Mechanical Properties for Composites with Dammar Resin Reinforced with Crushed Corn Cob

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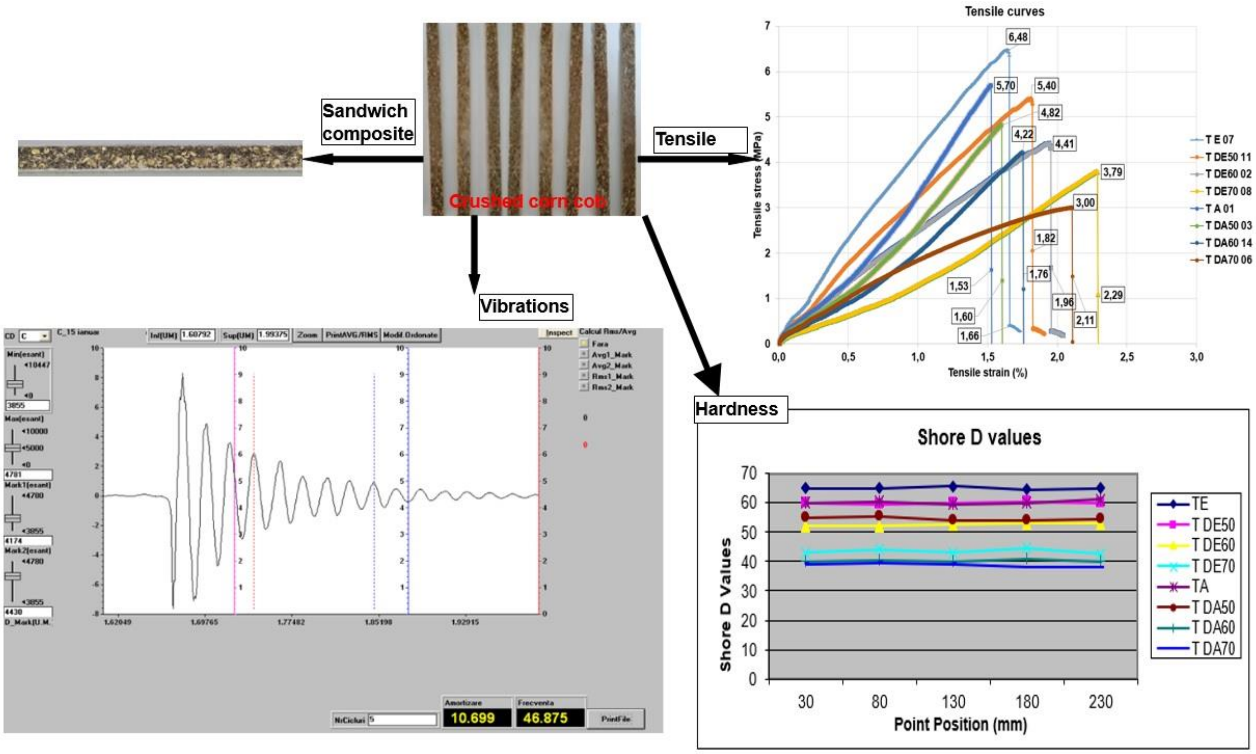
GRAPHICAL ABSTRACT



Mechanical Properties for Composites with Dammar Resin Reinforced with Crushed Corn Cob

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The study focused on the potential use of agricultural waste (corn cob) in the manufacturing of composite materials. In the first stage, composite materials were manufactured and tested using synthetic matrices (epoxy and acrylic) and hybrid matrices based on dammar resin (50% dammar, 60% dammar, and 70% dammar). Since it was observed that the samples had low mechanical properties under tensile and bending loads, the study was expanded to the production of sandwich-type composites with silk fabric facings. It was found that, by utilizing silk fiber, both tensile and bending strength increased from a few hundred percent up to a few thousand percent, compared to the samples that are only reinforced with crushed corn cob.

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Keywords: Crushed corn cob; Hybrid resin; Dammar; Compression; Bending; Vibrations; Tensile test

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INTRODUCTION

Biomass is the biodegradable part of products, waste, and residues from agriculture, including plant and animal matter, forestry, and related industries, as well as the biodegradable part of industrial and urban waste. Thus, the lignocellulosic fibers from biomass can be an alternative source for wooden materials. It is known that the fibers and powders from agricultural materials are similar to wood fibers and particles (Binci *et al*. 2016). Due to their low density and high strength, fibers and particles from agricultural residues can be used as insulating materials in construction (Schiavoni *et al*. 2016; Bovo *et al*. 2022). Among the agricultural residues that can be recycled and used in construction, there can be mentioned the next ones: sunflower seed husks (Mahieu *et al*. 2019; Stănescu and Bolcu 2022), flax shavings (Mahieu *et al*. 2019), elephant grass stalks (Klímek *et al*. 2018), corn cobs (Ramos *et al*. 2021; Bovo *et al*. 2022), rice straw (Zhang *et al*. 2021), and wheat straw (Bolcu *et al*. 2022).

Corn cob is a part of agricultural waste that is obtained after corn production and represents a rich biomass resource (Menardo *et al*. 2015; Czajkowski *et al*. 2019). In the countries with large agricultural surfaces, corn is produced in around 4.6 milions of tons/ year, resulting in 1.7 milions of tons/year of corn cob and husk (Lawanwadeekul *et al*. 2023). After extracting the corn, the corn cob is considered to be an agricultural waste. A good economic benefit may result in finding some areas where it can be used.

From the chemical structure point of view, some studies have shown that the corn cob is made of 32.5% to 45.6% cellulose, 39.8% hemicellulose, and 6.7 to 13.9% lignin (Velmurugan *et al*. 2011). Similar results were found several years later in (Zhou *et al*.

2021), but in addition it was found out that the corn cob is structurally divided into pith, woody ring, and glume. Some tests were done to corn cobs (axial compression, radial compression, and three-point bending) and it was found that the woody ring is the primary source of mechanical strength.

The elementary chemical composition, the macrostructure and microstructure of corn cob, density, water absorption, fire resistance, and thermal insulation capacity were investigated (Pinto *et al*. 2011, 2012). From the experimental results, it was found that the corn cob can be used as a raw material to process thermal insulating products, light partition walls, ceiling coating, and indoor doors or furniture.

In recent years, there have been published studies regarding the manufacturing of some composite materials that have the corn cob as a reinforcement. Composite materials reinforced with corn cob powder and lignosulphonate matrix were developed in (Tribot *et al*. 2018). The samples were tested for compression, and it was found that the mechanical properties increase as the corn cob particle sizes decrease and with the increase of compaction pressure.

Composites reinforced with corn cob particles and the biopolymer poly lactic acid (PLA) were manufactured and investigated in many studies. In Chun and Husseinsyah (2014), composites with 10 to 40% corn cob power with a coconut oil based coupling agent were manufactured. The samples mechanical, thermal, and morphological properties were investigated. The presence of the coconut oil based coupling agent improved the adhesion of corn cobs and PLA matrix. Composites made from PLA reinforced with corn cob and wood particles were manufactured and tested (Faludi *et al*. 2013). Percentages in the range 5 to 60% for the corn cob particles were used. The samples were tensile tested and their microstructure was investigated. It was obtained a decrease in the tensile strength with the volume fraction increase and debonds of matricles were observed through microscopy. Composites made from PLA reinforced with a small quantity of corn cob and kraft lignin were investigated (de Baynast *et al*. 2022). Percentages between 5 and 10% of corn cob and 10 to 15% kraft lignin were used to build composites. The aim of the study was to partially replace the PLA to decrease the overall cost and the carbon footprint.

Another usage of the corn cob is to be inserted in clay bricks. A first approach to this kind of research was presented in Lawanwadeekul *et al*. (2016), where corn cobs were inserted as an additional material in clay bricks. It was found that the corn cob particles decreased the clay bricks compressive strength and increased their porosity. The studies were continued in Njeumen Nkayem *et al*. (2016), where corn cobs between 2 and 15% were inserted in clay bricks. The samples were fired between 900 and 1100 °C. It was observed that apparent density, flexural strength, and linear shrinkage increased with temperature and decreased with increasing corn cob, while the water absorption and the porosity decreased with higher temperature and increased with the amount of added corn cob. Another study of corn cob insertion in clay bricks was presented in (Lawanwadeekul *et al*. 2023), and it was found that, in order to increase the strength of the clay bricks, waste glass must also be added to the mixture. The porosity and strength of clay brick could be increased by inserting corn cobs and waste glass using the low firing temperature because corn cobs added porosity to the bricks, and waste glass acted as a flux, promoting sintering and forming the mineral albite in the end, which improved the strength of the bricks.

In other research, the corn cob was burned until it became ash and then it was inserted in concrete to replace the cement. An example is the research from Shakouri *et al*. (2020), where untreated corn cob ash was used to replace the cement in concrete at replacement levels of 3% and 20% by mass of cement. The insertion of corn cob ash accelerated cement hydration but decreased the compressive strength, the bulk resistivity, and the formation factor. The results suggested that the untreated corn cob ash is not a promising pozzolanic material, and may even be somewhat harmful to the concrete. Other research was continued in Oluremi *et al*. (2023), where 10% corn cob ash was inserted in concrete to replace cement. Compression and tensile tests were made, and the results showed that the insertion of corn cob ash to replace Portland cement decreased the early development of compressive and tensile strengths of the concrete. In Wang *et al*. (2023), the corn cob was used as coarse aggregate to build green low carbon recycled concrete. It was found out that the low carbon recycled concrete had carbon emissions reduced up to 31%, comparable bending compression ratio, poorer shrinkage, and poorer insulation properties compared to ordinary cement.

This paper studied the mechanical behavior of some composite materials reinforced with crushed corn cob and several types of matrices: an acrylic one, an epoxy one, and six hybrid resins based on the natural dammar resin. The novelty of this research is the combination between crushed corn cob and hybrid resins in order to build composite materials. A percentage of 60% crushed corn cob from the composite total mass was used for each sample type. A hybrid resin is a resin used as a matrix in building composites and it involves the combination of two parts: a natural part that is organic and a synthetic that is inorganic (Ishimura *et al*. 2010; Kanehashi *et al*. 2010; Stănescu 2015).

EXPERIMENTAL

Materials

For this research, crushed corn cob was used as reinforcement, acrylic resin Clarocit type with its hardener, epoxy resin Resoltech 1050 with its hardener, and six types of hybrid resins with different proportions of natural dammar resin were used as matrices. All of these resins with their abbreviations are presented in Table 1.

Table 1. Resins Used in this Research Determined in Mass Percentages

Criteria number	Mass percentage of the synthetic resin Rescoltech 1050 (%)	Mass percentage of the dammar resin (%)	Abbreviation
1	100	0	E
2	50	50	DE50
3	60	40	DE60
4	70	30	DE70
	Mass percentage of the synthetic resin Clarocit (%)	Mass percentage of the dammar resin (%)	Abbreviation
5	100	0	A
6	50	50	DA50
7	60	40	DA60
8	70	30	DA70

Mechanical and chemical properties for these type of hybrid resins were previously studied (Stănescu 2015; Mirițoiu *et al*. 2020; Franz *et al*. 2021; Ciucă *et al*. 2022).

Methods

The natural dammar resin was dissolved in turpentine to be brought into liquid state. If it is kept in closed containers, it has a long curing time. One of the methods for rapid polymerization of dammar resin has been to combine it with a minor percentage of synthetic resin and its related hardener (Stănescu 2015; Stănescu and Bolcu 2022; Bolcu *et al*. 2022).

In this research, the following synthetic resins were used for dammar polymerization: epoxy resin Resoltech 1050 type with its hardener and acrylic resin Clarocit type with its hardener. Technical data sheets for the synthetic resins cand be found on the manufacturer's website: Resoltech 1050 (2023) for the epoxy resin and Clarocit Kit (2023) for the acrylic one.

For each type of test that will be presented in the next paragraphs, plates and cylindrical samples were casted with crushed corn cob as reinforcement and the resins mentioned in Table 1. The casting of the samples was carried out at an ambient temperature of 21 to 23 °C. To ensure de complete polymerization of the plates and cylindrical samples, the specimens with synthetic resin as matrix were cut 5 days after casting and the specimens with hybrid resin were cut after 10 days after casting. In addition, a uniform pressure of 27 kN/m^2 was applied to the composite plates and cylindrical specimens.

Test Standards and Characterizations

Tensile test

For the tensile test, plates from composite materials reinforced with crushed corn cob (with a 60% mass percentage from the plate mass) and 8 types of resins (mentioned in Table 1) were casted. From each plate a number of 15 specimens were cut. The specimens were abbreviated with T (tensile), then the resin abbreviation from Table 1 followed by the specimen number (from 01 to 15). An example with the 15 samples from the group T DE50 was presented in Fig. 1.

Fig. 1. Samples from the T DE50 group

The tensile test was done according to ASTM D3039 (2014). The samples dimensions were: 250 mm – length, 25 mm – width and 8 mm – thickness. A universal testing machine INSTRON 1000 HDX was used.

The sandwich samples with side face from silk, core from crushed corn cob and hybrid matrices (DE50, DE60, DE70, DA50, DA60, DA70 mentioned in Table 1) were tested according to the same tensile standard (ASTM D3039 (2014)) and had the next dimensions: 250 mm – length, 25 mm – width and 10 mm – thickness (the core from the crushed corn cob 8 mm thickness). All the sandwich samples will have the letter S (silk) at the end of their abbreviation. An example with a sample from the T DE50 04 S is presented in Fig. 2.

Fig. 2. An example with the sample T DE50 04S

Compression test

For the compression test, from the same parts used to make the plates for the tensile test, 8 sets of 15 cylindrical samples/ set were casted. The specimens were abbreviated with C (compression), then the resin abbreviation from Table 1 followed by the specimen number (from 01 to 15). An example with the 15 samples from the group C DE50 is presented in Fig. 3.

Fig. 3. Samples from the C DE50 group.

The compression test was done according to ASTM D695 (2016). The samples dimensions were: 60 mm – length, 30 mm – diameter. A universal testing machine LGB Testing Equipment with a device for compression tests was used.

Bending test

For the bending test, plates from composite materials reinforced with crushed corn cob (with a 60% mass percentage from the plate mass) and 8 types of resins (mentioned in Table 1) were casted. From each plate a number of 15 specimens were cut. The specimens were abbreviated with B (bending), then the resin abbreviation from Table 1 followed by the specimen number (from 01 to 15).

The bending test was done according to ASTM D790-17 (2017), and the samples had the next dimensions: 200 mm – length, 32 mm – width, and 8 mm – thickness. For this test, a universal testing machine LGB Testing Equipment with a device for three points bending was used.

The sandwich samples with side face from silk, core from crushed corn cob, and hybrid matrices were tested according to the same bending standard (ASTM D790-17 (2017)) and had the next dimensions: 232 mm – length, 40 mm – width, and 10 mm – thickness (the core from the crushed corn cob had 8 mm thickness). All the sandwich samples will have the letter S (silk) at the end of their abbreviation. The support span was chosen 16 times higher than the thickness of the beam according to ASTM D790-17 (2017).

Vibration test

For the vibration test, samples with the same dimension and type, such as those presented at tensile test subsection, were used. The specimens were clamped at one end and left free at the other end where an accelerometer Bruel&Kjaer (with the sensitivity of 0.04 pC/ms^{-2}) was placed. The accelerometer was connected to a signal conditioner Nexus which was also connected to a data acquisition system SPIDER 8. The SPIDER 8 equipment was plugged in a notebook where the experimental values were stored.

Shore D hardness test

The Shore D hardness test was made according to the ASTM D2240-15 (2017) standard. There were used samples with the same dimensions as the ones specified in the tensile test subsection. Five measurements were made in the points placed at 50 mm from each other in the sample's length, and the extreme left and right points are placed at 25 mm from the sample edge. The points were chosen in the middle of the sample width.

Water absorption

The water absorption test was made according to the ASTM D570 (2022). The samples were weighted and immersed in distilled water. The distilled water was placed in Berzelius glasses. The samples had the next dimensions: 76.2 mm length, 25.4 mm width, and 8 mm thickness. After 24 hours, the samples were removed from the water, all the surface water was wiped off with a dry cloth, and then the samples were weighted with an analytical balance SHIMADZU type with 0.01 g precision. The measurement was repeated until the difference in weight of the test specimens from one day to the next was below 0.05 g. After this, the samples were dried at room temperature for 48 h and the final weight was measured.

RESULTS AND DISCUSSION

After testing samples with the resins described in Table 1, the study was extended to build sandwich samples with the side faces from silk fabric, core from crushed corn cob, and the matrices from the hybrid resins (DE50, DE60, DE70, DA50, DA60, DA70) mentioned in Table 1. For each samples side, 4 layers of silk were used with the specific mass of 102 g/m^2.

Besides the crushed corn cob, other types of agricultural waste are used to manufacture composite materials, such as: wood dust, bagasse, rice husks or any other edible-parts of fruits and vegetables (Phiri *et al*. 2023).

Tensile Test

For the destructive testing, 15 specimens of each material type were cast (with hybrid matrices DE50, DE60, DE70, DA50, DA60, DA70). For each specific material type that was tested, an arithmetic average of the obtained mechanical properties was determined. In the following figures, characteristic curves for each material type, which closely approach the arithmetic average values, were plotted on the same graph. The specimens whose mechanical properties closely matched the arithmetic average values will be referred to as representative samples. For example, out of the 15 specimens of type T E tested for tensile strength, specimen 7 exhibited mechanical properties close to the arithmetic average values, and its characteristic curve was represented in Fig. 4. The sample T E 07 was named as the representative sample. Representing the characteristic curves on the same graph was chosen to facilitate a clearer observation of what happens in the tested material as the proportion of dammar natural resin increases and also when changing from epoxy synthetic resin to acrylic one. The results obtained from the tensile test for all the representative samples (stress – strain curves) are presented in Fig. 4.

From Fig. 4 it was seen that low mechanical properties (breaking strength under 7 MPa and the elongation at break under 2.5%) were obtained for the samples reinforced with crushed corn cob and various resins used as matrices. An explanation of this result might be that the crushed corn cobs have irregular and sharp shapes that could lead to stress concentrations in the sample structure which favored the specimen's breakage at low force values. The samples that had epoxy resin in the matrix composition had better mechanical properties compared to the ones that had acrylic resin in the matrix composition. This result could be explained by the fact that the epoxy resin has increased mechanical properties compared to the acrylic one. From Fig. 4 it was concluded that the breaking strength decreases with the increase of the dammar percentage. An explanation of this result might be that the natural dammar resin has decreased breaking strength compared to the synthetic resins. Another conclusion could be extracted from Fig. 4: the elongation at break increased with the dammar percentage. An explanation of this result might be that the natural dammar resin is more elastic than the synthetic resins and a high percentage of dammar would lead to a ductility increase for the specimens.

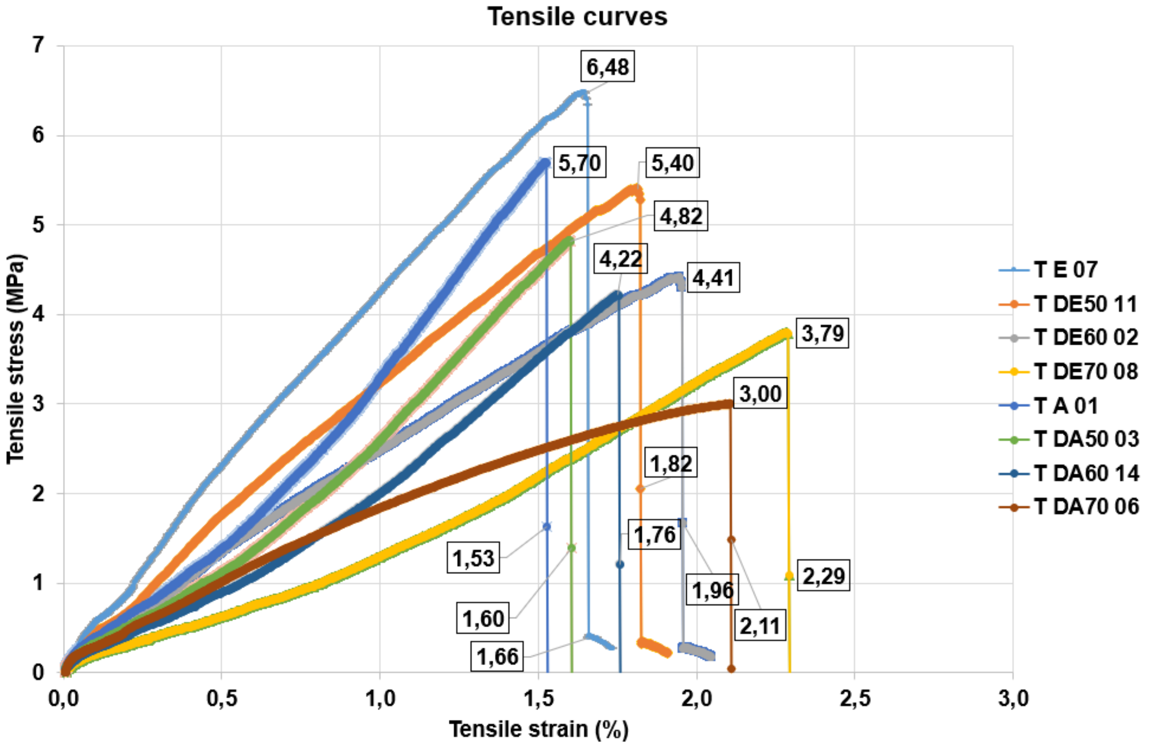


Fig. 4. Stress – strain curves from the tensile test, drew for a representative sample from each material type.

Similar materials with hybrid matrix from epoxy and dammar/pine/cashew nut shell resins reinforced with bagasse were studied in Patil *et al*. (2023). Tensile tests were made and the strength ranged between 1 and 3 MPa; the results were lower than those obtained in this study. In Arumugam *et al*. (2021) composite samples with epoxy resin and rice husk or saw dust were manufactured. The materials were tensile tested, and for the rice husk samples values between 6.9 and 7.4 MPa were obtained. For the saw dust samples, values between 6.2 and 7 MPa were obtained. The results were a little higher than the ones from this study and could be explained by the fact that the samples had a 50% percentage of epoxy resin in Arumugam *et al*. (2021), which was higher than the level of 40% used in this study. If the number of particles inserted in a matrix was increased, then the strength properties of the sample decreased. This phenomenon could be explained by the fact that the particles have irregular surfaces with corners, which insert stress concentrators into the body and reduces its strength (Bolcu *et al*. 2022). In Hemnath *et al*. (2021), composite materials with polyester resin and reinforced with a rice husk and sugarcane bagasse were manufactured. In the tensile test, values between 1.7 and 2.6 MPa were obtained, lower than the ones from the present study. In other research, increased mechanical properties were obtained only if small quantities of reinforcement percent by weight were inserted. For example, tensile strength values between 11 and 12.5 MPa were obtained in Rodriguez *et al*. (2011) for composites with polyester resin and a 5 percent by weight sugarcane bagasse untreated or modified by estherification.

In order to remove the disadvantage of low mechanical properties, sandwich samples with the side faces from silk, core from crushed corn cob, and the matrices from the hybrid resins were manufactured and tested. The results obtained from the tensile test (stress-strain curves) are presented in Fig. 5.

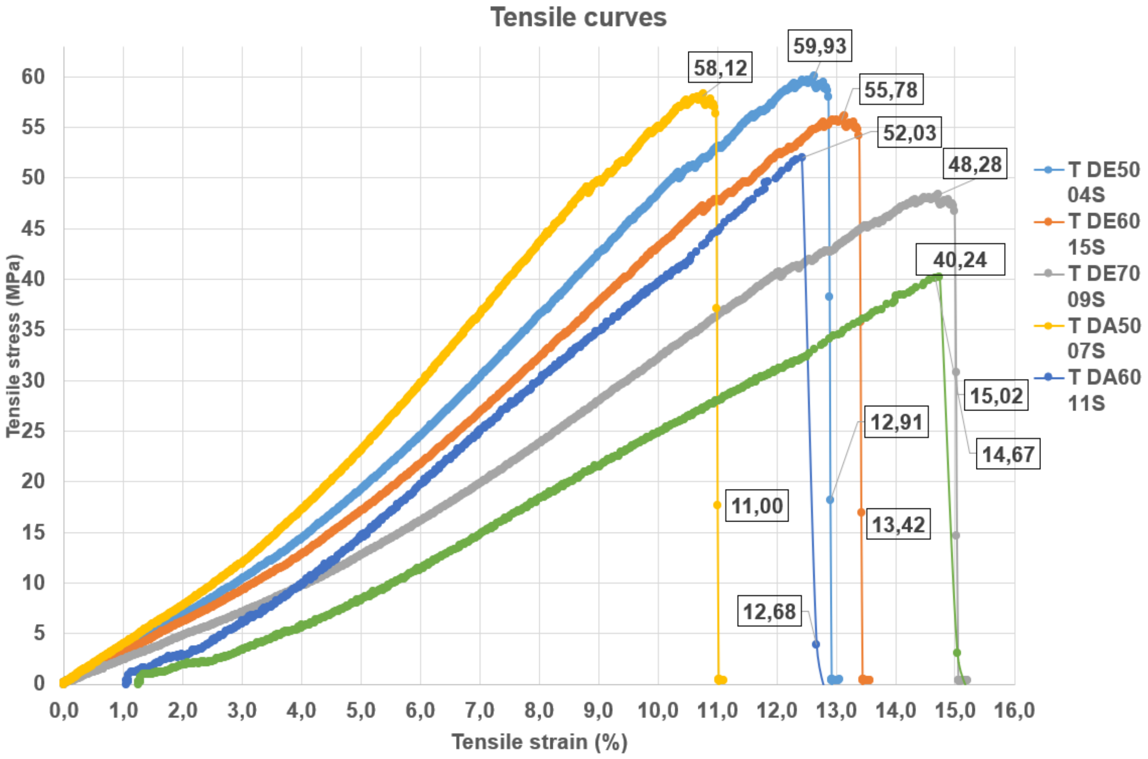


Fig. 5. Stress – strain curves from the tensile test, drew for a representative sample from each sandwich sample type.

From Fig. 5, similar tendencies to Fig. 4 were observed: the breaking strength decreased and the elongation at break increased with the increase of dammar percentage. Also, the samples that had epoxy resin in the hybrid matrix had increased mechanical properties compared to the ones with acrylic resin in the hybrid matrix. By adding silk faces, the mechanical properties were increased. By comparing Figs. 4 and 5, it is apparent that the breaking strength was increased by between 825 and 1240% and the elongation at break was increased by between 555 and 587% if sandwich samples were used with the faces reinforced with silk fibers. An explanation could be that during the tensile test, first the core broke and all the loading was supported by the silk fiber which had better tensile resistance compared to crushed corn cob and the hybrid resins.

Compression Test

The results obtained from the compression test (force – traverse stroke curves) are presented in Fig. 6. The arithmetic mean values, from all the 15 tested samples for each material type, for the stress results are reported in Table 2.

Table 2. Stress Values Obtained from the Compression Test for Each Material Type

Sample type	C E	C DE50	C DE60	C DE70	C A	C DA50	C DA60	C DA 70
Stress Values (MPa)	23.1	19.8	17.5	10.3	22.2	19.6	17.1	9.5

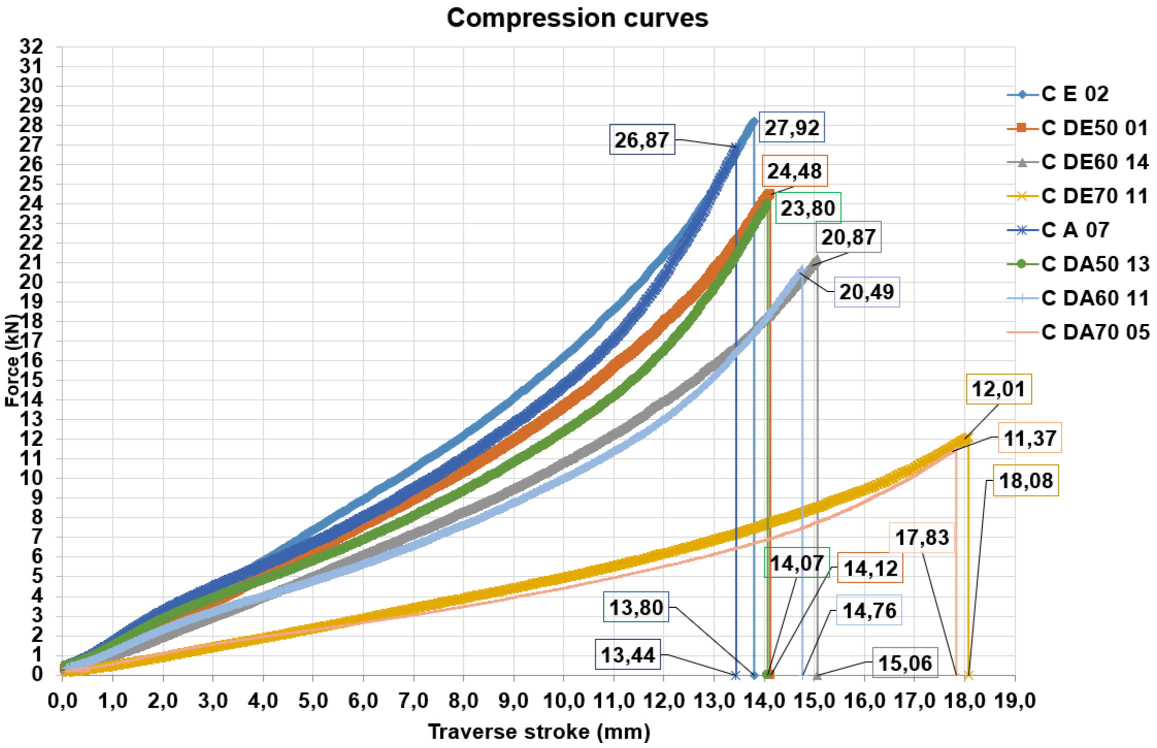


Fig. 6. The force – traverse stroke curves from the compression test, drew for a representative sample from each material type

From Fig. 6 and Table 2, similar tendencies as in the tensile test were observed: the breaking strength at compression decreased and the traverse stroke increased with the increase of dammar percentage. The samples that had epoxy resin in the matrix composition had better mechanical properties compared to the ones that had acrylic resin in the matrix composition. As stated before, this result could be explained by the fact that the epoxy resin increased mechanical properties compared to the acrylic one. From Table 2 it was concluded that the compression breaking strength values decreased with the increase of the dammar percentage. An explanation of this result might be that the natural dammar resin has decreased breaking strength compared to the synthetic resins. Another conclusion could be extracted from Fig. 6: the traverse stroke increased with the dammar percentage. An explanation of this result might be that the natural dammar resin is more elastic than the synthetic resins, and therefore a high percentage of dammar would lead to a ductility increase for the specimens.

Bending Test

The results obtained from the bending test (force-traverse stroke curves) are presented in Fig. 7. The arithmetic mean of bending strength for each sample is reported in Table 3.

From Table 3 and Fig. 7, the next conclusions were extracted: the bending strength was very low, as in the case of the tensile strength; similar tendencies of force – traverse stroke curves were observed as for the compression or tensile test. Similar materials were tested in Patil *et al*. (2023) with hybrid resins from epoxy and dammar/pine/cashew nut shell resins reinforced with bagasse. Low bending strength values were obtained, ranging between 2.5 and 5 MPa, but a little increased compared to the ones obtained in this study. In Hemnath *et al*. (2021) composite materials with polyester resin and reinforced with a rice husk and sugarcane bagasse were tested for bending, and values between 1.6 and 2.6 MPa were obtained, lower than those from the present study.

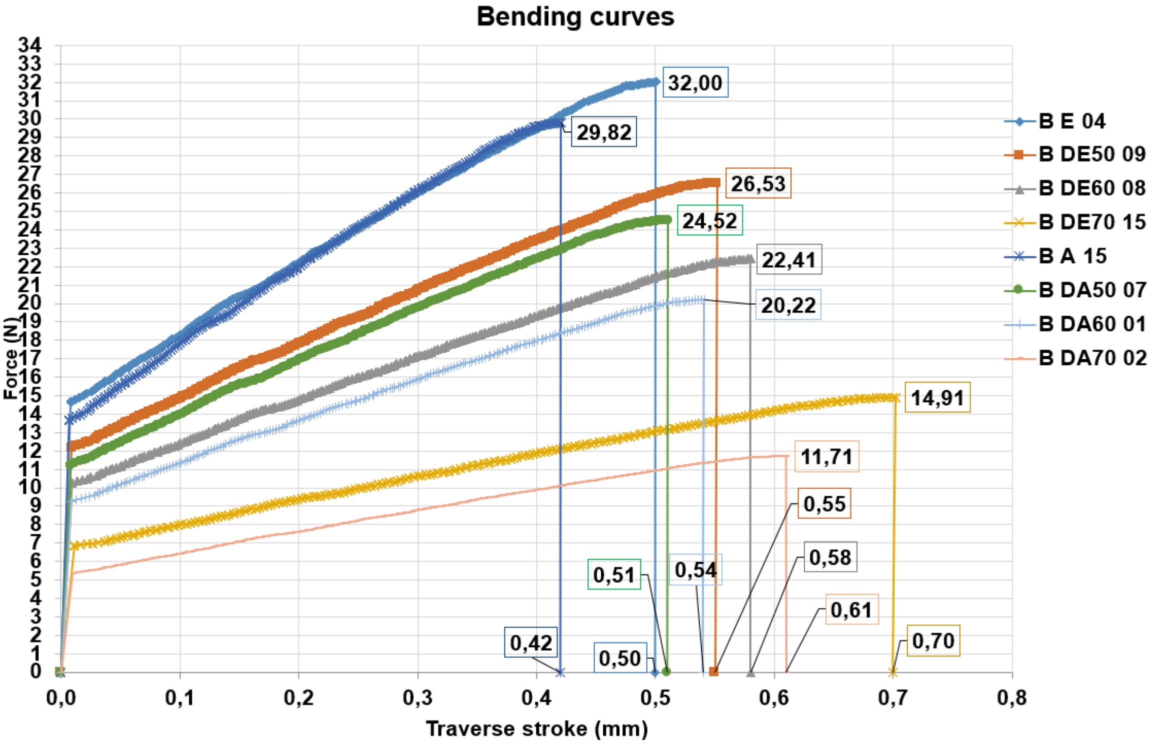


Fig. 7. Force – traverse stroke curves from the bending test, drew for a representative sample from each material type

In order to remove the disadvantage of low mechanical properties, sandwich samples with the side faces from silk, core from crushed corn cob and the matrices from the hybrid resins were manufactured and tested. The results obtained from the bending test (force – traverse stroke curves) are presented in Fig. 8. The arithmetic mean of bending strength for each sample is reported in Table 4.

Table 3. Bending Strength Obtained for Each Material Type

Sample type	B E	B DE50	B DE60	B DE70	B A	B DA50	B DA60	B DA 70
Bending strength (MPa)	3	2.5	2.1	1.4	2.8	2.3	1.9	1.1

Table 4. Bending Strength Obtained for Each Material Type

Sample type	B DE50S	B DE60S	B DE70S	B DA50S	B DA60S	B DA 70S
Bending strength (MPa)	26.03	24.8	19.72	24.88	23.1	18.5

From the results in Table 3, Table 4, Fig. 7, and Fig. 8, it was apparent that, by adding silk fibers faces, an increase of bending strength between 767% and 1536%, an increase of maximum force between 1310 and 2768%, and an increase of traverse stroke between 447 and 479% were obtained.

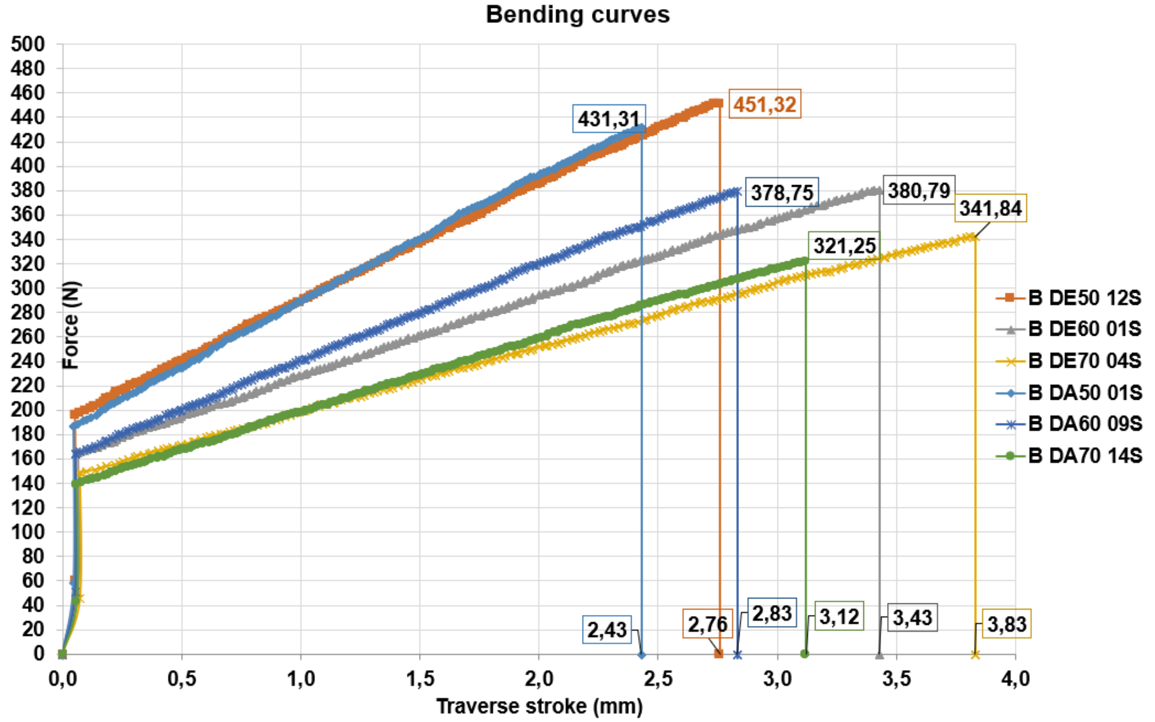


Fig. 8. Force – traverse stroke curves from the bending test, drew for a representative sample from each sandwich sample type

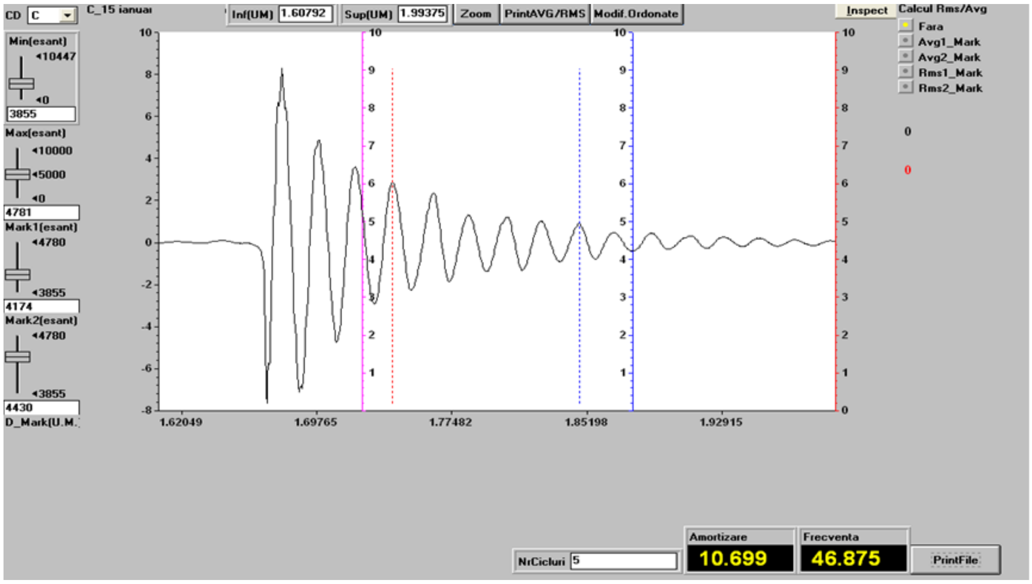
Vibration Test

For the vibration analysis, the specimens were fixed at one end with a jaw vise on a big table. Each sample had the next free lengths: 100, 120, 140, 160, and 180 mm. The logarithmic decrement method was used to determine the system damping. The calculation of the damping factor was made by using the Eq. 1 (Stănescu and Bolcu 2019).

$$\mu = \frac{1}{t_2 - t_1} \cdot ln \frac{v_2}{v_1} \tag{1}$$

In Eq. 1, the t_1 and t_2 parameters were the time values for two peaks from the amplitude diagram and the v_1 and v_2 were the peak amplitudes at t_1 and t_2 time values. The damping factor and natural frequency results for the vibrations of the TA sample is presented in Fig. 9.

The results obtained from the vibration test (damping factor versus free length and natural frequency versus free length) are presented in Figs. 10 and 11. From Figs. 10 and 11 it can be seen that both the natural frequency and the damping factor decreased with the increasing of the sample’s free length.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Sup(UM) 1.99375
Min(esant) 3855
Max(esant) 4781
Mark1(esant) 4174
Mark2(esant) 4430
NrCicluri 5
Amortizare 10.699
Frecventa 46.875

Fig. 9. The vibration recording (damping factor and natural frequency) for the specimen TA with a free length of 160 mm

The differences between the natural frequency values of the samples can be explained by the differences in the elastic modulus values of the materials used. It can be seen that the samples made of acrylic resin (TA) or hybrid resin with acrylic part (T DA50, T DA60 and T DA70) had decreased natural frequency and damping factor compared to the samples that are made of epoxy resin or hybrid resin with epoxy part. This result can be explained by the fact that the acrylic resin has decreased mechanical properties compared to the epoxy. This tendency can also be seen from the tensile test, where the samples with epoxy resin or with hybrid and epoxy part exhibited increased breaking strength and elongation at break compared with the acrylic ones.

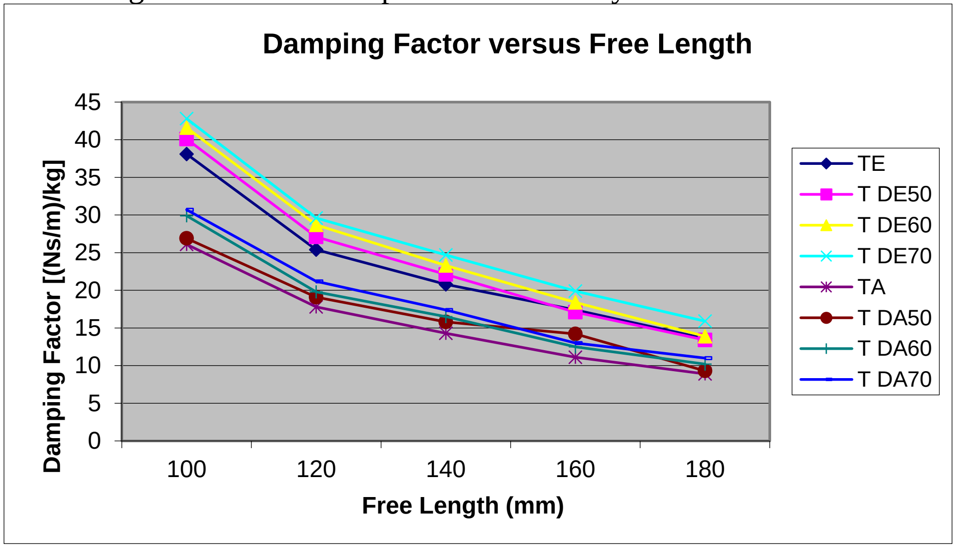

Fig. 10. The results obtained from the vibration test for the damping factor

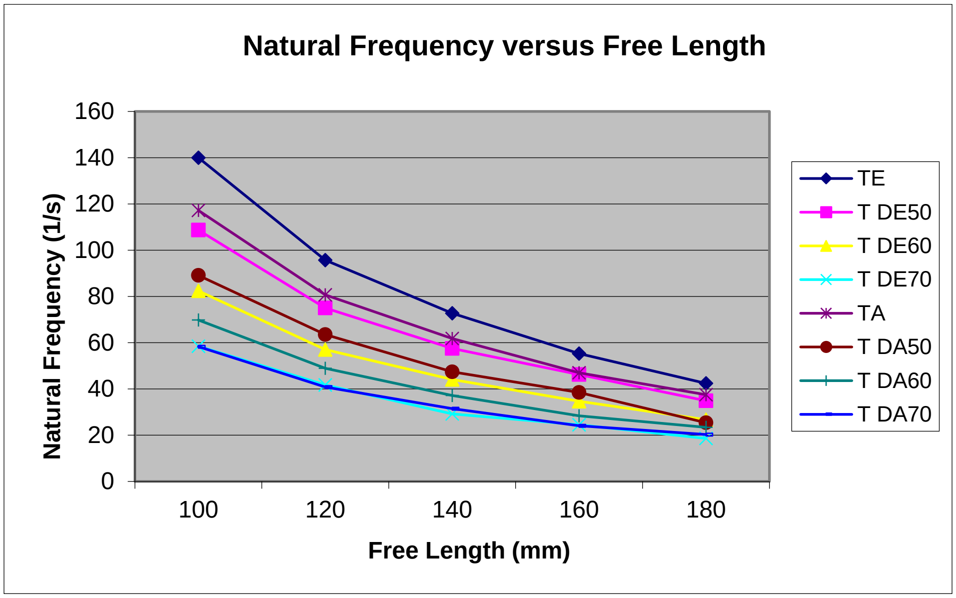

Fig. 11. The results obtained from the vibration test for the natural frequency

Like in the previous sections, sandwich samples reinforced with silk were tested for free vibrations with the same free lengths: 100, 120, 140, 160, and 180 mm. The damping factor and natural frequency calculus for the T DA60 S sample was presented in Fig. 12. The results obtained from the vibration test (damping factor versus free length and natural frequency versus free length) are presented in Figs. 13 and 14.

From the vibration results (Figs. 13 and 14) it was apparent that by adding silk layers, the samples frequency increased with a slight decrease of the damping factor. This can be explained by the fact that the silk fibers have increased elastic modulus compared to the samples that are reinforced only with crushed corn cob which also increased the samples stiffness.

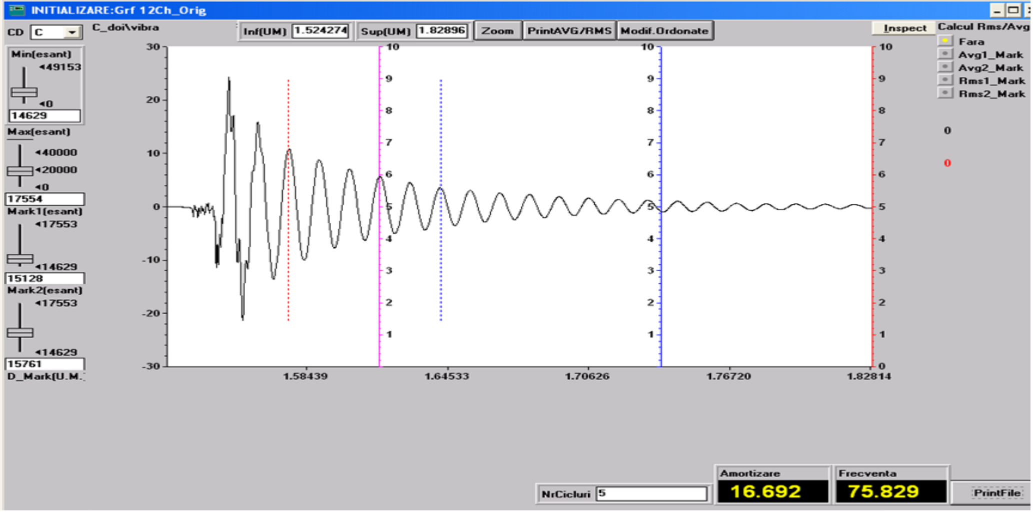
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Fig. 12. The vibration recording (damping factor and natural frequency) for the specimen T DA60 S with a free length of 140 mm

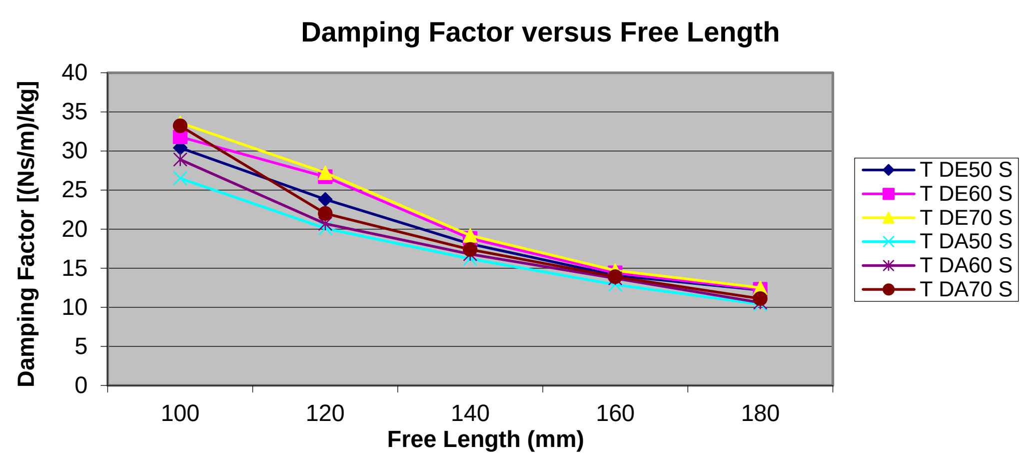

Fig. 13. The results obtained from the vibration test for the damping factor of the samples reinforced with silk fibers

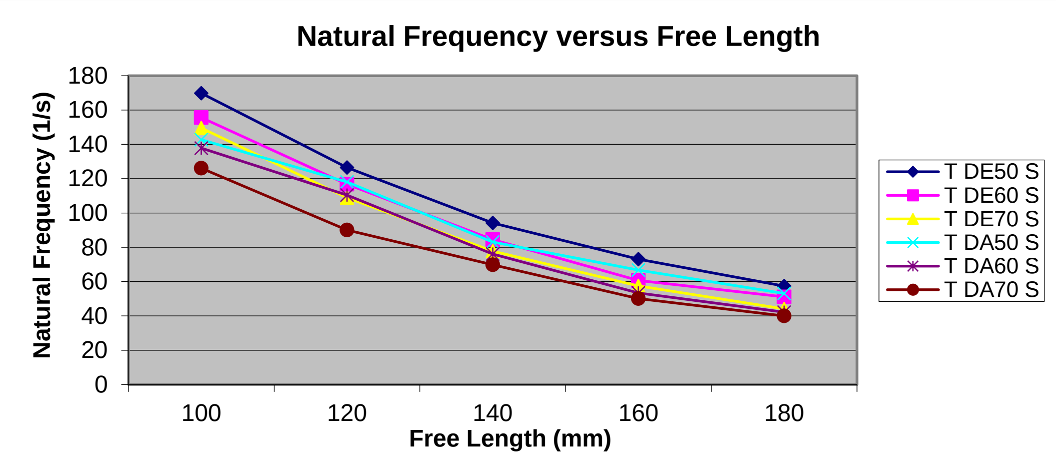

Fig. 14. The results obtained from the vibration test for the natural frequency of the samples reinforced with silk fibers

Shore D Hardness Test

All the Shore D hardness values are presented in Fig. 15.

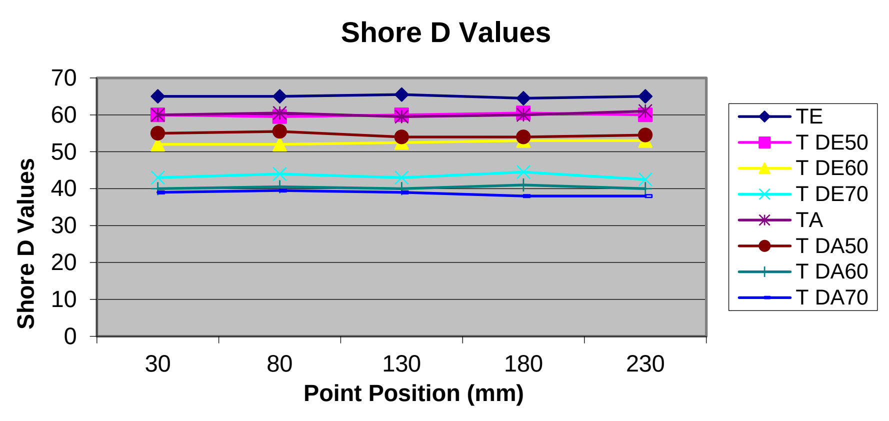

Fig. 15. Experimental results for Shore D hardness values

From the results in Fig. 15, the Shore D values decreased with the increase of dammar percentage. This result can be explained by the fact that the dammar resin increased the samples' elasticity. From Fig. 15 it was also apparent that the samples that had epoxy resin in the matrix had increased Shore D hardness compared to those that had acrylic resin. This result could be explained by the fact that the epoxy resin has increased mechanical properties compared to the acrylic one; a similar conclusion was observed also from the tensile (Fig. 4) and vibrations tests (Fig. 10 and Fig. 11).

Water Absorption Results

All the experimental results for water absorption are presented in Fig. 16.

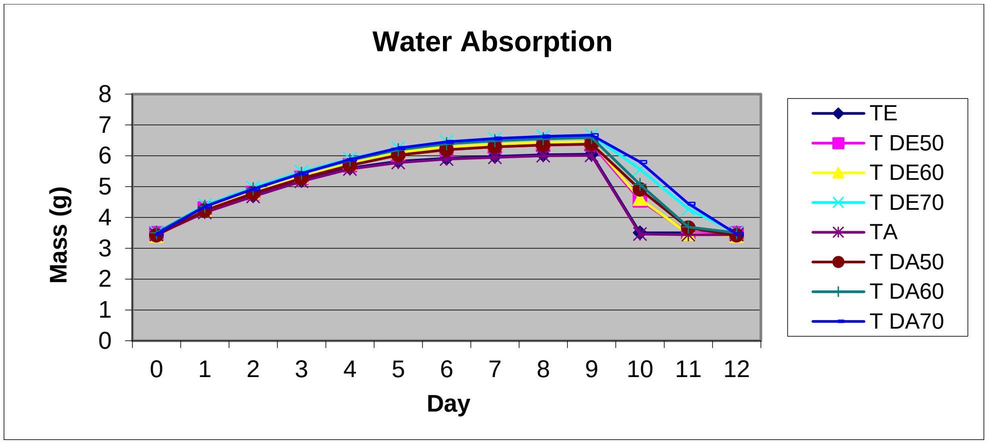

Fig. 16. The experimental results for the water absorption

Figure 16 shows that the samples absorbed water daily at an almost constant rate. The water absorption occurred due to crushed corn cob since all the matrix components (synthetic and hybrid ones) were not soluble in water. It is known that the crushed corn cob is composed of cellulose, hemicellulose, and lignin (see Tsai *et al*. 2001). Cellulose and hemicellulose are highly hydrophilic components when exposed to water implying a mass increase of the composite immersed in water (see Adhikary *et al*. 2008).

CONCLUSIONS

1. Crushed corn cob can be used as a reinforcement to build composite materials. Such composites exhibited higher compression strength performance in comparison to tensile strength performance. In this respect, the composites with corn cob reinforcement showed similarity in performance to unreinforced concrete.
2. If silk fabric is used as a reinforcement for the faces of sandwich materials with a core made of crushed corn cob, all the mechanical properties obtained from destructive tests can be expected to be increased by a few hundred percent up to a few thousand percent, compared to the samples that are only reinforced with crushed corn cob.
3. Hybrid resins based on the natural dammar resins can be used in combination with crushed corn cob or silk fiber, to build composite materials.

4. If hybrid resins are used as matrix for composites, then the tensile, compression and bending strengths will decrease while the elongation at break and traverse stroke will increase.
5. Increasing the dammar percentage in samples leads to a Shore D hardness and natural frequency decrease because the dammar resin is less rigid compared to the synthetic ones.
6. Water absorption occurred due to crushed corn cob's hydrophilic nature, because it has cellulose and hemicellulose in its structure.

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