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Study of Composite Bar Damping from Dammar Hybrid Resin Reinforced with Natural Fibers

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Abstract*. At the moment, the tendency in the composites field, is to use natural resins and fibers to obtain „environmental friendly" materials, that are compostable and biodegradable. In this paper there is an experimental study of the depletion capacity of the vibration from the composite beams, using the hardener made of cotton, flax, hemp, silk textile and the three types of the Dammar hybrid resin matrix. The damping factor and the eigenfrequency of the vibrations was determined experimentally for these bars. Based on the acquired results, the dynamic elasticity modulus and the loss factor were calculated, for each composite material studied.*

Keywords*: composite materials, natural fibers, damping factor, eigenfrequency*

1. Introduction

In the study of the vibration an important role is the damping capacity that reduces noise and contributes to the smooth operation of machines and the suppression of the self-excitation vibrations. The study on damping materials is important because it significantly influences the behavior of vibrating systems, especially when operating close to resonant frequencies or when they have to pass through resonance zones during unstable operating regimes. The experimental study is necessary because the damping properties of many materials, primarily new, are not yet properly known.

Damping process results from physical processes occurring in solid body materials during their yielding [1, 2]. The internal damping of composite materials is influenced by fissures and deteriorations, the orientation of the fibers, the chemical composition and physical properties of the matrix and the treatment of the fibers surface. The explanation of the physical phenomena regarding internal friction in the composite materials is a very complex matter to which a lot of research is still devoted. The damping of materials and various damping theories relating to unidirectional composite materials can be found, for example, in [3, 4].

Experiments conducted by many researchers have proven that the behavior of composite materials deviates from the idea of viscous damping. These findings increased interest in the development of non –viscous damping models, which would represent the dissipation of energy in a more general way. Various approaches to the implementation of material damping in mathematical models are reported in the academic literature.

In [5] a method of identifying viscous damping parameters is provided when the actual damping of the structure is not viscous. The methods presented allows, from complex modes and natural frequencies, to obtain a complete but disproportionate viscous depletion matrix. In [6] a procedure for identifying the damping mechanism based on the exponential relaxation function is developed and discussed. This method involves knowing the mass matrix of the system and uses experimentally identified complex modes and complex natural frequencies. The analysis is limited to systems that exhibit linear behavior and to the assumption that damping is light. An alternative hysterical damping pattern is discussed in [7] and [8] used a generalized Maxwell theoretical model to analyze the behavior of viscoelastic joints and

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introduced a method of experimentally identifying model parameters based on the use of a hysterical curve. Different approaches developed lately for identifying damping parameters and evaluating them are made in [9-11].

Recently, there is a growing interest in investigating renewable resources. The development of high-performance engineering products made from composites reinforced with natural fiber has gradually increased. Damping properties have been studied for natural rubber composites reinforced with short coir fibers (coconut) [12], polyester reinforced with banana fibers [13], polypropylene reinforced with flax and hemp fibers [14], polyester reinforced with hybrid fiber ramie/glass [15], with Luffa cylindrica [16] or Sansevieria cylindrica [17]. The damping mechanism of fiber-reinforced composites is different from that of ordinary metals. Energy dissipation approaches in fiber-reinforced composites mainly include the viscoelastic characteristics of the matrix and fibers, damping due to the interface region and matrix cracks, and viscos-plastic damping [18, 19]). Currently there is also a tendency to replace synthetic resins with natural or hybrid resins. The damping properties of dammar-based hybrid resin matrix composite materials reinforced with flax, cotton or hemp fabrics are studied in [20], and those reinforced with paper waste are studied in [21].

In these studies, the effects of cross-sectional fiber orientation and their volume fraction on depletion coefficients were analyzed. The results of these analyses indicated that the longitudinal loss factor is determinated by the shape of the reinforcing fibers, and the orientation of the fibers and the stacking sequence significantly affect the damping behavior. It has been observed that the damping can be improved with a slight decrease in the rigidity of the composite by generating a greater number of interfaces. Various methods of improving damping by reducing the diameter of the fiber used are studied, without compromising the dimensions of the composite and the volume fraction of the fibers [22]. It has been found that composites reinforced with short fibers have a greater energy dissipation capacity than that of long fibers due to the presence of several fiber heads. This is explained by the fact that in composites reinforced with short fibers, the number of interfaces between matrix and fibers that are subjected to elastic and plastic deformations [23] is higher.

The vibration depletion capacity for composite bars with the matrix of three types of Dammar hybrid resins and reinforced with fabrics made of cotton, linen, hemp and silk is studied in this work. The depletion factor and the eigenfrequency of vibrations at the bars made of these materials, which were recessed at one end and free at the other, was experimentally determined. Based on the results obtained, in the case of each composite material studied, the dynamic elasticity modulus and the loss factor were calculated.

2. Materials and methods

Bars are structural elements often encountered in practice and are usually studied with the Euler-Bernoulli, model based on the assumption that a flat and normal section on the medium fiber before deformation, remains flat and normal on the average fiber throughout the deformation. Thus, the equation of free and unamortized transverse vibrations of the bar is [24, 25]:

$$\ddot{w}(x;t) + a^2 \cdot \frac{\partial^4 w(x;t)}{\partial x^4} = 0, \quad (1)$$

with

$$a = \sqrt{\frac{EI}{\rho A}}, \quad (2)$$

where:

- ρ is the density, and E is the modulus of elasticity for the bar material;
- A is the area of the bar section, and I is the moment of inertia of the bar section.

Damping is taken into account by introducing into the equation of motion some terms of the form $2c_0 \dot{w}$, or $-2c_1 \frac{\partial^2 w}{\partial x^2}$, or $2c_2 \frac{\partial^4 \dot{w}}{\partial x^4}$ [25, 26].

Solving the equation when the previous three terms are present is difficult. Therefore, it will be considered the case when the equation contains only one of the three themes, for example $2c_2 \frac{\partial^4 \dot{w}}{\partial x^4}$, and which corresponds to the so-called Kelvin-Voigt model of internal damping, one of the models most used for the study of vibration damping [27, 28]. In this case the equation of motion becomes:

$$\ddot{w}(x;t) + 2c_2 \frac{\partial^4 \dot{w}(x;t)}{\partial x^4} + a^2 \frac{\partial^4 w(x;t)}{\partial x^4} = 0 . \qquad (3)$$

The initial conditions are given by:
- the state of movements at the initial moment

$$w(x;0) = f(x) ; \qquad (4)$$

- the state of the speed at the initial moment

$$\dot{w}(x;0) = g(x) . \qquad (5)$$

Equation (3) is solved with the method of separating variables by looking for the solution as a product of two functions:

$$w(x,t) = W(x)T(t) , \qquad (6)$$

where the $W(x)$ function depends only on the x variable, and the $T(t)$ function depends only on time.

Replacing the relation (6) in equation (3), it can be processed to the form:

$$\frac{W''''(x)}{W(x)} = -\frac{\dot{T}(t)}{2c_2 \dot{T}(t) + a^2 T(t)} . \qquad (7)$$

The term to the left of equality (7) is a function only of the variable x, and the term on the right is the function of time only Under these circumstances, equality (7) is true only if the two terms are equal to a constant, denoted by λ^4 (to simplify calculations).

Consequently

$$\frac{W''''(x)}{W(x)} = \lambda^4 \qquad (8)$$

and

$$-\frac{\ddot{T}(t)}{2c_2 \dot{T}(t) + a^2 T(t)} = \lambda^4 . \qquad (9)$$

The general solution of equation (8) is:

$$W(x) = C_1 \sinh(\lambda x) + C_2 \cosh(\lambda x) + C_3 \sin(\lambda x) + C_4 \cos(\lambda x) . \qquad (10)$$

The constants shall be determined from the limit conditions. A common case encountered in practice is that of the bar with a recess at one end. Considering the embedding for $x = 0$, results in the conditions:

$$W(0)=C_2+C_4=0, W'(0)=C_1+C_3=0, \qquad (11)$$

From which you get:

$$W(x)=C_1(\sinh(\lambda x)-\sin(\lambda x))+C_2(\cosh(\lambda x)-\cos(\lambda x)). \qquad (12)$$

If at the end with $x=L$ the bar is free we have the conditions:

$$W''(L)=0, W'''(L)=0, \qquad (13)$$

Then the resulting system:

$$\begin{aligned} &C_1(\sinh(\lambda L)+\sin(\lambda L))+C_2(\cosh(\lambda L)+\cos(\lambda L))=0 \\ &C_1(\cosh(\lambda L)+\cos(\lambda L))+C_2(\sinh(\lambda L)-\sin(\lambda L))=0 \end{aligned}. \qquad (14)$$

For this system to have different solutions from the trivial solution, it must be

$$\cosh(\lambda L)\cos(\lambda L)=-1. \qquad (15)$$

The string of solutions to this equation is:

$\lambda_1 L=1.875104069$, $\lambda_2 L=4.694091133$, $\lambda_3 L=7.854757438$, $\lambda_4 L=10.99554073$,
$\lambda_5 L=14.13716839$, $\lambda_6 L=17.27875953$, $\lambda_7 L=20.42035225$, $\lambda_8 L=23.56194490$,
$\lambda_9 L=26.70353756$, $\lambda_{10} L=29.84513021$,

and for $n>10$ the formula can be used $\lambda_n L=\frac{(2n+1)\pi}{2}$ (solutions of the equation $\cos(\lambda L)=0$).

The sequence of proper functions in this case is form:

$$W_n(x)=C_n(\sinh(\lambda x)-\sin(\lambda x)-\frac{\sinh(\lambda_n L)-\sin(\lambda_n L)}{\cosh(\lambda_n L)+\cos(\lambda_n L)}(\cosh(\lambda x)-\cos(\lambda x)). \qquad (16)$$

Constants C_n which appear in relations (16) are determined by the normalization conditions for their own functions.

For each natural number, the characteristic equation attached to the equation (9) is:

$$r^2+2c_2\lambda_n^4 r+a^2\lambda_n^4=0. \qquad (17)$$

There is a natural number n_0 so the discriminant $\Delta_n<0$ for $n<n_0$, and $\Delta_n\geq 0$ for $n\geq n_0$.

Therefore, the vibration of the bar will be:

$$w(x,t)=\sum_{n=1}^{n_0-1} e^{-\mu_n t}\left[\frac{g_n+\mu_n f_n}{\sqrt{\omega_n^2-\mu_n^2}}\sin(\sqrt{\omega_n^2-\mu_n^2}t)+f_n\cos(\sqrt{\omega_n^2-\mu_n^2}t)\right]W_n(x)+ \\ +\sum_{n=n_0}^{\infty} e^{-\mu_n t}\left[\frac{g_n+\mu_n f_n}{\sqrt{\mu_n^2-\omega_n^2}}\sinh(\sqrt{\mu_n^2-\omega_n^2}t)+f_n\cosh(\sqrt{\mu_n^2-\omega_n^2}t)\right]W_n(x), \quad (18)$$

where

$$\mu_n=c_2\lambda_n^4, \quad (19)$$

$$\omega_n=a\lambda_n^2, \quad (20)$$

thus

$$f_n=\int_0^L f(x)W_n(x)dx, \quad (21)$$

$$g_n=\int_0^L g(x)W_n(x)dx. \quad (22)$$

In general, the presence of damping, the free vibration of the bar is the shape (18), each of its own modes of vibration having its own damping factor. The term $2c_0\dot{w}$ leads to a constant damping factor, the term $-2c_1\frac{\partial^2\dot{w}}{\partial x^2}$ leads to a damping factor inversely proportional to the square of the length of the bar, and in the presence of the term $2c_2\frac{\partial^4\dot{w}}{\partial x^4}$ the damping factor is inversely proportional to the fourth power of the bar length.

The determination of the damping mechanism for each test piece and material can only be done by experimental determinations.

2.1. Carrying out the test pieces for the vibration test

Tiles based on Dammar natural resin were made. The chemical and structural composition of Dammar are analyzed in [29, 30], while the mechanical properties for composites made of hybrid Dammar based resins reinforced with natural fiber fabrics are studied in [20, 31]. Three hybrid resins obtained by mixing natural Dammar resin with Resoltech 1050 synthetic resin and the corresponding hardener 1058S [32] were used for the composite materials. The three hybrid resins are:

- HD50 hybrid resin with 50% synthetic resin and 50% natural Dammar resin;
- HD60 hybrid resin with 40 % synthetic resin and 60 % natural Dammar resin;
- HD70 hybrid resin with 30 % synthetic resin and 70 % natural Dammar resin.

Based on these hybrid resins, composite slabs reinforced were made:

- 22 layers of cotton fabric, with specific mass 130 g/m^2. These composite materials are abbreviated B-HD50, B-HD60 and B-HD70;
- 11 layers of fabric mixed with 40% cotton and 60% flax, with specific mass 240g/m^2. These materials will be considered reinforced with flax and are abbreviated as I-HD50, I-HD60 and I-HD70;
- 18 layers of fabric mixed with 60% silk and 40% cotton, with specific mass 160 g/m^2. These materials will be considered reinforced with silk and are abbreviated as: M-HD50, M-HD60 and M-HD70;
- 6 layers of hemp, with specific mass 350g/m^2. These composite materials are abbreviated as: C-HD50, C-HD60 and C-HD70.

The main mechanical properties of the fibers are being presented in Table 1.

Table 1. The main mechanical properties of the fibers used (adapted by [33-36]

Fiber	Density [g/cm³]	Elongation [%]	Tensile strength [MPa]	Elastic Modulus [GPa]
Cotton	1.5-1.6	7.0-9.0	287-800	5.5-12.6
Flax	1.5	2.7-3.2	345-1100	27-39
Hemp	1.4-1.5	2-4	310-750	30-60
Silk	1.3-1.4	18-33	160-260	4-6

The number of layers was chosen so that the slabs were as close as possible. Table 2 shows the characteristics of plates obtained.

Table 2. The characteristics of slabs

Composite type	Mass proportion of resin	Bar thickness [mm]	Density [g/cm³]
B-HD50	0.54	5.3	1.23
B-HD60	0.55	5.4	1.20
B-HD70	0.54	5.3	1.18
I-HD50	0.54	5.4	1.26
I-HD60	0.53	5.4	1.24
I-HD70	0.53	5.3	1.21
M-HD50	0.50	5.5	1.29
M-HD60	0.49	5.5	1.26
M-HD70	0.50	5.5	1.24
C-HD50	0.56	5.4	1.16
C-HD60	0.54	5.3	1.14
C-HD70	0.55	5.3	1.13

Sets of test pieces were cut from the slabs. The all test pieces' dimensions, both those made of hybrid resins and those made of composite materials were: 250 mm long, 25 mm wide [37].

In Figure 1a the three types of hybrid resins are being presented, while in Figure 1b specimens of all types of composite materials made with 60% Dammar hybrid resin matrix are presented.

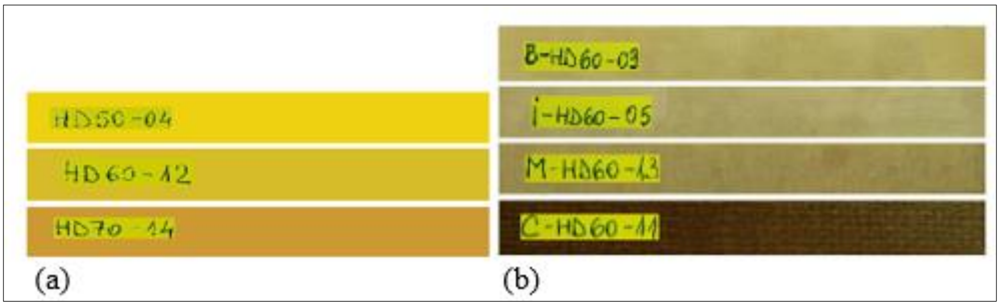

Figure 1. Test pieces from those three types of hybrid resins (a); test pieces of all types of composite materials made with Dammar hybrid resin matrix (b)

3. Results and discussions

For the experimental study of vibration behavior, from each set of test pieces, 3 test pieces were randomly selected. The damping coefficient wad determined experimentally for these sets of test pieces, which were embedded at one end, and the vibration measurement was made at the free end. The free length for each bar studied was 120 mm, 140 mm, 160 mm,180 mm and 200 mm.

The SPIDER 8 data acquisition system with NEXUS 2692-A-0I4 signal conditioner was used for measurements, and the eigenfrequency measurement range was set from 0-2.400Hz. The accelerometer was used with a sensitivity of 0.04 pC/ms^{-2}, and the given set of purchases was made using CATMAN EASY software.

Figure 2 shows an experimental vibration recording for a hemp-reinforced specimen, C-HD50 and 120 mm free length. This recording was chosen because it is the one with the highest vibration eigenfrequency.

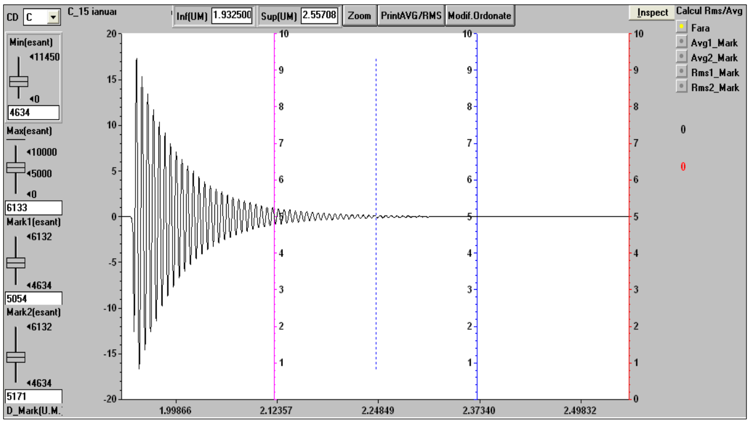

Figure 2. Experimental vibration recording for a hemp-reinforced test tube, C-HD50 and 120 mm free length

Figure 3 shows how to determine the depreciation factor for the Figure 2 recording. The determination of the damping factor per unit mass of the bar was made with the relation [20, 25]:

$$\mu = \frac{1}{t_2 - t_1} \ln \frac{w_1}{w_2}, \qquad (23)$$

where

- t_1 it is the time for the maximum of the beginning, and t_2 the moment of time for the maximum end of the area in the experimentally recorded diagram, used to calculate the damping factor;
- w_1 is the maximum value for the moment of time t_1, and w_2 is the maximum value at the moment of time t_2.

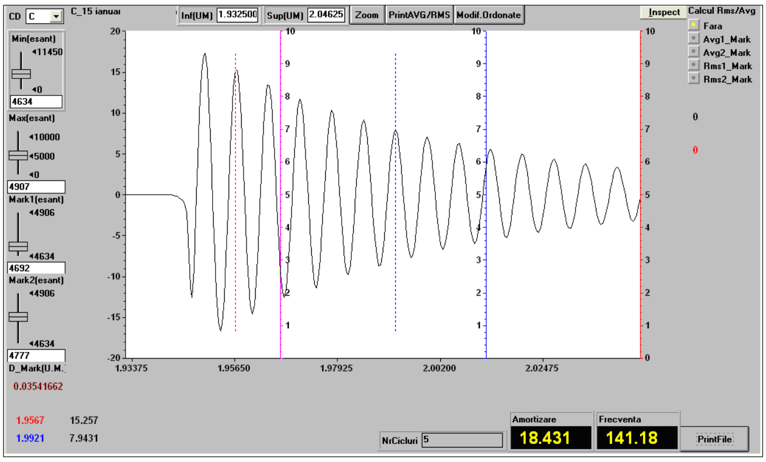

Figure 3. Damping factor determination for the C-HD50 hemp-reinforced specimen and the free length of 120 mm

Tables 3-6 show the average values of the damping factor and the eigenfrequency, measured experimentally, for the four sets of samples.

Table 3. Damping factor and eigenfrequency of cotton-reinforced specimens

Resin / Length	B-HD50		B-HD60		B-HD70	
	Damping factor, [s^{-1}]	**Eigen-frequency, [Hz]**	**Damping factor, [s^{-1}]**	**Eigen-frequency, [Hz]**	**Damping factor, [s^{-1}]**	**Eigen-frequency, [Hz]**
120 mm	21.16	96.4	22.24	91.3	23.99	81.4
140 mm	15.76	70.4	16.99	65.0	17.76	58.8
160 mm	12.33	54.1	13.89	51.3	14.33	44.3
180 mm	9.54	41.7	9.74	40.6	11.28	35.0
200 mm	7.57	34.1	8.88	32.3	9.39	28.9

Table 4. Damping factor and eigenfrequency of flax-reinforced specimens

Resin / Length	I-HD50		I-HD60		I-HD70	
	Damping factor [s^{-1}]	**Eigen-frequency [Hz]**	**Damping factor [s^{-1}]**	**Eigen-frequency [Hz]**	**Damping factor [s^{-1}]**	**Eigen-frequency [Hz]**
120 mm	25.43	122.5	30.33	118.8	35.89	112.2
140 mm	18.87	89.6	22.83	87.6	27.80	81.6
160 mm	14.29	70.2	17.60	67.8	21.09	61.4
180 mm	10.55	53.8	13.39	50.2	15.61	47.9
200 mm	8.77	43.4	10.32	41.1	12.27	39.1

Table 5. Damping factor and eigenfrequency of silk-reinforced specimens

Resin / Length	M-HD50		M-HD60		M-HD70	
	Damping factor [s^{-1}]	**Eigen-frequency [Hz]**	**Damping factor [s^{-1}]**	**Eigen-frequency [Hz]**	**Damping factor [s^{-1}]**	**Eigen-frequency [Hz]**
120 mm	28.31	90.6	30.96	87.6	33.67	77.4
140 mm	22.50	65.4	23.78	63.6	24.36	55.8
160 mm	17.05	49.8	18.48	48.5	19.61	44.1
180 mm	13.61	39.2	14.38	37.9	15.59	33.9
200 mm	10.31	31.9	11.26	30.1	12.71	27.5

Table 6. Damping factor and eigenfrequency of hemp-reinforced specimens

Resin / Length	C-HD50		C-HD60		C-HD70	
	Damping factor [s^{-1}]	**Eigen-frequency [Hz]**	**Damping factor [s^{-1}]**	**Eigen-frequency [Hz]**	**Damping factor [s^{-1}]**	**Eigen-frequency [Hz]**
120 mm	20.43	141.2	22.42	136.4	24.31	123.1
140 mm	15.85	103.6	17.11	100.8	18.11	90.8
160 mm	12.06	78.9	13.71	75.8	15.16	69.2
180 mm	9.76	61.5	10.39	59.3	11.24	53.5
200 mm	7.91	50.6	8.18	46.9	8.53	43.7

The damping factor characterizes the vibration damping capacity for the studied bars and depends on the length of the vibrating bar. In order to assess the damping capacity of the materials from the specimens are made, the loss factor η, is determined with the relation [20]:

$$\eta = \frac{\mu}{\pi\nu}, \qquad (24)$$

where the modulus of elasticity is E with the relation [38].

$$E = \frac{48\pi^2\rho\nu^2 l^4}{\beta^4 h^2}, \qquad (25)$$

where ρ is density, ν represents the eigenfrequency, l is the bar length, *h* is bar thickness, and β depends on the limits conditions. For the built-in bar at one end and free at the other we have β=1.875.

In Table 7 the experimental results are presented for all the studied specimens, obtained as an average of the values calculated for each free length considered.

Table 7. Experimental results for all studied test pieces, obtained as an average of the values calculates for each free length considered

Composite type	Loss factor η	Modulus of elasticity E [MPa]
B-HD50	0.0714	3174
B-HD60	0.0822	2666
B-HD70	0.0998	2134
I-HD50	0.0650	5110
I-HD60	0.0824	4361
I-HD70	0.1047	4042
M-HD50	0.1063	2726
M-HD60	0.1186	2479
M-HD70	0.1425	1936
C-HD50	0.0488	6202
C-HD60	0.0551	5841
C-HD70	0.0650	4974

4. Conclusions

The mechanical behavior of composites is being influenced by the components of the materials, but also by the proportions and geometrical arrangements of those. Natural fibers can have different properties which are influenced by climatic conditions, soil, harvesting and storage conditions. Therefore, the mechanical properties of composite reinforced materials with natural fibers must be made using experimental methods.

The analysis of the obtained data shows that the eigenfrequency is proportional to the inverse of the square of the free length of the bar. A similar dependence is obtained for the depreciation factor. Therefore, the damping factor is proportional to the vibration pulsation. This shows that the type of hysteretic damping is predominant and the damping force is proportional to the bending speed of the bar.

The damping capacity increases with the proportion of Dammar in the hybrid resin, the lowest values for the loss factor were obtained for the composite materials with the hybrid resin HD50, and the highest were obtained for the composite materials with the hybrid resin HD70. So the dynamic modulus of elasticity the trend is reversed, the lowest values were obtained for composite materials with HD70 hybrid resin, and the highest were obtained for those made with HD50 resin.

The mechanical properties of the composite materials made, depend on the reinforced materials. The highest values of the modulus of elasticity were obtained for the reinforced materials with hemp, but still these have the lowest loss factor. In change with that, the highest values of the loss factor were obtained for the reinforced composite materials with silk, these ones have the lowest modulus of elasticity. To conclude the loss factor variation is reversed with the one from the modulus of elasticity.

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