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RESEARCH ARTICLE

A Numerical Study for Determining the Effect of Raffia, Alfa and Sisal Fibers on the Fiber-matrix Interface Damage of Biocomposite Materials

Bouchra Achour[1], Allel Mokaddem[2,*], Bendouma Doumi[2,3,**], Abdelkader Ziadi[1,***], Lahcen Belarbi[4] and Ahmed Boutaous[5]

[1]Smart Structures Laboratory/DGRSDT, Mechanical Engineering Department, University of Ain Temouchent, Algeria; [2]Laboratoire d'Instrumentation et Matériaux Avancés, Centre Universitaire Nour Bachir El-Bayadh, BP 900 route Aflou, 32000 El Bayadh, Algérie; [3]Faculty of Sciences, Department of Physics, Dr Tahar Moulay University of Saïda, 20000 Saïda, Algeria; [4]Applied Chemical laboratory/DGRSDT, Ain Temouchent University, Algeria; [5]Faculté de Physique, Département Technologie des Matériaux, USTO-MB, Oran

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Abstract: ***Background***: Nowadays, natural fibers are used in all industrial fields, particularly in automotive technology and civil engineering. This great emergence is due to their biodegradability, recyclability and have no environmental effect.

Objective: In this article, the effect of raffia, alfa and sisal fibers on the damage of biocomposite materials (raffia/PLA (polylactic acid), alfa/PLA and sisal/PLA), subjected to the same mechanical shear stress, has been investigated.

Method: To calculate the damage to the interface, the genetic operator crossing is employed based on the fiber and matrix damage.

Result: The results have shown that the raffia / PLA and alfa/PLA biocomposite materials are better mechanical properties compared to sisal / PLA, this observation has been confirmed by different values of interface damage of the biocomposite studied.

Conclusion: The numerical results are similar and coincide perfectly with the results of Cox where he demonstrated that the Young's modulus of fibers improves the resistance of the interface. These conclusions are in very good agreement with our numerical data presented by the red cloud, and in good agreement with the work presented by Antoine Le Duigou *et al.* and Bodros *et al.* in which they have shown that natural fibers greatly improve the physical characteristics of composite materials.

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Keywords: Alfa, interface, PLA (polylactic acid), raffia, shear damage, sisal.

1. INTRODUCTION

The intertropical zone conceals plants with fibers often underexploited. The raffia fiber is one of these resources, and it is a multifunctional plant par excellence: nuts are extracted for food and cosmetic oil, the petioles and raw leaves are used as building materials and the epidermis of leaves is extracted for fiber [1-3]. This fiber is traditionally used to make ceremonial outfits, rugs (Kassai velvet), blankets and works of art, while elsewhere (especially in Europe) it is used among others as ligature for grafting. Today, it is also used in the manufacture of clothing, shoes, handbags, etc. In addition, like other plant fibers, it could potentially be used as a reinforcement in composites with a polymer matrix [4-6].

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*Address correspondence to this author at the Laboratoire d'Instrumentation et Matériaux Avancés, Centre Universitaire Nour Bachir El-Bayadh, BP 900 route Aflou, 32000 El Bayadh, Algérie; E-mail: mokaddem.allel@gmail.com (Allel Mokaddem), Faculty of Sciences, Department of Physics, Dr Tahar Moulay University of Saïda, 20000 Saïda, Algeria; E-mail: bdoumma@gmail.com (Bendouma Doumi) and Smart Structures Laboratory/DGRSDT, Mechanical Engineering Department, University of Ain Temouchent, Algeria; E-mail: aekziadi@yahoo.com (Abdelkader Ziadi)

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The term 'Raffia' defines both the palm tree and fiber which is extracted from it, and it originated from Malagasy. Raffia is a plant fiber used in many ways. As amazing as it may seems, it comes from a palm tree native to Madagascar named Raffia farinifera which is part of the Arecaceae family [7-9].

This palm tree is not very high (10 m high) but produces palms that can reach up to 20 meters in length, which is a record among palms. The heart of young shoots is consumed in salads or in ready meals in the country of origin. This palm tree owes its adjective 'farinifera' to the flour which is obtained from it after processing and which is made into pancakes [10, 11].

The Raffia fibers have a number of uses, ranging from the weaving of hats, baskets, mats, hammocks and ceremonial costumes [12]. In addition, like other plant fibers, these fibers could potentially be used as a reinforcement in composites with a polymer matrix [4-7] to make geotextiles or to lighten earthen bricks or concrete [13-15].

In composite materials, the interface fiber-matrix has an important role in ensuring the transfer of applied load from the matrix to the fiber, and for this reason, the choice of fiber quality becomes more than necessary, the fiber-matrix interface remains the most delicate area for controlling the resistance of composite material

- There is a recurring problem of compatibility, a priori, between hydrophilic plant fibers and most matrices which are generally hydrophobic. The rheological and mechanical properties of composites being strongly linked to the properties at the interface.
- A bad interface will have negative consequences on the performance of the material. To modify and control this interface, it is possible to act either on the polymer matrix or on the fibers, by means of physical or chemical methods [16].

For the modeling of the fiber / matrix interface in the case of composites based on vegetable fibers, there are many analytical and numerical methods that describe the shear of the fiber-matrix interface ("Pull-out" test, release of a micro-drop, Diabolo compression test, Micro-indentation and push-out test, Cox model, Kelly model, Weibull statistical approach,...) [17]. But to our knowledge, few methods and models have studied fiber-matrix interface damage. To model this damage, a probabilistic approach has been used based on the damage to the fiber and the matrix proposed by Weibull and the genetic operators (selection, crossing and mutation) in our approach to calculate the optimum values of the damage of the interface are employed [18]. The selection operator is used to choose the most appropriate solutions in order to have an optimal and convergent result. This operator is the application of the adaptation principle of Darwin's theory. The Crossing operator, or crossing-over, is the result obtained when two chromosomes share their peculiarities. This allows the genetic mixing of the population and the application of the principle of inheritance of Darwin's theory. The Mutation consists of altering a gene in a chromosome according to a mutation factor. This factor is the probability of a mutation being made in an individual. This operator applies the principle of variation of Darwin's theory and allows, at the same time, to avoid a premature convergence of the algorithm towards a local extremum [18].

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The Polylactic Acid (PLA) is a biopolymer and a compostable aliphatic polyester that has been used in several areas of application. PLA has very interesting mechanical and physicochemical properties such as resistance, rigidity and gas permeability, which have been shown to be comparable to those of traditional petrochemical-based polymers [19-21].

Our contribution is to investigate the effect of raffia fiber on fiber matrix interface damage of biocomposite materials; raffia/PLA (polylactic acid), alfa/PLA and sisal/PLA subjected to the same mechanical shear stress ranging from 450 N / m² up to 650 N / m², using a genetic algorithm, To calculate interface damage using fiber and matrix damage, the genetic operator crossing has been employed based on the Weibull approach.

2. SIMULATION METHODS AND MODELS

2.1. Physical and Mechanical Characteristics of the Materials Used

2.1.1. Raffia, Alfa and Sisal Fibers

The raffia fiber is a layered overlay. The structure of the outermost layer, that is, the one in con-

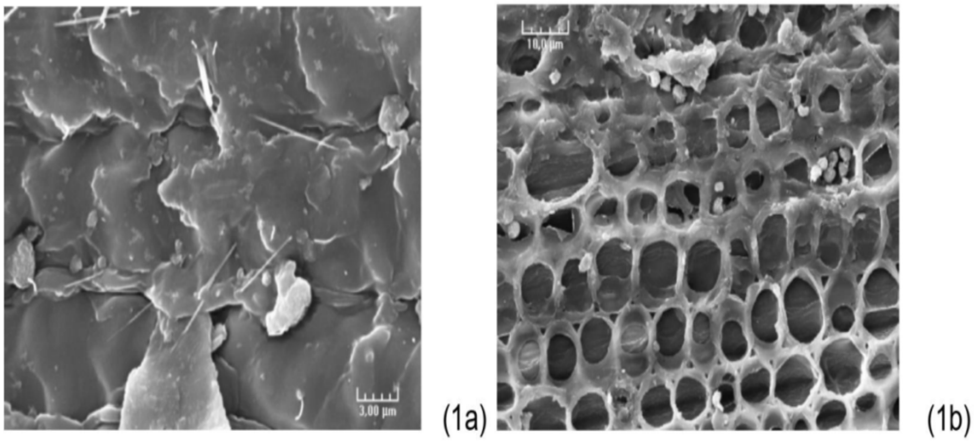

Fig. (1). SEM examination of the structure of hookeri raffia fiber. (**1a**) external face; (**1b**) internal face [3,22].

tact with air (Fig. **1a**), is a juxtaposition of filaments parallel to each other along the length of the fiber. The average width of these filaments is about 10µm. Fig. (**1**) shows that unlike other plant fibers which are smooth [3,22], raffia fiber is formed of kinds of scales and platelets, similar to wool fiber. Each scale, between 6-20 µm in length, covers this entire width of the fiber. It is this structure that makes this fiber a relatively waterproof material, which makes it usable as a roof covering. The underside of the fiber (Fig. **1b**) is in contact with the body of the sheet. It has a honeycomb-shaped structure, alveolar. These cells have a diameter of 6 to 13 µm and a wall approximately 0.5 µm thick.

The Young's modulus of the fiber is between 28 - 36 GPa while the tensile strength varies between 148 - 660 MPa and the elongation at break is around 2%. The great variability of the stress at break can be explained by the presence of defects along with the sample (irregularity in thickness and width, presence of micro notches linked to handling during shelling or storage). On other plant fibers, a variation in mechanical properties was also observed, which is explained by the presence of defects and the variable structure of these materials. Indeed, the composition and structure of plant fibers depend on several factors: cultivation conditions, degree of maturity, method of extraction, length of the fiber, and water content [3, 23-30].

Alfa's plant has two parts; upper and lower. The lower or underground part, Rhizome, consists of a complex network of highly branched roots, about 2 mm in diameter and 30 to 50 cm deep, which end in young shoots. The upper part is made up of several branches carrying nested sheaths, surmounted by long blades of 30 to 120 cm. The underside of the leaf blades is slightly shiny, and the upper surface has strong veins. Both are covered with an insulating wax which helps the plant resist drought [30-31]. The stem is hollow and cylindrical and is regularly interrupted at the level of the node by entanglements of the bundles. At the same level, there are buds that will give birth either to an internode or to a stem, or remains in the form of a reserve which will enter into activity when the strain is exhausted. The leaves are cylindrical, very tenacious, and 50 to 60 centimeters long. The flower is protected by two glumes of equal length. The upper lemma appears to be partially separated into 2 parts and the lower lemma is thinner. Generally, the flowers appear in late April early May and are green in color. The fruit is a caryopsis (a kind of grain) which is 5 to 6 mm in length. Its upper part is brown and often bears dried traces.

The sisalana agave fiber (sisal) is one of the different natural fibers used for the manufacture of biocomposites. This fiber is very interesting and characterized by its great availability on the current market, a possibility of cultivation on marginal soils, and has good rigidity and mechanical resistance. It is combined with low cost and good compatibility with many polymeric matrices [32-48]. It has the highest hardness, comparable to that of fiberglass; the close similarity with aramid fibers (kevlar, etc.) suggests good impact and breaking behavior. Therefore, its advantageous use for the manufacture of innovative energy absorption devices in various fields of industrial production such as automobiles, shipbuilding, earthmoving

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Table 1. Mechanical characteristics of the fibers used.

Fibers	Young's modulus (GPa)	Young's modulus (GPa) (values used in genetic algorithm)	Deformation at break (%)	Deformation at break (%) (values used in genetic algorithm)	Stress at break (MPa)	Stress at break (MPa) (values used in genetic algorithm)
Raffia [3,23-28]	28-36	32	2	2	148-660	404
Alfa [23-30]	13-18	15.5	1.5-2.4	2	134-220	177
Sisal [32-36]	9-22	15.5	3 – 7	5	80-840	460

machinery. However, these properties have not yet been clearly demonstrated, most of the work in the literature is mainly concerned with the evaluation of the static mechanical properties of these biocomposites [48].

In Table **1**, some mechanical characteristics of the fibers used have been presented.

2.1.2. Damage level

Chaboche (1988) [47] defined the damage of a finite element of a solid as follows:

S: area representative volume element identified by its norm *n*

Se: effective resistance area if $Se < S$

Sd: damaged area $Sd = S - Se$

The mechanical measurement of local damage in relation to *n* is characterized by:

$D = Sd/S$

If $D=0$: the material is not damaged.

If $D=1$: the volume element is broken into two parts along the plane normal to *n*.

If $0 < D < 1$: D characterizes the state of damage level.

2.1.3. Polylactic Acid Matrix

The PLA is synthesized through the polymerization of lactic acid, which was first discovered in 1780 by Swedish chemist Scheele by examining curds and then marketed for the first time in 1881 [48,49]. Lactic acid is naturally present in many foods and can be produced by fermentation of various renewable resources such as corn, potatoes, beet sugar, and sugarcane [48,49]. PLA has many interesting characteristics; its renewable resources, biocompatibility, biodegradation, good mechanical performance, and transparency of final material [49,50]. Also, a broad spectrum of flow properties is available by simple architectural modification of PLA, thus allowing the use of this biopolymer in many transformation processes [49, 50]. PLA was then widely used in the biomedical, packaging and textile fields [49, 51]. Thus, poly (lactic acid) is expected to compete with petrochemical polymers such as PET, PP and PS. Unfortunately, the high cost, the lack of thermal and hydrolytic stability as well as the low resilience limit the use of this biopolymer. These faults are mostly overcome by mixing PLA with other polymers, fillers, as well as chemical modification of the polymer. This literature study will assess recent developments made to improve the properties of PLA. PLA's Young's modulus and tensile strength are high, in the order of 3 GPa and 50-70 MPa, respectively. Such physical properties guarantee a wide range of application to this material, comparable to that of polystyrene or PET and more important than HDPE and PP [49,52]. Unfortunately, the mechanical properties of PLA are characterized by low impact resistance, as well as low elongation and brittle behavior. In Fig. (**2**), Scanning Electron Microscope (SEM) Images PLA fracture surfaces have been presented [53].

2.2. Weibull Probabilistic Formalism

Our results were obtained by a genetic simulation based on the Weibull equations.

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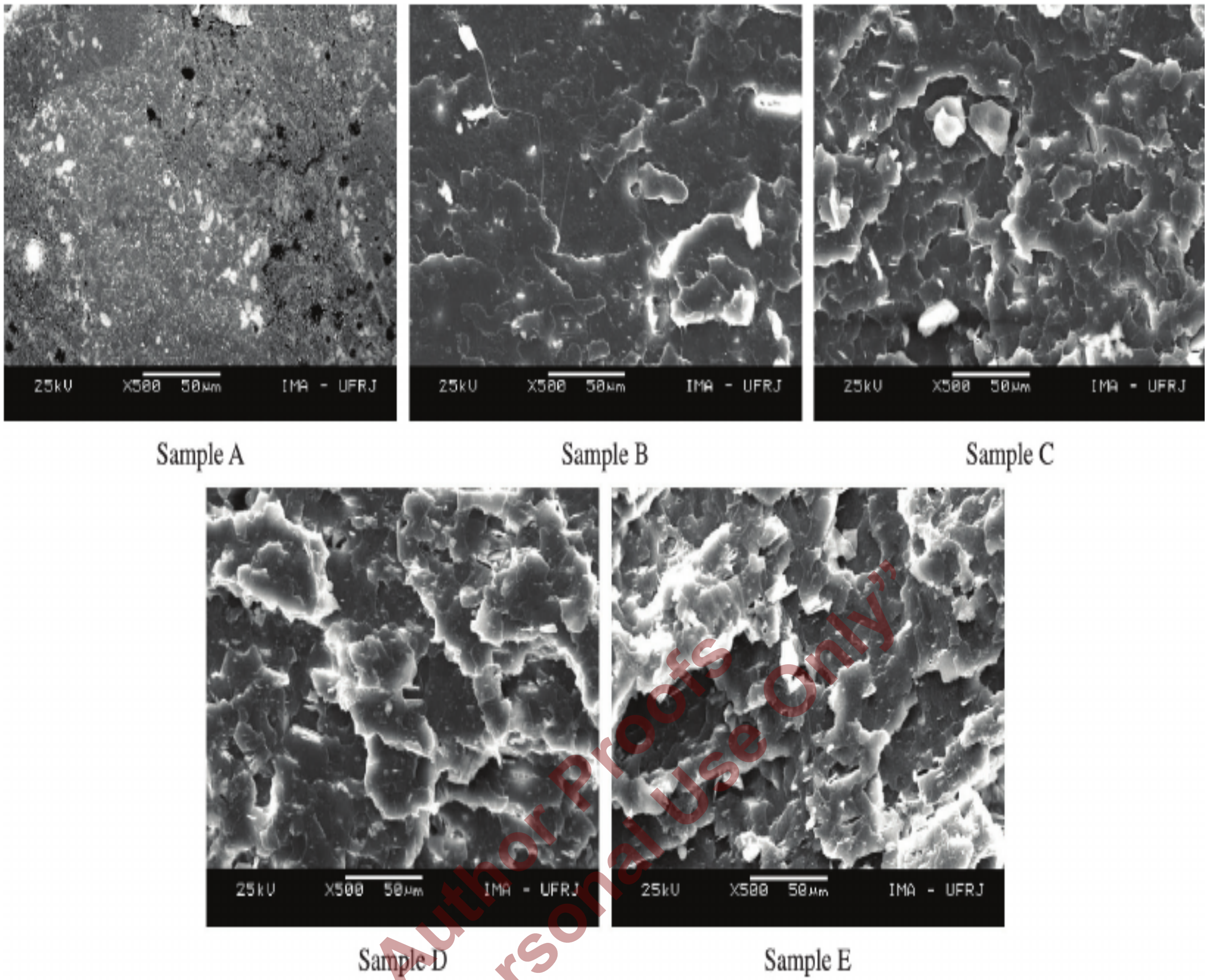
Sample A

Sample B

Sample C

Sample D

Sample E

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Fig. (2). SEM Images PLA samples fracture surfaces [53].

Damage to the matrix is given in equation (1) [54-59]:

$$D_m = 1 - exp\left\{-\frac{V_{eff}}{V_0}\left(\frac{\sigma_f}{\sigma_0}\right)^m\right\} \quad (1)$$

- (σf): mechanical stress;
- (V_{eff}): Matrix volume;
- $(m \; and \sigma_0)$: parameters of Weibull.
- (Vo) :matrix volume initial

The second equation presents the law of the fracture of a fiber [60, 61].

$$D_f = 1 - exp\left\{-A_f * L_{equi} * \left(\frac{\sigma^f_{max}}{\sigma_{of}}\right)^{m_f}\right\} \quad (2)$$

- $\sigma^f_{\max}$: the maximum mechanical stress applied.
- σ_{0f} : the initial stress.
- m_f : parameters of Weibull.
- A_f =π*a².
- L_{equi} : the fiber length at equilibrium.

In Table **2**, the main functions relating to the genetic operators (selection, crossing and mutation) have been presented to determine the damage at the fiber-matrix interface of each material studied.

3. RESULTS AND DISCUSSION

The effect of raffia and alfa plant fibers on fiber-matrix interface damage of biocomposite materials (raffia / PLA, alfa / PLA and sisal / PLA) has been investigated. The genetic simulation is based on the Weibull model (equations 1 and 2), the operator crossing is used to calculate the interface damage of our materials. An initial population of 1000 individuals [55] was generated, then improved with a set of genetic operators (selection, crossing and mutation) and in each case, the young modulus of each fiber is used (Tables **1** and **2**). The population consists of chromosomal genes representing the following variables: the shear stress (450, 550 and 650 N / m²), Young's modulus, the modulus of the matrix shear, the fiber diameter and the half distance R. The roulette selection and an equal mutation value of 0.25 have been chosen for optimizing our results (interface damage values).

Table 2. The main functions relating to the genetic operators (selection, crossing and mutation).

```
function x = Gen_Pop_Init(Npop_init,To)
    x(:,1) = rand(Npop_init,1);
    x(:,2) =rand(Npop_init,1)*10e-5;

function [enf1, enf2]=cross(p1,p2)
nbVar = length(p1);
enf1=[]; enf2=[];
a = rand+0.2;
enf1 = p1*a + p2*(1-a);
enf2 = p2*a + p1*(1-a);
return

function [enf1] = mutate(enf1,probMut,To,Te)

bound2=[To  Te];
bound1=[0  1000];
[nbenf nbvr]=size(enf1);
df1 = bound1(2) - bound1(1); df2 = bound2(2) - bound2(1)
for k=1:nbenf
a = rand;
if a < probMut
mPoint = round(rand * nbenf);
if mPoint ~= 0
    L=round(2*rand);
    if L~= 0
        if L ~= 2
            enf1(k,L) = bound1(1)+ rand*df1;
           else
            enf1(k,L) = bound2(1)+ rand*df2;
        end
    end
end
end
end
```

3.1 Sisal/PLA Biocomposite Material

In Figs. (**3-5**), the damage (D) at the interface begins for a value of D = 0.18 for mechanical shear stress equal to 450 N / m² (Fig. **3**). It increases linearly when the stress increases and reaches a maximum value of 0.33 for a shear stress of 650N / m² (Fig. **5**). Symmetry of damage was observed in the middle of the interface. The red cloud explains that the damage is concentrated at the ends compared to the middle of the fiber, as has already been demonstrated by the micromechanical model of Cox [62].

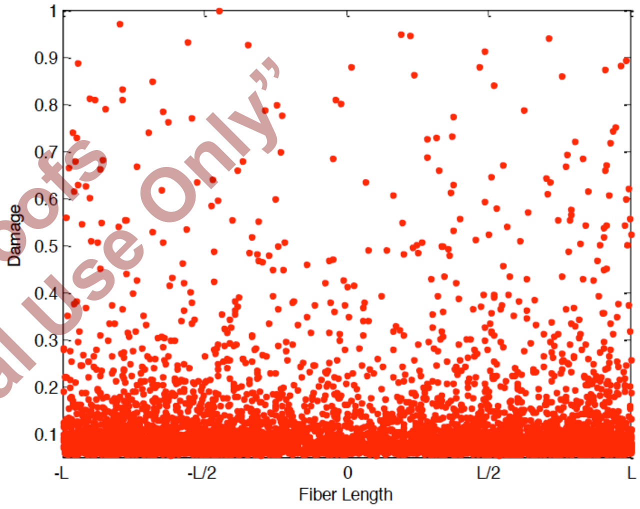

Fig. (3). Interface fiber-matrix damage level of sisal/PLA for σ=450 N/m².

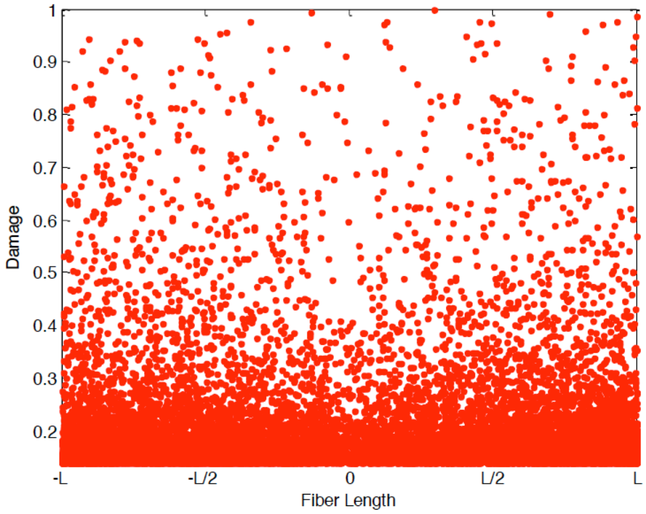

Fig. (4). Interface fiber-matrix damage level of sisal/PLA for σ=550 N/m².

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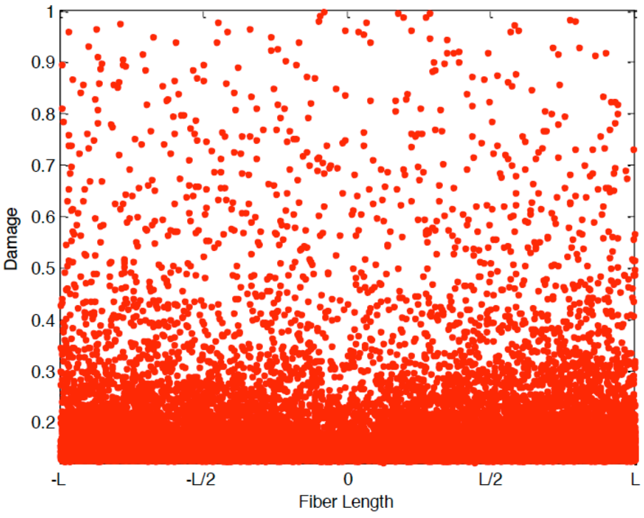

Fig. (5). Interface fiber-matrix damage level of sisal/PLA for σ=650 N/m².

3.2. Alfa/PLA Biocomposite Material

Figs. (**6-8**) show that the level of sheer damage begins for a damage value D = 0.21 (Fig. **6**) when σ = 450N / m², and it reaches a maximum value D = 0.26 (Fig. **8**) for a maximum stress σ = 650N / m². Symmetry of damage was observed in the middle of the interface. The red cloud explains that the damage is concentrated at the ends compared to the middle of the fiber, as has already been demonstrated by the micromechanical model of Cox.

The genetic results faithfully showed the real behavior of the two materials according to their mechanical properties, in particular, the values of the three Young's modulus. We have concluded that the fiber with the largest Young's modulus, its fiber-matrix interface, is the most resistant to mechanical stresses.

3.3. Raffia/PLA Biocomposite Material

Figs. (**9-11**) show that the level of sheer damage begins for a damage value D = 0.12 (Fig. **9**) when σ = 450N / m², and it reaches a maximum value D = 0.22 (Fig. **11**) for a maximum stress of σ = 650N / m². Symmetry of damage was observed in the middle of the interface. The red cloud explains that the damage is concentrated at the ends compared to the middle of the fiber, as it has already been demonstrated by the micromechanical model of Cox.

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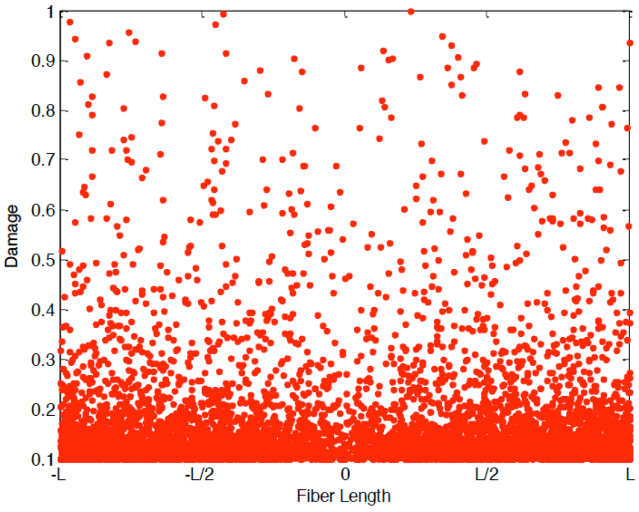

Fig. (6). Interface fiber-matrix damage level of alfa/PLA for σ=450 N/m².

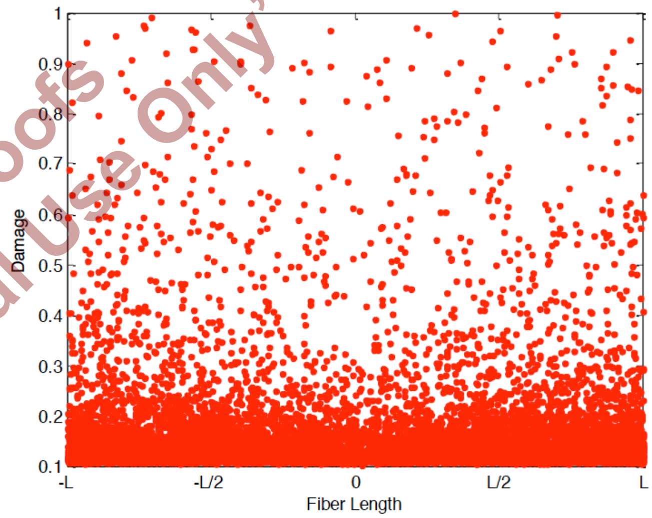

Fig. (7). Interface fiber-matrix damage level of alfa/PLA for σ=550 N/m².

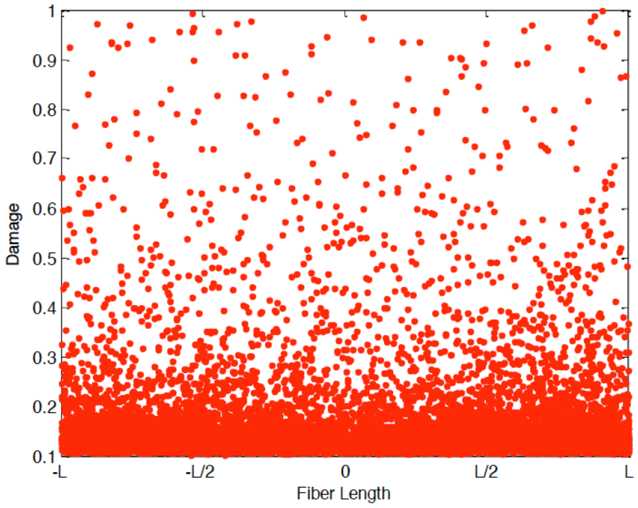

Fig. (8). Interface fiber-matrix damage level of alfa/PLA for σ=650 N/m².

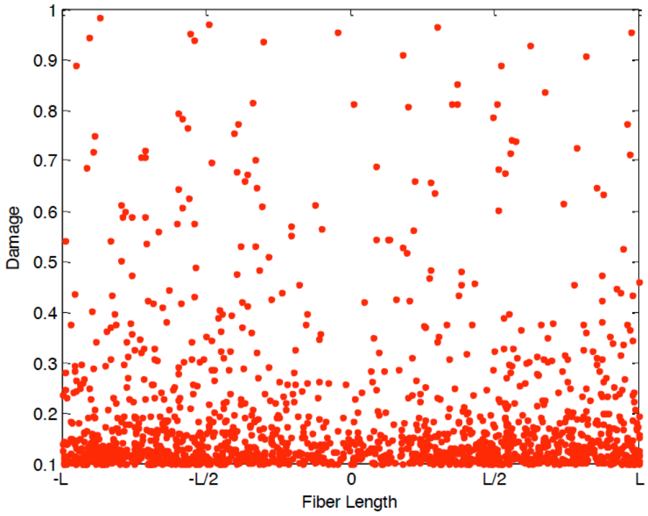

Fig. (9). Interface fiber-matrix damage level of raffia/PLA for σ=450 N/m².

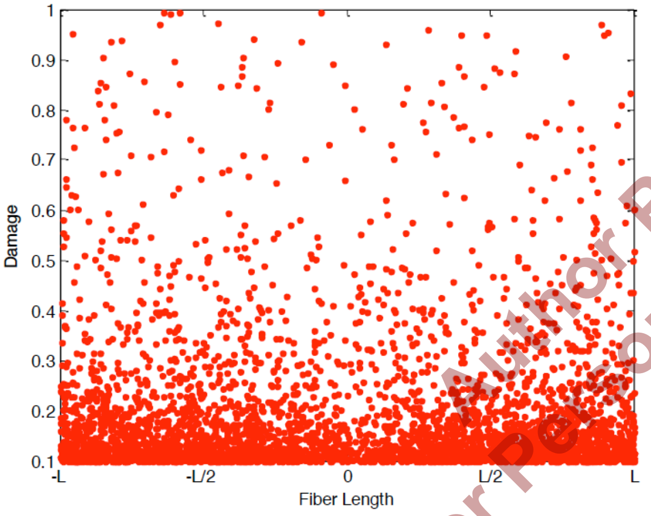

Fig. (10). Interface fiber-matrix damage level of raffia/PLA for σ=550 N/m².

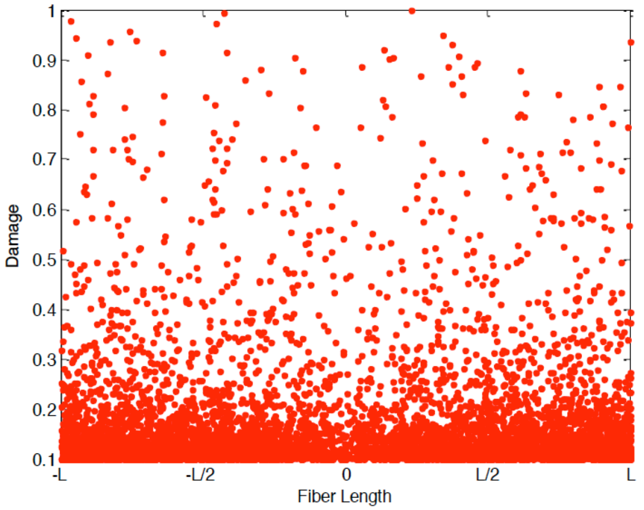

Fig. (11). Interface fiber-matrix damage level of raffia/PLA for σ=650 N/m².

CONCLUSION

This work focused on the study of the effect of raffia, alfa and sisal fibers on fiber-matrix interface shear damage of the three biocomposite materials studied, and which is consisted of the same matrix of PLA. To calculate interface damage, the genetic operator crossing has been employed based on the Weibull approach. The results obtained by genetic modeling have shown that the raffia / PLA and alfa/PLA biocomposite materials are better mechanical properties compared to sisal / PLA. This observation has been confirmed by the different values of interface damage of the biocomposites studied; the numerical results are similar and coincide perfectly with the analytical results of Cox [62], where he proved that Young's modulus of fibers improves the resistance of the interface. These results are good agreement with our results found by genetic approach [63]. The experimental work by Antoine Le Duigou et al. [64] and Bodros et al [65] showed that the use of natural fibers greatly improve the mechanical properties of biocomposite materials.

ETHICS APPROVAL AND CONSENT TO PARTICIPATE

Not applicable.

HUMAN AND ANIMAL RIGHTS

No Animals/Humans were used for studies that are the basis of this research.

AVAILABILITY OF DATA AND MATERIALS

Not applicable.

CONSENT FOR PUBLICATION

Not applicable.

CONFLICT OF INTEREST

The authors declare no conflict of interest, financial or otherwise.

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