THE INFLUENCE OF THE THEORETICAL FIBERS ARRANGEMENT MODEL ON THE MECHANICAL PROPERTIES OF THE VEGETAL FIBER REINFORCED COMPOSITES

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Abstract *The aim of this work is to make a comparative analysis of the mechanical properties of vegetal fiber reinforced biocomposites, properties that are theoretically determined based on mathematical fiber distribution models, and to interpret the obtained results. In order to perform the theoretical studies on the mechanical properties of vegetal fiber reinforced biocomposites it was necessary to develop some geometrical computational models regarding the arrangement of the fibers in the biocomposite: parallel arrangement using the hexagonal or square packing and the random arrangement. For all the analytical models studied, the geometry and volume fraction of the fiber in the biocomposites, influence their mechanical properties.*

1 Introduction

1.1 Generalities

Vegetal fibers began to be used increasingly more often in producing polymer composites, as reinforcing elements. These fibers have many advantages such as: small density, good mechanical strength, they are recyclable, renewable, they have good acoustic properties.[1]

In case of fiber reinforced composites with polymer matrix, the structural performance of the composite is determinated by the strength and stiffness of the reinforcing elements. Important factors that contribute to the influence of fibers on the structural performance of the composite are: the orientation and length of the fibers in the composite, the fiber-matrix interaction, mechanical properties of the fibers and the volume fraction of the fibers/matrix. [2].

Regarding the fiber –matrix adhesion, a poor wettability and an inadequate adhesion between natural fibers and matrix leads to under-utilisation of the fiber potential and properties. The mechanical properties of the fibers may be variable because of the non-uniform fiber cross-section. This high variability of their mechanical properties is one of the factors constraining the widespread use of natural fibers as the reinforcement in polymer matrix composites. This variability makes the process of accurately predicting the composite properties using the existing micromechanical models, difficult. The vegetal fibers which attract the most interest in using them as reinforcement elements in biocomposite materials are bast fibers like flax, hemp, jute or kenaf. It is important to gain an in-depth understanding of the variation of the fiber physical and mechanical properties, as these fibers begin to emerge increasingly more often as a realistic alternative to synthetic fiber reinforcements, [2].

Vegetal fibers used in biocomposites are classified in long or short fibers. Short fibers can be orientated unidirectional, bidirectional or randomly orientated in three directions in the biocomposite, [3].

This paper analyzes the mechanical properties of a biocomposites material reinforced with short fibers.

Matrices used in biocomposites reinforced with vegetal fibers are thermoplastic or thermoset polymers. Thermoplastic polymers are heated above the melting temperature during composite processing until they become fluid in order to hold the fibers together. After this they are cooled in different forms of molds. Thermoplastics can be melted and cooled multiple times without changing their properties. Thermoset polymers are typically in liquid form and they are applied to fibers into a final shape of a matrix form where they are then heated. At high temperatures, the mechanical properties of thermoset polymers do not degrade. It is important to establish several tools in order to predict the mechanical properties of biocomposites reinforced with vegetal fibers, in order to be able to use them for various engineering applications, [3].

1.2 Theoretical modeling of mechanical properties

1.2.1 Halpin-Tsai micromechanical model

One of the most popular micromechanical model to predict longitudinal, transverse and shear modulus in biocomposites is the Halpin-Tsai model. This model was initially developed for continuous fiber composites and was derived from the self-consistent models of Hermans and Hill, [6]. The mechanical properties of the fibers and the matrix are used in the Halpin-Tsai equations [7,8] for calculating the properties of the composite. The Halpin-Tsai equations are employed for composites with unidirectional short fibers. The equation can be expressed in a common form [6,9,8]:

$$\frac{E}{E_m} = \frac{1+\xi\cdot\eta\cdot V_f}{1-\eta\cdot V_f} \tag{1}$$

where $E_{f,m}$ represents the Young Modulus of fiber respectively matrix, [14], $V_{f,m}$ is the fiber respectively matrix volume fraction in the composite, ξ is a parameter that depends on the fiber geometry, fiber distribution and fiber loading conditions and is called reinforcing efficiency parameter. For the Young modulus, $\xi=2l/d$, where l is the fiber length, and d is the fiber diameter. The variation of ξ denotes that the dimensions of the reinforcement elements are influencing the composite stiffness.

$$\eta = \frac{\dfrac{E_f}{E_m}-1}{\dfrac{E_f}{E_m}+\xi} \tag{2}$$

For the case of aligned short fiber composites ξ can be expressed by [3]:

$$\xi = 2\cdot\frac{l}{d} + 40V_f^{10} \tag{3}$$

1.2.2. Modified Halpin-Tsai equation

Nielsen modified the Halpin-Tsai equation by including the maximum packing fraction V_{fmax} of the reinforcement, in order to predict the modulus and strength of random, discontinuous fiber composites [13,14]. According to this:

$$E = E_m \left(\frac{1 + \xi \cdot \eta \cdot V_f}{1 - \eta \cdot \psi \cdot V_f} \right) \tag{4}$$

$$\sigma = \sigma_m \left(\frac{1 + \xi \cdot \eta^* \cdot V_f}{1 - \eta^* \cdot \psi \cdot V_f} \right) \tag{5}$$

$$\eta^* = \frac{\dfrac{\sigma_f}{\sigma_m} - 1}{\dfrac{\sigma_f}{\sigma_m} + \xi} \tag{6}$$

$$\psi = 1 + \left(\frac{1 - \varphi_{\max}}{\varphi_{\max}^2} \right) \cdot V_f \tag{7}$$

where ψ depends on the particle packing fraction and φ_{max} is the maximum packing fraction of the reinforcement. The values of φ_{max} for square and hexagonal packing are 0.785 respectively 0.907.

1.2.3. Cox model

Cox model deals with the net tensile load across fibers of length l and radius r which must be balanced by the shear force and the fibre matrix interface, [5]. Cox used a fiber length efficiency factor into the ”rule-of-mixtures” equation for the composite stiffness, for modelling the stiffness E of short fiber reinforced composites and in order to determine the influence of the fiber length on the mechanical properties of the biocomposite . When a fiber composite is under a uniaxial tension, the axial displacements in the fiber and in the matrix will be different because of the differences in tensile properties of these two components, [10]. This means that the interfacial tension between fibers and matrix is influenced by the fiber length [1, 12]. The micromechanical model used to predict the composite elastic modulus is defined as rule of mixture:

$$E = \eta_l \cdot E_f \cdot V_f + E_m \cdot (1 - V_f) \tag{8}$$

$$\eta_l = 1 - \frac{\tanh\left(\dfrac{\beta \cdot l}{2} \right)}{\dfrac{\beta \cdot l}{2}} \tag{9}$$

$$\beta = \frac{1}{r} \cdot \sqrt{\frac{G_m}{E_f} \left(\frac{2}{\ln\left(\dfrac{R}{r} \right)} \right)} \tag{10}$$

where r is the radius of the fiber, G_m is the shear modulus of the matrix and R is centre to centre distance of the fibers:

- for hexagonally packed fibres [5,12]:

$$R = \sqrt{\frac{2\pi r^2}{\sqrt{3} \cdot V_f}} \tag{11}$$

- for square packed fibres:

$$R = r \cdot \sqrt{\frac{\pi}{4 \cdot V_f}} \tag{12}$$

According to Cox model the tensile strength of composite becomes:

$$\sigma = \eta_l \cdot \sigma_f \cdot V_f + \sigma_m (1 - V_f) \tag{13}$$

1.2.4. Cox Krenkel model

The theory of Cox was extended by Krenkel who add fiber orientation into the ‘rule-of-mixtures’ equation.

$$E = \eta_0 \cdot \eta_l \cdot E_f \cdot V_f + E_m (1 - V_f) \tag{14}$$

where η_o is the fiber orientation factor, [4]:

$$\sigma = \eta_0 \cdot \eta_l \cdot \sigma_f \cdot V_f + \sigma_m (1 - V_f) \tag{15}$$

For a two-dimensional (in-plane) random orientation of the fibres η_o=3/8, and for a three-dimensional random fibre orientation η_o=1/5.

1.2.5. Kelly and Tyson model

Kelly and Tyson extended the rule of mixture model developed by Cox and Krenkel for composite stiffness to predict the rule of mixture model for short fibers composite strength and stiffness, [1]:

$$\sigma = \eta_o \cdot \eta_{ls} \cdot \sigma_f \cdot V_f + \sigma_m (1 - V_f) \tag{16}$$

$$E = \eta_o \cdot \eta_{lE} \cdot E_f \cdot V_f + \sigma_m (1 - V_f) \tag{17}$$

where η_{ls} and η_{lE} are the fiber length efficiency factor for composite tensile strength respectively composite stiffness developed by Kelly and Tyson. Curtis, Bowyer and Bader [5,14] introduced fiber length efficiency factor in rule of mixture of thermoplastic composites reinforced with short fibers as a function of critical length of the fiber. The critical fiber length L_c of the fiber is the length of the fiber at the point of equality of fiber strain to matrix strain.

$$L_c = \frac{\sigma_f \cdot r}{\tau} \tag{18}$$

Where τ is the shear stress between fiber and matrix in composite and is obviously experimentally determined. The experimentally measure of fiber critical length and interfacial shear stress is difficult to realize and it can assume that there is a good adhesion between the fiber and matrix. According with [11] τ can be matched with the shear strength of the matrix, $\tau = \tau_m = \sigma_m/\sqrt{3}$, for $l > L_c$:

$$\eta_{ls} = 1 - \frac{s_c}{2s} \tag{19}$$

and, for $l < L_c$:

$$\eta_{ls} = \frac{s}{2s_c} \tag{20}$$

The parameter s is called the fiber aspect ratio, $s = l/d$ and the parameter s_c is called the critical fiber aspect ratio, $s_c = l_c/d$:

$$\eta_{lE} = \frac{1 - \tanh(\beta \cdot s)}{\beta \cdot s} \tag{21}$$

where β has the significance of relation (10).

2 Materials and testing methods

The study was performed on a biocomposite material based on PP J700 polypropylene matrix reinforced with 40% flax and hemp short fibers. The biocomposite formula is: PP J700 -57%; -Short fibres from flax and hemp scraps -40%; -compatibility agent Licocene PPMA -3%. In Figure 1 is shown the SEM aspect in fracture of the biocomposite. The matrix and fibers properties are the following: E_f=30000 MPa, E_m=1368 MPa, σ_f=600 MPa, σ_m=28,6 MPa, G_m=507 MPa, l=22*10^{-4} m, d=2*10^{-4} m, V_f = 40%, V_m = 60%.

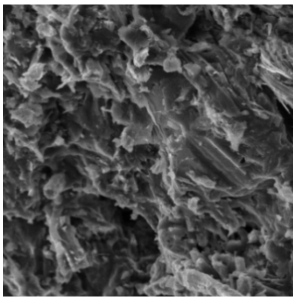


Figure 1. SEM aspect in fracture of the biocomposite with 60% PP and 40%short fibers of flax and hemp

Tensile mechanical properties of the biocomposite were determined in accordance with SR EN ISO 527-2:1996, [15]. Tensile test was performed on Zwick/Roell Z005 device. The mechanical characteristics for the tensile test are the following: loading testing speed is 5 mm/min, calibrated measuring length: 30 mm. The dimensions of the testing specimens in transverse section are: width - 4 mm, thickness - 1 mm. The form of the tensile testing specimens is shown in Figure 2. The tensile mechanical properties of the biocomposite were determined as the average for five specimens. The experimental values of the tensile mechanical properties for the tested biocomposites were: E_{exp}=2532 MPa, σ_{exp}=32.3 MPa

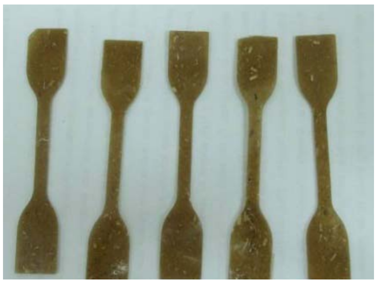


Figure 2. Tensile test specimens

3 Results and discussions

The theoretical results for the micromechanical models used are presented in the following tables: Table 1 for the Halpin Tsai model, Table 2 for the modified Halpin Tsai model, Table 3 for the Cox model, Table 4 for the Cox Krenkel model, Table 5 for the Kelly-Tyson model. The fibers orientation in the biocomposite studied in this work is randomly in three dimensions.

ξ	**η**	**E [MPa]**
20.004	0.499	8536

Table 1. Mechanical properties by Halpin-Tsai micromechanical model

Packing arangement	**ξ**	**η**	**η***	**ψ**	**φ_{max}**	**E [MPa]**	**σ [MPa]**
hexagonal	20.004	0.499	0.487	1.113	0.907	8783	179
square	20.004	0.499	0.487	1.349	0.785	9349	190

Table 2. Mechanical properties by the modified Halpin-Tsai micromechanical model

Packing arangement	**η_l**	**R [m]**	**E [MPa]**	**□[MPa]**
hexagonal	0.995	0.0003	6850	155.8
square	0.989	0.105	2726	55.2

Table 3. Mechanical properties by the Cox micromechanical model

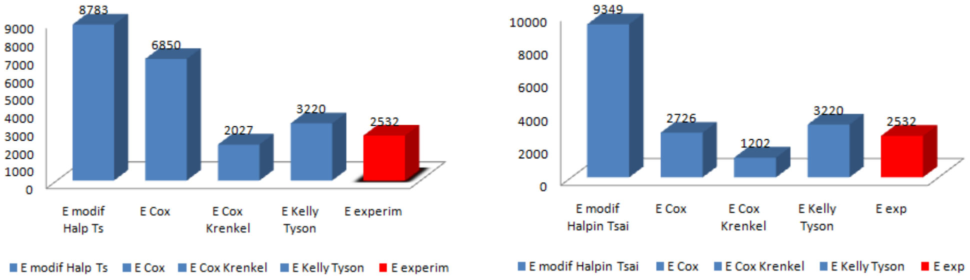
Packing arangement	**η_l**	**R [m]**	**η_o**	**E [MPa]**	**σ [MPa]**
hexagonal	0.502	0.0003	0.2	2027	41.3
square	0.989	0.105	0.2	1202	24.8

Table 4. Mechanical properties by the Cox- Krenkel micromechanical model

Packing arangement	**η_o**	**L_c [m]**	**s**	**s_c**	**η_{ls}**	**η_{lE}**	**E [MPa]**	**σ [MPa]**
hexagonal	0.2	0.004	11	18.1	0.05	1	3220	25.5
square	0.2	0.004	11	18.1	0.174	1	3220	25.5

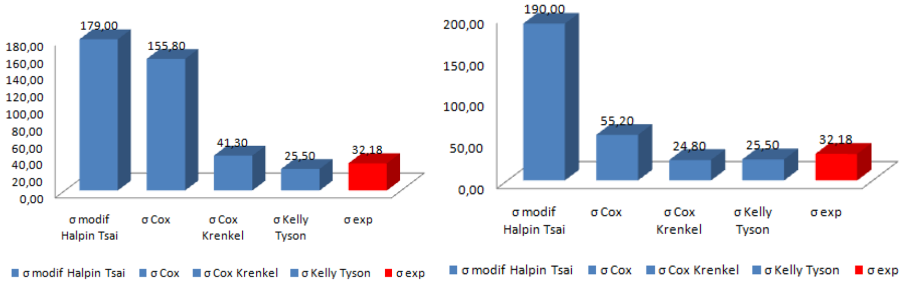
Table 5. Mechanical properties by the Kelly- Tyson micromechanical model

Figure 3a and Figure 3b show the theoretical results of the Young Modulus *E* for the hexagonal respectively square packing of the fibers in comparison with the experimental results obtained from the biocomposite tensile tests. Figure 4a and Figure 4b show the theoretical results of the Young Modulus *E* for the hexagonal respectively square packing of the fibers in comparison with the experimental results obtained from the biocomposite tensile tests.



3a. hexagonal packing **3b.square packing**

Figure 3. Young Modulus E for hexagonal packing (3a), respectively square packing (3b) of the fibers



4a. hexagonal packing **4b.square packing**

Figure 4. Tensile strength σ for hexagonal packing (4a), respectively square packing (4b) of the fibres

Concussions:

The mechanical properties of the vegetal fibers reinforced composites are determined from both the volume fraction of the fibers and the geometrical parameters of fibers arrangement within the matrix such as: fiber dimensions (length and diameter) and packing arrangement of the fibers. The micromechanical models used to approximate the mechanical properties can be used in the composites designing process. From the theoretical micromechanical models used in this work for predicting the tensile properties of a biocomposite based on polypropylene reinforced with short flax and hemp fibers, the Kelly Tyson and Cox Krenkel models approximate better the theoretical values than Halpin Tsai models. From the results obtained in this work regarding the aproximation of fiber packing arrangement within the composite, it had been found that the square packing approximates better the tensile properties than the hexagonal packing.

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