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Comparison Between Ultrasonic and Mechanical Young's Modulus of a Bio-composite Reinforced with Olive Wood Flour

Slim Souissi¹(✉), Karim Mezghanni^{1,2}, Nesrine Bouhamed^{1,2},
Pierre Marechal², Mohamed Benamar¹, and Olivier Lenoir²

¹ Laboratory of Electromechanical Systems, LASEM/ENIS, University of Sfax,
Sfax, Tunisia

Slim.souissi@ymail.com

² Laboratory Waves and Complex Environments LOMC,
University of Le Havre, Le Havre, France

Abstract. Ultrasonic testing is a technique frequently used in the field of nondestructive evaluation given the fact that ultrasonic waves are directly related to the mechanical behavior of materials. It is for this reason that mechanical waves are often involved in solid material testing and the evaluation of their mechanical properties. As such, ultrasonic velocity is often used to identify so-called healthy concrete in comparison to deteriorated concrete. The objective of the present study is to determine Young's modulus of a bio composite using two methods: ultrasonic and mechanical methods. For this, a bio-composite based on polypropylene (PP) as a matrix and the olive wood flour (OWF) as a reinforcement was elaborated with extrusion using a twin extruder following by the injection in the form of 4 mm thick plate for ultrasonic control and standardized specimens for tensile testing. The longitudinal and transversal velocity of propagation of the wave in the plates is measured with the technique of immersion in water using transducer at 5 MHz center frequency in order to determinate the ultrasonic Young's modulus. Results show that the ultrasonic Young's modulus of the studied bio-composite is different than that mechanical Young's modulus. The causes of this difference will be studied.

Keywords: Ultrasonic Young's modulus · Mechanical Young's modulus
Bio-composite · Polypropylene · Olive wood flour

1 Introduction

Increasing attention to environmental protection from industrial pollution has raised interest in biomaterials, and in particular towards bio-composites, materials obtained usually by reinforcing matrices by means of natural fibers [1]. In this context, Natural fibers have recently become attractive for researchers, engineers and scientists as an alternative component for composite materials. Due to their low cost, fairly

good mechanical properties, high specific strength, non-abrasive, eco-friendly and bio-degradability characteristics, they are exploited as alternative for the conventional fiber, such as glass, aramid and carbon [2, 3]. To evaluate properties of these kinds of materials, ultrasonic non-destructive testing techniques and mechanical testing have proven to be effective and they were used to measure the Young's modulus. In fact, an important parameter to characterize the stiffness of material is the Young's modulus and its accurate determination is required in many fields ranging from medicine to structural mechanics [4].

In this paper, a bio-composite made of PP and OWF is elaborated, the longitudinal and transversal velocity of the composite are experimentally determined, the ultrasonic Young's modulus will be obtained through these velocities, then standardized specimens will be submitted to tensile tests through a tensile machine in order to determine the Young's modulus.

2 Materials and Methods

2.1 Materials

The PP used is a fluid injection-molding grade with a melt flow index of 25 g/10 min to facilitate the dispersion and process ability of the composite material. It is characterized by its low density, high inertia to chemical attack, high resistance to shocks and with temperatures of use higher than 100 °C.

OWF used as a reinforcement for PP composites. It is obtained by vacuuming woodwork waste from craft objects made by olive wood. The OWF used has an average grain diameter of 110 µm.

2.2 Methods

The composite plates are elaborated going through three steps:

The mixture used consists of two components: olive wood flour (OWF) and polypropylene (PP) in the form of granules. Three rate of reinforcement used in our mixtures are prepared: 10%, 20%, and 30%, PP plate using 0% reinforcement will also be elaborated.

The mixtures are extruded using a twin extruder containing three heating zones, the temperature used is 180 °C, the rotational speed is 100 towers per minute and the feed rate is 200 g/h.

This gives PP granules mixed with OWF.

After the preparation of the granules, they are putted in an injection machine in order to be injected in the form of plates having 4 mm of thickness and standard test pieces (ISO 1/2).

3 Ultrasonic Young's Modulus E_{ultra}

The ultrasonic Young's modulus is determined from the following expression

$$E = \frac{\mu(3\lambda + 2\mu)}{\lambda + \mu} \quad (1)$$

$$\lambda = \rho C_L^2 - 2\mu : \quad \text{first Lamé coefficient} \quad (2)$$

$$\mu = \rho C_T^2 : \quad \text{second Lamé coefficient} \quad (3)$$

To determinate the ultrasonic Young's modulus of plates, it is necessary to determine first the longitudinal and transversal velocity and the density of every plate. We will study now the case of a 10% reinforcement plate.

3.1 Longitudinal Velocity

The longitudinal velocity of propagation of the wave in the plate is determined with the technique of immersion in water at normal incidence. The transducer at 5 MHz center frequency and the plate are placed in the water bath and maintained with a support (Fig. 1).

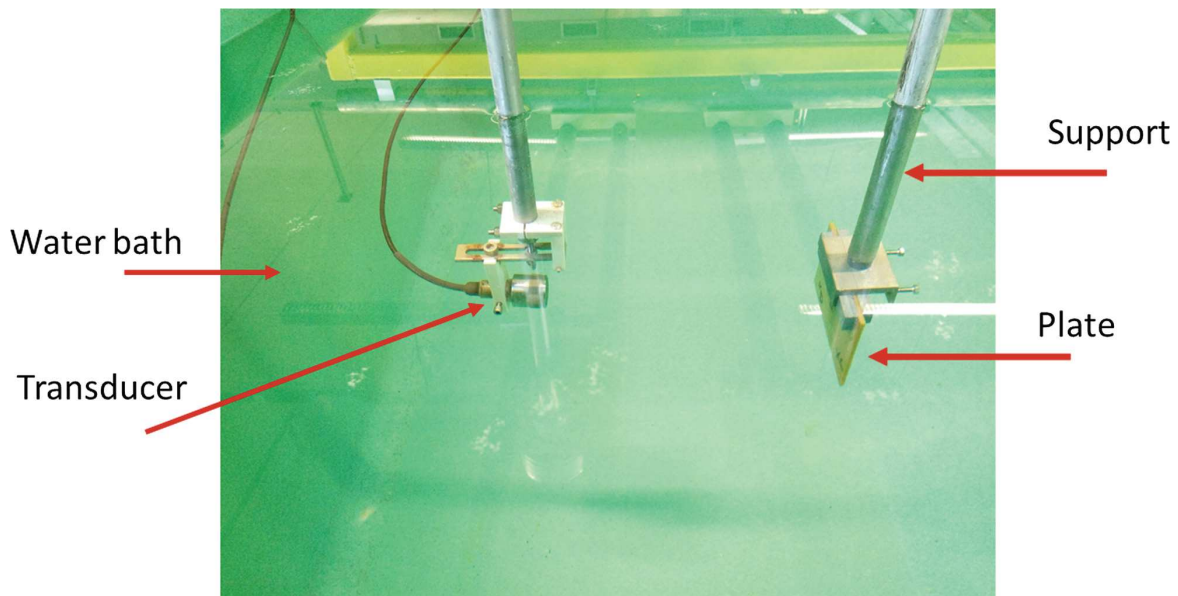


Fig. 1. Immersion control at normal incidence.

The signals obtained after the measurement made by the transducer, which inform about the longitudinal velocity, were processed using MATLAB software according to two estimation methods: the time of flight and the spectral method.

Time of Flight Method

The time of flight is the course time of a wave. This method consists in evaluating properties in the temporal domain from two echoes by measurements of time of flight and amplitude ratio as it's shown in Fig. 2.

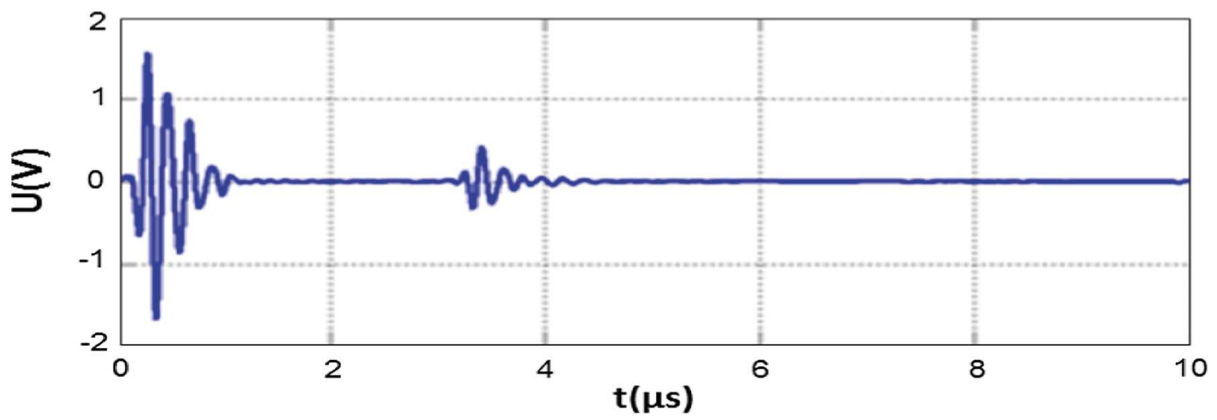


Fig. 2. Temporal signal of 10% reinforcement plate.

The longitudinal velocity in the plate is calculated through the following equation [5]:

$$C_L = \frac{2e_p}{\Delta t_L} \quad (4)$$

e_p is the plate thickness, $\Delta t_L = t_{2L} - t_{1L}$, with t_{1L} is the projection on the time axis of the maximum of the first echo $s_1(t)$, et t_{2L} is the projection on the time axis of the maximum of the second echo $s_2(t)$ (Fig. 3).

$$e_p = 4 \text{ mm.}$$

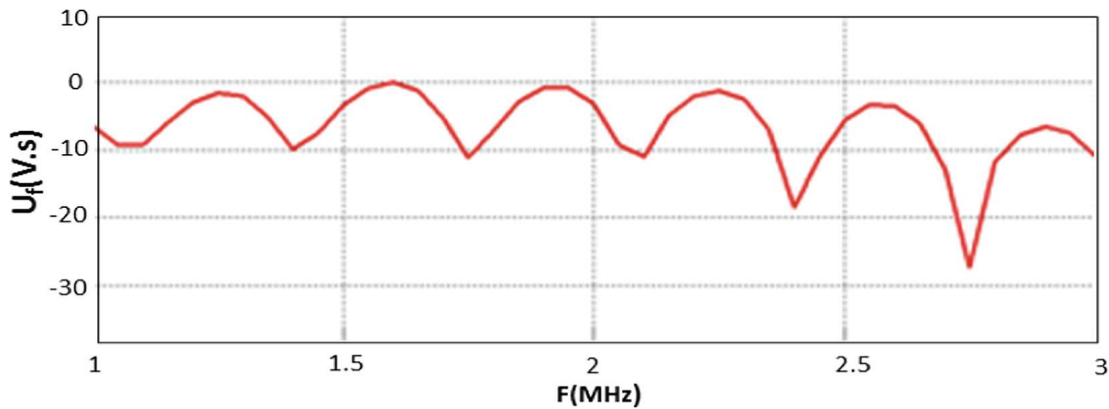


Fig. 3. Spectrum of 10% reinforcement plate.

The time between the two echoes is: $\Delta t = 3.4 - 0.4 = 3 \text{ } \mu\text{s}$. $C_L = \frac{2e_p}{\Delta t_L} = \frac{2 \times 4 \cdot 10^{-3}}{3 \cdot 10^{-6}} = 2664 \text{ m/s}$.

Spectral Method

The spectral method consists in expressing the temporal signal as a function of the spectral ratio of two echoes, in the case where frequency evolutions of speed and can be observed (Fig. 4).

By making the Fourier Transform of the signal $s(t)$ with Matlab, we obtain the spectrum $\underline{S}(f)$ whose module is shown in Fig. 3.

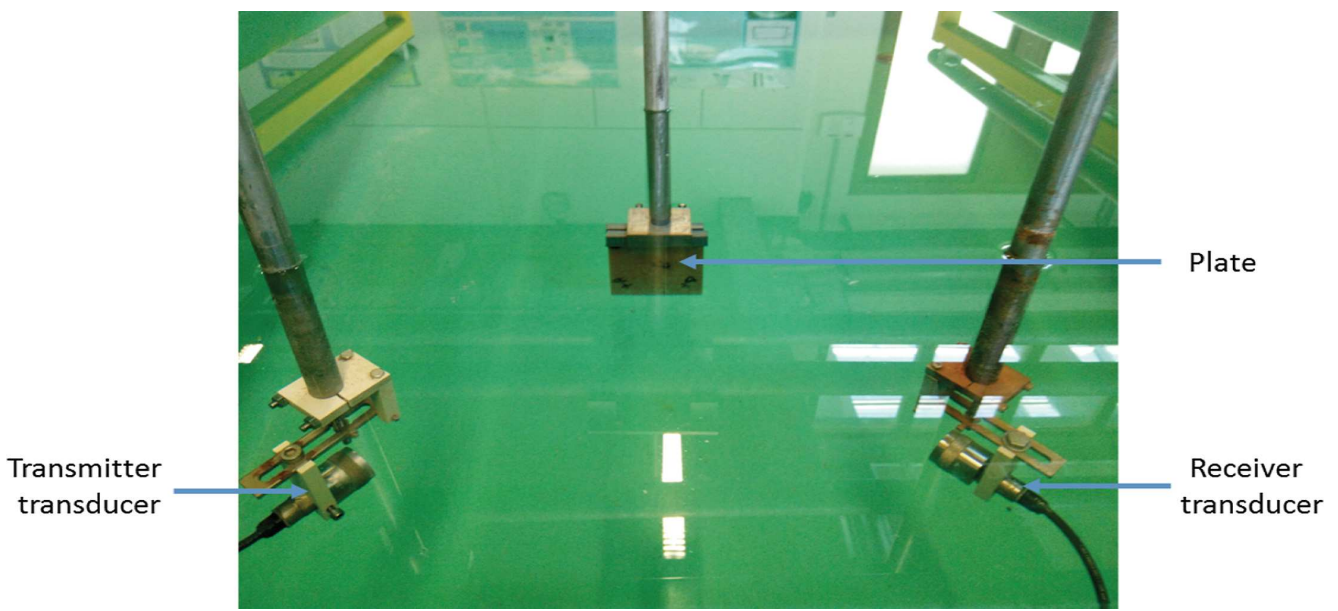


Fig. 4. Immersion in water control at oblique incidence.

The spectral method allows to calculate the longitudinal velocity C_L [6] in the plate through the following expression:

$$C_L = 2e_p \cdot \Delta f \quad (5)$$

Δf : interval between two consecutive minimums of frequencies.

According to the following spectrum $\Delta f = 0.333 \text{ MHz} = 333 \text{ kHz}$.

$$C_L = 2e_p \cdot \Delta f = 2 \times 4 \times 333 = 2664 \text{ m/s}$$

These steps are repeated to calculate the longitudinal velocity of all plates.

3.2 Transversal Velocity

The transverse velocity of wave propagation in plates is determined through immersion in water method at oblique incidence. The experimental device is constituted of a water bath in which the plate and two 5 MHz center frequency transducers are placed. The first transducer acts as a transmitter, the second is a receiver. The angle made by the two transducers is set according to the Snell–Descartes law.

After the recovery of data and their analysis through Matlab software, we obtain the following spectrum:

The transverse velocity of 10% reinforcement plate is determined from the spectrum in Fig. 5.

The transverse velocity is obtained through the following expression [5]:

$$C_T = \frac{2e_p \cdot \Delta f}{\sqrt{1 + \left(2e_p \cdot \Delta f \frac{\sin \theta}{C_E}\right)^2}} \quad (6)$$

With C_E : water velocity = 1470 m/s.

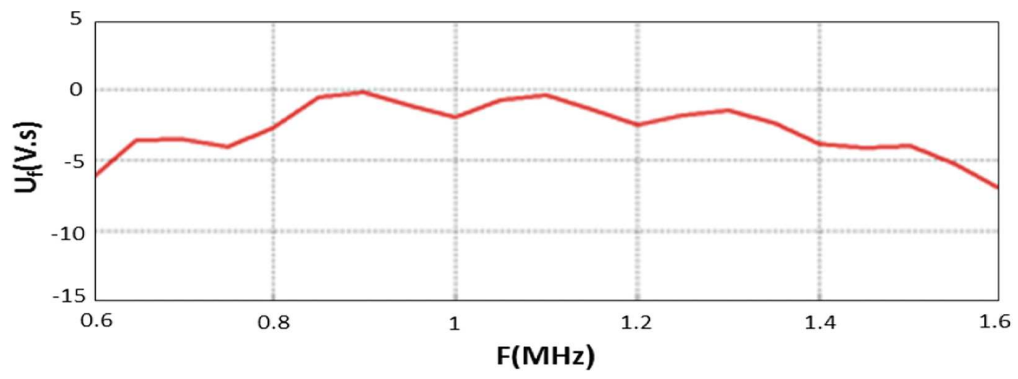


Fig. 5. Spectrum of 10% reinforcement plate.

From this spectrum, $\Delta f = 200$ kHz

$$C_T = \frac{2e_p \cdot \Delta f}{\sqrt{1 + \left(2e_p \cdot \Delta f \frac{\sin \theta}{C_E}\right)^2}} = \frac{2 \times 4 \times 200}{\sqrt{1 + \left(2 \times 4 \times 200 \times \frac{\sin 40}{1470}\right)^2}} = 1272 \text{ m/s}$$

All previous steps are repeated for other plates at different percentages of reinforcement.

Table 1. C_L and C_T values.

% OWF	0	10	20	30
CL	2600	2664	2750	2816
CT	1230	1272	1311	1322

Table 1 presents the values of longitudinal and transverse plates velocities at different reinforcement percentage.

3.3 Density

The density was calculated practically by measuring the mass and volume of each plate with (Table 2):

$$\rho = \frac{m}{v} \quad (7)$$

Table 2. Densities values.

% OWF	0	10	20	30
ρ (g/cm ³)	0.905	0.928	0.953	0.979

From the values of C_L , C_T and ρ , the first and second coefficient of Lamé are determined (Table 3)

The values of the ultrasonic Young's modulus are shown in Table 4.

Table 3. λ and μ values.

% OWF	0	10	20	30
λ (GPa)	3.37	3.41	3.56	3.82
μ (GPa)	1.36	1.57	1.63	1.71

Table 4. Ultrasonic Young's modulus values.

% OWF	0	10	20	30
E_{Ultra} (GPa)	3.71	4.05	4.39	4.60



Fig. 6. Specimens before and after rupture.

4 Mechanical Young's Modulus E_{mec}

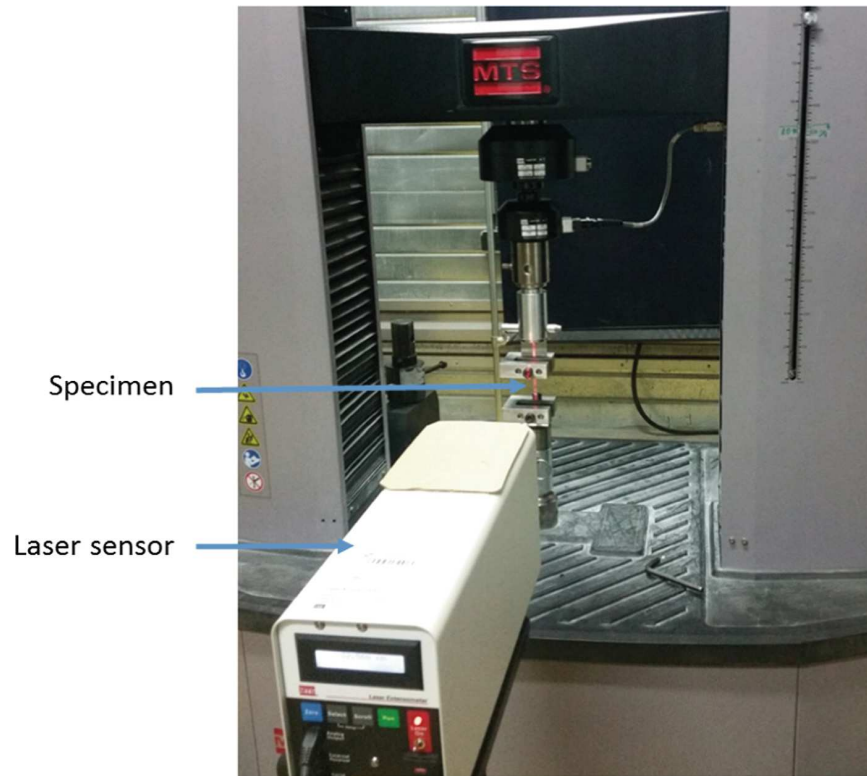
To determine the mechanical Young's modulus of the bio-composite, standard test specimens (ISO 1/2) were developed (Fig. 6) with the same material and the same portions of reinforcement of the composite plates (Table 5).

These specimens were subjected to tensile tests through a tensile machine (Fig. 7).

From the curves presenting the stress as a function of the deformation $\sigma = f(\varepsilon)$ obtained, the mechanical Young's modulus E_{mec} is determined

Table 5. Mechanical Young's modulus values.

% OWF	0	10	20	30
E_{mec} (GPa)	2.02	2.33	2.83	3.36

**Fig. 7.** Traction machine.**Table 6.** Comparison between E_{ultra} and E_{mec} of plates.

% OWF	E_{ultra} (GPa)	E_{mec} (GPa)	Ratio
0	3.71	2.02	1.83
10	4.05	2.33	1.73
20	4.39	2.83	1.55
30	4.60	3.36	1.36

5 Comparison Between E_{ultra} et E_{mec}

Table 6 presents a comparison between the Young's modulus obtained by ultrasonic method and those obtained by mechanical method of our bio-composite.

Figure 8 presents a comparison between the Young's modulus obtained by ultrasonic method and those obtained by mechanical method.

From the results found, we notice that the ultrasonic Young's modulus is more important than the mechanical Young's modulus with a ratio that varies between 1.36 and 1.83 (Fig. 9).

These results are expected and can be explained by the fact that we do not work in the same field of deformation for the two methods:

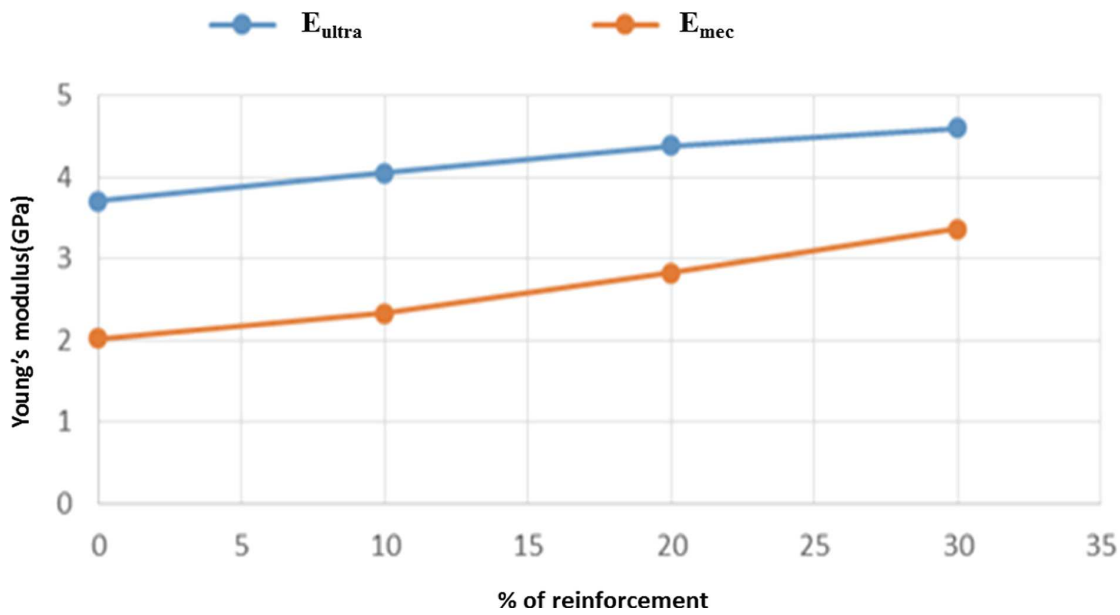


Fig. 8. Variation of E_{ultra} and E_{mec} .

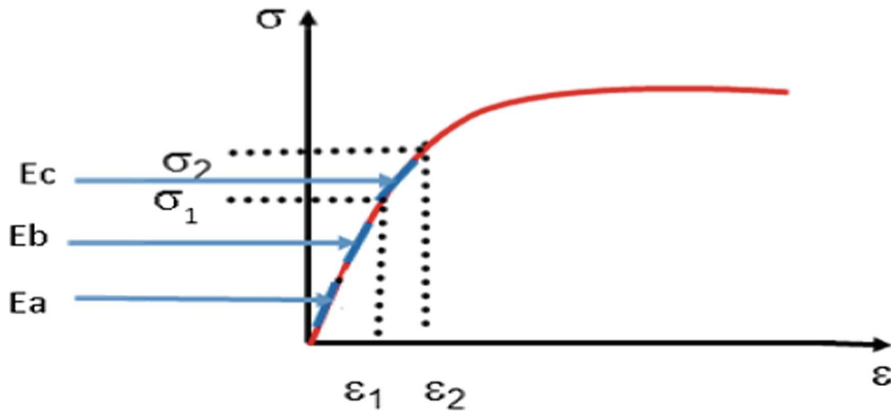


Fig. 9. Deformation domains.

According to ISO 527-1 [7], for the mechanical method, we work in the field ‘Ec’ for which:

- σ_1 is the stress in MPa measured at a strain $\varepsilon_1 = 0.05\%$.
- σ_2 is the stress in MPa measured at a strain $\varepsilon_2 = 0.25\%$.

For the ultrasonic method, one works in the field ‘Ea’, whose strain domain is between $\varepsilon_{A1} = 0\%$ et $\varepsilon_{A2} < \varepsilon_1 = 0.05\%$.

For this deformation domain, the slope of E is greater than that of the ‘EC’ domain, which explains this difference in values between the two ultrasonic and mechanical methods with $E_{ultra} > E_{mec}$.

These results can be explained by the fact that the deformation domain is not the same [7, 8]. In addition, the deformation rates are not the same for both methods [9, 10]. To this it can also be added that although the compositions and methods of preparation are strictly the same for the test specimens and the plates, the geometries, the thicknesses and the stress sections are different for the ultrasonic and mechanical tests.

6 Conclusion

In this work, we have elaborated and characterized a bio-composite material based on PP as polymer matrix and OWF as reinforcement. The ultrasonic and mechanical Young's modulus was studied according to the rate of reinforcement.

The ultrasonic Young's modulus is more important than the mechanical Young's modulus, this is due to the difference of deformation domain, we also note that when the percentage of reinforcement increases, the Young's modulus increases also, hence a better rigidity of the plates.

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