

MOISTURE DIFFUSION PROPERTIES OF FABRIC COMPOSITE (GLASS FIBER/EPOXY RESIN)

A. Naceri

Laboratory of Materials, Faculty of Sciences and Engineering, University of M'sila
P.O. Box 166, M'Sila, Algeria
abdelghani_naceri@yahoo.fr

(Received: February 29, 2008 – Accepted in Revised Form: December 11, 2008)

Abstract In this study, the effect of hygrothermal conditioning on the moisture diffusion properties of the fabric composite (glass fiber/epoxy resin) was investigated. The water uptake of the specimens conditioned in humid environment at different relative humidities (0, 60 and 96 % r.h) at constant temperature (60°C) was evaluated by weight gain measurements. The moisture diffusion properties of the fabric composite (glass fiber/epoxy resin) were determined using standard weight gain method. The weight gain experiments were performed to determine the equilibrium moisture content M_m of the fabric composite as a function of relative humidity (r.h). The measured weight gain is then fit to the solution to the diffusion equation (Fick's law) to determine the diffusivity D . The comparison carried out between the values obtained of the characteristic parameters (D and M_m) of the kinetics of water absorption by the hygrothermal test of conditioning carried out into the laboratory and those given by Loos and Springer confirms the following principal remarks clearly: the diffusion coefficient D and the maximum weight gain M_m depend not only on the nature of material but also of the environmental conditions (hygrothermal conditioning). The maximum concentration of water (matrix+interface) obtained from calculations based on measured values, where a homogeneous diffusion phenomenon is assumed inside the material ($D_i=0$), shows clearly that the presence of fibers in a polymeric matrix reduces the water up-take of the matrix by about 4 times.

Keywords Moisture Diffusion Properties, Hygrothermal Conditioning, Fabric Composite Materials

چکیده در این مقاله اثر جذب حرارتی آب بر خواص نفوذی رطوبت در الیاف مرکب (رشته‌ای شیشه‌ای/چسب اپوکسی) بررسی و جذب آب نمونه‌های خوابانده شده در محیط مرطوب با درصد رطوبت‌های نسبی متفاوت (۰، ۶۰ و ۹۵ درصد) در دمای ثابت ۶۰°C به روش اندازه‌گیری افزایش وزن تعیین شد. خواص نفوذی رطوبت الیاف مرکب (رشته‌ای شیشه‌ای/چسب اپوکسی) به روش استاندارد افزایش وزن اندازه‌گیری شد. از این روش برای تعیین تغییرات رطوبت تعادلی (M_m) بر حسب رطوبت نسبی استفاده شد. سپس با پردازش اعداد به دست آمده بر فرمول فیک، ضریب نفوذپذیری (D) به دست آمد. از مقایسه مقادیر نمونه‌وار متغیرهای (M_m , D) سینتیک جذب آب (در آزمون جذب حرارتی آب در آزمایشگاه) با ارقامی که لوس و اسپرینگر گزارش کرده‌اند این موارد به خوبی تأیید می‌شود: ضریب نفوذپذیری (D) و بیشترین افزایش وزن (M_m) تابع ماهیت ماده، و نیز شرایط محیطی (خواباندن در محیط مرطوب) است. بیشترین غلظت آب (زمینه+فصل مشترک) که موجب نفوذ همگن درون ماده می‌شود ($D_i=0$) به خوبی نشان می‌دهد که حضور الیاف در یک زمینه پلی مری کمیت آب جذب شده در زمینه را تا ۴ برابر کاهش می‌دهد.

1. INTRODUCTION

Fiber reinforced polymer matrix (FRP) composites are extensively used in airframe structural applications. Carbon (CFRP), Glass (GFRP) and Kevlar (KFRP) are the most commonly used composite materials in aeronautical and aerospace industries [1]. Polymeric composites are being investigated for use in a variety of structural

applications in which they will be subjected to adverse environmental conditions while under load.

All polymer composites absorb moisture in humid atmosphere and when immersed in water. The effect of absorption of moisture leads to the degradation of fiber-matrix interface region creating poor stress transfer efficiencies resulting in a reduction of mechanical properties [2,3].

Moisture diffusion in polymeric composites has

been shown to be governed by three different mechanisms [4,5]. The first involves diffusion of water molecules inside the micro gaps between polymer chains. The second involves capillary transport into the gaps and flaws at the interfaces between fiber and the matrix. This is a result of poor wetting and impregnation during the initial manufacturing stage. The third involves transport of microcracks in the matrix [6,7].

Moisture absorption is characterized by the migration of molecules down the concentration gradient, which occurs through diffusion. The properties of the matrix (resin) can also change significantly during exposure to an aqueous environment. Furthermore, the water can diffuse between the fibers and the matrix, weakening or destroying the bond at the fiber/matrix interface. The amount of moisture absorption during of specific period of time (t) depends on the diffusion coefficients of the individual component in the plastic/composite. For fiber reinforced plastic composites, the diffusion coefficient depends on the following three factors: volume or weight fraction of fibers, diffusion coefficient of the matrix (base resin) and temperature [8].

Presence of moisture in the epoxy matrix and in the fiber-matrix on the glass fibers are thought to be the main reasons for reduced strength of glass fiber reinforced polymer matrix (GFRP) woven fabric composite material in wet condition. In general moisture diffusion in a composite depends on factors such as volume fraction of fiber, voids, viscosity of matrix, humidity and temperature [9].

The inhomogeneities in the material, such as voids, micro-porosity, and damages related to thermo-mechanical loading history of the material, may affect the diffusion coefficient. The driving force for moisture diffusion is the gradient in the moisture concentration. For homogeneous materials, the moisture diffusion follows Fick's law.

In service, composite materials are exposed to varying humidity and temperature conditions. In this study, the effect of environmental conditions (different relative humidities) on the moisture diffusion properties of fabric composite material was investigated [10].

The objective of this work was to study the moisture absorption and absorption kinetics of fabric composite: Influence of hygrothermal conditioning (water uptake) kinetics and characteristics of the

water absorption.

Different models have been developed in order to describe the moisture absorption behavior of the materials [11]. For one-dimensional moisture absorption each sample is exposed, on both sides, to the same environment, the total moisture content G can be expressed as follows [12]:

$$G = \frac{m - m_i}{m_m - m_i} \quad (1)$$

$$G = 1 - \frac{8}{\pi^2} \sum_{j=1}^{\infty} \frac{1}{(2j+1)^2} \exp\left[-\frac{(2j+1)^2 \pi^2 D_x t}{h^2}\right] \quad (2)$$

Where m_i is the initial weight of the moisture in the material and m_m is the weight of moisture in the material when the material is fully saturated, in equilibrium with its environment. D is the mass diffusivity in the composite. This is an effective diffusivity since all the heterogeneities of the composites have been neglected. h is thickness of the specimen and t is the time. The moisture content is measured by finding the weight gain of the material.

The percent moisture content of the composite as a function of time was measured according to mass gain, using the following formula [13,14]:

$$M(\%) = \left(\frac{W_{\text{wet}} - W_{\text{dry}}}{W_{\text{dry}}}\right) \cdot 100 \quad (3)$$

Where the wet and dry weights are denoted by W_{wet} and W_{dry} . The moisture absorption was calculated by the weight difference. The percentage weight gain of the samples was measured at different time intervals and the moisture content versus square root of time was plotted.

Solving the diffusion equation for weight of the moisture, and rearranging in terms of percent moisture content, following relation is obtained:

$$D = \pi \left[\frac{h}{4M_m}\right]^2 (\text{slope})^2 \quad (4)$$

$$\text{Slope} = \frac{M_b - M_a}{\sqrt{t_b} - \sqrt{t_a}} = \frac{4M_m}{h\sqrt{\pi}} \sqrt{D} \quad (5)$$

Where M_m is the equilibrium moisture content of the sample. Using the weight gain data of the material with respect to time, a graph of percent moisture content of the material Vs square root of time is plotted.

2. EXPERIMENTAL

The aim of this experimental work was to study the moisture absorption and absorption kinetics of a laminate made of 12 layers of glass fiber fabric/epoxy resin: Influence of hygrothermal conditioning (water uptake) kinetics and characteristics of the water absorption.

The physical properties of woven fabric composite (glass fiber fabric/epoxy resin) studied are presented in Table 1.

The test is carried out on specimens machined (profiled specimen) with a radius of 1000 mm, length 200 mm, thickness 3,2 mm and width of 30 mm at the end and 20 mm at the center (Figure 1). The detail of this choice is discussed in the reference [15].

After total drying, samples were exposed to various moist environments at constant temperature and different relative humidities. A periodic weighing allowed ensuring that a physical equilibrium had been reached before testing.

In this second study, the effect of hygrothermal conditioning on the moisture diffusion properties of the fabric composite (glass fiber/epoxy resin) was investigated. The water uptake of the specimens conditioned in humid environment (Figure 2) at different relative humidities (0, 60 and 96% r.h) at constant temperature (60°C) was evaluated by weight gain measurements. The moisture diffusion properties of the fabric composite (glass fiber/epoxy resin) were determined using standard weight gain method. The diffusivity, D is measured by exposing a dry sample to a humid environment and measuring the mass of water absorbed (weight gain) as a function of time. The weight gain experiments were performed to determine the equilibrium moisture content M_m of the fabric composite as a function of relative humidity (r.h). The measured weight gain is then fit to the solution of the diffusion equation (Fick's law) to determine the diffusivity D .

The equilibrium moisture content of material

TABLE 1. Physical Properties of Woven Fabric Composite.

Composite	Thickness (mm)	Density (g/cm ³)	Fiber Volume Fraction in (%)
Woven Fabric	3.2	1.94	55

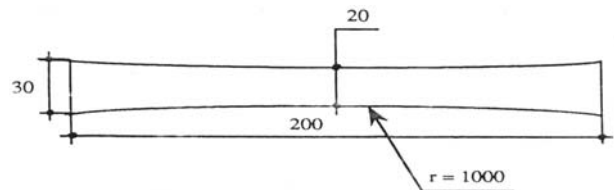


Figure 1. Profiled specimen with a radius of 1000 mm.

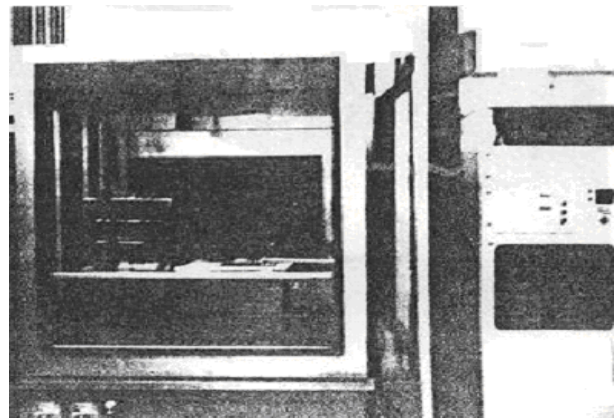


Figure 2. Environmental chamber of hygrothermal conditioning.

was reached at about six months. The aim of this work is to study the environmental (moisture absorption) behavior of glass fiber fabric/resin epoxy. This method is used to calculate the diffusivity D and the maximum moisture content M_m of the woven fabric composites.

3. RESULTS AND DISCUSSION

The influence of environmental conditions (water

uptake) for the lamina (glass fiber fabric/epoxy resin) is discussed. Figure 3 shows percentage of weight gain as a function of square root of time for fabric composites at different relative humidities (0,60 and 96 % r.h) at constant temperature (60°C). Table 2 presents the experimental results (D and M_m) of moisture absorption of composite (glass fiber fabric/epoxy resin). It can be seen that the maximum moisture content (M_m) value increases (Figure 4) with an increase in relative humidity (r.h) and the diffusion coefficient (D) decreases (Figure 5) with an increase in the relative humidity (r.h).

The weight gain depends mainly on three parameters: time (t), equilibrium moisture content (M_m) and diffusion coefficient (D). The values (characteristic parameters) of the kinetics of moisture absorption (M_m and D) obtained by the experimental moisture conditioning method confirms clearly the principal remarks observed: the diffusion coefficient (D) depends on the temperature and the equilibrium moisture content (M_m) depends on the relative humidity (r.h). Diffusivity is independent of relative humidity and maximum moisture content is independent of temperature.

The absorption behavior of the fabric composite was investigated at 60°C under different relative humidities. Two relative humidity conditions (60 and 96 % r.h) were selected and equilibrium weight gain was obtained as a function of relative humidity (r.h). To estimate the variability, the tests were performed with samples cut from different plates (four plates at 60 % r.h-60°C and four plates at 96 % r.h-60°C). The parameters G and P represent the ratio of M compared to M_m and the ratio of \sqrt{Dt} compared to h.

The experimental data of moisture absorption (results obtained) can be collapsed to a single curve, or master plot, by plotting G vs. P as in Figure 6. That the experimental data collapse to a single curve shows that Fick's law is a good model for moisture diffusion. Good agreement is found between the experimental and theoretical (Fick's law) results.

$$G = \frac{M}{M_m} \quad (6)$$

$$P = \frac{\sqrt{Dt}}{h} = \frac{\sqrt{D \cdot t}}{h} \quad (7)$$

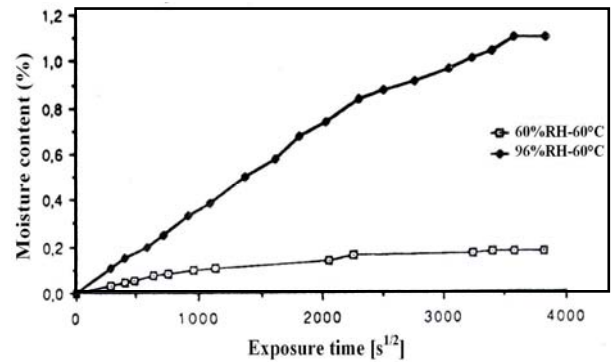


Figure 3. Moisture content of composite (glass fiber fabric/epoxy resin) under environmental exposure as a function of square root of time.

TABLE 2. Experimental Results of Moisture Absorption of Composite (Fabric Glass E Fiber/Epoxy Resin) at 60°C-60 and 96 % r.h.

Relative Humidity (r.h) in %	60	96
Diffusivity of Composite (D) in $\text{cm}^2/\text{s} \cdot 10^{-8}$	1,20	0,21
Maximum Weight Gain of Composite (M_m) in %	0,18	1,10
Maximum Weight Gain of Resin (M_m) in %	0,62	4,00

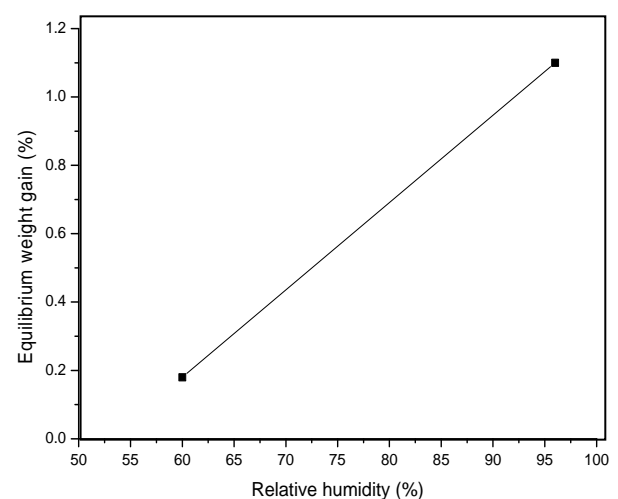


Figure 4. Maximum moisture content vs. relative humidity.

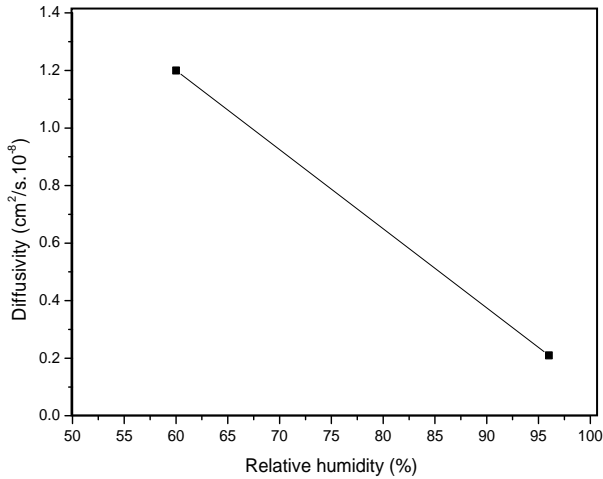
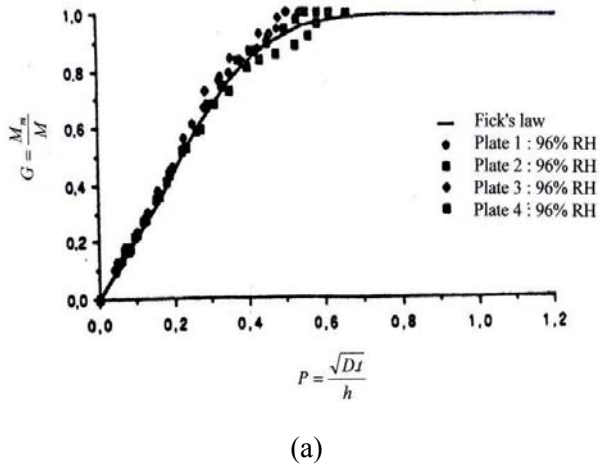
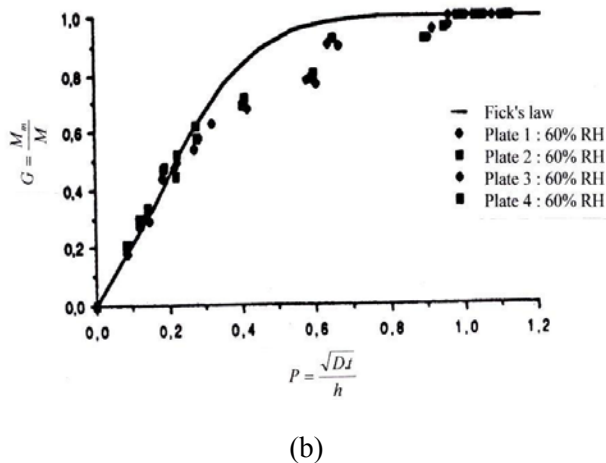


Figure 5. Diffusion coefficient vs. relative humidity.



(a)



(b)

Figure 6. Comparison between experimental data of moisture absorption and theoretical fick's law of fabric composite, (a) 96 % r.h-60°C and (b) 60 % r.h-60°C.

One notices that the kinetic absorption at 60 % RH significantly seems slower than the kinetic of Fick's (problem which could be due to a variation of the hygrothermic degree inside the climatic chamber of conditioning in vapor medium and to the periodic interruption in moisture absorption caused by removing the samples from the environmental chamber for weighing affects the results to a measurable degree).

Table 3 presents the Parameters characteristic of water absorption of the composite (glass E/polyester) given by Loss, et al [10]. The comparison carried out between the values obtained of the characteristic parameters (D and M_m) of the kinetics of water absorption by the hygrothermal test of conditioning carried out in the laboratory and those given by Loos and Springer confirms the following principal remarks clearly: the diffusion coefficient of water D and the maximum weight gain M_m depend not only on the nature of material but also of the environmental conditions (hygrothermal conditioning).

The maximum concentration of water (matrix + interface) obtained from calculations based on measured values, where a homogeneous diffusion phenomenon is assumed inside the material ($D_f=0$), shows clearly that the presence of fibers in a polymeric matrix reduces the water up-take of the matrix by about 4 times (see Table 2).

$$M_m(\text{Matrice}) = M_m(\text{Composite}) \cdot \frac{1}{1 - \frac{\rho_f}{\rho_c} V_f} \quad (8)$$

$$V_c = V_f + V_r = 1 \quad (9)$$

TABLE 3. Parameters Characteristic of Water Absorption of the Composite (Glass E/Polyester) Given by Loss, et al [10] at 65°C-60 and 100 % r.h.

Relative Humidity (r.h) in %	60	100
D in (cm ² /s. 10 ⁻⁸)	23,0	3,80
M_m in (%)	0,45	2,75

With:

- ρ_f : Density of Glass Fiber ($\rho_f = 2,54 \text{ g/cm}^3$),
 ρ_c : Density of Composite "Glass Fiber
Fabric/Epoxy Resin", ($\rho_c = 1,94 \text{ g/cm}^3$),
 ρ_r : Density of Resin "Epoxy Resin", ($\rho_r = 1,$
 17 g/cm^3),
 V_f : Fiber Volume Fraction ($V_f = 55\%$),
 V_r : Resin Volume Fraction ($V_r = 45\%$).

4. CONCLUSIONS

The moisture diffusion properties of the fabric composite (glass fiber/epoxy resin) were determined using standard weight gain method. The weight gain experiments were performed to determine the equilibrium moisture content M_m of the fabric composite as a function of relative humidity (r.h). The measured weight gain is then fit to the solution to the diffusion equation (Fick's law) to determine the diffusivity D .

The comparison carried out between the values obtained of the characteristic parameters (D and M_m) of the kinetics of water absorption by the hygrothermal test of conditioning carried in the laboratory and those given by Loos and Springer confirms the following principal remarks clearly: the diffusion coefficient of water D and the maximum weight gain M_m depend not only on the nature of material but also on the environmental conditions (hygrothermal conditioning). The maximum concentration of water (matrix+interface) obtained from calculations based on measured values, where a homogeneous diffusion phenomenon is assumed inside the material ($D_i=0$), shows clearly that the presence of fibers in a polymeric matrix reduces the water up-take of the matrix by about 4 times.

5. REFERENCES

1. Abdel-Magid, B., Ziaee, S., Gass, K. and Schneider, M., "The Combined Effects of Load, Moisture and Temperature

- on the Properties of E-glass/Epoxy Composites, *Composite Structures*, Vol. 71, (2005), 320-326.
2. Bonniau, T. and Bunsel, A.R., "A Comparative Study of Water Absorption Theory Applied to Glass-Epoxy Composition", *Journal of Composite Materials*, Vol. 15, (1981), 272-285.
3. Verpoest, I. and Springer, G.S., "Moisture Absorption Characteristics of Aramid Epoxy Composites", *Journal of Reinforced Plastics and Composites*, Vol. 17, (1988), 21-32.
4. Avena, A. and Bunsel, A.R., "Effect of Hydrostatic Pressure on the Water Absorption of Glass Fiber-Reinforced Epoxy Resin", *Composites*, Vol. 19, (1988), 355-357.
5. Aveston, J., Kelly, A. and Sillwood, J.M., "Long Term Strength of Glass Reinforced Plastics in Wet Environments", *Journal of Materials Science*, Vol. 17, (1982), 3491-3498.
6. Bian, X.S., Ambrosio, L., Kenny, J.M., Nicolais, L. and Dibenedetto, A.T., "Effect of Water Absorption on the Behavior of E-Glass Fiber/Nylon-6 Composites", *Polymer Composites*, Vol. 12, (2004), 333-337.
7. Colombini, D., Martinez-Vega, J.J. and Merle, G., "Influence of Hygrothermal Ageing and Thermal Treatments on the Viscoelastic Behaviour of DGEBA-MCDEA Epoxy Resin", *Polymer*, (2002), 1983-1992.
8. Chateauminois, A., Chabert, B., Soulier, J.P. and Vincent, L., "Hygrothermal Ageing Effects on the Static Fatigue of Glass/Epoxy Composites", *Composites*, Vol. 7, (1998), 547-555.
9. Zchang, Y.C. and Wang, X., "Hygrothermal Effects on Interfacial Stress Transfer Characteristics of Carbon Nanotubes-Reinforced Composites System", *Journal of Reinforced Plastics and Composites*, Vol. 25, (2006), 71-88.
10. Loos, A.C. and Springer, G.S., "Environmental Effects of Composites Materials, Technomic Publishing Company, Westport, (1981), 34-49.
11. Castaing, P. and Lemoine, L., "Effects of Water Absorption and Osmotic Degradation on Long-term Behavior of Glass Fiber Reinforced Polyester", *Polymer Composites*, Vol. 16, (2004), 349-356.
12. Lundgren, J., Gudmundson, P., "Moisture Absorption in Glass-Fiber/Epoxy Laminates with Transverse Matrix Cracks", *Composites Science and Technology*, Vol. 59, (1999), 1983-1991.
13. Arnold, J.C., "The Effects of Physical Aging on the Brittle Fracture Behavior of Polymers", *Polymer Engineering and Science*, Vol. 35, (2004), 165-169.
14. Al-Dulajjan, S.U., Al-Zahrani, M.M., Nanni, A., Boothby, T.E. and Boothby, T.E., "Effect of Environmental Pre-Conditioning on Bond of FRP Reinforcement to Concrete", *Journal of Reinforced Plastics and Composites*, Vol. 20, (2001), 881-900.
15. Naceri, A. and Vautrin, A., "Proposition D'un Modèle Expérimental Pour La Caractérisation De La Réponse Mécanique D'un Composite (Tissu De Verre/Résine Époxyde)", *Journal De Physique IV*, Vol. 124, (2005), 201-206.