Workshop « Soft Material Models »

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Multi-Scale Modeling of Phosphate Glass Fiber-Reinforced Polyester Composites : Numerical and Experimental Analysis

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Abstract

Today, numerical simulation and modeling are essential for designing and developing new products to meet the requirements of the industry of the future. This involves using mathematical models and computational techniques to virtually test different configurations and find the optimal design before launching production, especially when the products are based on composite materials. Recognized for their lightness and incomparable performance, composite materials are widely used in industry and are even critical for certain industries.

This work explores the use of phosphate glass fibers as reinforcements for the polyester matrix. Multi-scale modeling is established using Abaqus software to understand the mechanical behavior of structures while minimizing development efforts.

Development and characterization tests of these composite materials have been carried out in the laboratory. Experimental results indicate that phosphate glass fibers exhibit mechanical properties comparable to silica glass fibers. These results were exploited to establish a numerical model facilitating the improvement of the designed products and the choice of the appropriate elaboration process. Numerical simulation is a valuable tool in the development of composite materials which highlights the potential for using phosphate glass fibers as reinforcing materials.

Valuable information on the influence of various factors such as fiber volume fraction, orientation distribution and interfacial properties on the mechanical properties of composite materials was obtained. This information can contribute to the development of high-performance composites and advances composite materials based on phosphate glass fibers.

Methodology

Composite materials were manufactured using the contact molding technique. A mixture of resin, hardener, and accelerator was prepared with concentrations of 13% and 0.13% respectively. The mixture was mechanically stirred at a speed of 900 rpm for 2 minutes before being poured into a waxed aluminum mold. After the resin cured, the parts were demolded. Specimens were prepared with dimensions of 170mm x 20mm x 5mm for tensile testing according to ISO 527 standard, and 80mm x 20mm x 5mm for bending testing according to ISO 14125 standard. The specimens exhibited linear elastic behavior following Hooke's law, represented by the equation σ = E.ε, where E is the Young's modulus. Fifteen specimens were prepared for bending tests according to ISO 14125 standard. To investigate the microscopic behavior of a composite material with randomly distributed short phosphate glass fibers, we utilized the Abaqus software by employing a homogenization approach. Specifically, we utilized the associated tool called Homtools to facilitate our analysis. This enabled us to gain insights into the composite's mechanical properties and understand its structural behavior at a microscopic level.

Fiber Mass (g)	0	0.5	1	1.5	2
Percentage of reinforcement (%)	0	13	27	41	55

Table 1: table of volume fractions according to the mass of the reinforcement of the specimens

Figure 1:*Tensile test specimen for composite materials according to ISO 527*

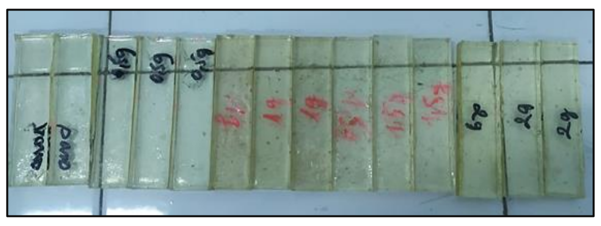
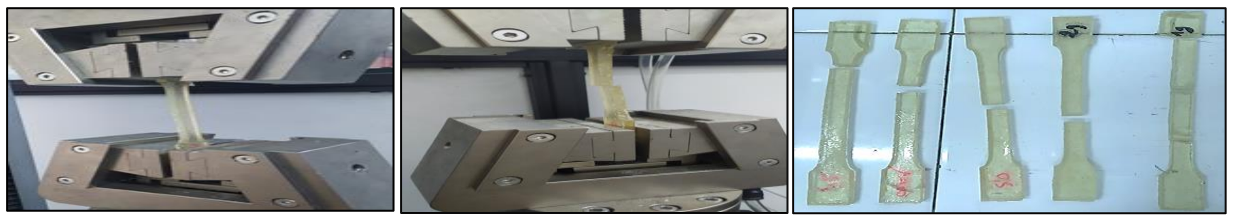


Figure 2:*Bending test specimen before fracture*

The results obtained from the uniaxial tensile test conducted on 15 specimens using the machine depicted in Figure 3.



(a) (b)

Figure 3 *:(a) tensile testing instrument and (b)specimens after rupture*

A linear isotropic material is a material whose physical and mechanical properties are identical in all directions. In other words, a linear isotropic material has the same physical properties and the same mechanical properties (such as tensile strength, stiffness) in all directions. The most general form of isotropic stress-strain relations is illustrated below:

$$\begin{bmatrix}\sigma_{xx}\\ \sigma_{yy}\\ \sigma_{zz}\\ \sigma_{yz}\\ \sigma_{zx}\\ \sigma_{xy}\end{bmatrix} = \begin{bmatrix}\frac{E(1-\vartheta)}{(1+\vartheta)(1-2\vartheta)} & \frac{E\vartheta}{(1+\vartheta)(1-2\vartheta)} & \frac{E\vartheta}{(1+\vartheta)(1-2\vartheta)} & 0 & 0 & 0\\ \frac{E\vartheta}{(1+\vartheta)(1-2\vartheta)} & \frac{E(1-\vartheta)}{(1+\vartheta)(1-2\vartheta)} & \frac{E\vartheta}{(1+\vartheta)(1-2\vartheta)} & 0 & 0 & 0\\ \frac{E\vartheta}{(1+\vartheta)(1-2\vartheta)} & \frac{E\vartheta}{(1+\vartheta)(1-2\vartheta)} & \frac{E(1-\vartheta)}{(1+\vartheta)(1-2\vartheta)} & 0 & 0 & 0\\ 0 & 0 & 0 & \frac{E(1-2\vartheta)}{2(1+\vartheta)(1-2\vartheta)} & 0 & 0\\ 0 & 0 & 0 & 0 & \frac{E(1-2\vartheta)}{2(1+\vartheta)(1-2\vartheta)} & 0\\ 0 & 0 & 0 & 0 & 0 & \frac{E(1-2\vartheta)}{2(1+\vartheta)(1-2\vartheta)}\end{bmatrix} \times \begin{bmatrix}\varepsilon_{xx}\\ \varepsilon_{yy}\\ \varepsilon_{zz}\\ \varepsilon_{yz}\\ \varepsilon_{zx}\\ \varepsilon_{xy}\end{bmatrix}$$

Data Analysis

The experimental results have been obtained through the tensile and bending tests presented below:

	Experimental Results	
	Résistance à la traction (Mpa)	Module de traction (MPa)
0 %	29,2276	693,4406
13%	240,504	2672.600
27%	301,675	4422,969
41%	312,26	4861,303
55%	399,199	6180,556

Table2: Table of values for the uniaxial tensile test

	Experimental Results	
	Résistance à la Flexion (MPa)	Module de Flexion (MPa)
0 %	209.458	2122.016
13%	1228.270	64067.163
27%	1339.236	76412.439
41%	1853.460	77169.233
55%	2687.028	127100.086

Table3: Table of values for the 3-point bending test

The mechanical properties of silica glass fiber were determined using the uniaxial tensile test :

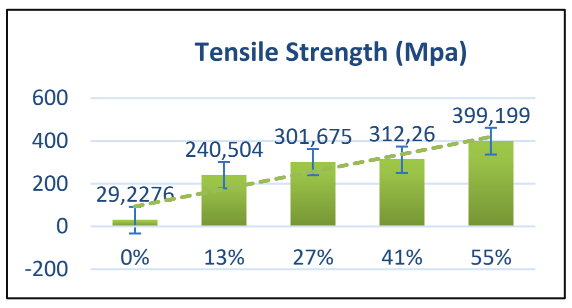


Figure 4: Tensile strength of silica glass fibers

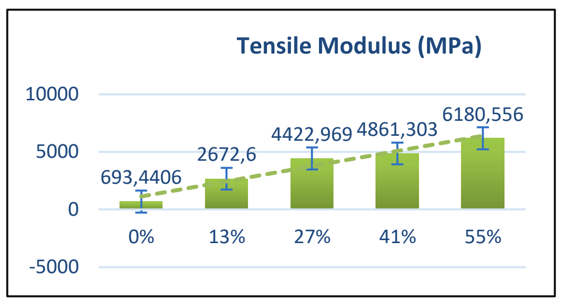


Figure 5: Tensile modulus of developed glass fibers

The mechanical properties of silica glass fiber were determined using the 3-point Bending test:

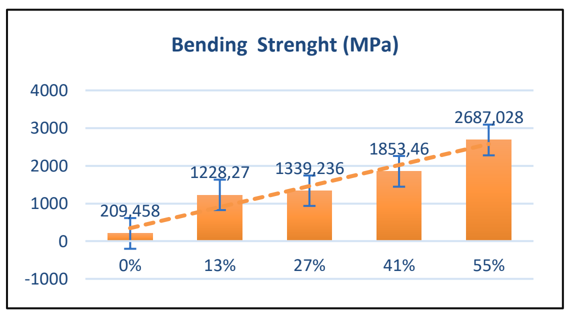


Figure 6: Bending strength of developed glass fibers

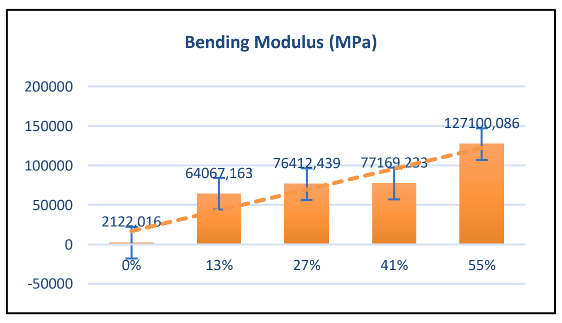


Figure 7: Bending modulus of developed glass fibers

Results

The objective is to calculate the stiffness matrix for polyester matrix without fiber inclusions to test our numerical model.

$$RF_1 = \frac{E(1-\vartheta)}{(1+\vartheta)(1-2\vartheta)} \qquad RF_2 = \frac{E\vartheta}{(1+\vartheta)(1-2\vartheta)}$$

However

$$RF_1 = 1022 \qquad RF_2 = 255.6 \qquad RF_3 = 255.6$$

Young's modulus : E ≈ 919.8MPa
Poisson's ratio : $\vartheta \approx 0.2$

Mechanical parameters	Experimental results	Simulated results
Young's modulus (Mpa)	920	919.8
Poisson's ratio	0.2	0.2

Table 4: Comparison between experimental and simulated results of Polyester Matrix

After simulating a polyester matrix composite with varying proportions of randomly distributed short phosphate glass fibers using the homogenization method and the Homtools interface, the obtained numerical results were post-processed using analytical equations. The results were summarized in a table and compared with experimental data for Young's modulus in a figure.

Spécimens	Experimental Young Modulus (GPa)*	Number of fibers	Simulated Young Modulus (Gpa)
polyester/ 8 % FVP	1.1	17	0.918
polyester/ 16 % FVP	1.42	34	0.918
polyester/ 24 % FVP	1.62	51	0.918
polyester/ 32 % FVP	1.8	68	0.918
polyester/ 40 % FVP	2.3	85	0.918

Table 5 : Comparison of simulated and experimental results for Young's modulus with fiber volume fractions included

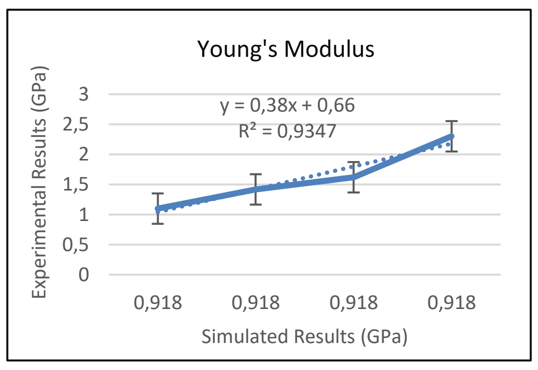
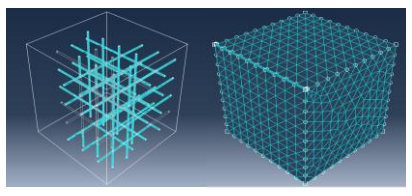


Figure 8: Representation of the correlation between simulated and experimental results of Young's Modulus

The stiffness matrix of randomly distributed short phosphate glass fibers -Reinforced Polyester Composites is:



$$\{C\} = \begin{bmatrix}1022 & 255.6 & 255.6 & 0 & 0 & 0\\ 255.6 & 1022 & 795.1 & 0 & 0 & 0\\ 255.6 & 255.6 & 1022 & 0 & 0 & 0\\ 0 & 0 & 0 & 383.25 & 0 & 0\\ 0 & 0 & 0 & 0 & 383.25 & 0\\ 0 & 0 & 0 & 0 & 0 & 383.25\end{bmatrix}$$

Conclusion and perspectives

About polyester matrix, it is observed that the Young's modulus and the Poisson's ratio are similar for the analytical case, confirming the robustness of the chosen method. For the case of a composite with a polyester matrix reinforced with random short fibers, it can be observed that the coefficient of determination R² close to 1 indicates a good agreement between the experimental and simulated values of the Young's modulus.

In other words, the closer the value of R² is to 1, the better the agreement between the experimental and simulated values is considered. This approves the validity of the chosen model.

When the percentage of fibers increases in a heterogeneous material with random fibers, the local variations introduced by the random fibers tend to compensate each other, leading to macroscopic properties that resemble those of a homogeneous material. The fibers can strengthen the material and reduce local variations, which could explain the observed similarity to a homogeneous material.

References

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