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The Study of Mechanical Properties of Sandwich Composites with a Hybrid Resin Matrix Based on Dammar, a Core of Chopped Corn Cobs and Natural Fabric Faces. Applications in the Furniture Industry

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Abstract*. From the desire to produce environmentally friendly composites, sandwich composites with a matrix made of a Dammar-based hybrid resin, a core of chopped corn cobs, and faces made of natural fabrics were cast and researched in terms of their mechanical properties. The low production cost and the mechanical characteristic values obtained for these sandwich composites have shown that they represent an alternative to MDF, or PAL (Medium Density Fiberboard, or Chipboard). As an application, two elements of a bathroom cabinet were made. The cabinet was exposed to a high-humidity environment, and it was found that the humidity level did not cause any changes in shape or appearance of the elements made from the sandwich composite.*

Keywords*: Hybrid resin, chopped corn cobs, natural fabrics, sandwich composite materials, mechanical properties*

1. Introduction

Natural resins are insoluble in water but are easily soluble in oil, alcohol, turpentine, and partially in gasoline. With certain organic solvents, they form solutions that can be used as coating lacquers [1-5]. A disadvantage of natural lacquers is that they cannot form thick resins [1, 2]. A solution to eliminate this inconvenience is the use of hybrid resins obtained by combining multiple constituents, of which at least one is organic and at least one is synthetic. Hybrid resins represent an environmentally friendly alternative compared to synthetic resins.

A natural vegetal resin that has begun to be used as a base for hybrid resins is Dammar. This resin is obtained from the Dipterocarpaceae family of trees in India and East Asia, and its structure and chemical composition have been determined in [6]. The study of certain chemical and mechanical properties of a Dammar-based hybrid resin (polymerized with epoxy resin) was conducted in [7].

In [8], the influence of non-uniformities on the mechanical behavior of Dammar-based hybrid matrix composites reinforced with hemp fabric was investigated, while in [9], some mechanical properties of Dammar-based hybrid matrix composites reinforced with two types of linen fabric were studied. In these papers, the Dammar-based hybrid resins were obtained in combination with epoxy resin. The polymerization of the natural Dammar resin can also be achieved using acrylic resin [10, 11].

The fabrication of composites with a high degree of environmental absorption involves the use of both hybrid resins and natural reinforcements, such as natural fibers, as an alternative to synthetic fibers [12, 13]. Other categories of natural reinforcements that can be used for obtaining composite materials include cereal straws, seed husks, coconut husks, and corn cobs, among others. Among these, corn cobs stand out as significant agricultural waste, as from one ton of corn kernels, 180-200 kg of corn cobs can be obtained [14]. In recent years, numerous studies have been conducted focusing on the mechanical properties and industrial applications of materials incorporating chopped corn cobs [15, 16].

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The replacement of river sand in lightweight structural concrete with chopped corn cobs, treated with cement paste so as to inhibit water absorption and improve the compatibility of the mixture with the cement matrix, represents an economical and sustainable alternative. Results obtained in [17] have demonstrated that, after treatment, chopped corn cobs exhibited lower water absorption and almost no inhibitory effect on the hydration products made of cement. Furthermore, the use of these mixtures has increased the ductility and thermal insulation of structural concretes.

The production of "green concrete" based on recyclable materials with low carbon content was investigated in [18]. The concrete was made from corn cob powder, used as coarse aggregate, recycled sand as fine aggregate, and industrial solid waste as the cementing material.

Chopped corn cobs can be used as a component for manufacturing bricks. Specifically, in [19], it was observed that incorporating 6% chopped corn cobs as an aggregate in the composition of bricks reduces thermal conductivity by 38% compared to traditional bricks.

The work [20] introduces an alternative use of corn cob granules, instead of expanded clay, cork particles, or expanded polystyrene, for producing lightweight concrete. It has been demonstrated that this type of concrete possesses mechanical and thermal properties suitable for non-structural applications.

The use of corn cob ash as an aggregate for concrete has been the subject of numerous studies. It has been found that this ash exhibits low water absorption and improved resistance to sulfur attack [21, 22]. The incorporation of corn cob ash in concrete produces a decrease in its tensile and compressive strength, but an increase in freeze-thaw resistance, as well as resistance to hydrochloric acid [23, 24]. Despite the decrease in mechanical properties, it has been demonstrated that concrete with corn cob ash can be used for flooring, mortar, or roofing tiles (as an alternative to asbestos tiles), where compressive strength is not as critical [25].

In this article, sandwich composites were fabricated with a hybrid matrix (based on Dammar natural resin and acrylic resin), a core made of chopped corn cobs (without grains), and face sheets made of natural fabrics, such as cotton, flax, and silk. The behavior of these composites under various types of mechanical stress was studied, including tensile stress, three-point bending, and vibrations. Two furniture elements were crafted from these sandwich composites as an alternative to MDF, and their behavior in a controlled humidity environment was examined.

2. Materials and methods

2.1. Manufacture of samples

The matrix used for casting the composite materials was a hybrid resin obtained by combining 60% Dammar natural resin with 40% Claro Cit resin and the corresponding hardener (the synthetic component was used to initiate polymerization). Some mechanical characteristics of the acrylic resin were studied in [26]. The hybrid resin will be abbreviated as B.

In the first part, corn cobs (without grains) were ground using a hammer mill. The mill screen was adjusted to achieve a particle size of 3 - 5 mm for the chopped cobs.

Three composite material plates of the same thickness were cast, each with a from type B hybrid resin matrix and reinforcement from chopped corn cobs. To ensure proper impregnation of the reinforcement with the matrix, a mass percentage of 40% chopped corn cobs was used for each plate. These plates were used as cores to create sandwich composites. Specifically, on each face of these cores, using type B hybrid resin as an adhesive, four layers of the same type of natural fabric (cotton, flax, or silk) were applied. A uniform pressure of 27 kN/m^2 was applied to the composite material plates and sandwich composites. Fifteen tensile samples (symbolized TBC, TBF si TBS) and fifteen three-point bending samples (symbolized BBC, BBF si BBS) were cut from each plate. From the three sets of samples subjected to tensile, was selected one sample for which the vibration behavior was studied. These samples were abbreviated with VBC, VBF and VBS.

All composite materials were cast at an ambient temperature of 21-23°C. To ensure complete polymerization, samples with an acrylic resin matrix were cut after 5 days of casting, and samples with hybrid resin matrices were cut after 10 days of casting.

Figure 1 illustrates the stages of the process of creating samples from sandwich composites, with the core made of chopped corn cobs and face sheets made of natural fabrics. The mass proportions of resins, types of fabrics used for face sheets (and their specific mass), dimensions of samples, their abbreviations, and the applied loads are provided in Table 1.

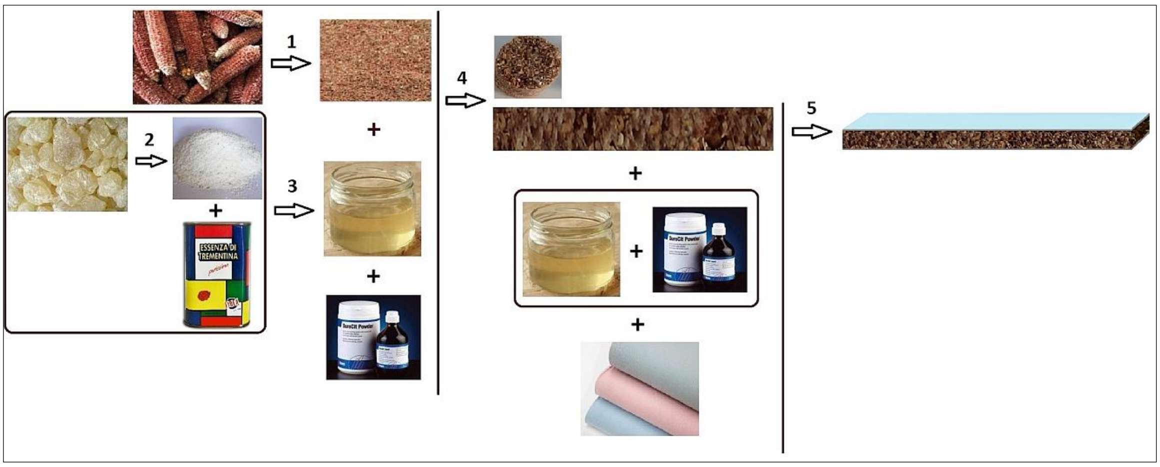


Figure 1. The stages of the specimen creation process

Table 1. Types of resins used, types of fabrics used for face sheets, dimensions of samples, applied loads, and their abbreviations

No.	Type of resin used	Type of fabric used for faces, specific mass, (g/m^2)	Sample dimension (mm)	Applied load	Abbr.
1	B	Cotton fabric 154 g/m^2	250 x 25 x 10.48 150 x 12.7 x 10.48 250 x 25 x 10.48	tensile bending vibrations	TBC BBC VBC
2	B	Flax fabric 149 g/m^2	250 x 25 x 10.37 150 x 12.7 x 10.37 250 x 25 x 10.37	tensile bending vibrations	TBF BBF VBF
3	B	Silk fabric 137 g/m^2	250 x 25 x 10.21 150 x 12.7 x 10.21 250 x 25 x 10.21	tensile bending vibrations	TBS BBS VBS

2.2. Equipment used for testing

The tensile test was conducted using a Walter+Bai LFM-L Series universal testing machine for static and dynamic tests, with a 25 kN load cell [27], while the three-point bending test was performed using an LBG Testing Equipment universal testing machine with a 100 kN load cell at a speed of v=10 mm/min. The mechanical tests performed adhered to the requirements, specifications, and characteristics specified in the corresponding standards: tensile – ASTM D3039/D3039M, and three-point bending – ASTM D790.

For the vibration analysis, a data acquisition system SPIDER 8 was used, connected to a signal conditioner type NEXUS 2692-A-0I4, and a notebook for recording experimental data. The connection between the notebook and SPIDER 8 was established using Catman Easy software. An accelerometer from B&K with a sensitivity of 0.04 pC/ms^{-2} was also connected to the signal conditioner.

3. Results and discussions

3.1. Tensile testing of samples TBC, TBF, and TBS

Based on the tensile testing of the sandwich composites, the characteristic curve, tensile strength R_m (MPa), elongation at breaking A (%), and longitudinal modulus of elasticity E (N/mm^2) were determined for each sample in the TBC, TBF, and TBS sets. From each set, a characteristic curve was selected and presented in Figure 2, representing values close to the arithmetic mean of the determined mechanical characteristics.

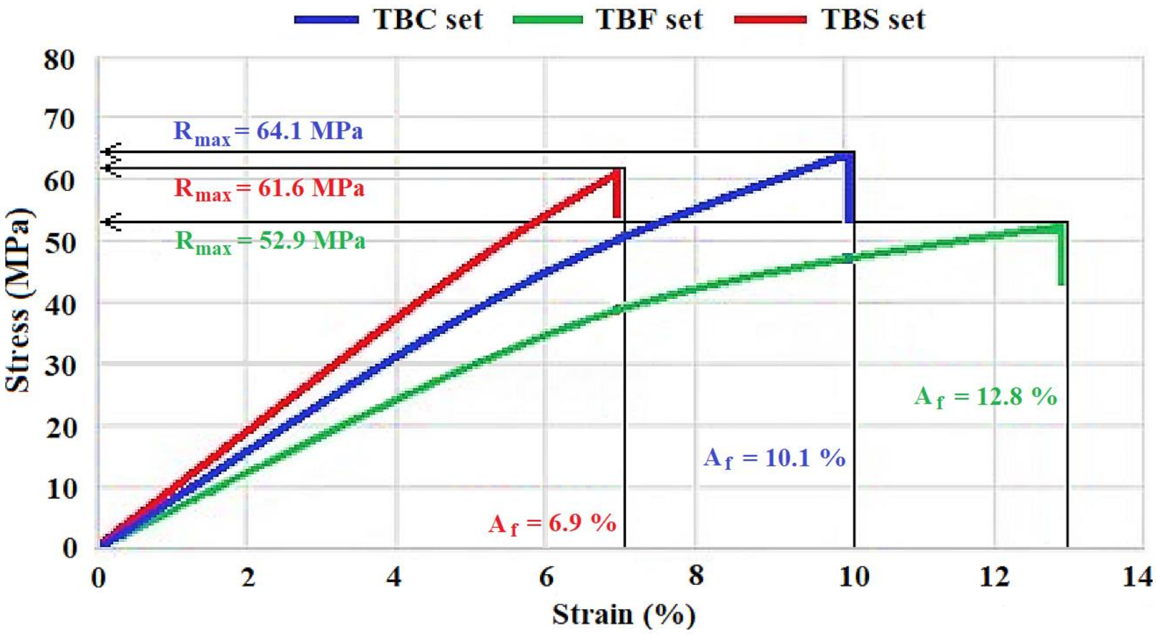


Figure 2. Characteristic curves obtained based on tensile testing, with values close to the arithmetic mean of mechanical properties, for samples from the TBC, TBF, and TBS sets

Using the data obtained from tensile testing, Table 2 compiles the average value, linear mean deviation, and quadratic mean deviation for the modulus of elasticity, tensile strength, and elongation at breaking for the sets of samples TBC, TBF, and TBS.

Table 2. The average value, linear mean deviation, and quadratic mean deviation for the modulus of elasticity, tensile strength, and elongation at breaking, obtained from the tensile testing of the sets of samples TBC, TBF, and TBS

Sample type	Modulus of elasticity E (N/mm^2)			Tensile strength R_m (MPa)			Elongation at breaking A (%)		
	$\bar{x}$	$\overline{d_x}$	$\overline{\sigma_x}$	$\bar{x}$	$\overline{d_x}$	$\overline{\sigma_x}$	$\bar{x}$	$\overline{d_x}$	$\overline{\sigma_x}$
TBC	4705	79.52	96.46	64.1	0.107	0.141	10.08	0.101	0.122
TBF	4170	17.022	23.89	61.52	0.219	0.269	6.9	0.102	0.134
TBS	2547	11.51	14.47	52.9	0.093	0.137	12.83	0.12	0.14

From the analysis of the characteristic curves obtained based on tensile testing, three phases can be highlighted:

- in the first phase, with a linear character, there was a proportionality between stress and specific strain. The load was carried by both the core of chopped corn cobs and the face sheets made of natural fabrics, specifically, the fibers from cotton, flax, and silk fabrics, which were longitudinally oriented in the direction of the load;
- in the second phase, with a nonlinear character, there was a point where apparent flow stress occurred, leading to residual specific strains of 0.2% after unloading. The specific strain in this stage was close to the strain at which resin breaking occurred, indicating a loss of adhesion between the

chopped corn cobs, fibers from cotton, flax, and silk fabrics, and the matrix. Pull-outs of the resin reinforcements occurred, and the load was transferred to the chopped corn cobs and fabric fibers, ultimately resulting in the breaking of the core;

- in the third phase, with a linear character, the fabric took on the entire load until the stress rupture was reached.

3.2. The three-point bending test of the samples BBC, BBF, and BBS

The sets of samples BBC, BBF, and BBS were subjected to three-point bending test. The characteristic curve, bending strength σ_{ab} (MPa), maximum transverse displacement L_{max} (mm), and maximum bending force F_{max} (kN) were determined for each sample. From each set, the characteristic curve for which values close to the arithmetic mean of the mechanical characteristics were recorded is selected and presented in Figure 3.

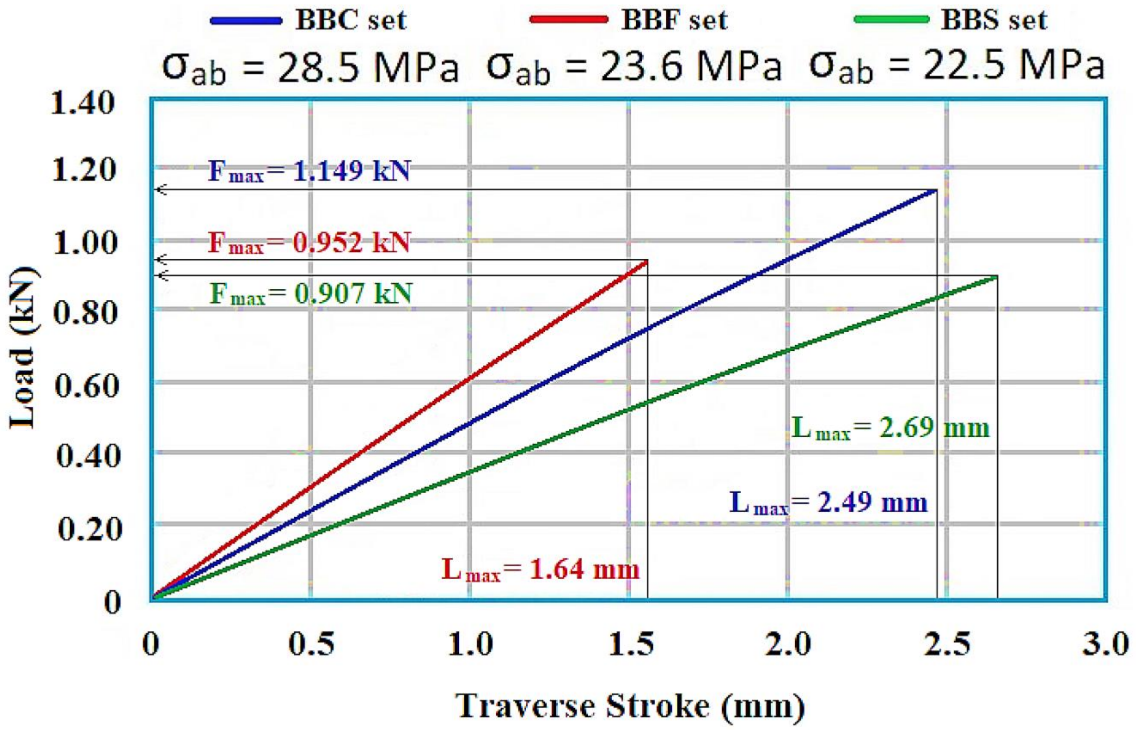


Figure 3. The characteristic curves obtained after the bending tests, with values close to the arithmetic mean of the mechanical properties, for samples from the BBC, BBF, and BBS sets

Based on the bending tests, Table 3 consolidates the average value, linear mean deviation, and quadratic mean deviation for the bending strength σ_{ab} (MPa), maximum transverse displacement L_{max} (mm), and maximum bending force F_{max} (kN) for the sets of samples BBC, BBF, and BBS.

Table 2. The average value, linear mean deviation, and quadratic mean deviation of the bending strength, maximum transverse displacement, and maximum bending force obtained from the bending tests for the sets of samples BBC, BBF, and BBS

Sample type	Bending strength σ_{ab} (MPa)			Maximum bending force, F_{max} (kN)			Maximum transverse Displacement, L_{max} (mm)		
	$\bar{x}$	$\overline{d_x}$	$\overline{\sigma_x}$	$\bar{x}$	$\overline{d_x}$	$\overline{\sigma_x}$	$\bar{x}$	$\overline{d_x}$	$\overline{\sigma_x}$
BBC	28.41	0.584	0.433	1.149	0.055	0.063	2.46	0.117	0.14
BBF	23.54	0.344	0.389	0.952	0.049	0.057	1.64	0.116	0.145
BBS	22.46	0.278	0.318	0.907	0.062	0.063	2.69	0.12	0.146

In the case of samples subjected to bending, as the same type of matrix and core were used, the differences in properties are due to the different behaviour of the fabric in the face sheets.

The analysis of the three characteristic curves in Figure 3 shows that there was a linear dependence between the loading force and the measured deformation throughout the loading. The samples with silk faces had the highest deformation, while those with flax faces had the lowest; the samples with cotton faces had the highest tensile strength, while those with silk faces had the lowest. The differences in force between the three types of tested sandwich sample were not significant because, in the initial phase, the load was taken by both the core made of chopped corn cobs and the face sheets made of natural fabrics. Subsequently, after the core began to break, the loads were entirely taken by the faces sheets until the final breaking of the sample. Additionally, the force variations between the three types of tested sandwich samples can be explained by the differences in thickness between them, differences resulting from the thickness of the applied fabric layers.

The obtained results show that the tensile strength, bending strength, and modulus of elasticity values of the investigated sandwich composites are higher than those of 18 mm thick melamine-faced MDF [28]. This thickness of melamine-faced MDF was chosen as it is the most commonly used in the production of furniture elements.

3.3. Vibration behaviour of VBC, VBF, and VBS samples

The vibration behavior of samples from sets VBC, VBF, and VBS was investigated as follows: the samples were clamped at one end and left free at the other end; an accelerometer was mounted 5 mm from the free end's edge to record the vibrations; the free length of the samples varied between 100 and 180 mm. The damping factor of vibrations and the natural frequency were determined for one sample from each set. In the same manner as Figure 4 illustrates the method for calculating the natural frequency and damping factor for the first mode of vibration of a VBC set sample, with values corresponding to a free length of 140 mm. The method for determining the damping factor of vibrations and the natural frequency is presented in [29, 30].

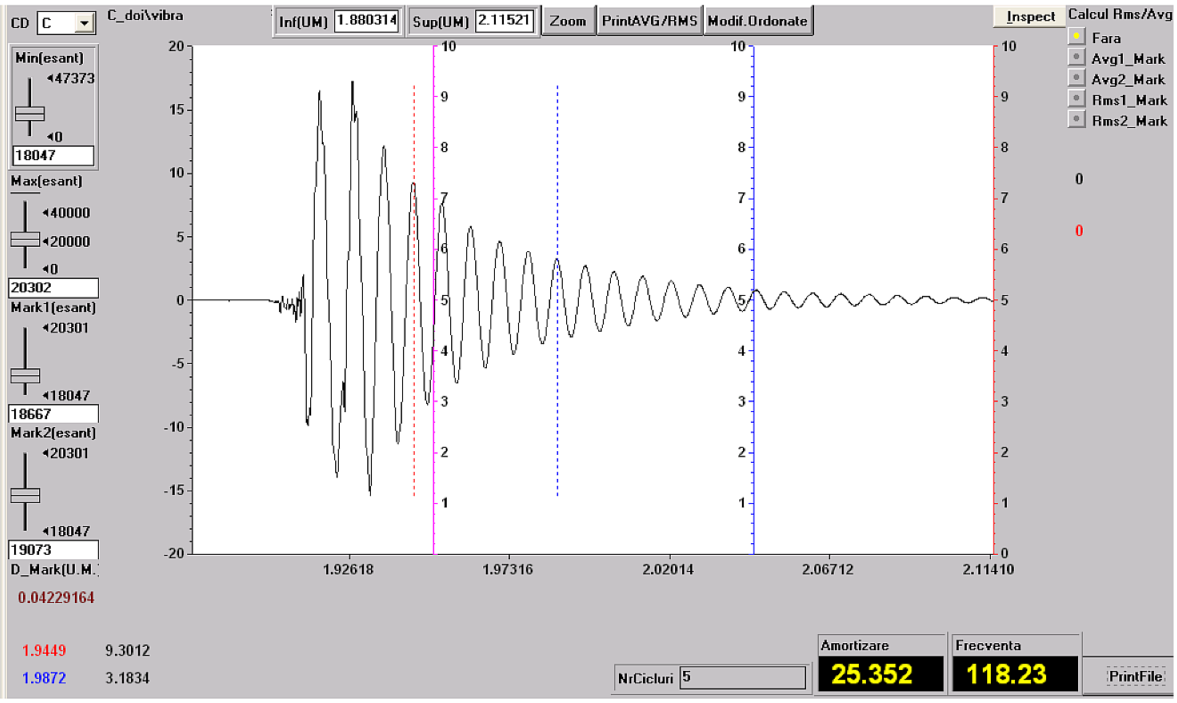


Figure 4. The recording of vibrations for a sample from the VBC set with a free length of 140 mm

Table 4 presents the experimental data regarding the vibrational behaviour of samples from the VBC, VBF, and VBS sets.

Table 4. The vibrational behavior of the samples from the VBC, VBF, and VBS sets

Free Length (mm)	VBC		VBF		VBS	
	Frequency $\nu(Hz)$	Damping $\mu(s^{-1})$	Frequency $\nu(Hz)$	Damping $\mu(s^{-1})$	Frequency $\nu(Hz)$	Damping $\mu(s^{-1})$
100	221.7	46.7	155	37.5	143.6	29.7
120	155.9	32.5	108.1	26.1	100.2	20.7
140	118.8	25.3	81.6	20.7	75.8	16.7
160	90.5	19.4	62.5	15.8	58.1	12.8
180	72.9	15.9	51.1	13.1	46.8	10.9

The variations in natural frequency and damping coefficient, depending on the specific mass of the fabric face sheets of the sandwich composite and the vibrating bar length, were as follows:

- both the frequency values and the damping coefficient decreased with the specific mass of the fabric face sheets, from VBC to VBF and then to VBS;
- he damping factor and vibration frequency exhibited similar variations depending on the vibrating bar length.

The damping capacity of the materials used in all investigated samples can be appreciated by calculating the loss factor η with the relation [29]:

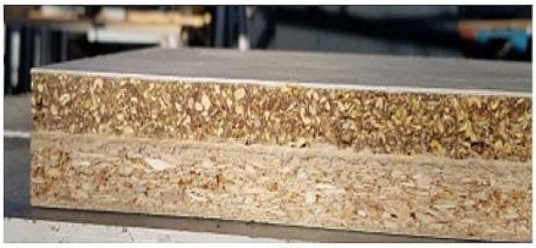
$$\eta = \frac{\mu}{\pi \nu}. \quad (1)$$

More precisely, for the studied composites, the average loss factor values are:

- $\eta = 0.06777$ for VBC composites;
- $\eta = 0.07934$ for VBF composites;
- $\eta = 0.06920$ for VBS composites.

3.4. Application

A sandwich composite plate with cotton fabric face sheets, core made of chopped corn cobs, and hybrid resin type B was cast, having the same thickness as the components of a wardrobe made of melamine-coated MDF. From this plate, a door and a shelf of an cupboard for storing bathroom accessories were cut out. In Figure 5a, a side view of melamine-coated MDF and the sandwich composite is presented, while Figure 5b displays the wardrobe with a door and a shelf made of the sandwich composite. To distinguish them from the original elements of the wardrobe (which are white), the door and the shelf of the composite were made using the hybrid resin matrix mixed with a brown pigment.



(a)

(b)

Figure 5. Side view of melamine-coated MDF and, respectively, the sandwich composite (a); the wardrobe with a door and a shelf made of the sandwich composite (b)

The behaviour of furniture elements made of melamine-coated MDF and those made of sandwich composites was studied in a high-humidity environment. In this regard, the wardrobe in Figure 5 was kept for a period of 7 days in a room with very humid air (Relative Humidity RH=80%). The air was humidified using a humidifier, and the humidity percentage was measured with a thermo-hygrometer. In the end, it was observed that the furniture elements made of:

- melamine-coated MDF had a swelling of 14% in thickness due to water absorption, and mold spots appeared on the surface of these elements;
- the sandwich composites had a swelling of 3% in thickness due to water absorption, and the surface of these elements remained clean.

A possible explanation for the absence of mold on the surface of the sandwich composite furniture elements could be that there was compatibility between the composite phases, given by the natural factor. Additionally, the longer polymerization period of the hybrid resin allowed it to incorporate the dispersed component of chopped corn cobs well. This good inclusion of the reinforcement in the matrix acted as an inhibitor for humidity.

4. Conclusions

The mechanical behaviour of the investigated sandwich composites, with hybrid resins based on natural resins, a core made of chopped corn cobs, and face sheets made of natural fabrics, shows that these materials constitute a viable and environmentally friendly alternative compared to MDF-type materials that use, for example, wood sawdust and various types of synthetic adhesives.

Regardless of the type of destructive testing, the best properties were obtained for sandwich samples with face sheets made of cotton fabric.

For all studied composite materials, the damping factor was inversely proportional to the square of the bar length. This corresponds to an energy dissipation mechanism where the damping force is proportional to the bending velocity of the bar.

From the recorded data, the best vibrational behavior among the studied sandwich composites was determined for those with face sheets made of cotton fabric.

The mechanical properties obtained for the studied sandwich composite materials recommend their use as a replacement of MDF, or Particleboard, in the field of constructions, to make formwork, or, in the furniture industry, to make furniture elements, interior decorations, window sills, kitchen countertops, etc.

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