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MECHANICAL PROPERTY CHANGES IN CASE OF EXTREME ENVIRONMENTAL CONDITIONED HYBRID POLYMERIC COMPOSITES

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Abstract: An integrated approach – theoretical predictions and experimental measurements – with the aim of characterizing the changes in the mechanical properties (e.g. effective Young modulus of bending) of hybrid polymeric composite structures of particle-fibre type subjected to different extreme environmental conditions such are the cryogenic temperatures respectively a summer desert temperature variation. The experimental data corresponding to the aimed mechanical property were retrieved using a 3-point bending device from Lloyd (UK) and further compared with the ones from a micromechanical modelling based approach. The environmental conditioning has different influences on the measured property, and this will be sized by comparing the theoretically predicted and experimentally retrieved data.

1. INTRODUCTION

Estimation of the effective heterogeneous material properties such is the mechanical (e.g. longitudinal, shear or bulk moduli, Poisson ratio, etc.), thermal (e.g. thermal conductivity or thermal expansion, etc.) or electric (e.g. electrical conductivity, etc.) in terms of the phase properties and microstructure is a lastingly standing issue [1,3,6].

Extreme environmental conditioning of the composite structures, no matter the materials used for their phases, do not represent a literature trend but practical significance due to the climate changes and engineering application of these type of materials. Technical literature provide numerous references with respect of the subject, ranging from high to low temperature environmental conditioning of the specimens, all under a conducted thermal aging process [5,7].

Theoretical predictions of the composite material properties were steping out from the macroscopic level, that fails to take into account the phases' material properties dependencies, moving to the microscopic level and toward to nano dimensions.

A micromechanical based approach will be used in the present paper to predict the multiphase polymeric composite structures developed and manufactured using a lay-up manufacturing technology [2]. The predicted data will be next compared with two sets of experimental data retrieved after conditioning the composite sample to different environmental conditioning.

Multiphase polymeric composites have found a niche into engineering applications that involve extreme environmental conditions, such as high and low temperatures or fluctuations between these, including different hygroscopic parameters. These engineered and engineering applications include electronic packaging and substrates, sensors and actuators, drive shafts, cylinders and brake rotors, pistons, bearings to name only few of them.

In order to design a suitable multiphase polymeric composite structure for the previous mentioned engineering applications several material properties have to be predicted and/or experimentally retrieved. Following this objective, an attempt has been made to analyze the behavior of a particle-fiber type multiphase polymeric composite material subjected to 3-point bending conditions.

Fiber reinforced composite materials are very sensitive to the mechanical loads, either tension, compression or bending. This is the reason for which such tests are conducted carefully. Furthermore, if subjected to environmental extreme conditioning these composite samples add a supplementary influencing factor to the evolution of their material properties.

Based on the previous mentioned ones this paper will focus on the mechanisms of elastic property degradation for a multiphase polymeric class of composite materials due to both environmental conditioning as well as phase related characteristics (e.g. volume fraction, etc.).

2. EXPERIMENTAL RESEARCH

This section describes the materials used to manufacture the composite samples, specimen preparation methods, testing procedure and experimental observation made during the investigation.

2.1 Materials

The multiphase composite samples were manufactured as having three phases – random fibres and particles - embedded in a different volume fraction into a polymeric matrix. The matrix material is commercially known as Synolite 8388 P2 from DSM Composite Resins (Switzerland), a polyester resin type.

The particle inclusions considered were ceramic materials (with a high content of Al_2O_3), made from a natural stone, characterized as having a relatively high purity and provided by Alpha Calcite (Germany) under the Alfrimal registered trade-mark and technical pure iron, respectively. Both particle types were mixed within the polyester resin mass in 5% and 10% volume fraction, respectively.

The 3rd phase chosen was E-glass type random fibres, commercially available under the MultiStrat^{TM} Mat ES 33-0-25 trade name (from Johns Manville, SUA) mixed as having a 65% volume fraction in the overall composite volume. The reference sample was made without any particle content and used for comparison purpose.

2.2 Environmental conditions setting

Six sets of test samples, each set consisting of five test specimens were prepared to study the effect of environmental conditioning on the mechanical properties (Young modulus, tensile strength in the longitudinal direction).

The samples were conditioned within a temperature controlled oven to an extreme environmental regime – a normal *summer desert day*, seven days long, 24 hours/day, at temperature range from -10^{0}C (during the night) to 40^{0}C (during the midday). The humidity levels, temperatures and hours corresponding to a single day thermal cycle, used as input data for the oven programming, are given in the Table 1.

Table 1 Input data for the oven programming – thermal cycle characteristics

Temperature [^{0}C]	Relative humidity level [%]	Time [h]
-10	45	8
0	50	1
10	50	1
20	55	1
30	60	1
40	65	8

Another extreme environmental regime was chosen to be a *cryogenic* environment, the composite samples being subjected 7 days long, 24 hours/day, at a temperature of -35^{0}C. A set of composite samples were kept unaffected by the environmental conditioning, subjected to the same mechanical testing like the previous counterpart and used further in data processing and comparison.

The mechanical measurements were performed using a LR5K plus 3-point bending device from Lloyd Ltd. Company, at a speed of 1 mm/min for rectangular shaped composite samples positioned on two supporting beds.

A computer program was used to analyze the experimental curves and to provide the corresponding statistics on each representative composite class under investigation. Experimental data were next subjected to further comparison by the aid of Microsoft Excel, as a common and graphical/statistics environment.

3 THEORETICAL APPROACH

A micromechanical based approach was developed herein with the aim of retrieving the effective mechanical moduli of elasticity in case of the particle-fibre multiphase polymeric composites. The *Mori-Tanaka* method proved to have a wider used comparatively with other theoretical models, due to its consistency and bounded trend within the upper and the lower limits of *Voigt* and *Reuss* models [2].

As a general specification, the use of the *Mori-Tanaka* micromechanical model to retrieve the material properties of hybrid structures made up from two inhomogeneous phases leads to different results based on which case is considered: *multi-step* or *multi-phase*. Differences among them rise from the phases embedding method considered in the homogenization process: phases embedded in different steps or phases embedded in the same time.

Herein, a multi-step homogenization process was used based to retrieve the mech

anical properties, taking the particle fillers, firstly, process leading to a so called equivalent matrix (due to their dilute limit) and next the long, random fibres as a second phase.

Following will be provided the expressions for the effective bulk modulus and the shear modulus associated to the first homogenization step among the polymer matrix and the particles:

$$\frac{K_{me}}{K_m}=1+\frac{V_p\left(\frac{K_p}{K_m}-1\right)}{V_p+f_1(1-V_p)};\ \frac{G_{me}}{G_m}=1+\frac{V_p\left(\frac{G_p}{G_m}-1\right)}{V_p+f_2(1-V_p)} \tag{1}$$

where:

$$f_1=1+\frac{3(K_p-K_m)}{3K_m+4G_m} \tag{2}$$

$$f_2=1+\frac{6}{5}\frac{(G_p-G_m)(K_m+2G_m)}{G_m(3K_m+4G_m)} \tag{3}$$

are the shape factors based on the bulk modulus and shear modulus of phases, respectively. Subscripts *m* and *p* are being associated to the matrix and particles, respectively, *me* being associated to the equivalent matrix from the homogenization process. The *V* parameter stands for the phase's volume fraction.

The second homogenization step applied upon the previously equivalent matrix and the long, random fibres was conducted using the well-known expressions of *Halpin-Tsai*, such as:

$$E_c = \frac{3}{8}E_L + \frac{5}{8}E_T \quad (4)$$

where E_L and E_T are the Young elasticity modulus in the longitudinal and transversal directions, respectively of an equivalent composite material reinforced with directional fibres. These elastic moduli are radius and length of fibres dependent and can be predicted based on the following expressions:

$$E_L = E_{me}\frac{1+2\eta_L V_f \frac{l_f}{d_f}}{1-\eta_L V_f} \quad (5)$$

$$E_T = E_{me}\frac{1+2\eta_T V_f}{1-\eta_T V_f} \quad (6)$$

where η_L and η_T are being given by:

$$\eta_L = \frac{\frac{E_f}{E_{me}}-1}{\frac{E_f}{E_{me}}+2\frac{l_f}{d_f}} \quad ; \quad \eta_T = \frac{\frac{E_f}{E_{me}}-1}{\frac{E_f}{E_{me}}+2} \quad (7)$$

The *f* subscript stands for the fibres. The Young modulus of fibres depends upon the fibres diameter d_f, in [m]. In the previous expressions were used: K – bulk modulus, [GPa]; G – shear modulus, [GPa]; E – Young modulus, [GPa]; L – longitudinal direction; T – transversal direction.

4 RESULTS AND DISCUSSION

Figure 1 represents a microscopic view (with an x500 magnification factor) of the 65% E-glass fibre and 5% particles reinforced hybrid polymeric composite samples. A closer look reveals the random widespread of the particles within the overall composite structure as well as their presence at the dilute limit.

In figure 2 is being plotted the experimentally retrieved and theoretically predicted effective Young modulus of elasticity of the hybrid structured under analysis. As it can be seen the extreme environmental conditioning has a direct influence of the measured property, leading to an overall degradation of this.

Moreover, the Young modulus is experiencing a decrease along with the increase of the particle filler volume fraction, either ceramic or metallic. This is generally acknowledged in the literature and valid for each theoretical model one may use for the micromechanical based approach mechanical property prediction. What makes the differences are the experimental values obtained for the same volume fraction reinforcement but different environmental conditions.

The cryogenic conditioning proved to lead to higher values of the elastic modulus that its counterpart conditioning considered in the analysis. In figure 3 is being plotted the relative error between the theoretically predicted and experimentally retrieved values of the hybrid composite samples analysed including the environmental effects (the notations stand for: T – theoretical values, C – cryogenic conditioning, S – desert environment).

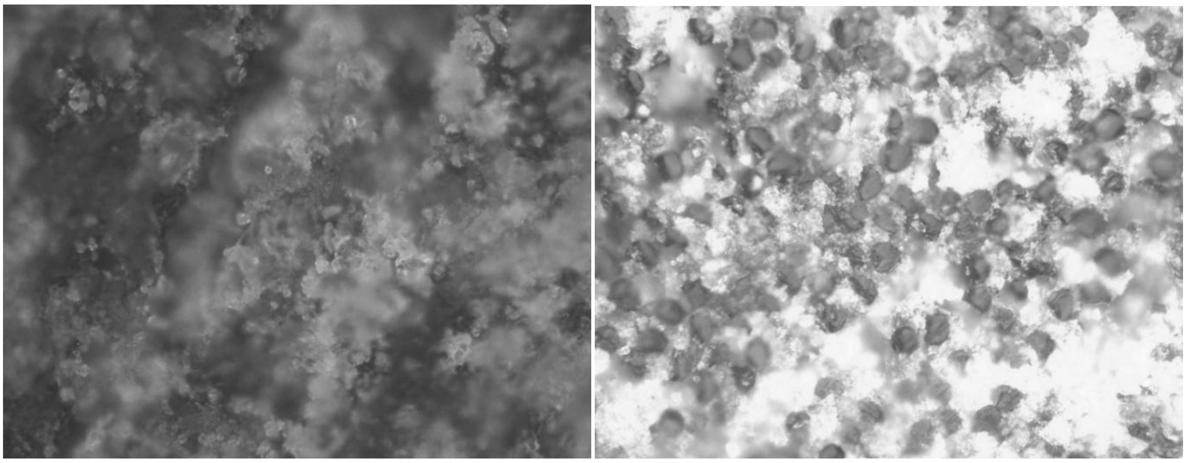

Fig. 1 Micrographic views of a particle-fibre type reinforced polymeric hybrid composite samples (x500 magnification) (left – ceramic particles, right – metallic particles)

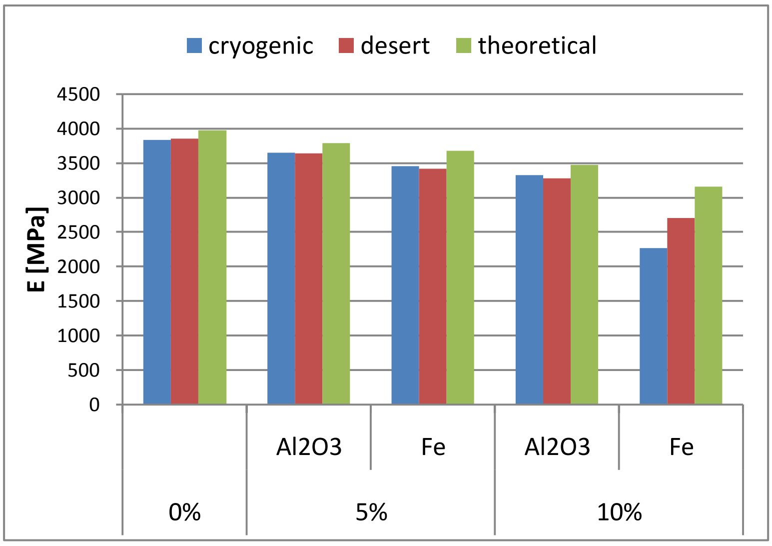

Fig. 2 Theoretical predicted and experimentally retrieved effective Young modulus for hybrid polymeric composite structures (ceramic and metallic particles along with glass fibres)

The ceramic particles are not so susceptible to the environmental conditions changes like their metallic counterparts, who proved to give higher differences in the elastic modulus.

The extreme environmental conditioning has influence on the polymeric chains and this in return influences the overall behaviour of the hybrid composite structure. A detailed analysis of such influence has not covered herein being outside the purpose of the paper subject.

As it can be seen from Fig. 3, the relative error between the conditioned polymeric hybrid composite samples and their unconditioned state reveals the influence of the extreme conditioning on the measured property. Moreover, a negative temperature conditioning has influence on the structural stability of the matrix material, and gives rise to great opportunities to use these types of materials in engineering applications for environments such is the North Pole, Siberia, etc.

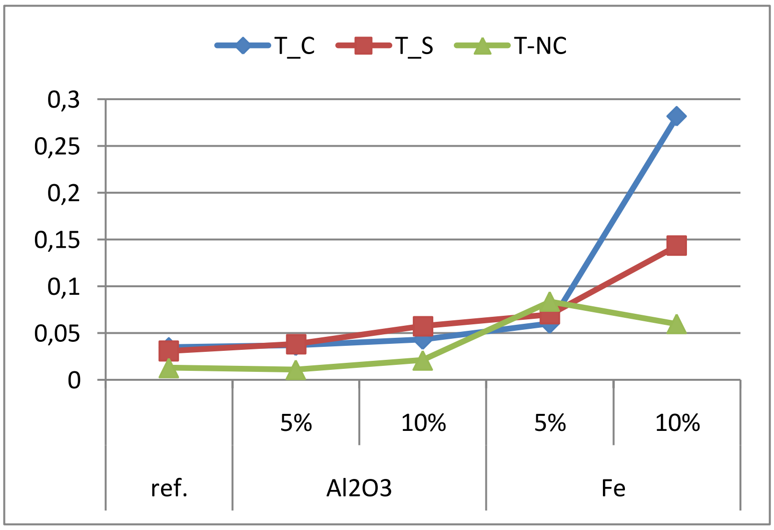

Fig. 3 Relative error between the theoretical predicted and experimentally retrieved elastic modulus of bending

5. CONCLUSIONS

Environmental conditioning of materials will remain an open and lasting standing issue in the process of modern material characterization. Either higher temperature values of lower ones, these extreme environmental conditioning have influence on the internal structure and overall mechanical, thermal or electrical polymeric based composite materials, usually proving to lead to material property degradation.

The micromechanical based theoretical models approach better the overall elastic properties of the composite materials no matter their morphology, type of materials or phase number but always seem to lead to higher values comparatively to the experimental ones. This observation is obvious and of practice relevance because the theoretical models such are the one used in this work do not encompass information with respect to the interaction of phases or morphology related modification as these heterogeneous materials are experiencing environmental changes.

The subject of herein paper is opening a niche with respect to the needs of modifying the micro mechanically based theoretical model in order to encompass these types of environmental related changes. Moreover, it leads to the possibility of approaching both theoretically and experimentally other multiphase composite structures such as fiber-fiber or particle-particle as well as other types of environmental regimes.

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