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Characterization of beet-pulp fiber reinforced potato starch biopolymer composites for building applications

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Highlights

This study shows the mechanical performance of the beet pulp composite materials.

The binding strength of the beet pulp composite depends on the material density.

The beet pulp composite shows a good thermal and acoustical properties.

The beet pulp material is classified as an excellent hygric regulator.

Keywords: Sugar beet pulp, Potato starch, Building insulation, Bio-sourced composite, Hygrothermal properties, Mechanical properties, Sound absorption, Porosity Moisture buffering value.

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Abstract:

This work deals with the making of a new renewable green material for building insulation from sugar beet pulp and potato starch. The material is both lightweight and ecofriendly. The influence of starch/ extruded sugar beet pulp mass ratio (S/EBP) is studied. Four mass ratios are considered, 10, 20, 30 and 40% (relative to the starch). Samples are characterized in terms of absolute and bulk density, sound absorption coefficient, compressive and flexural strength, as well as and hygrothermal properties (the moisture buffering value and thermal conductivity). The sound absorption coefficient shows that this material is a good sound absorber, especially in medium and high frequencies. The sound absorption capacity depends on the fiber content and the humidity content. The best values are between 0.6 and 0.8. The compressive strength increases linearly with the S/EBP weight ratio to reach 0.52 MPa and the compressive strain is 30%. The elasticity modulus and the Poisson's ratios were also studied. The transversal and vertical strain were measured using ARAMIS optical system. The moisture buffering value was measured according to Nordtest Protocol. The recorded moisture buffering value was between 2.6 and 2.8 g/(%RH.m²) and shows that the sugar beet pulp-starch composite is an excellent hygric regulator. The thermal conductivity is to around 0.070 W/(mK). The results obtained shows that increasing starch amount tends to decrease composite porosity but increases thermal conductivity and mechanical properties. Depending on the starch content, beet pulp composites have a good thermal and acoustical performance and can be used as building materials.

1. Introduction

Energy consumption is rapidly increasing in the world. It doubled in the period 1970–2000, and according to some studies it might double again in 2020. The building sector in Europe is responsible for 25% of the total energy consumption and 11% of all greenhouse gas emissions. In this context, developing innovative building material from locally available renewable resources is of primary importance. It allows to upgrade the energy characteristics of buildings and induce changes in energy consuming behavior [1].

Several studies have already been published on the use of crop by-products for building applications. Boussetoua et al. [2] studied the elaboration and the characterization of a cork-cement composite. The results show that increasing the amount of cork granule increases the moisture buffering value but decreases the thermal conductivity and mechanical properties. In addition, Bourdot et al. [3] and Umurigirwa et al. [4] studied the characterization of hempstarch composite.

The results show that hemp-starch is an excellent hygric regulator, and that increasing hemp content tends to increase the moisture buffering value and decreases slightly the mechanical properties. However, Le et al [5] deduced that the mechanical properties depends strongly on the hemp/starch ratio and the hemp shives sizes. Furthermore [6], worked on the development of hemp-clay composite. The measurement of moisture buffering value ($MBV = 2.68 \text{ g}/(\text{m}\cdot\%RH)$) shows that hemp-clay material is an excellent hygric regulator.

Sugar beet (*Beta vulgaris* var. *saccharifera*) is widely grown in France (44 million tons in 2017). The process of producing beet sugar generates enormous quantities of by-products [7]. One of these by-products is sugar beet pulp. In the factory, clean beets emerge from the washhouse and fall into the root cutter, where knives, driven by a large diameter disk, cut the roots into thin, rigid strips called *Cossettes*. After extraction of the sugar from the *Cossettes*, the remaining pulps shreds are generally pressed to 20–30% dry matter called Fresh pulp [7]. The sugar beet pulp is then mechanically compressed and extruded at elevated temperature to produce the extruded sugar beet pulp pellet (EBPP) (Fig. 1a).

EBPP is recognized as an excellent feed for livestock due to its high nutritional value and palatability [8]. In recent years, beet pulp has become an important source of gelling pectin. The pectin is extracted from the pulp of the sugar beet from various extraction procedures [9–11], and used in food and cosmetics industries. It has also been used as a bioadsorbent for the removal of heavy metals [12].



Fig.1 (a)- Extruded beet pulp pellet (EBPP), (b)-Beet pulp (EBP). Fig. 1. (a)- Extruded beet pulp pellet (EBPP), (b)-Beet pulp (EBP).

The extruded pulps are composed mainly of pectin, cellulose and hemicellulose. The different EBP components are shown in Fig. 2.

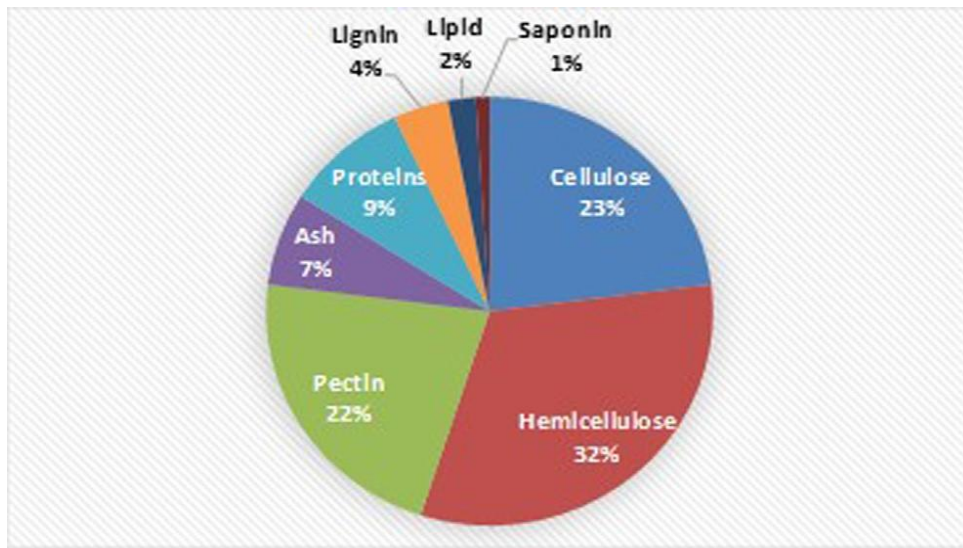


Fig. 2. The components of the extruded sugar beet pulp [19].

One study has already been published on beet pulp based concrete using cement as a binder. In this study, authors present various chemical and physical treatments carried out on EBP to modify its properties, one treatment using cement in association with linseed oil showed the best results in reducing the potential of pulps to absorb enormous quantities of water and swell [13].

Starch is the main carbohydrate reserve of higher plants. It represents a significant weight fraction in many agricultural raw materials such as cereals (30–70%), tubers (60–90%) and legumes (25–50%). Starch is composed of two polymers with a different primary structure: Amylose, (linear), and amylopectin (branched)

[14].

Starch is already widely used in many industrial sectors, mainly paper, textile and also food via the beverage, confectionery and baked goods industries. The chemical industry uses starch in fermentation processes to produce bioethanol, surface treatment products, formulation of adhesives, encapsulation of pharmaceutical products, cosmetics, and biodegradable plastics [15]. Starch was used to elaborate an agro-material for building applications such as starch-hemp composite, starch-date palm fiber and Cassava/sugar palm fiber reinforced cassava starch [3,16–18].

Based on the above-mentioned literature review, the present work describes the elaboration of a new agro-composite based on sugar beet pulp and potato starch as a bio-sourced binder. Physical mechanical and hygrothermal characteristics are measured with different compositions designed to be used in the building sector for walls and floor insulation applications.

2. Materials and methods

2.1. *Materials*

2.1.1. Extruded beet pulp

Due to the fast biodegradability of fresh pulp-dried extruded beet pulp (EBP) was used in this study exclusively. The 8–10 mm diameter extruded beet pulp pellets EBPP (18% humidity) (Fig. 1a) were provided by Cristal Union factory (Pomacle, France). Before the use of EBP, they were immersed in water until their saturation. Then, EBP were dried at 50 C (Fig. 1b). To ensure proper conservation in the lab the pulps were kept at 20 C until use.

2.1.2. Potato starch

Potato starch was purchased from ROQUETTE, Lestrem, France.

Potato starch has a high polymerization degree which gives a viscous binder and provides a good mechanical property for the EBP – starch formulas.

2.2. Beet pulp characterization

The properties of the elaborated composites were conditioned by the EBP morphology and their adhesion with the binder within the matrix. This morphology was studied by a microscopic analysis and image analysis software.

2.2.1. Microscopic analysis

A KEYENCE microscope was used to analyze the pulp particles at microscopic level. The microscope was equipped with a camera that allowed to capture of microscopic photos with a very high depth of field (x50).

2.2.2. Image analysis

The computer analysis program (ImageJ, National Institutes of Health) was used to process and analyze plain EBP macroscopic images. The geometrical characteristics of individual centimeter size pulp chunks and model regular geometrical shapes such as rectangle and ellipse were determined. The experiments were spread out. More than 2000 particles were dispersed in such a way that they did not touch each other. The resulting images were processed and analyzed using the *ImageJ* software.

2.2.3. EBP granulometric analysis

The pulp was sieved using a vibrating sieve (Controlab) to analyze the particle size distribution. The sizes of sieves were between 0.125 mm and 8 mm. After the sieving process, the aggregates retained in each sieve were weighed and the cumulative masses were then calculated with their mass percentages. The granulometric curve was obtained by representing the cumulative mass percentages on the ordinate as a function of sieve size in logarithmic scale.

2.2.4. Porosity

The porosity is an essential characteristic for evaluating insulation properties. To evaluate the porosity of the EBP composite, the bulk density was measured using the Eq. (1):

$$\rho_{\text{bulk}} = (\text{mass of the sample}) / (\text{volume of the container}) \quad (1)$$

The method used for the measurement of absolute density was the one already described by Bourdot et al. [3]. In summary, the pycnometer was filled with a given mass of crushed sample and half its volume with cyclohexane, which is a non-polar solvent and does not affect EBP composition and mass (M). The system

was kept under reflux (see Fig. 3) for 6 x 10 min. boiling then cooling cycles, during which air was released from the pulps voids and replaced by cyclohexane. During the 6th cycle the system is kept under Argon atmosphere to avoid humidity from being reabsorbed in EBP. At ambient temperature (20°C) the flask was filled up to the top and sealed with a dedicated glass top, allowing the excess solvent to overflow and avoiding the retention of bubbles, in order to have a constant volume inside the measuring system. The system was then weighed to a 10⁻³ g accuracy. The absolute density was calculated according to this formula (2):

$$\rho_{\text{abs}} = (M1 \times \rho_{\text{cyc}}) / (M1 - (M2 - M3)) \quad (2)$$

where ρ_{abs} is the absolute density, ρ_{cyc} the density of cyclohexane, M1 the mass of dried sample, M2 the mass of the pycnometer containing a cyclohexane and the dried sample, and M3 the mass of the pycnometer containing only the cyclohexane. Care was taken to avoid the reflux of condensed humidity back in the mixture.

Each measurement was carried out at least three times to be representative. The porosity was calculated using the following Eq. (3):

$$\Phi = 1 - (\rho_{\text{bulk}} / \rho_{\text{abs}}) \quad (3)$$

where Φ is the porosity of composite, ρ_{bulk} the bulk density in kg/m³ and ρ_{abs} the absolute density in kg/m³.

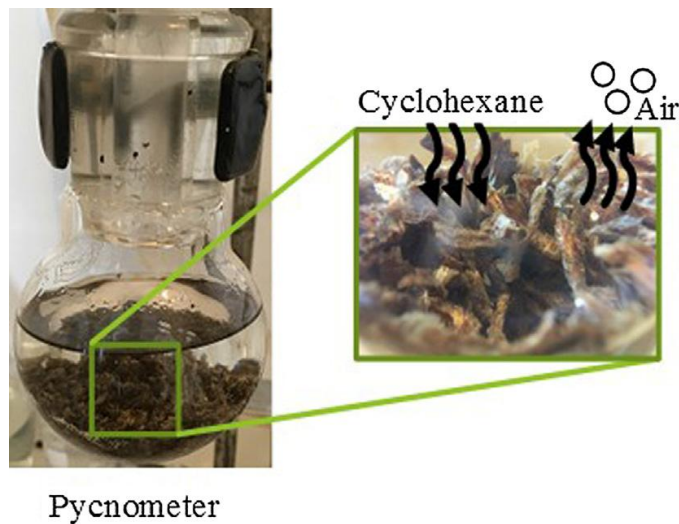


Fig. 3. The system of absolute density measurement.

2.3. Composite characterization

2.3.1. Composite preparation

The EBP pellets were immersed to swell in distilled water until saturation (350%). The wet pulp was mixed with the appropriate amount of dry potato starch powder. The obtained mixture was then placed in an autoclave and heated for 30 min to jellify the starch granules. The obtained formulas were poured into the wooden molds.

The molds were used with a fitted wood piston on the upper part to compact the mix and provide a flat surface on each side. To keep the compaction level steady during drying the piston was kept in a custom-made clamp system consisting of two long screws holding two pieces of wood pressing onto the piston. A layer of 5 mm thick cardboard was placed between the piston and the mixture to help the water vapor released to diffuse from the sample (see Fig. 4).



Fig. 4. Presentation of wooden molds and piston used.

The filled-up molds were then frozen at -80°C and the obtained frozen discs were dried using a Freeze dryer under a pressure of 2 mbar. Different drying methods were carried out and several molds were constructed in such a way to accelerate the permeation of the moisture from the sample during the drying process by drilling a series of 1 mm bit holes spaced at 1 cm from each other.

Four compositions were prepared with four EBP- starch mass ratio S/EBP 0.1, 0.2, 0.3 and 0.4. The samples were compacted under a pressure of 44 kPa.

2.3.2. Sound absorption coefficient

The sound absorption coefficient is defined as the ratio of the sound energy absorbed by a composite to the sound energy incident upon its surface.

Sound absorption coefficient was measured by BandK Type 4206 impedance tube with two microphones according to the standard ISO (10534-2) procedure. Acoustic samples were fixed in the impedance tube with two different diameters 2.9 and 9.9 cm (see Fig. 5).



Fig. 5. Kundt tube.

The samples were prepared previously and equilibrated at ambient conditions. The acoustic parameter of 9.9 cm diameter cylindrical samples was measured in the 50 Hz–1.6 kHz frequency range, whereas the samples with a 2.9 cm diameter were measured in the 500 Hz–6.4 kHz frequency range. The device determines the sound absorption coefficient by measuring the pressure at two fixed points caused by a stationary random sound propagating as plane wave in the tube.

The sound absorption coefficient was measured in the frequency range from 50 Hz to 6.4 kHz. Three 9.9 cm diameter and 4 cm thick samples and three 2.9 cm diameter and 4 cm thick samples were tested for each formula.

2.3.3. Mechanical properties

2.3.3.1. Experimental procedure.

For this test, a series of samples (12 samples $10 \times 10 \times 10$ cm and 12 samples $16 \times 4 \times 4$ cm) were prepared by varying the Starch/Beet pulp (S/EBP) ratio (S/EBP = 0.1, 0.2, 0.3 and 0.4). The samples were made by the procedure in the paragraph 2.3.1.

Compression test and bending test in four-point (see Fig. 6) were recorded by using Instron 8801 machine with a constant rate of 0.1 mm/s for the bending test and 0.2 mm/s for the compression test. Compression and bending test were performed in the pressure direction.

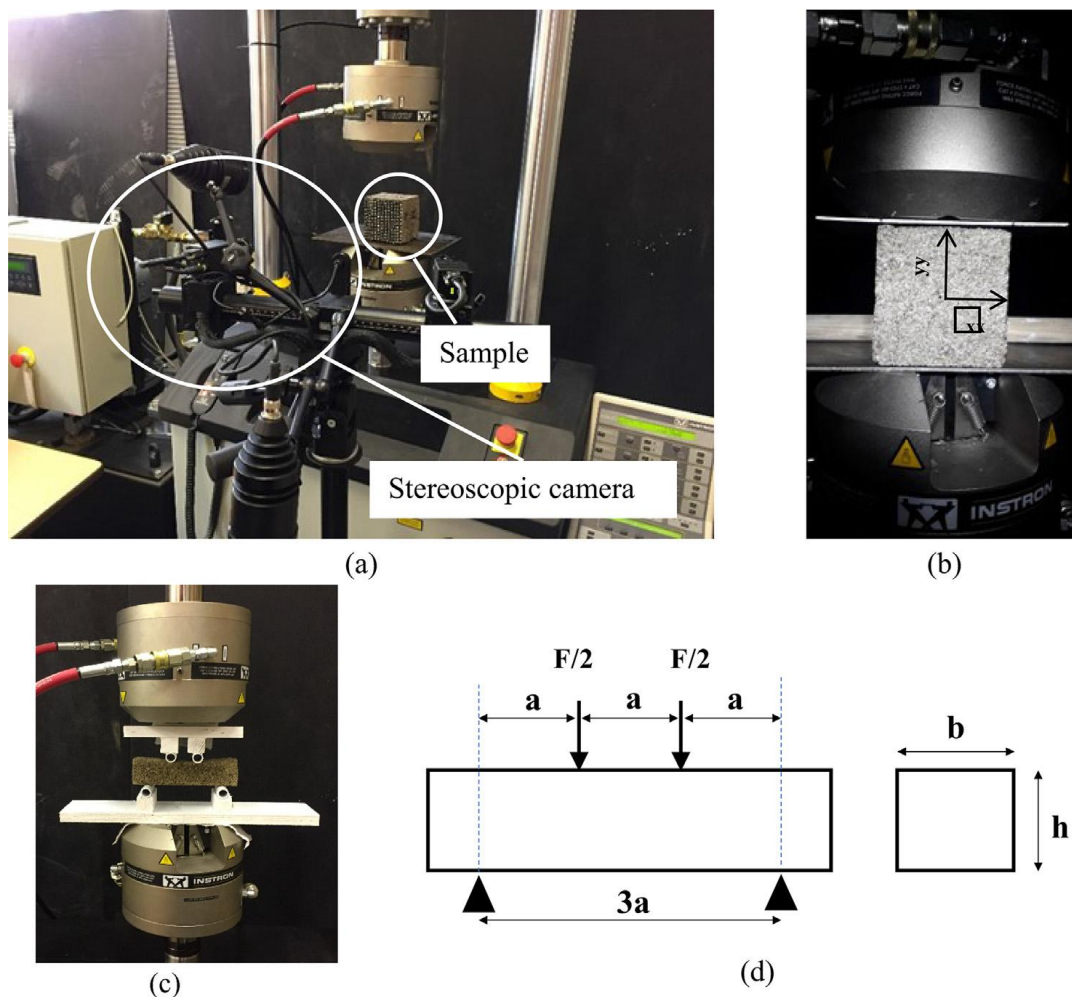


Fig. 6. (a) Aramis stereo optical system, (b) Compressive test, (c) and (d) Bending test.

The tensile strength was determined by using the Navier Eq. (4):

$$\sigma_t = (M_f \times y) / I \quad \text{Navier equation(4)}$$

with $M_f = (F/2) a$, F : the maximum load, $y = h/2$, h : the sample height, I : the sample inertia $I = b \times h^3/12$, a and b are shown in the Fig. 6d.

The transversal and longitudinal strain respectively (ϵ_{xx} , ϵ_{yy}) were determined using an Aramis optical system (see Fig. 6a). This system is a high performance optical system which determines both sample displacement and strain during loading through digital image correlation methods [5,3]. The elasticity modulus (E) and Poisson's ratio (ν) were calculated using the Eqs. (5) and (6) where σ_c is the compressive strength, ϵ_{yy} is the longitudinal strain and ϵ_{xx} is the transversal strain.

$$E = \sigma_c / \epsilon_{yy} \quad (5)$$

$$\nu = \epsilon_{xx} / \epsilon_{yy} \quad (6)$$

ARAMIS stereo cameras were rigidly connected to measure the displacement fields and the 2D deformations from one pair of images corresponding to several instants of strain of samples. Before measuring, all the samples were placed at the same distance to the camera (34 cm) to obtain a sharpness image.

2.3.4. Moisture buffering value (MBV)

The Moisture Buffering Value [20] measures the capacity of the composite to regulate the relative humidity of the medium [21,3,2,6]. The Nordtest protocol defines cyclic step-changes in relative humidity after stabilization, between high (75%) and low (33%) values for 8 and 16 h, respectively.

Four 9.8 cm diameter and 4 cm thick cylindrical samples were tested for each formula. The edges and the back-sides of samples were sealed with duct tape to obtain a one-dimensional moisture flow. Samples were dried at 50°C and 10% R in a climatic chamber and then stabilized at 23°C and 50% RH. They were weighted until they reached equilibrium (see Fig. 7). During the periodic exposure, samples

were weighted five times during the adsorption phase and twice during desorption. The velocity is given by the climatic chamber manufacturer and it is about 0.5 m/s. When the mass variations between three consecutive days were under 5%, the experiment was stopped and the moisture buffering value (MBV) was calculated according to the Eq. (7):

$$MBV = \Delta m / (A \times (RH_{high} - RH_{low})) \quad (7)$$

A (m²) is the area of the sample that is in contact with air. The RH_{high} and RH_{low} respectively represent high relative humidity (75% RH) and low relative humidity (33% RH) and Δm represents the change in mass during the absorption/desorption phase (g).



Fig. 7. The MBV samples in climatic room.

2.3.5. Thermal conductivity

A series of cubic samples (10 x 10 x 10 cm) were made to study the thermal behavior of the starch-Beet Pulp composite. Before the measurement, all samples were dried in a climatic chamber at 50°C and 10% RH. The thermal conductivities were measured using a *Isomet 2114* (Applied Precision) device by which applies a dynamic measurement method to reduce the measurement time in comparison with steady state measurement methods. This measurement analyzes the temperature response of the measured composite to heat flow impulses. The heat flow is produced by an electrical heating of resistor heating in direct contact with the tested sample. The thermal conductivity was evaluated by periodically recording the sampled temperature as function of the time. Built-in menu system on color graphic display and the alphanumeric keypad provides a good utilization of the device. The measurement reproducibility of the device was 3% + 0.001 W/(m·K), the measurement was done at ambient temperature (20°C) and 10 %RH. The thermal conductivity of the Starch-Beet Pulp was measured on three samples for each formula [22].

3. Results and discussion

3.1. Aggregate morphology

The extruded pulps have a cavernous shape and an irregular rough surface, both characteristics provide a good adhesion within the matrix (see Fig. 8).

The air-filled cavities in EBP reduce the thermal conductivity of the elaborated composite. In addition, the resulting bulk density is very low, which results in a lightweight composite with good acoustic and thermal insulation properties.

3.1.1. Image analysis

From a macroscopic point of view, the image software was used to calculate the surfaces and perimeters of each pulp, the lengths and widths of the aggregates (see Figs. 9 and 10), as well as the major and minor axis of the ellipse associated to each particle.

The surface has an average of 7.9 mm^2 , and a perimeter 11.37 mm . The surfaces and the perimeters of the geometric shapes were calculated, as well as the quadratic error of each parameter. The best calculated model for the pulp shape was the rectangular form.

3.1.2. Particle size analysis by sieving

The results presented in Fig. 11, show that the particle size is continuous, that no granulometric fraction is missing. The largest fraction found was between 2 and 4 mm with 62% of the beet particles. The EBP particles have a specific long shape originating from the root cutter knives design, which offers a larger perimeter and good adhesion with the matrix.

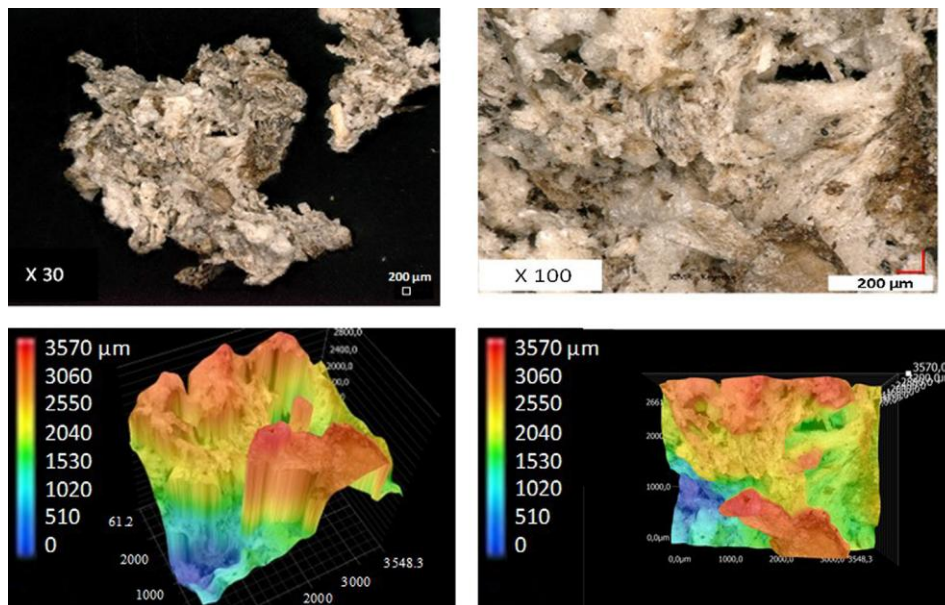


Fig. 8. Microscopic photos of EBP.

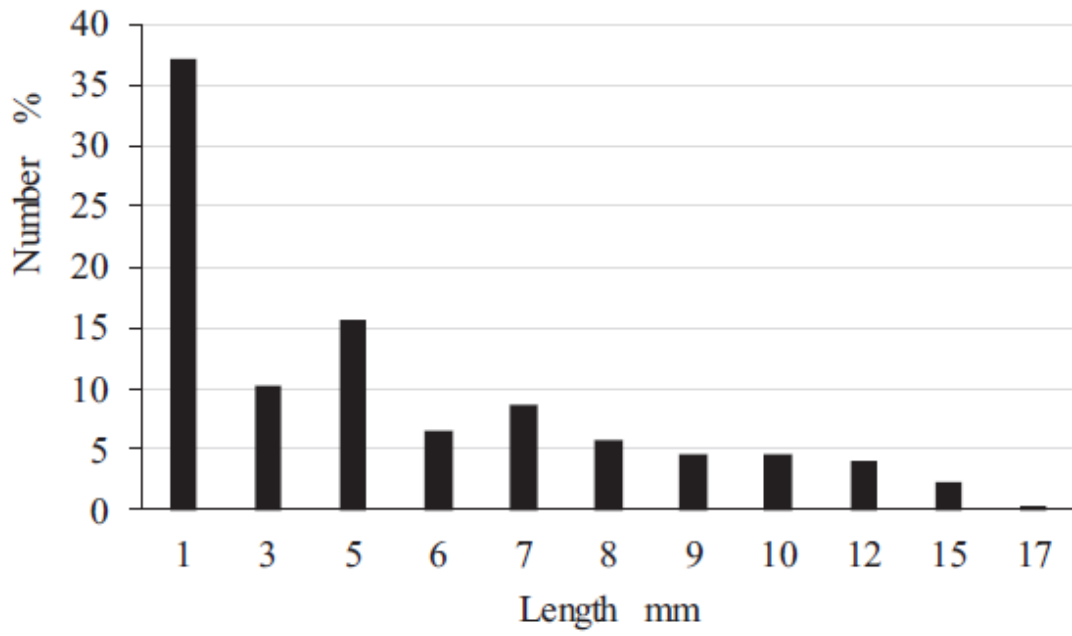


Fig. 9. Length distribution of the pulps.

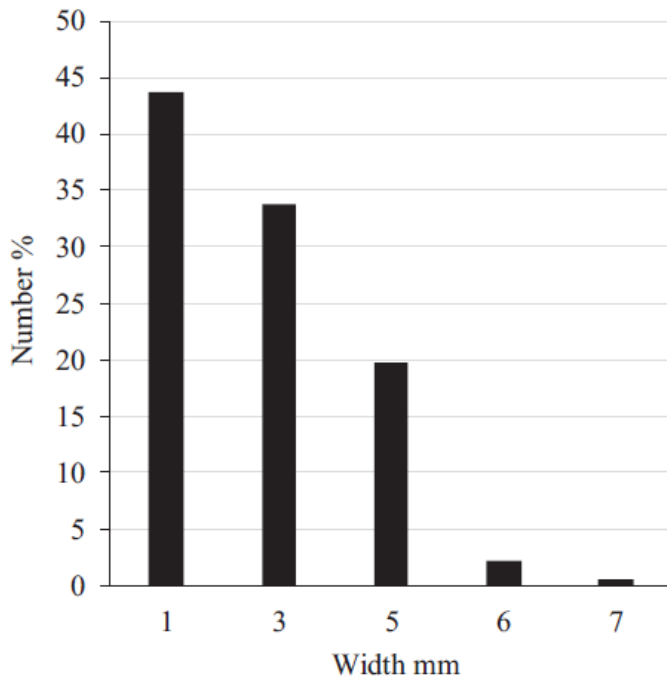


Fig. 10. Width distribution of the pulps.

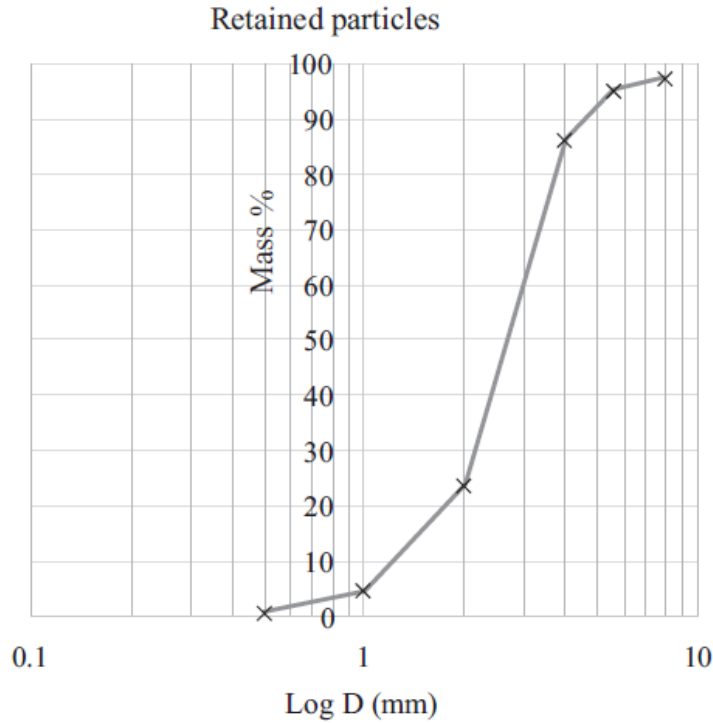


Fig. 11. Curve of retained particle size during sieving.

3.1.3. Density and porosity

The bulk density was measured for EBP before and after extrusion. Table 1 shows the bulk and the absolute density of sugar beet pulp. In both cases the extruded EBP appears denser, probably due to the strong compression during the extrusion process.

Table 1

Bulk and absolute density of different aggregates.

Aggregates	ρ_{bulk} (kg/m ³)	ρ_{abs} (kg/m ³)	Porosity (%)
Fresh beet pulp	134 ± 6.7	911.61 ± 45.6	85.30
Extruded beet pulp	194 ± 7.9	1073.38 ± 53.7	81.93
Hemp shive 5 mm ^(a)	135 ± 6.75	1271 ± 63.5	91.35
Hemp shive 20 mm ^(a)	110 ± 5.5	1266 ± 63.3	89.34

^(a) Bourdot et al. [3].

3.2. Composite analysis

3.2.1. Results of dried samples

During oven drying of the samples, microscopic cracks appear on the composite surface due to extensive shrinkage. As both the beet pulp and starch are highly hydrophilic, water gradients inside and anisotropy of the drying within the composite sample probably cause irregular shrinkage of the composite. Large

dimensional variations were observed after classic oven drying at 100°C, the sample underwent a (33%) irregular retraction, which caused large millimeter size cracks. Drying under vacuum at 40°C resulted in much more regular shapes, the composite retracted, there were no macroscopic cracks observed and the surface was flatter.

When dried under the freeze dryer, the EBP-starch composites release water more regularly, and consequently retract less, which results in rigid and light composite blocks. The blocks present a uniform volume shrinkage (8%). Therefore, freeze drying provided the best results (see Fig. 12).



Fig. 12. Freeze-dried composite blocks.

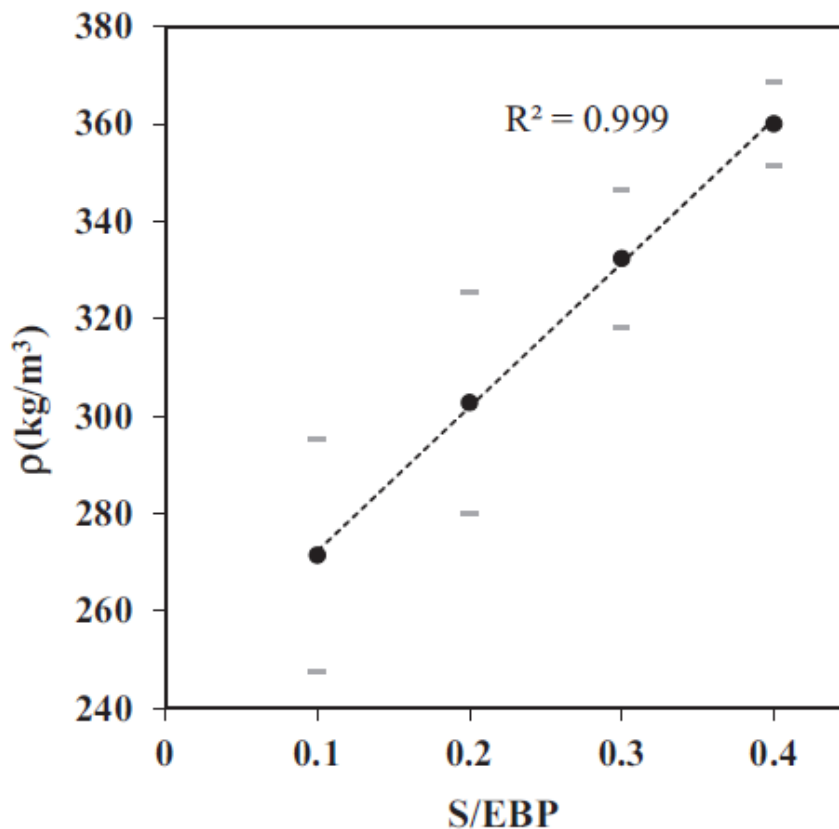


Fig. 13. Density of the composite material with different Starch/pulp ratio.

3.2.2. Density and porosity

Fig. 13 shows the variation in the density of the completely dried composite material in climatic room at 50°C and 10 %RH, as a function of the S/EBP weight ratio. It can be observed that the composite material density increases linearly with S/EBP weight ratio. The bulk density increases from 271.4 kg/m³ to 360 kg/m³, noting that the average density of the Cement- Beet Pulp concrete ranged between 570 kg/m³ and 770 kg/m³ [13].

The bulk density of the samples can be expressed as function as S/EBP weight ratio between 0.1 and 0.4 by the following Eq. (8):

$$\rho = 295.42 \times (S/EBP) + 242.8 \quad (8)$$

Results of density and porosity are shown in Table 2. The absolute and bulk density increase with S/EBP weight ratio. However, the porosity of the composite decreases logarithmically. Therefore, the sample having the lowest amount of starch (S/EBP = 0.1), has the higher porosity (79.75%) and the lowest absolute density ($\rho_{abs} = 1222 \text{ kg/m}^3$). The total porosity was between 70.60% and 79.75% and decreasing the S/EBP weight ratio seems to increase the total porosity. The starch influence is consistent with results obtained by Rahim et al. [23] and Bourdot et al. [3]. The presence of starch gel increases the bulk density and decreases the total porosity by filling the inter-particle space between pulp particles and filling or sealing the pores. Therefore, the composite would contain more or less accessible closed and open pores.

Table 2
The density and the porosity of EBP composite.

S/EBP	ρ_{abs} (kg/m ³)	ρ_{app} (kg/m ³)	Porosity (%)
0.1	1222.18 ± 44.83	271.44 ± 13.19	77.8
0.2	1240.25 ± 52.94	302.77 ± 10.18	75.6
0.3	1284.92 ± 68.87	332.38 ± 13.95	74.1
0.4	1293.42 ± 53.17	360.04 ± 14.32	72.1

3.2.3. Sound absorption coefficient

In this section, the effect of the binder amount in the formula on the sound absorption of the composite material is analyzed. The porosity and the pore size influence the dissipation of the sound waves. The sound absorption of the sugar beet pulp-starch composite depends on the origin of the pulp and the starch/sugar beet pulp mass ratio.

Fig. 14 shows the sound absorption variation as a function of sound frequency and for different S/EBP ratios. The increase of the binder content in the mixture decreased the porosity and increased mass density. Therefore, the sound absorption of the composite material decreased slightly. The sound absorption

curve was also shifted to the lower frequencies. This result is in correlation with Glé study [24].

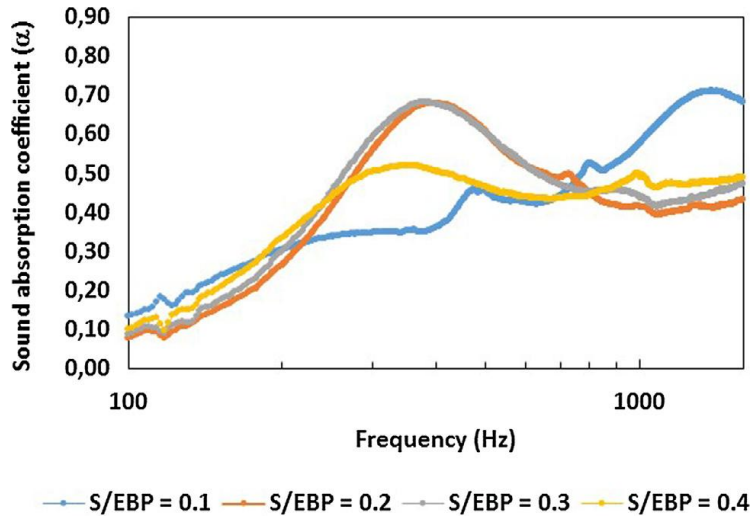


Fig. 14. Sound absorption according to the starch content.

Fig. 15 shows the comparative sound absorption coefficient of a hemp-starch material, two samples manufactured from starch and date palm fiber (F and WF) and four samples from starch-EBP.

At 500 Hz, samples of sugar beet pulp fiber (S/EBP 0.2 and 0.3) and the samples composed of 20% palm fiber and 80% starch solution absorbed 40% of sound waves. Hemp-based material only absorbs 40% of the sound waves at this frequency [18,5].

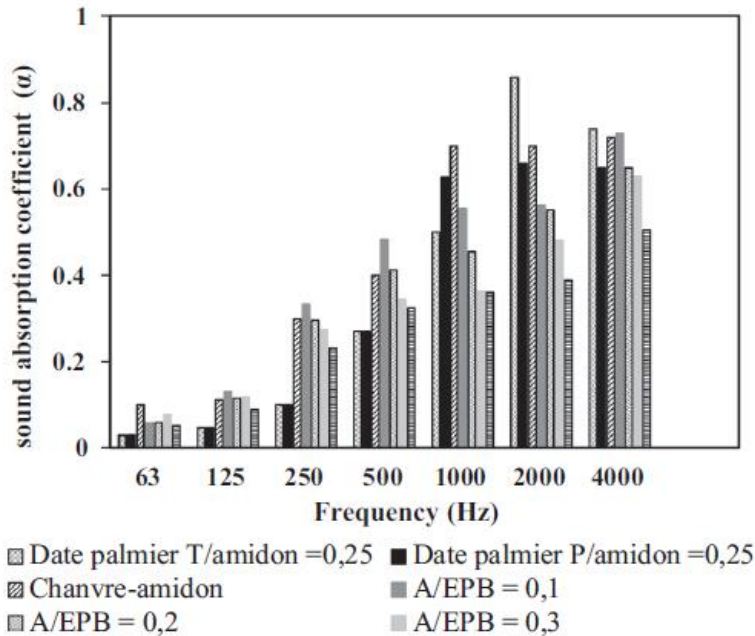


Fig. 15. The sound absorption coefficient of several green materials.

These results show interesting acoustical absorption performances of these materials at high frequencies. At 1000 Hz, the hemp composite absorbs 70%, of the soundwave, whereas the sound absorption of sugar EBP samples (S/EBP = 0.1) is only 55%, and 50% for the (F 20% – St 80%) palm fiber samples. We can observe that when the frequency decreases the sound absorption capacity of the considered samples decreases to very low values.

The superior performance of EBP-based material as compared to date palm composite and hemp-starch material, for medium and low frequencies, is due to the thickness of the samples used by [18] and [5] which was 4 cm; while in the other studies, it was 3 and 3.5 cm thickness.

For frequencies lower than 500 Hz, the starch-EBP showed higher acoustical absorption efficiency as compared to the other composites. It absorbs 60% of sound waves. Increasing the starch mass increases the sound absorption coefficient of sugar beet pulp-starch composite. However, for frequencies higher than 500 Hz, this composite absorbs 50% of sound waves whereas the hemp – starch composite absorbs 70% of the sound waves [18].

Increasing the starch mass decreases the sound absorption coefficient of EBP-starch composites. Therefore, by increasing the starch content in the sugar beet pulp-starch composite to 40% the material becomes denser, the binder fills the EBP pores and consequently the sound absorption coefficient of the composite decreases.

3.2.4. Mechanical properties

All mechanical properties shown in this section: tensile strength, compressive strength, elasticity modulus and Poisson's ratio were measured on four S/EBP weight ratio between 0.1 and 0.4.

The compression test led to the failure of the sample. The compressive strength variation of the aforementioned samples is shown in Fig. 16. At 10% of the strain of the sample for the samples of 10 x 10 x 10 cm with S/EBP = 0.1, 0.2, 0.3 and 0.4, the corresponding stress is 0.20, 0.23, 0.24 and 0.32 MPa respectively. It is useful to indicate that the Starch-beet pulp composite is deformable and compressible. However, the sample can be crushed with load greater than load limit. The compressive strength was obtained for longitudinal strain ϵ between 22% and 27%. The compressive strength of the Starch- Beet Pulp increased from 0.37 MPa to 0.52 MPa. For the starch-hemp composites, the mechanical behavior was also studied [3,5,25,26]. The average compressive strength is ranged between 0.40 and 0.63 MPa [3,5,25]. It can be seen that the compressive strength of the Starch-Beet Pulp is comparable. It seems to indicate that the compressive strength of the Starch-Beet Pulp increases with increasing the starch amount. However, the influence of the variation in the density on the compressive strength of the Starch-Hemp composites is not significant [3,5,25].

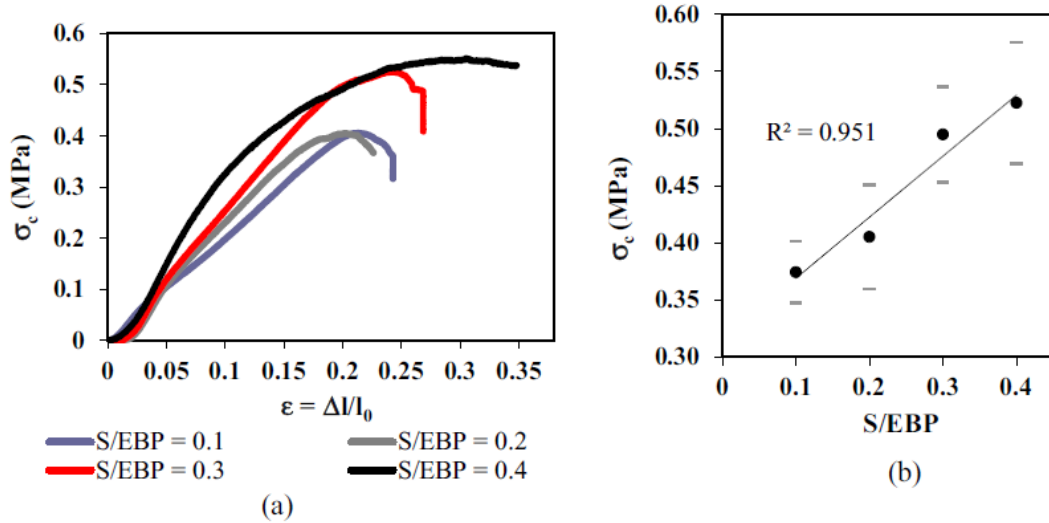


Fig. 16. (a) Compressive strain-stress curves for different S/EBP weight ratios, (b) Compressive strength-S/EBP weight ratio curves.

The typical tensile stress-displacement curves for different S/EBP weight ratio are represented in Fig. 17a. Fig. 17b shows that the tensile strength increases when the starch content increases. The average tensile strength increases from 0.11 MPa to 0.21 MPa.

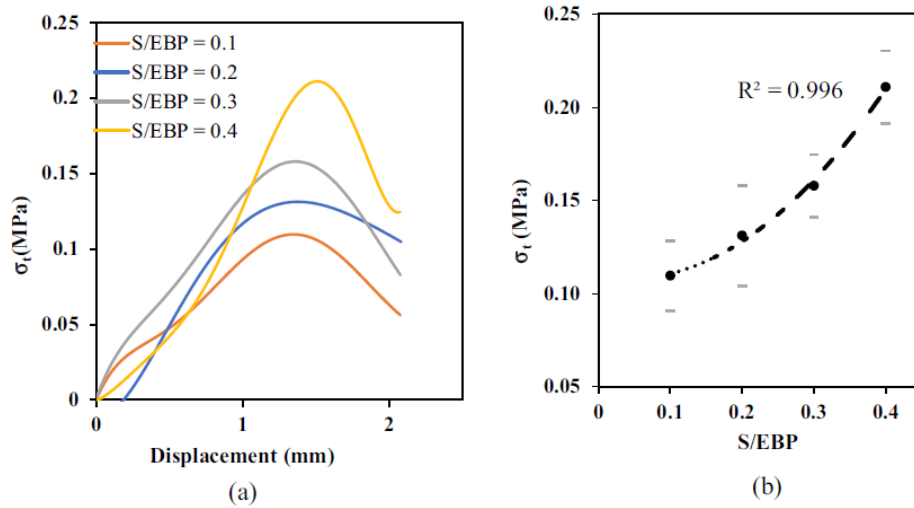


Fig. 17. (a) Tensile stress-displacement curves for different S/EBP weight ratios, (b) Flexural strength-S/EBP weight ratio curves.

These values are greater than those measured on the Starch-Hemp composites 0.08–0.11 MPa [3]. These results are probably due to a better coating of the EBP by the starch binder during manufacturing of the material. The tensile strength of the Starch-Beet Pulp composite (σ_t) can be expressed as function as the S/EBP mass ratio by the Eq. (9).

$$\sigma_t = 0.79 \times (S/EBP)^2 - 0.06 \times (S/EBP) + 0.11 \quad (9)$$

Fig. 18a shows the elasticity modulus curve measured by compression test. The average elasticity modulus of the Starch-Beet Pulp is ranged between 2.06 MPa and 3.17 MPa.

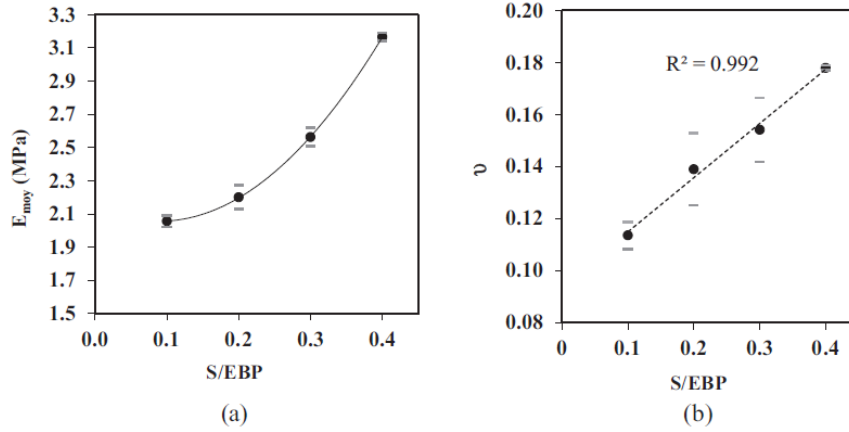


Fig. 18. (a) Elasticity modulus, (b) Poisson's ratio.

It can be seen that the elasticity modulus increases when the S/EBP mass ratio increases from 0.1 to 0.4. The average elasticity modulus of the Starch-Hemp composites varies between 1.63 and 2.04 MPa. The Starch-Beet Pulp composites have an elasticity greater than those of Starch-Hemp composites. That is can be explained by the fact that the Beet Pulp being finer, the Beet Pulps are coated by the binder during the manufacturing [5,25]. The elasticity Modulus E can be expressed as function as S/EBP mass ratio in the Eq. (10).

$$E = 11.5 \times (S/EBP)^2 - 2.06 \times (S/EBP) + 2.15 \quad (10)$$

The average Poisson's ratio of the studied samples is shown in Fig. 18b. The results show that the Poisson's ratio increases linearly with S/EBP weight ratio from 0.11 to 0.18. This can be partially explained by the decrease of the composite porosity. Increasing the starch amount will fill the pores and decreases the porosity of the composite material, consequently the Poisson's ratio increases. The average measured Poisson's ratios are comparable with those of Starch-Hemp composites [3,5,25]. The relation between the Poisson's ratio and S/EBP weight ratio is linear and can be represented by the Eq. (11).

$$\nu = 0.21 \times (S/EBP) + 0.09 \quad (11)$$

The Aramis method used gives the distribution of longitudinal and transversal strain (ϵ_{xx} and ϵ_{yy}). Fig. 19 shows the typical cartographies of the strain for several samples studied with different S/EBP weight ratio for $\sigma = \sigma_{\text{max}}/3$.

The iso-strain value ($\epsilon_{\max} - \epsilon_{\min}$) was more important in the sample with a greater starch amount ($S/EBP = 0.4$) (see Table 3). It can be seen that the iso-strain tends to increase when the S/EBP weight ratio increases from 0.1 to 0.4. It seems to indicate the iso-strain of the Starch-Beet Pulp is less than that of the Starch-Hemp [3], which can confirm that when the particles used in the composite materials is finer, the particles (Beet Pulp) are well distributed in all directions of the composite and more homogenous.

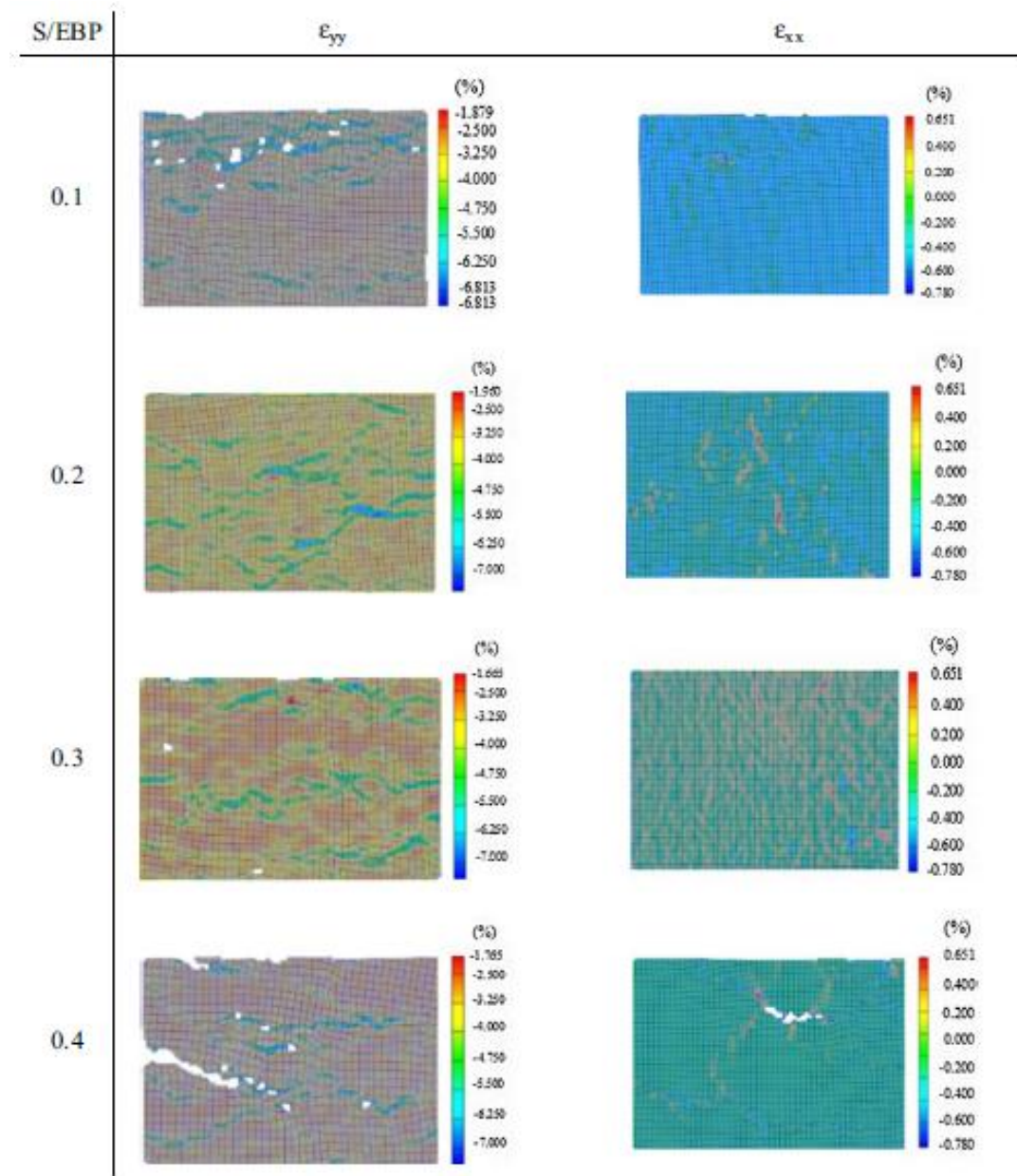


Fig. 19. Cartographies of compressive strain (transversal and longitudinal strain) under loading obtained by ARAMIS method for $\sigma_{30\%} = \sigma_{\max}/3$ for different studied formula.

3.2.5. Moisture uptake and release

Fig. 20 shows mass variation of beet pulp-starch composites under variations in relative humidity between 33% and 75% at 23°C. It can be seen that the composite absorbs moisture at 75% RH and releases moisture at 33% RH. For the last three cycles, the mass variation of the samples appears to have stabilized.

The results presented in Fig. 21 clearly show that the composite is an excellent regulator of the relative humidity of the environment ($MBV > 2 \text{ g}/(\%RH. \text{m}^2)$) according to the classification proposed by Rode [20]. The samples present MBV values between 2.6 and 2.8 $\text{g}/(\%RH.\text{m}^2)$, which are comparable with the MBV values of hemp-starch composites [3]. It can be observed that the variation in moisture buffering value as a function of the starch/sugar beet pulp is linear and can be presented by the Eq. (12). Besides increasing the mass of starch, increases the MBV value, because of starch high moisture buffering. The samples with more starch, have the highest MBV value, around 2.8 $\text{g}/(\%RH.\text{m}^2)$.

$$MBV = 0.62 \times (S/EBP) + 2.55 \quad (12)$$

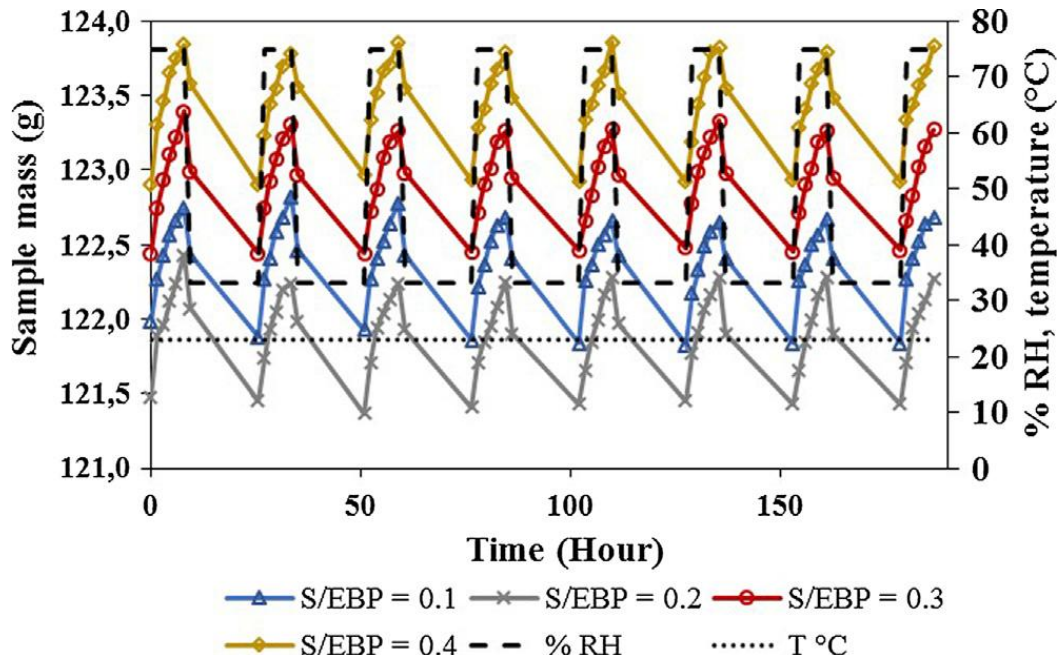


Fig. 20. Moisture uptake and release for the EBP-starch concrete during cyclic relative humidity variation in climatic chamber.

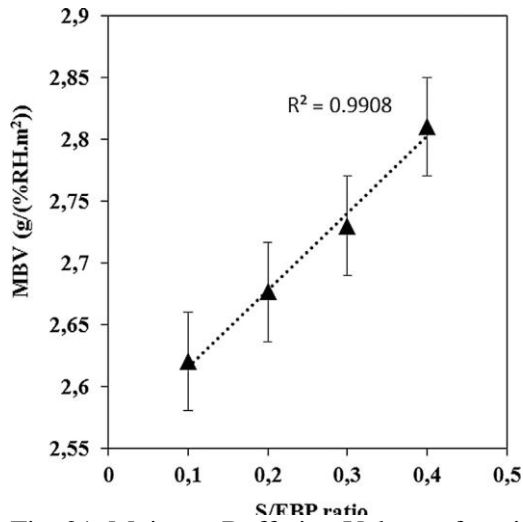


Fig. 21. Moisture Buffering Value as function of S/EBP ratio.

3.2.6. Thermal conductivity

Fig. 22 shows the evolution of the thermal conductivity λ versus the S/EBP weight ratios. The thermal conductivity of the starch-beet pulp increases linearly from 0.0695 W/(m·K) to 0.0757 W/(m·K) when the S/EBP weight ratio increases from 0.1 to 0.4.

Increasing the starch amount (S/EBP), the composite porosity decreases and increases consequently the thermal conductivity of the composite material. According to RILEM classification, the Starch-Beet Pulp having thermal conductivity lower than 0.3 W/(m·K), can be used as thermal insulation material. This value range of thermal conductivity is close to values for hemp-starch composites measured by authors [3].

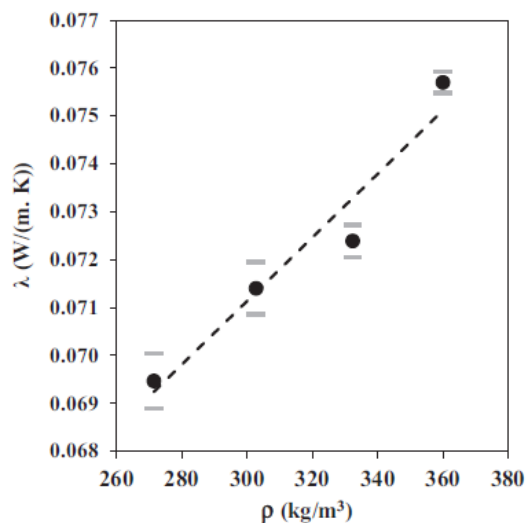


Fig. 22. Variation of the thermal conductivity as function of the S/EBP weight ratio.

4. Conclusions

In this paper, the physical properties of the extruded sugar beet pulp were studied (morphology, porosity, densities and particles size). Several methods and designs were used to elaborate and dry the EBP-starch composites.

The properties of a new agro-composite based on EBP and potato starch are presented. Different formulations were studied with EBP-starch ratios varying between 0.1 and 0.4.

The bulk density of the Starch-Beet Pulp composite depends of the S/EBP weight ratio. The bulk density of the composite increases when the amount of the potato starch increases. The results show that the starch- beet pulp is heavier than starch- hemp composites.

The starch-beet pulp composite absorbs up to 60% of the sound waves for the high frequencies depending of the starch amount of the composite.

The average of the tensile strength evolved from 0.11 MPa to 0.21 MPa when the S/EBP weight ratio increased from 0.1 to 0.4. These values were greater than those measured on the Starch- Hemp composites 0.03 MPa 0.13 MPa. The elasticity modulus increased from 2.06 MPa to 3.17 MPa when the S/EBP weight ratio increased from 0.1 to 0.4. These results were comparable with those obtained with the Starch- Hemp composites. The difference can be explained by the better adhesion that the finer particles used (Beet pulp) provide to the composites and consequently increased elasticity. The Poisson's ratio from 0.11 to 0.18 increases linearly with the S/EBP weight ratios.

The cartographies obtained by ARAMIS method show that the Starch-Beet Pulp is more homogenous that Starch- Hemp composites, but the cracks already existing in the samples increased the strain.

The studied EBP-starch composites showed interesting hygrothermal properties. The Moisture Buffering Values (MBV) was 2.62–2.80 g/(m² %RH) classifying them as excellent hygric regulators. The increase of starch content increases the moisture buffering value of the composites. Starch- beet pulp composite have a low thermal conductivity to around 0.070 W/(m·K). The thermal conductivity increases when the S/EBP weight ratio increases, which can be, explained the reduction of the pores filled by the starch binder.

Finally, the EBP-starch composite S/EBP = 0.4 can be considered as the optimal composition in terms of the hygrothermal properties. However, the S/EBP 0.1 presents the optimal composition for acoustical properties.

Conflict of interest: None.

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