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Development and Characterization of a Composite Material with a Polymer Matrix Reinforced by Sawdust from Cassava and Plantain Peelings

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ABSTRACT

Various processes are used to transform Cassava and Plantain into other sub-products. During these transformations, waste is produced and released into the environment. This work focuses on studying the physico-mechanical properties of a composite material incorporating Cassava and Plantain peelings in an expanded polystyrene polymer matrix. The main objective is to evaluate the impact of different proportions of polystyrene resin on the characteristics of the composite. To achieve this, we carried out a rigorous mixing and molding process, varying the proportions of resin from 10% to 40%, combined with Cassava and Plantain peelings sawdust. The resulting samples were subjected to several tests, including analyses of 3-point flexural strength, compressive strength, density and water absorption rate. We observed a marked improvement in flexural strength, from 1.03 MPa to 1.47 MPa, for 20% of the resins, and in compressive strength, from 6.13 MPa to 8.78 MPa at 30% resin content. Similarly, density measurements showed consistent variations, confirming the efficiency of the manufacturing process. Water absorption was significantly reduced, from 31.2% to 4.6%, in 2h and from 43.2 to 10.5% in 24h. In the case of samples with a higher proportion of resin, a lower water absorption was observed, highlighting the direct impact of this component on the hydrophobic properties of the composite. Similarly, the thickness swelling rate was significantly reduced, from 1.1% to 6.8%, in 2h and from 11.3 to 2.2% in 24h. These results demonstrate the performance of our composite material based on Cassava and Plantain peels, and the potential to use it like a particleboard building where lightness, robustness and ecological aspects are essential criteria.

Keywords: Composite materials; Cassava peeling; Expanded polystyrene; Physico-mechanical properties; Plantain peeling.

1. Introduction

Waste disposal has always been a growing problem for processing industries in Cameroon, due to its negative impact on the economy and the environment. Huge quantities of plant-based waste are produced by these companies every year. Similarly, in recent years, polystyrene foam, otherwise known as expanded polystyrene (EPS), mass-produced to meet the growing needs and demands of the packaging industry, is ending up in the waste stream in a similar pattern [1],[2]. In addition, the environmental problems associated with traditional methods of waste disposal such as incineration and landfills are of concern due to the rising cost of landfill disposal [3]. Composite materials incorporating plant particles are ubiquitous in the modern world, offering advantages in terms of durability, performance and reduced environmental impact [4]. In Africa, and particularly in Cameroon, their growing use is helping to valorize local plant resources such as cassava and plantain. Biosourced materials based on banana and manioc peels improve material performance, reduce dependence on imports and stimulate economic development through the valorization of agricultural waste. What's more, by combining the mechanical properties of plant fibers with polymer matrices such as plastic (EPS), we can obtain materials that are light, resistant and sometimes even endowed with specific properties such as electrical or thermal conductivity, depending on requirements [5].

Plastics, omnipresent in our lives, undeniably bring their share of benefits, but also raise major challenges linked to their end-of-life management. In recent years, growing awareness of these environmental issues has catalyzed the emergence of the "eco" or "bio" concept, aimed at creating materials from renewable resources to preserve our environment and better manage the consumption of increasingly scarce fossil resources [6]. Among the most commonly used plastics, polystyrene poses a major problem due to its low recycling rate and environmentally harmful spread (density ranging from 10 to 45 kg/m^3) [6]. At the same time, the increase in demand and the evolution of yields for products such as cassava and plantain in Africa, and in Cameroon in particular, which have risen from less than 6,000 tons/ha in 1961 to 15,000 tons/ha in 2018, underline the urgent need to recycle agricultural waste, particularly peelings, to reduce pollution and promote a sustainable development model [7]. In addition, modern industries such as mechanical engineering, civil engineering, transport and aeronautics are looking for lightweight, strong, environmentally-friendly materials with a long service life and good mechanical and chemical resistance.

One way of recycling plant waste, coupled with plastic waste, is to produce bio-materials, specifically particleboard. Thermoplastic matrices have poor mechanical properties. Reinforcing them (usually with short fibers) improves mechanical strength, dimensional stability and temperature resistance. A great deal of work has been carried out on the use of various plastic wastes as resins, including polyethylene terephthalate (PET) by [8], epoxy (EP) by [9], polyvinyl chloride (PVC) by [10], polypropylene (PP) by [11] and others by [12]. Despite the attractiveness of polystyrene, municipalities and organizations are faced with a growing problem when it comes to disposing of polystyrene packaging and products. Being large, bulky and light, polystyrene takes up a lot of space in waste garbage cans, which means that garbage cans fill up more quickly and need to be emptied more often, and it is easily blown around and can cause nuisances in the surrounding area [13]. In addition, a number of studies have been carried out on the mechanical characterization of biomaterials based on plants [14]. Authors in [15] have carried out a study on the mechanical characterization of palm wood waste; this extract shows that plant fibers are an interesting alternative to inorganic and synthetic fibers because of their ability to be recycled. Authors in [16] have carried out a tensile mechanical characterization of a bio-composite based on date palm waste, with two types of plastic resin. They showed that increasing the percentage of binder reduces stress at break and strain, and causes a slight increase in Young's modulus. Authors in [17] and [18] study the Influence of expanded polystyrene resin content on the thermomechanical properties of a stabilized wood chip composite; this study shows that the use of polystyrene resin as a binder enables the development of composites whose mechanical properties improve with increasing binder content. Authors in [19] studied the technological properties of a wood-plastic composite produced in Benin. According to this work, the smaller the particle size, the better the properties of the composite, since the finer the particle size, the more homogeneous the material and the more isotropic its behavior. Authors in [20] studied composite panels made with corncob and sugarcane bagasse as reinforcements, and the binder was cassava starch and formaldehyde urea. They showed that panels with 90% corncob sawdust had good mechanical properties.

1.1. Study Objectives

Most of the scientific studies carried out in the field of mechanical characterization and recovery of plant waste have not taken into account particle composites, more specifically the mixture of cassava and plantain peel particles. This is the background to our study, which proposes the creation of a composite material based on expanded polystyrene and manioc/plantain peelings sawdust. The aim is twofold: to reduce the environmental impact of traditional plastics while recycling agricultural waste, with significant economic and ecological spin-offs.

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The main objective is to understand the behavior of these new materials when subjected to different types of mechanical stress (using standardized tests), in order to create or determine the behavior law of these composites. This is with the aim of producing new materials that can be used as insulating panels in construction or in the automobile for the structural elements of the passenger compartment.

2. Materials and Methods

2.1. Material

2.1.1. Plant material

The reinforcement used in our composite material is of plant origin. It takes the form of particles or short fibers. It comes from two sources: - Manioc peelings, scientific name Manihot esculenta; manioc is a tuberized root native to Central America. It is grown in the Adamoua region (North Cameroon) and is used as a foodstuff after peeling, in various forms. - Plantain peelings; the plantain consumed in the Adamaoua region comes from eastern Cameroon. Figure 1 shows photos of cassava tubers and plantain fingers before peeling used for our experience.

a) Cassava tubers b) Plantain fingers

Figure 1. Photo of plant material used

2.1.2. Preparation of the reinforcement

The reinforcement of the composite material consists of cassava and banana peel particles. These particles are obtained as described in Figure 2 below.

Figure 2. Steps for Preparing Composite Material Reinforcement Particles

The peelings are collected from households and household waste storage sites in the town of Ngaoundere (Adamaoua region). They are then sorted to select only those peelings that have not yet begun to decompose. Drying is carried out by exposure to the sun until the garbage is perfectly dry, which can be seen and felt.

Figure 3. Photo of sun-dried cassava peelings (A) crushed (B)

The peelings are then ground in a locally-made hammer mill fitted with two hammers and a 2 mm sieve. The sawdust is then sieved using a 0.5 mm sieve. The sawdust retained on the 0.5 mm-sieve is used to make our composite material.

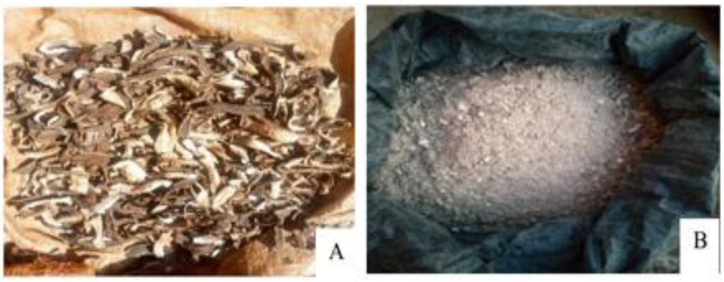

Figure 4. Dried plantain peelings (A) ground (B)

In this study, we will use a mixture of cassava and plantain peel particles with sizes ranging from 0.5 to 2 mm. Figure 3 and Figure 4 present the dry peeling particles and sawdust of different vegetable fiber used to produce our composite material.

2.1.3. The polystyrene Foam

The matrix used is expanded polystyrene (EPS), a thermoplastic resin from the polypropylene family. It was collected from garbage cans and stores in the markets of the town of Ngaoundere (Adamaoua region). The polystyrene is used as an anti-shock material for packaging household appliances, see Figure 5 below.

Figure 5. Expanded Polystyrene Foam

Once any impurities have been removed, the polystyrene is dissolved in heptane. This dissolves the polystyrene, reducing its volume by 98% and making it more cost-effective to collect [21]. The result is a resin that serves as a binder for composites. EPS is dissolved in a ratio of around 0.7 kg of EPS to one liter of solvent [17].

2.1.4. Laboratory equipment

Weighing was carried out using a digital balance. Dimensions were measured with a caliper to an accuracy of 0.01 mm.

2.2. Methods

2.2.1. Characterization of reinforcing sawdust of peeling cassava and plantain

Before moving on to composites, it's important to know the mechanical properties of the fiber. As the reinforcement is in powder or bulk form, we are only interested in two properties.

2.2.1.1. Density of different sawdust

The absolute density of sawdust obtained by grinding Cassava and Plantain peels was determined by weighing 10 g of particles on a precision balance. This experiment was repeated three times for each type of vegetable particle. After covering them with a layer of kerosene, we weighed them, noting the total mass, then immersed them in an initial volume of water (V_1 = 100 ml) contained in a beaker, observing a variation in the water level (V_2), hence the volume occupied ($\Delta V = V_2 - V_1$). The results will enable us to determine the density of the reinforcement using the formula in (equation 1):

$$\rho_{sawdust} = \frac{m_p}{V_2 - V_1} \qquad (1)$$

2.2.1.2. Water absorption rate of different sawdust

In our experiment, we weighed 25g of crushed hull in a precision balance, then immersed it in water at an initial volume V_3 equal to 100 ml in a beaker, shaking it and leaving it to stand for 18 h. The final volume V_4 is measured and the water absorption rate Ta is calculated using the following formula (equation 2):

$$WA_{saxdust} = \frac{V_4 - V_3}{V_3} \times 100 \qquad (2)$$

2.2.1.3. Sample preparation method

The samples were prepared in several stages, summarized in Figure 6. Resin dissolved in heptane is poured over ground Cassava and Plantain peel particles. The mixture is mixed by hand, using a chopstick to homogenize it. The various test samples were produced by simple molding, and compacted with a hydraulic press at 5 bar pressure for 8 hours.

A quantity of the mixture is taken and compacted in molds to obtain specimens in the shape of 20x25 mm^2 test tubes 200 mm in length.

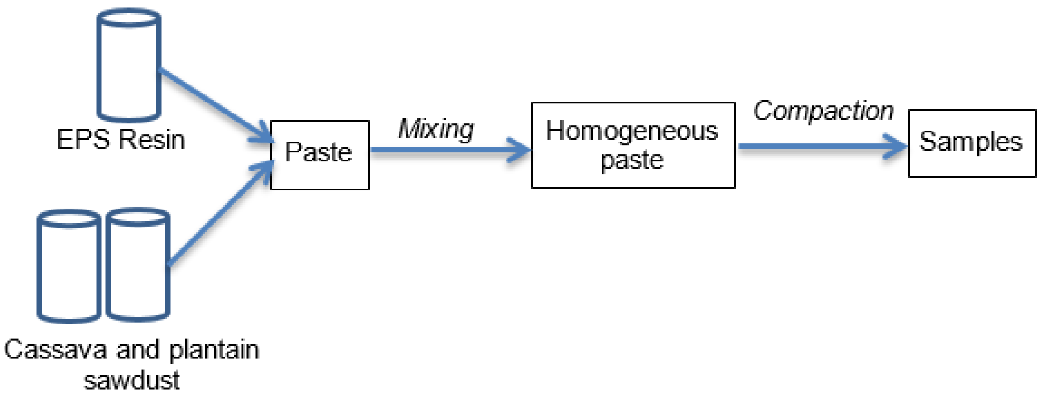

Figure 6. Sample preparation method

Different samples were made by varying the mass proportion of resin by 10, 20, 30 and 40%, while keeping the percentages of Cassava and Plantain peel particles stable and equal to the remaining proportion of the composite, as shown in Table 1.

Table 1. Sample composition

Sample		A	B	C	D
Resin (%)		10	20	30	40
Sawdust from peelings (%)	Cassava	45	40	35	30
	Plantain	45	40	35	30
Total (%)		100	100	100	100

Each sample is sun-dried for 3 hours before being conditioned in a conditioning oven for 14 days at 20°C and 53% relative humidity.

2.2.2. Characterization of produced composites

Before moving on to composites, it's important to know the mechanical properties of the fiber. As the reinforcement is in powder or bulk form, we are only interested in two properties.

2.2.2.1. Produced composites density

Test specimens, 25x20 mm^2 in cross-section, 25 mm long and of mass me, were fully immersed in a given volume of initial water (Vi) contained in a beaker. The final volume of water (V_f) is taken and the change in volume ($\Delta V = V_f - V_i$) is used to determine the absolute density of the composite material by using (equation 3) below:

$$\rho_{composite} = \frac{m_{sample}}{\Delta V} \qquad (3)$$

Specimens with a cross-section of 25x20 mm^2 and a particulate density $\rho_{particulate}$ were determined using the mixing rule. The following material characteristics were used:

- Expanded PS density: $\rho_o = 0.678\ g.cm^{-3}$;

- Density of cassava peel sawdust: $\rho_{cassava\ peel\ sawdust} = 1.195\ g.cm^{-3}$;

- Density of plantain peel sawdust: $\rho_{plantain\ peel\ sawdust} = 1.275\ g.cm^{-3}$.

Depending on their contents in the composite (α_o for expanded PS and α_m for reinforcing sawdust), its particulate density is given by (equation 4):

$$\rho_{particulate} = \alpha_o \rho_0 + \alpha_m \left(\rho_{cps} + \rho_{pps}\right) \qquad (4)$$

It should be noted that the mixing rule is the method used for all the samples studied.

2.2.2.2. Thickness swelling and water absorption rates

In order to determine the water sensitivity of the composite material, the thickness swelling rate (TS) was assessed by measuring the thickness of the specimens with a 1/20 caliper before and after immersion. Five specimens of each formulation (25 mm × 25 mm × 20 mm) were immersed in 250 ml of distilled water at (28 ± 1) °C for 2 h and 24 h.

The thickness swelling rate is given by the following relationship (equation 5):

$$TS = \frac{e_{before} - e_{after}}{e_{after}} \times 100 \qquad (5)$$

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Where e_{before} and e_{after} represent the thickness of the composite material before and after immersion in distilled water respectively.

Similarly, the water absorption rate (TA) was assessed by taking the mass of the samples before and after 2h and 24h immersion in water. This absorption rate is assessed in accordance with standard NF EN 1609 for insulating materials: Short-term water absorption by partial immersion [22]. For each formulation, the measurement is repeated on three samples whose bulk density and mass before immersion are determined prior to the test. This method uses a steel tank with a continuous water supply. The water level is maintained constant throughout the test, with a drain 10 mm from the bottom of the tank. A mass is placed on top of the samples to prevent them from floating. The mass of the samples after 24 hours of immersion is recorded. The short-term water absorption rate, noted as TA in %, is determined by the following (equation 6):

$$TA = \frac{M_{before} - M_{after}}{M_{after}} \times 100 \qquad (6)$$

With *TA* the short-term water absorption rate (%) and M_{before} and M_{after}, sample mass after and before immersion respectively (g)

2.2.2.3. Three-point bending strength measurement

The three-point bending characterization test was carried out on samples of dimensions 200x20x25 mm^3 in accordance with ASTMD 790-81 [23]. The specimens to be characterized were placed on two (02) single supports spaced by L*, equal to 150 mm. A third support was placed on the upper face at mid-distance from the supporting supports. The schematic diagram of the three-point bending test and the test apparatus are shown in Figure 7a below. The specimen is then progressively loaded with the press until it breaks. The maximum breaking load $\boldsymbol{F_{fmax}}$ is noted. The bending strength is given by (equation 7):

$$R_f = \frac{3F_{f\max}L^*}{2le^2} \qquad (7)$$

With R_f: bending strength (MPa); $\boldsymbol{F_{fmax}}$: maximum bending breaking load (N); L*: distance between supports (mm); l: specimen width (mm); e: specimen thickness (mm).

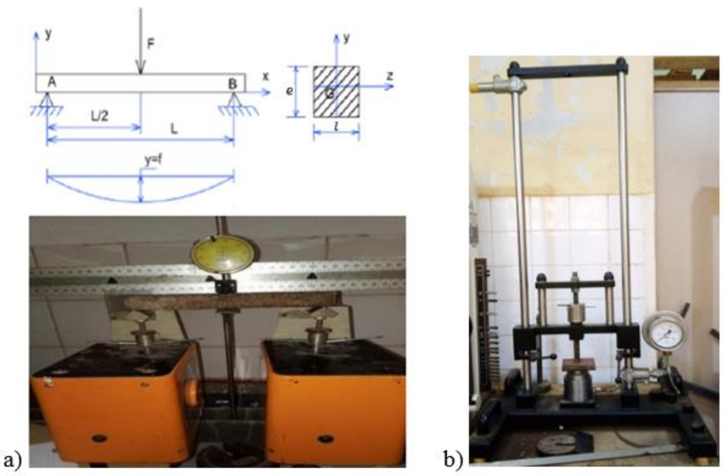


Figure 7. Testing apparatus a) flexion, b) compression

2.2.2.4. Compressive strength measurement

The compression test is used to characterize the behavior of a material subjected to crushing between two plates (End-Loading principle). This test was carried out in accordance with ASTM D695 to determine the stress to stiffness and Young's modulus in compression of composites based on EPS as a binder, and plant fibers from manioc and banana peel sawdust [24]. For this test, parallelepiped samples with dimensions of 100 x 25 x 20 mm^3 were cut from the base sample. The test specimen is placed on its cross-section (20 x 25 mm^2) required for optimum estimation of compressive strength. The Gunt WP 120 testing machine is used to perform the tests, as shown in Figure 7b. It is then progressively loaded until it breaks. The deformation corresponding to the breaking load Fc applied is recorded, and the maximum breaking load F_{cmax} is determined. So the compressive strength (Rc) is given by the formula below (equation 8).

$$R_c = \frac{F_{c\max}}{l \times e} \qquad (8)$$

With R_c: compressive strength (MPa); F_{cmax}: maximum compressive load (N); l: specimen width (mm); e: specimen thickness (mm).

3. Results and Discussion

3.1. Characterization of Reinforcement Particles

The properties of the reinforcement particles studied are easily influenced by several factors, including plant origin, variety, growing and harvesting conditions.

3.1.1. Density of cassava and banana peeling sawdust

Tables 2 and 3 below show the values obtained for density of cassava peeling sawdust and plantain peeling sawdust.

Table 2. Absolute density of cassava peel sawdust

Test N°	Mass (g)	ΔV (cm^3)	Density (g/cm^3)
1	10	8.23	1.215
2		8.51	1.175
3		8.36	1.196
Average			1.195 ±0.02

The density of the sawdust produced is 1.195 g/cm^3 for Cassava and 1.275 g/cm^3 for Plantain. This is higher than that of distilled water (1 g/cm^3). These peelings are therefore heavier than water.

Table 3. Absolute density of plantain peel sawdust

Test N°	Mass (g)	ΔV (cm^3)	Density (g/cm^3)
1	10	7.87	1.271
2		7.92	1.263
3		7.75	1.290
Average			1.275±0.014

The density of these peelings is higher than that of “Telovolana” fermented Cassava root flours (0.58 g/cm^3) [25], plantain flours (0.64 g/cm^3) [26], and white-fleshed, white-skinned sweet potato tubers [27] with 0.57 g/cm^3. These bulk particles are therefore heavier than these three types of flour. This can be explained by particle size. The size of our particles varies from 0.5 mm to 2 mm, whereas for these flours the size is between 0.25 mm and 1 mm.

3.1.2. Water absorption rate of reinforcement particles

The water absorption rate of sawdust is 12.50% for Cassava peels (Table 4) and 13.33% for Plantain peels (Table 5). These values are low compared to that of sweet potato tuber flour, which is 15.52% [28], and close to equal to those of the flours of three Malagasy cassava varieties [29], which are 12.34, 14.27 and 13.36% respectively.

Table 4. Water absorption rate of cassava particles

Test N°	V_3 (ml)	V_4 (ml)	Water absorption rate (%)
1		225	12.50
2	200	226	13.00
3		224	12.00
Average			12.50 ±0.5

These differences may be due to the inequality of amylose and amylopectin content between these sawdusts and the starch granules of these flours.

Table 5. Water absorption rate of plantain particles

Test N°	V_3 (ml)	V_4 (ml)	Water absorption rate (%)
1		227	13.50
2	200	226	13.0
3		227	13.50
Average			13.33±0.23

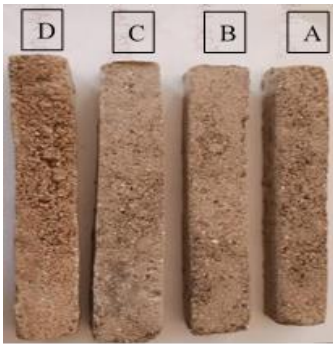
Based on the values obtained for the characteristics of cassava and plantain peel sawdust, these products can be classified as light, porous bulk products.

3.2. Characterization of Composites

3.2.1. Sample obtained

Figure 8 shows the produced composites with different resin percentages. Composite A, with 10% binder in the sample and an equal percentage of vegetable fiber incorporated (45% for Cassava peelings sawdust and 45% for Plantain peelings sawdust). And, composite B with 20% binder; Composite C with 30% resin and Composite D 40% resin.

Drying times are similar, around 15 days, and identical for the different composite proportions. The composites show slight deformation and visible cavities after drying. These shrinkage phenomena depend on the type and proportion of filler, as well as on the proportion of binder. Another cause may be that the mixture is not well homogenized due to the manual operation. However, with a resin content of 20% and 30%, less shrinkage is observed.



A: 10% resin sample
B: 20% resin sample
C: 30% resin sample
D: 40% resin sample

Figure 8. Different samples of produced Composite

3.2.2. Density for different percentages

Density is a key property in determining the mechanical performance of composite materials. For the various samples studied in the present work, the particulate and apparent densities were evaluated. The particulate density of the samples was evaluated both analytically (law of mixtures) and experimentally Table 6 presents the values obtained. The analytical density is 1.18 g/cm^3 for samples containing 10% binder (sample A) and 1.01 g/cm^3 for samples containing 40% binder (sample A). It is observed that the values obtained experimentally decrease as the percentage of binder in the material increases. This variation is also observed for the actual values of the density obtained experimentally. Across all samples, the differences between analytical and experimental values are small (less than 3%). The analytical values of the particle density are therefore valid.

Table 6. Density of different samples

Sample	Mass of sample (g)	Theoretical density $\rho_{théo}$ (g/cm^3)	Actual Density $\rho_{réel}$ (g/cm^3)
A	13.5	1.31	1.35
B	13.3	1.27	1.33
C	12.8	1.23	1.28
D	12.1	1.18	1.21

The results presented in Table 6 show that the density, whether experimental or theoretical, decreases with increasing resin content. Similarly, it appears that the increase in resin also affects the difference between the theoretical and experimental density values. It can therefore be seen that at the 10% resin rate, the real density is 1.35 g/cm3 while for a resin content of 40%, we have a density of 1.21 g/cm^3. In general, all of these composites have a low density, in the same density range as the building materials used in false ceilings. With an average density of 1.3 g/cm^3, our material can be used as a false ceiling.

3.2.3. Water absorption rate and thickness swelling rate

The results of the water absorption rate and the swelling rate are presented in Figures 9 and 10 below, for 2 and 24 hours of immersion in water for the samples studied.

Figure 9 shows us that the absorption varies according to the proportion of the quantity of the constituents, the higher the percentage of the matrix the material absorbs less water, regardless of the immersion time of the samples. The rate is highest for sample A containing 10% matrix.

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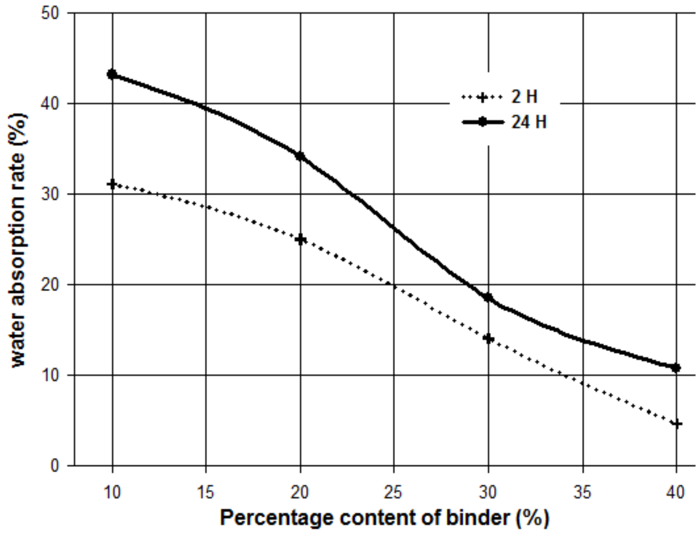

Figure 9. Water absorption rate of composite as a function of the percentage of EPS

With the increase in resin content, there are fewer water residence sites and therefore less water absorbed. The water absorption of the most resin-rich panels was 4.6% and 10.46% after 2 h and 24 h of immersion respectively, while the water absorption of the most resin-poor panels was only 31.15% and 43.18% after immersion respectively. The swelling of the panel thickness increased with water absorption and therefore had a similar trend to water absorption with respect to the impact of the particle-to-resin ratio.

The swelling values of the most resin-rich panel thickness were only 1.08% and 2.15% after 2 and 24 hours of immersion in water respectively, while the swelling values of the panel thickness were only 6.77% and 11.31% after 2 and 24 hours of immersion in water respectively. In general, panels manufactured with a higher resin content had greater dimensional stability properties.

No significant difference in swelling in thickness was observed between the 4 samples after 2 hours of immersion of the specimens. On the other hand, after 24 hours of immersion, it is observed that the swelling increases overall with the size of the particles.

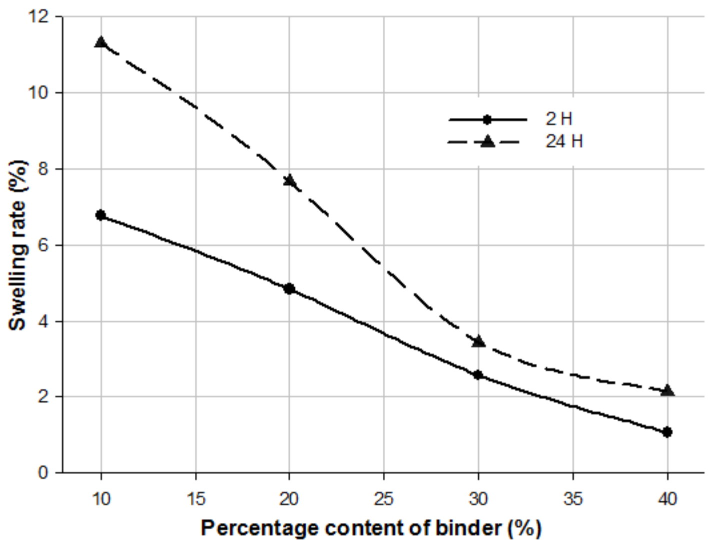

Figure 10. Thickness swelling rate of composite material as a function of the percentage of EPS

It is noted that the rates of water absorption and swelling in thickness of the samples (after 2 H or after 24 H) increase with the reinforcement composition they contain. When the composite has less binder, i.e. more reinforcement, the swelling rate is higher, because of the presence of plant material particles that have absorbent properties than EPS.

The results on the absorption rate and the thickness swelling rate, compared to previous work, indicate an excellent overall performance and are in line with national and international standards. The superiority of our study over previous work lies in the minimal swelling of the thickness compared to the water absorption that is general in all composites containing sawdust. The resin content has made the material more water-resistant and can be considered more chemically stable in a humid environment. The superiority of the PBR used in this work over previous practices is evident when compared to other work on the same subject where the resin/binder has been synthesized by the condensation method. This is not surprising because, primarily, condensation polymers are susceptible to degradation under the effect of water, and multiple exposures such as humidity and heat can lead to accelerated deterioration. The increase in absorption and swelling rates in thickness with particle size is related to the fact that swelling is a consequence of water absorption,

3.2.4. Flexural tensile strength

The evolution between the flexural stress and the strain for the flexural strength (three points) of composites is shown in Figure 11. From Figure 11, we can see that the values of the stress vary according to the deformation, and this results in a maximum deformation which represents the deflection F_{fmax} and which has a value of 2.3 mm; 3.4 mm; 2.42 mm and 2.05 mm, respectively, for samples A, B, C, and D. The dissipations of the curves can be explained by the geometric nonlinearity of the specimens during the shaping of composites.

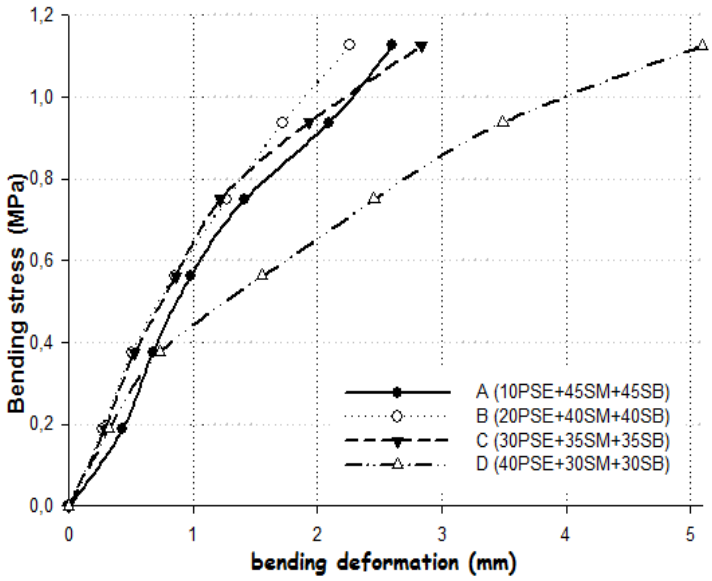

Figure 11. Stress-strain curve of different samples

The flexural modulus of elasticity and fracture strength values were determined to study the mechanical and physical properties of composite materials based on sawdust, cassava peelings and plantains at different EPS contents, as shown in Table 7 below.

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Table 7. Flexural mechanical characteristics of different samples

Sample	E (MPa)	R_f (MPa)	F_{fmax} (N)
A (10PSE+45SM+45SB)	227.46	1.025	27.34
B (20PSE+40SM+40SB)	228.31	1.475	39.64
C (30PSE+35SM+35SB)	213.19	0.975	26.02
D (40PSE+30SM+30SB)	151.96	0.585	15.42

To analyze the results, we took out the graphs of Young's modulus and maximum flexural strength. Figure 12 shows the histogram of the variation of Young's modulus and maximum bending stress as a function of formulations.

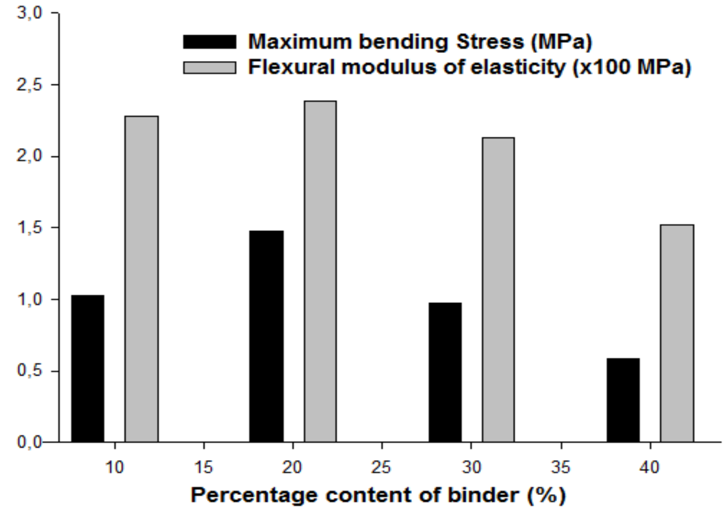

Figure 12. Variation of Young's modulus and bending stress as a function of formulations

Looking at Figure 12, the flexural strength of composites increases as the binder content (PSE) of the samples increases to the threshold of 20% of the incorporated binder. Beyond this percentage, the flexural strength decreases. Thus, for contents of 10% to 20% resin, the strengths increase from 1.025 MPa to 1.47 MPa for samples.

The hypothesis of this somewhat low flexural strength may be due to the looseness between particles which propagates rapidly due to poor compaction and manual mixing which may prove insufficient to homogenize the pulp properly.

3.2.5. Compressive strength

The static compression tests on the samples allowed us to determine the classic values of the compressive modulus of elasticity and the maximum compressive strength, presented in Table 8 below.

Table 8. Mechanical characteristics in compression

Samples	E_C (MPa)	R_c (MPa)	F_{cmax} (N)
A (10PSE+45SM+45SB)	306.28	6.13	3063
B (20PSE+40SM+40SB)	392.21	6.72	3360.5
C (30PSE+35SM+35SB)	418.06	8.78	4390
D (40PSE+30SM+30SB)	219.41	4.17	2084.5

From Figure 13, we see that compressive strength increases as the binding content of samples increases. Thus, for binder contents ranging from 10% to 30%, the strengths range from 6.13 MPa to 8.78 MPa. Here too, the resistance tends to increase to 30% of the binder, before falling to 40%.

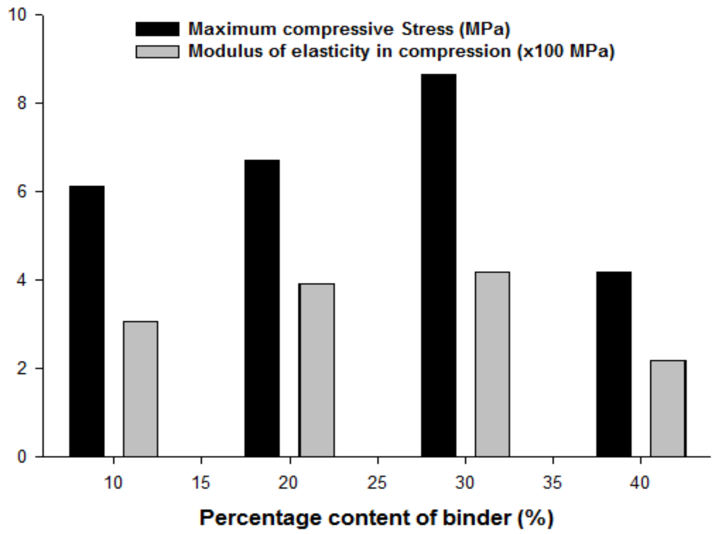

Figure 13. Variation of Young's modulus and compressive stress as a function of formulations

The increase in strength (in bending and compression) with the increase in the binder in composites can be related to the improved bonds between the particles of Plantain peels, Cassava and the resin of (EPS). Indeed, the increase in binder content leads to better impregnation and greater coating of the particles of plantain and Cassava peels by the binder, which results in a strengthening of the bonds during drying [17]. The compressive strengths exhibited by the hybrid composite samples (6.13 – 8.78 MPa) cannot be used like ceiling boards because the tested sample did not meet the specified compressive strength of 448 – 868 MPa for ceiling boards [30].

4. Conclusion

At the end of this work, which is an in-depth study of the physico-mechanical properties of a composite material, integrating cassava and plantain peelings into a polymer matrix of expanded polystyrene. An evaluation of the impact of different proportions of polystyrene resin on the characteristics of the composite made it possible to vary the resin proportions from 10% to 40%, combined with cassava and plantain peelings. The resulting samples were subjected to several tests, including 3-point flexural strength, compressive strength, density, and water absorption capacity. The results show a significant improvement in flexural strength from 1.025 MPa to 10% and 1.47 MPa to 20% and from 1.025 MPa to 10%. Compressive strengths, from 6.13 MPa to 10% and 8.78 MPa to 30% depending on the resin content.

From these results, we can see that the flexural strength is max at 20% resin and for compression at 30%. Similarly, mass measurements showed consistent variations, confirming the efficiency of the manufacturing process. Water absorption and swelling were significantly reduced for samples with a higher proportion of resin, highlighting the direct impact of this component on the hydrophobic properties of the composite. These results demonstrate the performance of the composite material based on cassava and plantain peelings, highlighting its potential in various applications where lightness, strength and eco-friendliness are key criteria.

The expanded Polystyrene foam had strong binding characteristics that could serve some industrial purposes when applied in the production of the particleboards at percentages above 20% to 30%. The property of the particleboard is a function of the percentage composition of the components. Polystyrene foam, sawdust of Cassava and Plantain peeling are available in our environment and they are often discarded as wastes. Thus, particleboards produced from these wastes are expected to be relatively cheaper than most commercially available boards and should be more environmentally friendly.

As a perspective to this work, it would be good to study the influence of the particle size of cassava and plantain peel particles on the physico-mechanical properties of the biomaterial, in order to determine the optimal particle size that will allow us to obtain the best characteristics. We could also be interested in the study of other physico-mechanical properties of the biomaterial, such as thermal conductivity

Declarations

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Competing Interests Statement

The authors declare no competing financial, professional, or personal interests.

Consent for publication

The authors declare that they consented to the publication of this study.

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