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Research paper



Proposal of Sandwich Composite from Bioresource and Polystyrene Waste Materials

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Abstract

Lately there is a renewed interest in the use of bio-resource materials for the production of ecological, sustainable and inexpensive building materials. Sandwich composite of minimum plastic matrix was manufactured, this was achieved by using the Thermoforming process in two steps. In the first step, the core layer was made when thermo pressed 100% hemp Shive particles under a high pressure. The second step was accomplished by wrapping the core layer with two thermoplastic composite layers of 60% of hemp tissue and 40% recycled Polystyrene. Interestingly, through the first step, elevated temperature treated the core surface (hydrophilic) and gave it greater adherence to the Polystyrene matrix (hydrophobic). Mechanical properties of this proposed sandwich composite of 80 % bio-resource were approximately four times of the Polystyrene resistance. Furthermore, the microscopic study was performed to investigate the bonding of the different components, especially for the binderless core layer. Each individual layer and the sandwich form were mechanically investigated, and the finite element method, via ANSYS, was used to illustrate the stresses in the sandwich structure.

Keywords: *Hemp Shive; Hemp Tissue; Recycled Expanded Polystyrene; Sandwich Composite; Thermoforming Process.*

1. Introduction

Evidence suggests that the use of agro-materials is an important environmental issue[1][2]. Thermoplastic composites of hemp fiber, when manufactured under high pressure, are equivalent to or slightly better than the composite of glass fiber at the same mixing ratio [3]. This indicates that hemp fiber composites have the potential to replace glass fiber composites [4][5]. The stem of the hemp plant has two main components. The first one is 30% hemp fiber, which has values of 857 MPa and 58 GPa for the tensile strength and modulus of elasticity, respectively [6][4]. Hemp fibres are usually used to produce hemp yarn [7]. however the mechanical interlocking between individual fibres of yarn is insufficient to transfer the tensile stress between the fibres, it is recommended to use a suitable binder to obtain the maximum properties. Another problems with plant fibres are that they are short in length and contain variable properties due to their nature which can affect the composite strength. Therefore, converting plant fibres into yarn is the best solution to overcome these problems. Yarn enables the fiber proportion to increase and the composite to obtain oriented reinforcement (unidirectional or bidirectional composite)[8].

The second component of the hemp plant stem is 55% woody core (hemp Shive) [9]. The first most important priority of this study was to evaluate hemp plant (hemp yarn and hemp waste (Shives)) to obtain green composite. Hemp Shive particles are classified as an agro-industrial waste after the extraction of hemp fiber. The high percentage of lignin (15 - 30) inside the hemp Shive particles can be softened to obtain its plasticized polymer (natural adhesive material)[10][11][12][13], by which a binderless composite can be produced to obtain the core layer. However, the binderless composite (100% hemp Shive particles) collapses when coming into direct contact with water[13], and therefore must be protected against water to increase its durability. The second important priority of this study was to reduce the negative impact of the expanded Polystyrene waste (EPSw) on the environment [14] [15] and give a new idea for using dissolved Polystyrene [16]. Acetone is a good solvent to Polystyrene, but it needs more than three weeks to evaporate. Therefore, fresh Polystyrene paste needs to an absorbent substance (natural fiber) to evacuate the acetone during short time. Then evaporate it through the shrinkage micro cracks, more than 95 % of acetone will evaporate within three hours when mixed with more than 50 % of hemp fiber. Acetone is preferable over many other organic solvents because of its low health hazards and its ability to be recovered through distillation [17] and reused. Furthermore, many chemical treatments for natural fibresare based on acetone solvents [18] [19]. The dissolved expanded Polystyrene (DisEPS) was used as a viscous matrix instead of a thermoset resin (non-recyclable polymer) [14] to produce a fully recyclable bidirectional composite (BDCOMPS). Due to the significant differences between the mechanical properties and the water resistance of binderless hemp Shive composite and bidirectional hemp tissue composite, it is best to use the sandwich form. The sandwich concept is usually used to protect a thick, weak core layer with two thin, high-resistant layers to modify the mechanical properties of the whole structure (stiffness and strength to weight ratio)[20][21].

The aim of this study is to propose a new process of manufacturing bio-resource sandwich composite of minimum Polystyrene content. Therefore, the mechanical properties and the flexural

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behaviour were investigated in order to characterize this green composite. Then the experimental data have been used in the numerical simulation by finite element (ANSYS) to validate a simple model which can developed to predict the critical stresses in the complex sandwich form (honeycomb or other structure form). Despite the importance of reuse the plastic waste, there remains a paucity in the technical process to reduce the plastic matrix inside the green composites (to be less than 20%).

2. Materials and Sample Preparation

This section describes firstly the raw materials that have a market value: the hemp tissue and the acetone solvent and secondly the waste materials: the hemp Shive particles and the expanded Polystyrene. It demonstrates also the manufacturing process by which a new ecological composite has been attained.

2.1. Materials

The hemp tissue had values of (385 ±35 g/1000m) for the linear density, (1.268 ±0.038 gm/cm^3) for the apparent density, (0.310 ±0.044 mm^2) for the cross sectional area, and (99 ±18 MPa) for the yarn resistance[22]. Hemp Shive Particles were purchased from CHANVRALIT France Ltd. They were washed with water and then air-dried at 100 ℃ for 24 hours. After that, they were ground by the universal cutting mill (PULVERISETTE 19)(figure 1) to obtain a particle size of less than 0.5 mm. The expanded Polystyrene waste, which had a density of (0.015 gm./cm^3), was collected from a destroyed building and then dissolved with acetone (figure 1). The acetone was purchased from ARDEA France Ltd. The saturation percentage of the acetone was 45% wt. (acetone/Polystyrene solution), resulting in a viscous liquid of Polystyrene with a density of (0.96 gm./cm^3), meaning that the volume was reduced by 98.4% from the original volume of the polystyrene waste.

2.2. Sample Preparation

The samples were prepared with aluminium moulds of (50 × 50 ×50 mm2) for the individual components (core and face layers), and (160 × 15 × 5 mm) for the sandwich samples. The core layer (100% hemp Shive particles) was thermo pressed at a pressure of 20 MPa for 30 minutes and at temperatures of 130, 150, 170 and 190℃, in order to investigate the temperature effect, then cooled to 60 ℃ under the same pressure. After that, the samples were released from the moulds (Figure 1). The effect of particle size on the mechanical properties are described in reference [13]. Therefore, particle size of less than 0.5 mm was used in this study. The facing layers, which consisted of a bidirectional composite (BDCOMP) of hemp tissue impregnated with dissolved Polystyrene, were pre-formed by the cold moulds at a pressure of 5 MPa. After acetone evaporation, this composite was thermo pressed at a pressure of 20 MPa and a temperature of 130 ℃ for 30 minutes, and then cooled to 60 ℃ under the same pressure. The samples were then released from the moulds (Figure 1). The manufacturing of sandwich sample was achieved by enveloping the core layer, immediately after the Thermoforming process at 170 ℃, in fresh BDCOMP of 60 wt. % of hemp tissue. During the following 10 minutes, the two faces of tissue layers, which had been impregnated by fresh dissolved Polystyrene, stuck to the core surfaces. Then, cold mould pressure of 5 MPa was applied to ensure the dispersion of the fresh matrix between the tissue layers and to transfer the matrix to the bonding surfaces with the core layer. The acetone was evaporated from BDCOMP60 (free evaporation during 24 hours. or by a vacuum machine during one hour) before beginning the Thermoforming process of 20 MPa at 130 ℃ for 30 minutes (Figure 1).



Fig. 1: Arrows refer to recycle and manufacturing process until final product.

3. Methods, Results and Discussions

3.1. Flexural Strength and Modulus of Elasticity

According to ASTM D790, ISO 178, composite samples of 100% hemp Shive and BDCOMP of (50 ×50 × 2.75±0:25 mm) were prepared individually then divided to five specimens of (50 ×10 × 2,75±0:25), the results of which were recorded by the universal tester (TA-XT2i) of cell load of (500 N) and crosshead speed of (6 mm/min) at 3-point of load. Then, the mean for the maximum flexural strength and the modulus of elasticity were calculated.

3.1.1. Effect of Thermoforming Temperature on the Core Layer Properties

The temperature had a direct effect on the mechanical properties in the presence of the high pressure of 20 MPa. The flexural strength increased up to 228 % when the temperature increased, even to 190 ℃, (Figure 2). This can be explained by the fact that the lignin components underwent some softening inside the hemp Shive particles and were then extracted to the outside of the particles due to the high pressure effect. These results were in agreement with those obtained from Kenaf core composite [12]. The dispersion of the results for each manufacturing temperature (Figure 2) can be explained by the fact of the agglomeration of the particles and the matrix quantity (the lignin). Indeed, the critical temperature for degradation of lignin composition occurs between 170 and 176 ℃ [23][24].

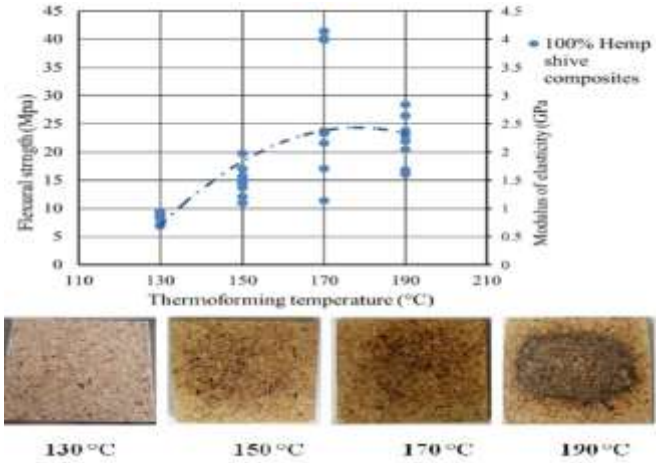


Fig. 2: Effect of thermoforming temperature on the mechanical properties.

The elevated temperature (170 ℃) can decrease the accessibility of the hydroxyl group to water and increase the dimensional stability of the hemp Shive particles [25][26], which would modify the adhesion between the particle surfaces and the Polystyrene matrix. However, at 190 ℃, we observed a spot of overheat degradation in the middle of the sample due to heat and vapour concentration.

3.1.2. Effect of Hemp Tissue Proportion on Facing Layer Properties

The mechanical properties of BDCOMP, which were thermoformed at a temperature of 130 ℃ and pressure of 20 MPa for 30 minutes, is illustrated in Figure 3. This high pressure was used to ensure the dispersion of the matrix between the hemp fibres and to eliminate the maximum amount of porosity. The mix proportion has been investigated in the composite, the highest percentages proportion were between 55 and 60 wt. % of hemp tissue. The mechanical properties will decrease after this mix proportion because there has not sufficient matrix to transfer the stresses between yarns. This observation was in accordance with the Equation 1, which determines the maximum yarn proportion in the composite [27].

$$V_f^{max} = \frac{0.7\pi}{4}\,(1 - 0.78\,e^{-0.0195\,T}) \quad (1)$$

T = twist number per one meter of length.

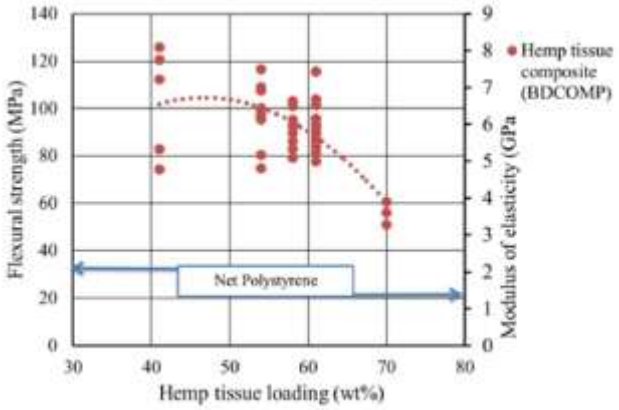


Fig. 3: Effect of hemp tissue load on mechanical properties.

The composite of 60 wt. % of hemp tissue absorbs only 4% after 24 hours of immersion in water. Therefore, it was adequate to protect the core layer against water contact.

3.2. Flexural Behaviour of Sandwich Composite

In the flexural test, the sandwich composite had more resistance and rigidity than each of its three components, Figure 4. These mechanical properties can be adapted to produce many high resistance engineering materials such as the skateboard deck, "Figure 1". According to the market selection and certification program for green building, this sandwich is preferable to be used as an internal finishing material (ceiling and walls) for a new green building. Indeed, this sandwich provides better modulus of rupture than most of wood types (≤ 117 MPa). It can be used for internal decorative panels.

There was no separation between the face layers and the core layer due to the Polystyrene matrix. Whereas the failure occurred due to shear stress that concentrated in the middle of the core layer, which had insufficient matrix (only 15 to 30% of hydrolyzed lignin) to transfer the stresses between the compressed hemp Shive particles (Figure 7 a). The maximum shear stress value can be calculated, according to ASTM (D2344), by the Equation 2.

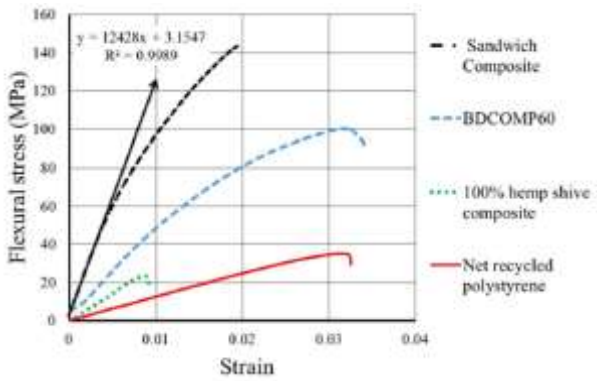


Fig. 4: Typical stress-strain curves for individual components and sandwich form.

$$\tau_c = 0.75\frac{P_m}{bh} \quad (2)$$

where τ_c, P_m, b and h represent shear stress in the core layer (MPa), maximum rupture load (N), width and total thickness in (mm) respectively.

There are no large differences in rigidity between the face and core materials ($E_f/E_c \leq 1.6$). Therefore, the normal stresses in the symmetric sandwich section can be calculated by the Equation 3 when the original sandwich section is equivalent to the I-section of one elastic material (Figure 5).

$$\sigma^{max} = \frac{M.z}{I_{eq}.E_c} \quad (3)$$

$$\sigma_f^{max} = \frac{P.l\left(t_f + \frac{t_c}{2}\right).E_f}{4.I_{equ}.E_c} \quad (4)$$

$$\sigma_c^{max} = \frac{P.l\left(\frac{t_c}{2}\right).E_c}{4.I_{equ}.E_c} \quad (5)$$

$$\text{Displacement} = \frac{P.l^3}{48.I_{equ}.E_c} \quad (6)$$

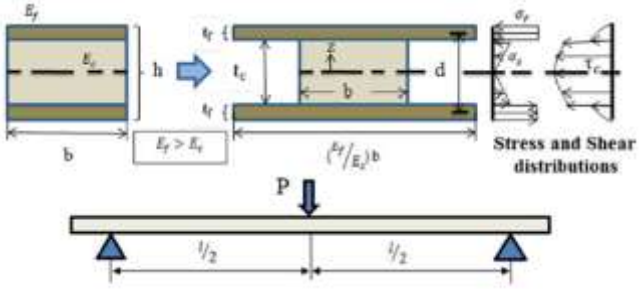


Fig. 5: Shear and stress distributions on transformed equivalent section of sandwich composite.

For simply supported beam of 3-point load, the maximum moment in the mid-span is ($M = P_m.l/4$), while the equivalent moment of inertia ($I_{equ.}$) of the transformed section can be calculated by the Equation 7 [28].

$$I_{equ} = \frac{\left\{\left(\frac{E_f}{E_c}.b.h^3\right) - \left(\frac{E_f}{E_c}.b - b\right).t_c^3\right\}}{12} \quad (7)$$

where h (or z), l, and tc represent the distance from the neutral axis, the span between the two supports, and the core thickness in (mm), while E_f and E_c represent the moduli of the face and core material (MPa), respectively.

This simplification allows to get a relationship between the thickness of each layer. This relation (Equation 10) can provide the typical thickness of each layer (economical section) since both materials of a symmetrical sandwich composite reach the maximum resistance at the same time (corresponding to the stress and the stiffness of each layer) [29].

$$\frac{M}{I_{equ}} = \frac{\sigma_c^{max}}{z} = \frac{\sigma_f^{max}}{z} \quad (8)$$

$$\frac{\sigma_c^{max}}{\frac{t_c}{2}} = \frac{\sigma_f^{max}}{\frac{E_f}{E_c}(t_f + \frac{t_c}{2})} \quad (9)$$

$$t_c = \left| \frac{2t_f}{\frac{\sigma_f^{max}.E_c}{\sigma_c^{max}E_f} - 1} \right| \quad \text{Where } \frac{\sigma_f^{max}.E_c}{\sigma_c^{max}E_f} \neq 1 \quad (10)$$

3.3. Numerical Simulation

A three dimensional simply supported sandwich of 3-point load was developed in order to compare the numerical and the experimental results. The numerical simulation was performed with the finite element software ANSYS. Static analysis of linear elastic and isotropic materials was conducted, considering the convergence time of the analysis, while the mesh (element size) was introduced as small as possible, considering the accuracy of the results. Figure 7(b and c) illustrates 50,566 quadratic elements of 8-nodes. To validate the macroscopic behaviour of bending sandwich, a perfect bond was assumed between the three layers. Force-displacement curve (Figure 6) can be used to compare numerical and analytical model with the experimental results, to verify each one is more adequate.

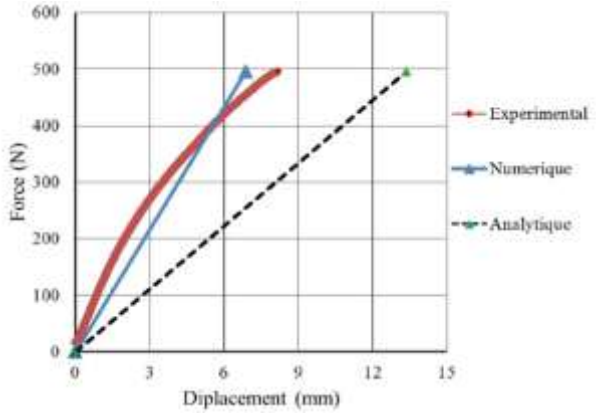


Fig. 6: Force-Displacement diagram for experimental, numerical and analytical model.

This result confirms: firstly, that the numerical model is more adequate to predict the stresses for any element. And secondly, that the mechanical properties which used in the model were very well experimentally defined (Table1). This table shows the experimental mechanical properties for each layer and the comparison between the analytical and finite element results of the simple supported sandwich.

Table 1: Input composite properties and comparison between analytical and numerical mechanical properties of sandwich composite under same maximum rupture load of 496 N.

Composite	σ MPa	E GPa	Poisson's ratio	Thickness mm	Analytical results (MPa)	Numerical results (MPa
BDCOMP 60	104 ∓15	4.88 ∓0.65	0.3	t_f=1.4	σ_f^{max}= 99.57	σ_f^{max}= 104.07
100% hemp Shive comp.	27 ∓11	3.12 ∓0.76	0.3	t_c=3.9	σ_f^{max}= 58.08 τ_c=3.71	σ_f^{max}= 59.7 τ_c=5.24

(σ and E represent flexural strength and modulus of elasticity respectively)

In the last two columns of the table, analytical and numerical results show that the tensile stress in the lower facing layer and core layer reached maximum stress values. While the numerical results of maximum shear stress exceeded the analytical results, this result predicts that the shear failure will occur in the middle of the core layer (Figure 7). This exactly what happened for the real sample test. Therefore, this numerical model can be used to predict also the effect of the thickness of each layer on the sandwich failure.

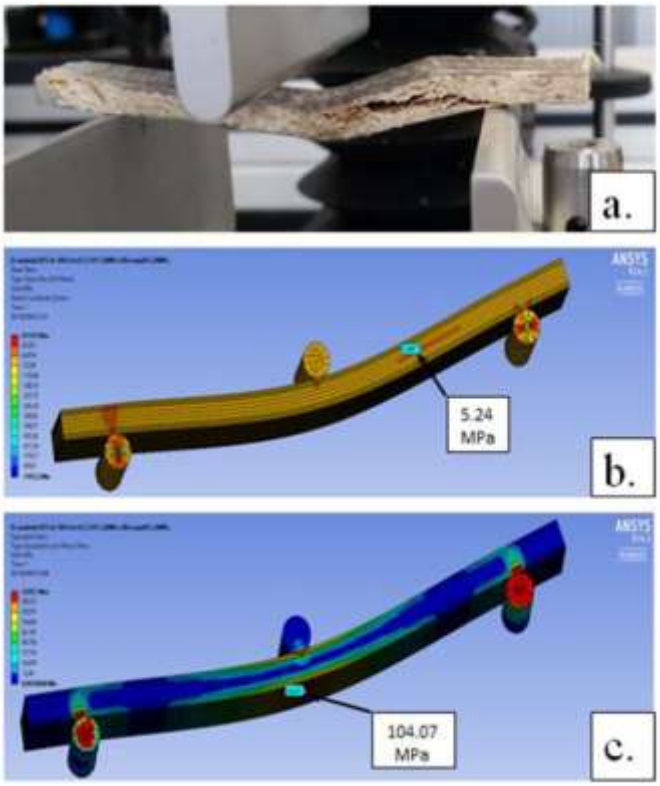


Fig. 7: Flexural test of 3-point of load, (a) Experimental (b) Numerical shear stress and (c) Numerical flexural stress

3.4. Microscopic Study

Scanning electron microscope (SEM) images of hemp fibres and hemp Shive composite are represented in Figure 8. It was observed that the hemp fibres were well surrounded by the Polystyrene matrix after the thermoforming process, (Figure 8a), and the Polystyrene matrix was responsible for transferring the stresses between the fibres. Therefore, it is preferable to surround all the fibres inside the hemp yarn.

When the hemp Shive particles contacted fresh DisEPS paste, (Figure 8b), these particles tried to absorb the acetone and attracted the Polystyrene, while the expanded gas bubble inside the fresh DisEPS paste pushed the thin layer of fresh DisEPS paste to contact the particles surface. This phenomenon would modify the compounding and the mechanical interlocking between the hemp Shive particles (core layer) and the Polystyrene which represents the matrix in the face layers. The lignin component in the hemp Shive particles was well softened at 170 ℃ and covered the exterior surface, (Figure 8c), working as a natural matrix to link the hemp Shive particles.

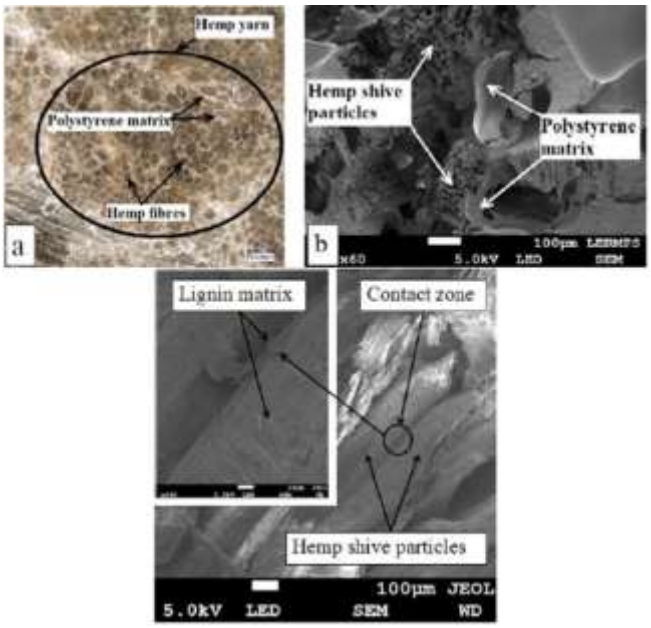


Fig. 8: SEM pictures of (a) hemp yarn composite, (b) contact between hemp Shive particles and fresh DisEPS paste, and (c) lignin matrix on exterior surface of 100% hemp Shive particles which were thermoformed at 170℃.

4. Conclusion

In this study, composites of 100% hemp Shive particles, composites of hemp tissue with recycled Polystyrene, and sandwich composite of less than 20% wt. of recycled Polystyrene, were manufactured. These materials characterized by high resistance, affordability, and being fully recycled, make them excellent options as ecological and sustainable materials. This sandwich has better mechanical resistance than the most of the woods and the particleboards as well as entirely free from the formaldehyde emission. The reasonable differences between the numerical and experimental results (due to non-linearity) will increase the confidence: firstly, the mechanical properties of each individual layer which were used in the numerical model. And secondly, the manufacturing process for assembling this sandwich material without needing for any adhesive materials between the layers. More research will be required to determine the thermal and acoustic performance, fire resistance, and biodegradability of these composites.

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