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Investigating the Impact of Core Type on the Properties of Novel Bio-Composites with a Sandwich Structure Derived from Date Palm Waste

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ABSTRACT

This paper aims to study the feasibility of implementing a new bio-composite with a sandwich structure made from date palm tree waste. This is done by valuing such waste, often left in palm groves and burned under most circumstances, which can be a vital resource at the lowest cost. This work has developed sseveral sandwich-structured composite plates based on this waste. The skins are composite materials based on an epoxy matrix and palm tree fibers (Epoxy/Rachis fibers); the core was made of raw wood or a composite with petiole wood particles. After three-point mechanical bending tests, macroscopic analysis and SEM micrographs were used to determine what kind of damage the specimen had. Characterization tests on the new bio-composites showed good thermal properties; with a thermal conductivity below 1W/mK is between 0.0148W/mK and 0.0178W/mK. It is also characterized by its low volumetric mass, less than 1.2g/cm^3. These properties make it a good thermal insulator, especially in environmentally friendly bio-construction areas making a sandwich-structured composite using palm tree waste is a very effective, environmentally friendly, and economically inexpensive option.

1. INTRODUCTION

The implementation technique of sandwich panels is a well-known and long-used technique in many industries. These structures are characterized by their lightweight and good properties, such as thermal and acoustic insulation, impact resistance, and fatigue resistance. These properties are directly related to the choice of material for the two skins and the core, and the quality of their interfaces. Plant-based materials are of great environmental interest in the production these sandwich panels. For this, several researchers have studied the mechanical behavior of bio-composites used in the manufacture of sandwich-structure d composite. The studies presented have demonstrated that composite materials' mechanical properties of composite materials improve when reinforced with fibers of plant origin. The mechanical and thermal properties of the polyester matrix are improved depending on the ratio of Diss or date palm fibers added, which is from 5% to 20% [1-3]. This was also observed when the epoxy matrix was reinforced with date palm tree fibers from different extraction zone [4, 5].

Furthermore, studies have shown an improvement in the mechanical, physical and thermal properties of sandwich structure after adding plant-based materials, such as cores or skins, to their composition [6-12].

Indeed, the current evolution of the production processes of bio-composite materials led us to observe an increase in the use of these materials in various sectors, particularly the manufacture of composite materials for the elements of insulation. This may be due to the good physico-mechanical properties of these materials [13-16]. Although the idea of using fibrous wood and fibers extracted from the waste date palm tree in the materials industry is recent, compared to the use of other varieties of wood and plant fibers [4-6], we find the use of fibrous palm wood as an alternative to traditional wood residues in the manufacture of various industrial wood panels (MDF, HDF, LDF, etc.). This technology is used by many industrial manufacturers worldwide [17, 18].

In this context, several studies have interested in the use of palm waste in the manufacture of sandwich structure and the study of their mechanical properties. The sandwich structure was prepared using "wooden" petioles to optimize the design of the sandwich core in the directions (longitudinal, transverse and diagonal) and short palm fibers (5%, 10%, and 15%) were used to reinforce epoxy skin. Three-point bending tests proved the mechanical efficiency of this sandwich structure. Despite the dominant failure modes in the lower part of the skin and the core center, the cracks also propagated in the direction transverse to the core. Furthermore, studies have also proven the effectiveness of particle boards made from date palm petiole in thermal insulation [19, 20].

However, most studies have been limited to exploiting date palm tree waste as a unique part of the components of sandwich structures, such as the core or skin. This raises the question of the possibility of developing a sandwich structure in which all the components are extracted from date palm tree waste.

Furthermore, these studies still need to be more extensive in number and insufficient to collect all the scientific information on the physical, thermal and mechanical properties of these bio-structures. The search for the ideal structure of this bio-composite remains an open area of study. This can be done by studying the thermal, physical and mechanical properties of the sandwich structure bio-composite. This will give us the information to choose the best places to use this new biocomposite.

This study focused on developing novel bio-composites with a sandwich structure derived from date palm tree waste. Different types of cores are used in these new sandwich structures. For example, agglomerated cork, fibrous wood from the petiole, and wood particle panels from the petiole are used as samples to study their mechanical, physical, and thermal properties. The skins of these new materials are made of a bio-composite material based on short rachis fibers and an epoxy matrix. These tests make it possible to determine this new compound's physical, mechanical and thermal properties depending on the results obtained, we can identify these new bio-composite and classify it as a new bio-structure compared to conventional sandwich-structured composite. This allows us to determine the possible areas of use for this bio-composite. As well as choosing the best core for thermal insulation.

Figure 1 represents a summary graph of the most important steps of the study, including the preparation method of the sandwich structure, the materials used, and the tests carried out in this study.

Figure 1. Graphical abstract

2. CHOICE OF COMPONENTS OF THE SANDWICH STRUCTURE SETUP

The selection of materials used in this study was based on the results obtained from previous studies [21, 22]. This provided a complete description of the materials used as skins and cores to prepare these novel bio-composites with a sandwich structure, as shown in Table 1.

Figure 2 shows the different materials used.

2.1 Skins

The skins used to prepare the new sandwich structure are composite materials based on an epoxy matrix and palm tree fibers (Epoxy/Rachis fibers) for a mass fraction of 10% of fibers (EFR10). Figure 3 represents the main stages of preparation of these composite material plates, EFR10. This selection is based on previous studies [21], which show that bio-composites have good mechanical, physical and thermal properties (Table 1) by comparing them to other bio-composite with different mass ratios of fibers (4%, 7%, and 15%).

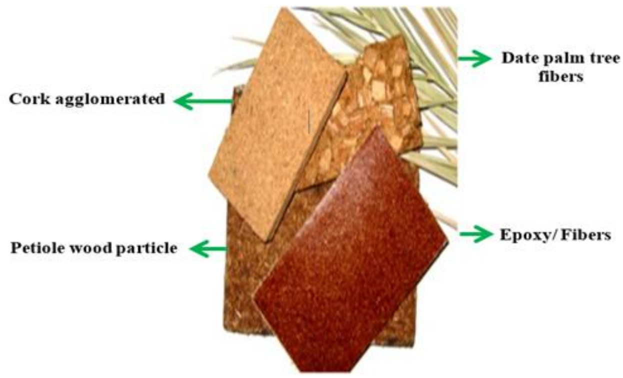

Figure 2. Materials used in novel bio-composites with a sandwich structure

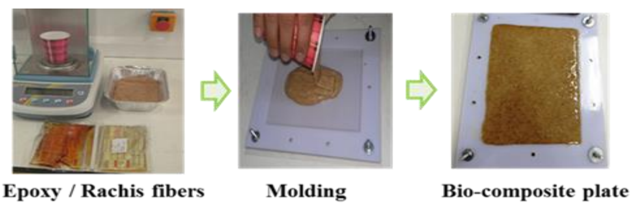

Figure 3. The main preparation steps of (EFR10) are used as the skin of the new sandwich-structured composite

Table 1. Physical, thermal, and mechanical properties of components used in the preparation of sandwich structured composite (Core and Skin)

Core	Physical [21]	Thermal [21]			Mechanical [21]	
	Density [g/cm^3]	Thermal Conductivity [W/mk]	Thermal Diffisivity [mm^2/s]	Specific heat [MJ/m^{3}K]	Flexural modulus [MPa]	Maximum stress [MPa]
BPB	0.19±0.05	0.093±0.001	0.598±0.011	0.135±0.004	585±10	10.5±2.5
CBP1	0.53±0.03	0.123±0.001	0.491±0.009	0.252±0.011	788±35	12.6±2.45
CBP3	0.23±0.04	0.120±0.001	0.461±0.015	0.259±0.006	200±51	4.01±1.33
CBP5	0.18±0.02	0.093±0.003	0.588±0.017	0.162±0.037	145±18	2.38±1.66

Skin	Physical	Thermal			Mechanical [22]		
	Density [g/cm^3]	Thermal Conductivity [W/mk]	Thermal Diffisivity [mm^2/s]	Specific heat [MJ/m^{3}K]	E [GPa]	ε_{max} [mm/mm]	σmax [MPa]
EFR10	0.98±0.34	0.232±0.004	0.219±0.007	1.063±0.028	0.52±0. 06	0.044±0.002	15.07±1.10

2.2 Cores

The materials used in elaboration of the cores are aw and composite with petiole wood particles. Raw petiole wood (BPB) was used for raw materials. The development and study of petiole wood particle (CBPx, x: 1, 3, 5) composites used are described in the studies [22]. In addition, cork agglomerated with granules of 2 to 3mm (PL3) was used to compare the properties obtained according to the nature of the core. Figure 4 presents the different materials used as the cores in sandwich structured composite.

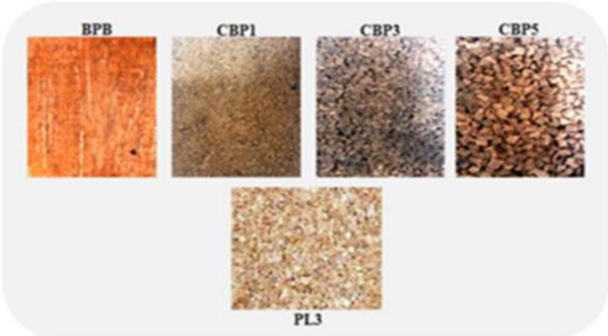

Figure 4. Materials used as the core of novel bio-composites with a sandwich structure

3. PREPARATION OF SPECIMENS

The preparation of new sandwich-structured composite plates was carried out by a method of direct adhesion with the skin matrix without the use of adhesive. This is done using a removable plastic mold used for the skin molding (EFR10). This allows us to obtain skin with smooth surfaces.

Next, the sheets of agglomerated cork (PL3), raw wood (BPB), or particles (CBPx) are placed on these molds for 20 minutes to obtain the bonding of the first side of the sandwich structured composite. In this case it depends on the property of the chosen matrix [21] and the weight of the core plate to be glued. Under the same ambient temperature conditions of 30°C, the second skin is glued using the same bonding protocol as the first.

Finally, after stabilizing the plates obtained from composite structure in sandwiches for 72 hours in an oven at a constant temperature of 25°C (Figure 5), the specimens were cut using a diamond disc saw. The specimens obtained after cutting are coded according to the nature and particle size of the core (SBPB, SBP1, SBP3, SBP5 and SPL3).

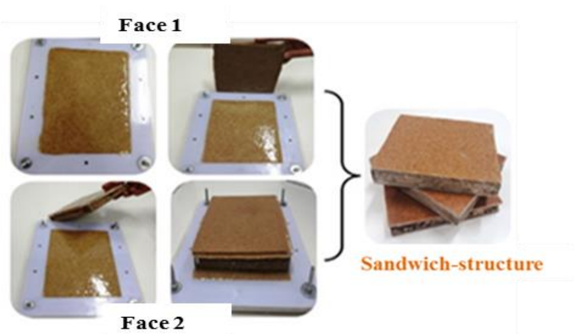

Figure 5. Protocol for the preparation of new sandwich-structured composite plates

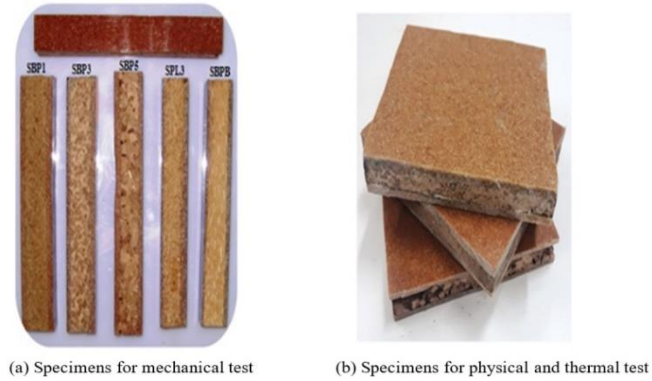

Figure 6. Sandwich structured composite specimens

Figure 6 represents standardized specimens obtained after cutting for physical, thermal and mechanical testing.

4. PHYSICAL AND THERMAL TEST

4.1 Density

The density is measured on six specimens from each sandwich structured composite plaque produced according to standard NF B51-005 (AFNOR, 1985a). We determine the weight of each sample at 12% moisture using an electronic balance (Kern V3.1) with an accuracy of 0.0001g. Moreover, this in a closed field conditioned at 20°C and 65% humidity. The specimen's size is determined geometrically. Dimensions are measured six times for one specimen using a measuring instrument with an accuracy of 0.01mm. The density (ρ) at 12% humidity, expressed in (g/cm³), is calculated according to the following relation.

$$\rho_{12\%} = \frac{m_{12\%}}{V_{s/12\%}} \tag{1}$$

where, $\rho_{12\%}$ is the density at 12% moisture, $m_{12\%}$ is the mass at 12% moisture, and $V_{s/12\%:}$ is the average volume of the specimen at 12% humidity.

4.2 Thermal properties

measured on specimens with dimensions of (100*100*20) mm^3, Measured with a HOT Disk TPS 500 thermal characterization device with a maximum temperature probe of 60°C. The measurements were made under 36°C temperature and 60% humidity. The measured thermal properties are thermal conductivity, thermal diffusivity, and specific heat of the sandwich's specimens, different by core type.

5. MECHANICAL CHARACTERIZATION

5.1 Three-point bending tests

The three-point bending tests on the sandwich beams make it possible to determine the overall modulus of rigidity of each type of these elaborate sandwiches. These tests were conducted on specimens of a beam size (140*20*20) mm^3 according to NF EN ISO 178 and ASTM C393-62. They were carried out by applying the load in the direction perpendicular to the upper surface of the specimen. The specimen was placed on two supports 80mm apart (Figure 7). These tests were conducted on a universal machine type INSTRON 5969 using a 5KN capacity cell with a 1mm/min displacement speed.

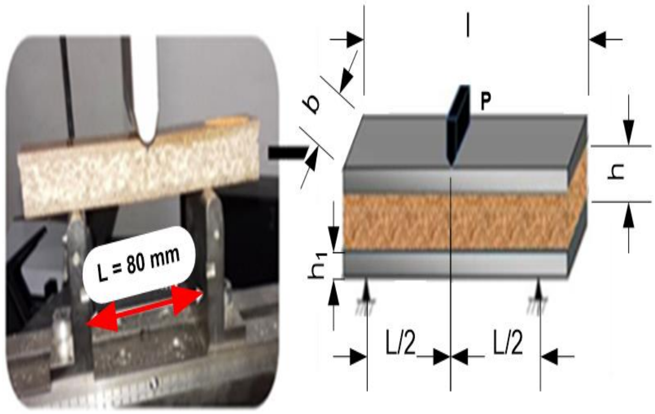

Figure 7. Sandwich beam specimens in three-point bending test

The sandwich beam dimension of length l and width b consists of two symmetrical skins of thickness h_1 and a core of thickness h stressed in bending three points.

The mechanical characteristics were calculated from the load-displacement curve obtained by five three-point bending tests for each type of sandwich beam.

The deflection δ of the sandwich structure at the loading point in the case of three-point bending tests is due to bending and shears deformations. Shear deformation is dominant in the core of the sandwich. Therefore, the elastic deflection can be expressed as follows [10, 11, 23, 24].

$$\delta = \delta_f + \delta_c \quad (2)$$

$$\delta = \frac{PL^3}{48D} + \frac{PL}{4S} \quad (3)$$

$$\delta = \left[\frac{L^3}{48D} + \frac{L}{4S}\right]P \quad (4)$$

$\delta = [F_G]P$ or $P = [D_G]\delta$

with;

$$D_G = \frac{1}{F_G} \quad (5)$$

P: The charge applied in the medium;
D: The bending rigidity of the sandwich;
S: Shear stiffness of the core;
F_G: The overall flexibility of the sandwich;
D_G: The overall stiffness.

The overall stiffness D_G is determined experimentally by the three-point bending test, where D_G represents the slope of the load-displacement curve. Eq. (5) is valid only for the beginning of bending tests when the deflection is relatively small (elastic zone) [7, 8].

5.2 Observations of fracture surfaces after three-point bending tests

This macroscopic analysis is based on taking digital photos of the samples and the fracture surfaces of the different types of sandwiches produced. These images are taken during continuous three-point bending tests until the specimen is destroyed. Images captured every 30 seconds with a camera fixed at 40cm from the test specimen are selected. From this experiment, we can determine the type of rupture and endurance for each type of structure depending on the type of core used. An electron microscope, TESCAN VEGA3, was also used to investigate the matrix/fiber cohesion at the skin level after the specimen was fracture. Samples were frozen in liquid nitrogen, broken, mounted, coated with silver, and observed using an applied voltage of 10kV.

6. RESULTS AND DISCUSSION

6.1 Density

The results obtained by calculating the volumetric mass of the sandwich-structured composite with different bio-cores are presented in the following Figure 8.

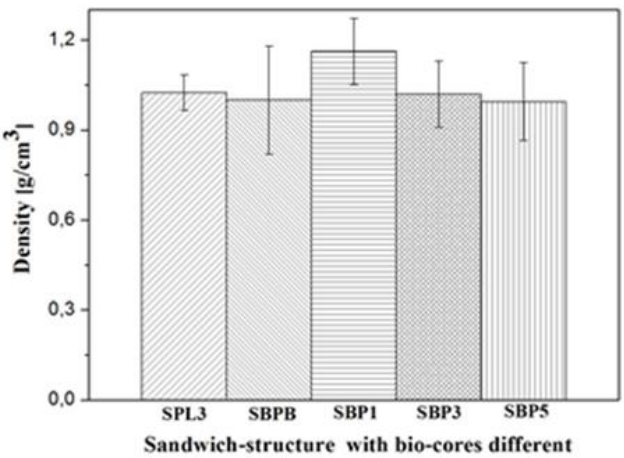

Figure 8. Density of sandwich-structured composite with different bio-cores

It can be seen from the results presented in Figure 8 that the density values of the sandwich-structured composite change depending on the type of bio-core used. The density values of SBP1 were much higher than the others. This is due to its high, core density value, which ranges between 0.50 and 0.56 g/cm^3. The density values of the structures SBP5 and SBP3 with SBPB of the raw wood core are remarkably identical. Values range from 0.68 to 1.56 g/cm^3. In general, using date palm waste as the core of the sandwich-structured composite gives the composite a density that can be considered very acceptable compared to the use of cork, as shown by the results in Table 2. Low density values for sandwich-structured composite are technically desirable, but variation in values obtained due to different cores can affect the mechanical and thermal properties of composite.

Table 2. Physical and thermal properties of new sandwich-structured composite

Properties	Thermal			Physical
Materals	Thermal Conductivity [W/mk]	Thermal Diffisivity [mm^2/s]	Specific heat [MJ/m^{3}K]	Density [g/cm^3]
SPL3	0.156±0.002	0.406±0.020	0.618±0.040	1.024±0.381
SBPB	0.161±0.011	0.407±0.004	0.596±0.002	0.999±0.332
SBP1	0.177±0.001	0.355±0.009	0.658±0.012	1.162±0.400
SBP3	0.176±0.001	0.341±0.016	0.662±0.008	1.019±0.320
SBP5	0.152±0.004	0.403±0.018	0.613±0.039	0.994±0.312

6.2 Thermal properties

We can observe that the thermal property values given in Table 1 for the materials used as cores in the sandwich of the new structure directly impact on the measured thermal property values of the new sandwich structure s, as shown in Figure 9.

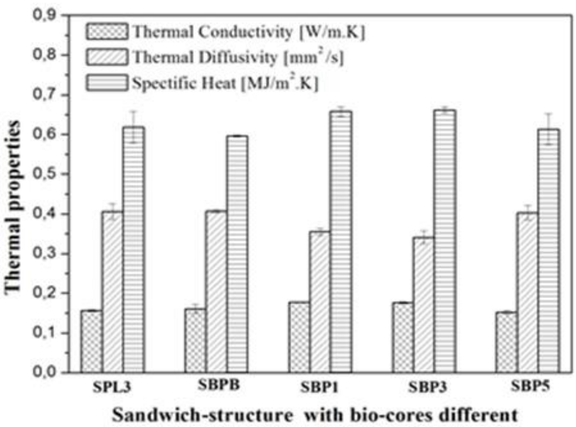

Figure 9. Thermal properties of new sandwich-structured composite with different bio-cores

We observe that the thermal conductivity of sandwich-structured composite (SBPx) materials decreases with increasing core particle size used. The values become very close to the thermal conductivity value of the composite with a cork core. Bio-composite (SBP5) has the lowest thermal conductivity value, 0.0148 to 0.0156W/mK. Generally speaking, a structure- sandwich with a date palm wood core, whether raw or particle has good thermal properties and can be considered a good insulator.

These results are considered very acceptable compared to those obtained with coconut wood, linen, wood fibers, and cork, which are between 0.042 and 0.087W/mK [24-26].

The results obtained by thermal and physical measurements on different sandwich specimens are presented in Table 2.

6.3 Three-point bending tests

The results of the three-point bending tests on different sandwich beams based on date palm tree (SBPB, SBP1, SBP3, and SBP5) are presented by load-displacement curves (Figure 10). The curves give the evolution of the applied load as a function of the arrow taken in the middle of the beam for different types of core. In all cases of the types of sandwich-structured composite tested, the three-point bending mechanical behavior is similar. The three main phases are a linear increase of the applied load with the deflection, a nonlinear behavior up to the maximum load, and the fall of the load until the final rupture of the specimen.

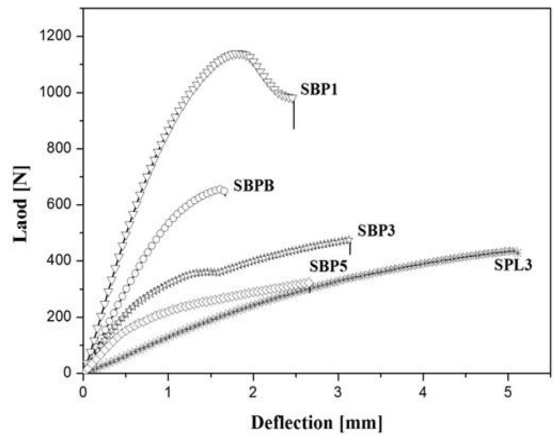

Figure 10. Example of load-displacement curves during three-point bending tests on different sandwich-structured composite beams

In the linear part, the overall stiffness D_G is determined by calculating the slope of the load-displacement curve (Formula 5).

The experimental values of the overall stiffness D_G (N/mm) and the maximum load of the new sandwich structure studied obtained from the load-deflection curves are presented in Table 3.

Table 3. Results of the three-point flexure test for new sandwich structure d composite specimens

Specimens	P_{max} [N]	δ_{max} [mm]	D_G [N/mm]
SBPB	551.33±120.8	2.82±1.79	550.23±7.74
SBP1	1058.69±70.04	1.91±0.06	818.91±32.77
SBP3	402.14±67.56	3.18±0.15	485.90±17.06
SBP5	329.93±16.64	3.06±0.44	355.83±34.74
SPL3	351.02±115.60	6.00±2.50	128.99±8.56

According to the results obtained and presented in Table 3.

We note that overall stiffness and maximum force values vary according to the type and size of particles used in the core. These results show an acceptable average of the standard deviations concerning the overall stiffness D_G measurement, with values reaching 23%. This is due to similar conditions when performing mechanical tests. Note that there is an improvement in the overall stiffness values of sandwiches with a particle core of petiole wood (CBP1) compared to the core of raw petiole wood (BPB), while the values of overall stiffness decrease with the increase in the size of the core particles CBP3 and CBP5.

On the other hand, it should be noted that the overall stiffness in petiole-based sandwiches is higher compared to sandwiches with an agglomerated cork core SPL3 (Figure 11). The variation in the values of overall stiffness in sandwich-structured composite depends on the nature and size of the core particles. Moreover, the variation of the overall stiffness according to the nature of the skins was studied by several researchers for the different sandwich-structured composite with cork core (PL3) [15, 18, 27, 28]. The results obtained were greater than the value of the overall stiffness of SPL3. This is due to the elasticity modulus of the skins used.

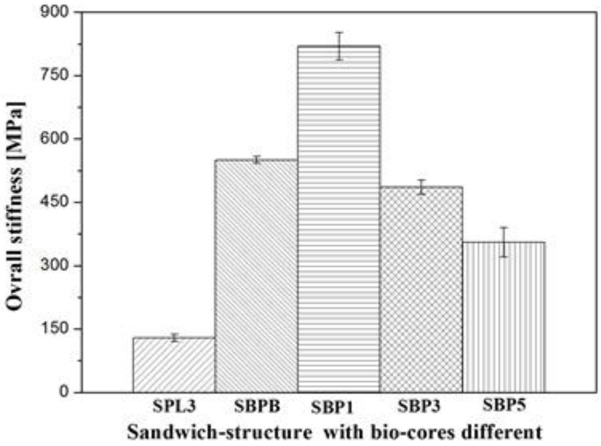

Figure 11. Variation of the overall stiffness of new sandwich structure d composite to different nature and size of the core particles

6.4 Observations of fracture surfaces after three-point bending tests

Digital images of the specimens are obtained during the bending test; they show the diffusion of the rupture surfaces of the different types of sandwich-structured composites tested by the three-point bending force.

Figure 12 allows us to observe the steps leading to the rupture of a sandwich structure specimen during the three-point bending test.

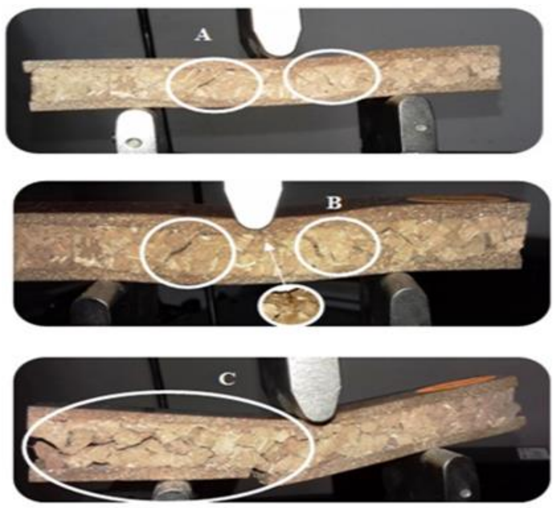

Figure 12. Macroscopic observations of the fracture stages of a specimen

These macroscopic observations observed two types of core failure: transverse shear failure "A" and longitudinal shear failure "C". The sandwich fracture begins with core damage by transverse shear failure "A". This is followed by compression damage to the upper skin. This deformation step is detected on the curves of Figure 10 after the linear part of the curves. The transverse shear failure began to develop from the upper skin and core "B" followed by the longitudinal shear in the medium plane to the end of the specimen "C" and thus the final ruin of the new sandwich-structured composite.

Figure 13 shows the fracture faces of the various sandwich-structured compositees (SBPB, SBP1, SBP3, SBP5, and SPL3) after the three-point bending tests. Skin repture and the examination area are also visible through the electron microscope.

From the macroscopic observation of the fracture surfaces of the sandwiches, a transverse rupture along the width of the specimen in the skins, visible in Figure 13 (F). Concerning the ruptures in the core of sandwiches, two different types of ruptures are noted according to the nature of heart. Transverse rupture in the cork core SPL3 (Figure 13 (C)) and longitudinal and transverse rupture according to fiber direction SBP1 (Figure 13 (B)) and SBPB (Figure 13 (A)). For particle sizes greater than 1mm, core breaks are tortuous through particles SBP3 (Figure 13 (D)) and SBP5 (Figure 12 (E)).

This difference may be due to the nature and size of the granules of the cores. The larger the particle size, the larger the space between them, thus increasing the ratio of the natural bonding matrix. This explains the propagation of the fracture around the core granules. We also observed that despite the complete crash of the different sandwich structure involving different cores, there was no damage between the skin and the core in this bio-composite. This may be due to the technique used to prepare these structures, the matrix's nature, and the material's morphology used as the core.

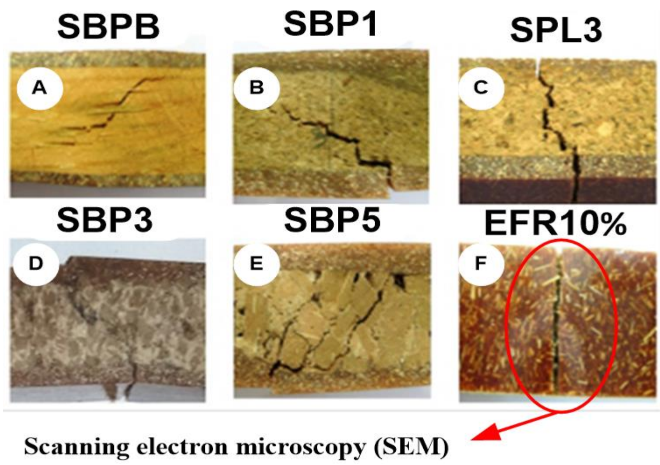

Figure 13. Macroscopic observations of the fracture surfaces of the various sandwich structures

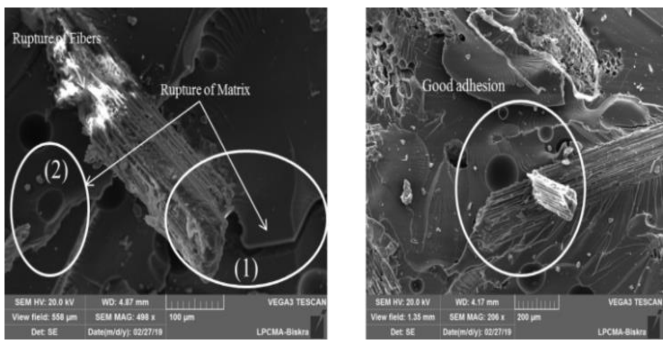

Figure 14. SEM micrographs of the skins after the three-point bending test

Figure 14 show SEM micrographs of fracture surfaces of skin bio-composite materials. Significant damage can be observed in the matrix, as there are two types of fractures; as shown in Figure 14 (a). However, despite the matrix's; destruction and the fibres' rupture within the skins, there is a good connection between the fibers and the matrix. This property could be the origin of the good mechanical properties of the new structure- sandwich.

7. CONCLUSIONS

This study conducted a physical, thermal and mechanical characterization of a new sandwich structure composite. The new sandwich structure composite was prepared with identical skins (Epoxy/fibers) but with different cores (Raw petiole wood, Petiole wood particle and, Cork agglomerated).

The load-displacement curves obtained by the three-point bending tests made it possible to calculate the overall stiffness D_G of each type of this bio-composite with sandwich-structured composite.

The overall stiffness value of the sandwich with a core particle size 3 is high compared to the core of raw petiole wood. The overall stiffness of palm wood-based sandwiches is higher than those with an agglomerated cork core. This is due to the type of matrix used and the morphological characteristics of the core used extracted from date palm wood, which is considered a very porous material.

The macroscopic observation of the fracture faces shows good adhesion between the skin and the heart. This is due to the method used in the bio-composite preparation, which shows its relevance since delaminating between the skin and the heart is absent.

This new type of sandwich-structured composite has good thermal properties because the thermal conductivity below 1W/m K is between 0.0148W/m K and 0.0178W/m K. It is also characterized by its low volumetric mass, less than 1.2g/cm^3. These properties are attracting interest, particularly in the insulating panel industry. This product will also be inexpensive, Ecological and recyclable.

In conclusion, using materials extracted from the date palm tree waste (Fibrous wood and Fibers) associated with the chosen implementation to prepare novel bio-composite with sandwich structures yields satisfactory physical, thermal, and mechanical properties. This makes it a good bio-insulator that we can count on in the thermal insulation adapted to the environment, especially the desert environment characterized by high temperatures exceeding 40°C.

Thus, we can utilize date palm waste by manufacturing low-cost ecological and efficient insulation structures because unexploited waste that is burned in the palm groves.

We can also emphasize the need to research new types of matrices used as skins. Then, study their effect on this new sandwich-structured composite's physical, thermal, and mechanical properties. Such a study opens the door to greater repurposing of this waste.

ACKNOWLEDGMENT

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NOMENCLATURE

CBPx,x:1,3,5	petiole wood particle
EFR10	composite materials 10% fibers
SBPx,x:1,3,5	sandwich structure d composite of different sized cores