and premature damage in the composite (matrix cracking, local deterioration, delamination, fiber debonding, and pull-out). Thus, the present book deals specifically with water absorption in vegetable fiber-reinforced



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unsaturated polyester composites. Emphasis is given to unsaturated polyester matrix composites reinforced with caroá, macambira and sisal natural fibers by theoretical (analytical and numerical) and experimental techniques.

Herein, based on the Fick´s second law and non-Fickian diffusion model (Langmuir´s model) different transient macroscopic models were proposed, and the mathematical formalism based on the finite-volume method (numerical solution), Laplace transform and Separation of variables (exact solution) were used to solve the governing equations. Experimental tests for water absorption were performed by immersing the composite samples in a bath of distilled water at different temperatures, and the water uptake was measured gravimetrically along the process. The unsaturated polyester composites reinforced by caroá, macambira and sisal fibers were manufactured by hand lay-up. For both, the theoretical and experimental analyses, the effect of the composite dimensions, water bath temperature, and water layer thickness above the composite surface were evaluated. Microscopic images on the vegetable fibers were also analyzed.

The content of this book has demonstrated that the water uptake process and its effects in fiber-reinforced polymer composites is now a well-understood topic.

From the experimental and theoretical results of apparent weight gain of the polymer composites associated with water absorption, it can be concluded that mechanical properties (Tensile strength, Young's modulus, impact resistance, and elongation at break) of these materials effectively are affected by moisture content and temperature. The proposed mathematical models adequately describe the process of water diffusion inside the fiber-reinforced polymer composites and simulations proved to be an essential tool in understanding the process. The Langmuir-type model proved to be able to predict both Fickian and non-Fickian moisture absorption with equal ease. For this purpose, it is only necessary to change the problabilities parameters intrinsic to the model to make it truly comprehensive.

It was verified that water absorption by composites increases with fiber loading and is higher than for the polymer matrix alone. Temperature strongly influences the kinetics of water absorption and the absorption rate is higher at higher temperatures. Also, the highest rates of water diffusion were obtained in the first stages of sorption, and the sorption rate decreases at longer water immersion times. At lower temperatures, sample thickness affects water absorption more than temperature, but, at higher temperatures, the opposite occurs, i.e., the temperature in the water absorption were more relevant than that due to changes in the sample´s area/volume ratio.

The knowledge of moisture distribution inside the polymer composite is very important and allows identification of more propicious areas for delamination problems (moisture induced degradation) due to the weakness of the fiber-matrix interface and, consequently, reduction in the composites mechanical properties. The data presented demonstrates that the regions in the neighborhood of the vertices (corners) of the polymer composite (rectangular prism) had the highest mass transfer rates, being more susceptible to crack and deformation.

The demands of vegetable fibers has effectively increased in the composite industry. Reasons for this increased demands include their ecofriendly nature, light weight, good set of mechanical properties, worldwide abundance and availability and low cost which effectively reduce the cost of composite materials and increase their sustainability. Vegetable fiber reinforced polymer composites have some disadvantages already mentioned in this book, particularly their sensitivity to moisture and temperature, which limit their widespread applications and affect service life. Future trends in polymer composite materials reinforced by vegetable fibers must focus on guaranteeing property control, so that there are minimum variations in these properties. There is a need to investigate ways to increase their mechanical propertries, thermal stability and decrease their moisture sensitivity through processing, drying and/or chemical modifications. Studies to define universal testing standards and establish a worldwide database directed to numerical and experimental investigation of continuous intrinsic problems are needed. These must include shape, dimension, manufacturing technique, composition, and microstructure of the samples, moisture absorption and other related effects, thermal degradation, inadequate toughness, and reduced long-term stability for outdoor application that require high load or yet high working temperatures. Therefore, research to improve the performance of vegetable fiber reinforced polymer composites such as thermal and chemical treatments, use of compatibilizer, addition of other fillers, polymer coating, and filler hybridization are strongly recommended. As for the matrix, the development of biodegradable polymers and blends, and optimization in the use of recyclable polymers are in demand. Under the mathematical point of view, the development of robust mathematical modelis to predict mechanical behavior of these polymer composites and related effects, especially in moist, corrosive, saline and heated environments, are also recommended.

Finally, the expectation of the authors is that the information outlined in this book may help researchers, designers, engineers and academics in their studies and making design decisions on the use of complex systems such as polymer composites, especially those reinforced with vegetable fiber, in technological applications.