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Destructive and nondestructive evaluations of the effect of moisture absorption on the mechanical properties of polyester-based composites

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ABSTRACT

In this study the effect of moisture absorption on the mechanical properties of glass-reinforced polyester composites is evaluated using both destructive and nondestructive tests. The composite resins were produced with two different production processes, while the mechanical properties of the composite materials were measured using DMA destruction tests. According to the DMA tests, the dependency in terms of temperature for the real component of the complex elastic modulus (E'), the imaginary component of the complex elastic modulus (E''), as well as $\tan(\delta)$ can be traced. For a more efficient use of the composite materials, the compliance tensor was obtained with nondestructive tests based on ultrasound. A method for the generation and reception of Lamb waves in plates of composite materials is described, based on using air-coupling, low-frequency, ultrasound transducers in a pitch–catch configuration. The results of the nondestructive measurements made in this study are in good agreement with those obtained when using the DMA destructive tests.

1. Introduction

The mechanical properties of a material determine its manufacturability, performance, and longevity. This means that a knowledge of the mechanical properties is essential for making good design decisions. Polymers are exceptionally complex materials – their mechanical properties depend on chemistry, processing, and the thermo-mechanical history, as well as on volume constraints. Thus, in order to gain useful information for making sound decisions when designing with polymer composites, mechanical property measurements should be made on a relevant sample in a relevant context [1–7]. Glass-fiber-reinforced polyester (GFRP) is the most "popular" composite, with a matrix based on cured, thermosetting resin. Its first main civilian application was for boat building. Other uses of GFRPs include hot tubs, pipes for drinking water and sewers, office plant-display containers and flat-roof systems. Mayer [1] showed that the mechanical performance of GFRP composites depends on the fibers' strength and modulus, the strength of the matrix and the chemical stability. In addition to this, Erden et al. [2] showed that matrix modifications can enhance the mechanical properties of glass-polyester composites. Rowell [3] demonstrated fiber-reinforced composite materials that offer a combination of strength and modulus that are either comparable to, or better than, many pure materials. But thermoplastics exhibit a hydrophobic nature, as was demonstrated by Kim et al. [8]. When glass–polyester composites are immersed in water, uptake of the water can occur. This is the result of the capillarity of the materials and the water absorption of the hydrophilic groups in the glass fiber and the unsaturated polyester. Huang and Sun [9] and Visco et al. [10] concluded that a reaction between the water molecules and the matrix could deteriorate the interface, resulting in a weaker material. Kouba et al. showed a simple modelling of impregnation in pultrusion process of thermoplastic composites [11].

The performance of GFRP pipes is critical in many engineering applications when they are subjected to a combination of high-temperature/high-humidity environments. The diffusion of water or an aqueous fluid into GFRP pipes may lead to changes in the thermo-physical, mechanical, and chemical characteristics. Many of these changes can result in a degradation of the material's performance. In order to properly predict the service life of a GFRP pipe, we need to understand the mechanisms that govern these changes.

Water absorption by the resin may cause both reversible and irreversible changes to the resin, including hydrolysis, plasticization, micro-cracking, and even the glass-transition temperature [12–15]. For a reversible process, the mechanical properties can usually be recovered by drying; however, for the irreversible case,

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the mechanical properties are permanently altered. Deniz et al. [16] described the effect of seawater on failure pressure and its impact on the behaviors of polymer–matrix composites.

Huang [17] used a common method to evaluate the failure behavior of materials with a dynamic mechanical analysis (DMA). Many studies have shown that temperature and the environment are the most critical factors in reducing the strength of GFRP materials. Ray [18] has demonstrated that the higher the temperature of the environment and the longer is the exposure time, the larger will be the decrease in the strength and modulus of the GFRP. In those applications in which GFRP composites are subject to heat and a mechanical load, it is essential to determinate the elastic properties using nondestructive methods. A nondestructive evaluation offers advantages compared to conventional polymer-characterization methods, and without extracting test specimens. Schmerr [19], Krautkramer and Krautkramer [20] and Rojek et al. [21] found that the best methods for elastic-properties determinations are the ultrasound methods. El-Sabbagh et al. [22] studied the feasibility of using an ultrasonic longitudinal sound wave in the definition of the fiber content and the distribution in natural fiber composites.

Grimberg et al. [23] proposed the use of measuring of propagation speed of longitudinal and transversal waves, as well as Lamb waves for characterization overheated zones in fiber reinforced plastics composites. Santos et al. [24] have used guided waves (Lamb waves) to characterize the effect of multiple impacts in laminate composites. The analysis of the impact has been made by two parameters; amplitude response and time shift. PZT sensors have been bonded to the samples in a pitch-and-catch configuration and the Lamb wave symmetrical mode (S_0) signal was used. Fahim et al. [25] have designed and developed a non-destructive monitoring technique based on ultrasonic transmission through thickness. A sensible analysis has shown that the Young modulus can be reasonably well identified.

2. Experimental procedure

2.1. Sample preparation

Samples of GFRP plates having as their reinforcement six sheets of ravings with 250 ± 50 gm^{-2} density and a matrix made from different types of unsaturated Orthophthalic polyester resins, made by Helios, Slovenia, were used in this study. The characteristics of the studied GFRP samples are presented in Table 1.

2.2. Water-absorption test

The effect of water absorption on the GFRP composites was investigated. Initially, DMA measurements on non-immersed samples and immersed samples were conducted on unconditioned samples. The obtained results were inconclusive. For this reason, the measurements were remade, this time on conditioned samples, i.e., with the water that might be in the initial samples being eliminated.

The conditioning involved maintaining all the samples in a drying oven at 50 °C for 5 days. For each type of composite, one sample was weighed in order to record the initial mass. This sample was marked. The immersion was carried out in distilled water and the immersion periods were 3, 6, 9, 12, 20, 40 and 100 days. As a result of a mistake, the sample from the 7524 composite immersed for 100 days is missing from the results.

After each period of immersion, two examples of each type of sample were removed, one of samples was used for the determination of the adsorbed water and the second one was used for the DMA measurements. The adsorbed water was determined from weighing samples after each period.

$$M_t(\%) = \frac{M_t - M_0}{M_0} \cdot 100 \tag{1}$$

where M_0 is the mass of the non-immersed sample after the conditioning and M_t is the mass of the same sample immersed for time t. Fig. 1 presents the dependency of $M_t(\%)$ on the immersion time for the three types of composites used in the study.

As reviewed by Weitsman [26], the water-absorption behavior of composite materials can be categorized into several types. It has been argued that under most conditions the moisture content of composites may be calculated using Fick's law [27]. Experimental evidence indicates that for most types of polymeric composite materials the hydrothermal behavior is Fickian in nature. The absorption and desorption curves when plotted against time are always concave towards the time axis and asymptotically reach the equilibrium value [28]. We can also find a new diffusion model that extends the classical Fickian theory to include the effects of the interaction of diffusing molecules with the chemical and physical structure of polymeric composites [29]. The curves in Fig. 1 denote linear Fickian behavior, where the moisture-related weight gain gradually attains equilibrium after a rapid initial take off.

In order to determine the water-diffusion coefficient in a composite, the data from Fig. 1 were converted so that the abscissa of the graphic in Fig. 2 is in the form of $\sqrt{t}$ expressed in $\sqrt{\text{sec}}$.

It is assumed that the studied composites absorb the water in accordance with the law of Fick, as shown in Shen et al. [30]:

$$\frac{M_t}{M_\infty} = \frac{4}{h}\sqrt{\frac{Dt}{\pi}} \tag{2}$$

where M_∞ represents the maximum quantity of water that diffuses into the composite and h is the thickness of the sample. The values for the diffusion coefficients are given in Table 2.

3. Results and discussion

3.1. DMA measurements

The measurements of the elastic modulus along the three directions were made with a Dynamic Mechanical Analyzer DMA 242C from Netzsch, Germany with a three-point bending fixture and using the analysis software Proteus v.4.8.5. The measurements were carried out at a frequency of 1 Hz.

Polymers are often employed in products because of their ability to both store and damp energy. The complex modulus E^* is a phase vector that incorporates both capacities:

$$E^* = E' + jE'' \tag{3}$$

where $j = \sqrt{-1}$.

Table 1
Studied GFRP samples.

Sample name	Matrix	Fiber volume ratio	Density (kg/m^3)	Observations	Production process
7201	COLPOLY 7201	0.43 ± 0.005	1550 ± 20	Medium reactivity resin	In two steps
7524	COLPOLY 7524	0.43 ± 0.005	1530 ± 20	Chemical resistance	In situ
7243	COLPOLY 7243	0.57 ± 0.005	1410 ± 20	Preaccelerated thixotropic	In two steps