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Novel composite sandwich structure from green materials: Mechanical, physical, and biological evaluation

Ahmed S. O. Mohareb,[1] Ahmed H. Hassanin,[2] Alaa A. Badr,[2] Khaled T. S. Hassan,[1] Ramsis Farag[3,4]

[1]Forestry and Wood Technology Department, Faculty of Agriculture, Alexandria University, Egypt
[2]Textile Engineering Department, Faculty of Engineering, Alexandria University, Egypt
[3]Polymer and Fiber Engineering Department, Auburn University, Auburn, Alabama 36849
[4]Textile Engineering Department, Faculty of Engineering, Mansoura University, Egypt
Correspondence to: A. S. O. Mohareb (E-mail: ahmed_mohareb@yahoo.com)

ABSTRACT: Flax and Jute fabrics were used as reinforcements with polyester resin to form composite skins while poplar particleboard was used as a core for making composite sandwich structures by applying vacuum assisted resin transfer molding (VARTM) technique. Mechanical, physical, and biological properties of these novel composite sandwich structures were evaluated. The results showed that the proposed engineered panels have superior mechanical properties that are suitable for different structural applications compared with conventional particleboards. When compared with the control panels, significant enhancement on Modulus of elasticity (MOE) and Modulus of rupture (MOR) were achieved. On the other hand, the results indicated that the proposed panel composites exhibit better dimensional stability compared with poplar particleboard control panels. In addition, the proposed composite sandwich structures proved resistant against the decay fungi after 12 weeks of fungal exposure. Obviously, the developed composite panels could be used in a wide variety of applications. © 2015 Wiley Periodicals, Inc. J. Appl. Polym. Sci. **2015**, *132*, 42253.

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INTRODUCTION

The last quarter of the previous century brought a new generation of composite materials that are characterized by their high strength to weight ratio, high specific stiffness, excellent fatigue resistance, and outstanding corrosion resistance compared to most common metallic alloys, such as steel and aluminum alloys. Other advantages of composites comprise their ability to entertain directional mechanical properties, low thermal expansion properties, and high dimensional stability. It is a combination of outstanding physical, thermal, and mechanical properties that makes composites attractive to replace metals in many fields of applications, especially when weight saving is required. Composites are now used in aircrafts, helicopters, spacecrafts, satellites, ships, wind turbine blades, submarines, automotive industries, chemical processing equipment, sporting goods, and civil infrastructures.[1–3]

The majority of the current commercial composites are made from synthetic polymers that are petroleum-based. Using petroleum based composites is facing obstacles such as uncertain future of petroleum supply and price, and concerns about environmental pollution. On the other hand, agricultural derived biomass, as well as residues of wood industry are accumulating to problematic levels. It remains a major challenge to expand the sustainable and profitable use of these waste-treated residues as a raw material for value-added products which require innovative and environmentally friendly solutions.[4–6] Consequently, the utilization of biomass (green resource), has gained a huge attention from the researchers.[7,8] Green composites are made up from natural fibers (such as wood pulp, kenaf, hemp, Flax, Jute, henequen, pineapple leaf, sisal, etc.) and natural resins.[9–11] In the wood-based product industry, particleboard is known as a panel product manufactured from lignocellulosic materials, primarily in the form of a relatively small particles, combined with a binder and bonded together under heat and pressure. The main difference between particleboard and other wood products, such as wafer board, oriented strand board, medium density fiberboard, plywood, and hardboard, is the type of used materials and particles size. The major types of wood particles used to manufacture particleboard include wood shavings, flakes, sawdust, wafers, chips, sawdust, strands, and wood wool.[12] Table I Shows MOR and MOE values defined by EN 312 (2010) concerning boards for use in dry conditions in different applications.[13] VARTM technique was used in this work.

Table I. Mechanical Property Requirements for P1, P2, P4, and P6 Board Types According to EN312:2010[13]

	P1, general purpose board for use in dry conditions	P2, board for interior fitments (including furniture) for use in dry conditions	P4, load bearing board for use in dry conditions	P6, heavy duty load bearing boards for use in dry conditions
MOR (MPa)	10.5	11.0	16.0	20
MOE (MPa)	–	1800	2300	3150

This technique has been increasingly used for consolidation of fiber reinforced composite preforms.[14,15] This method was developed to reduce manufacturing costs and enhance the performance of composites processing by speeding up the process of resin infusion through preforms and obtaining composite structures with no or minimum voids in order to avoid defects and premature failure.

Various studies have been carried out to improve the mechanical and physical properties of wood particleboard using different materials and treatments. Huge efforts are being intensified to elaborate their applications.[16–22] The aim of this study is to develop and evaluate a novel sandwich structure (Figure 1) using a lightweight and relatively thick core materials in form of particleboard panels from local and cheap lignocellulosic resources attaching to two thin, and stiff woven fabric skins using VARTM technique to construct high performance structure for use in various technical applications.

EXPERMENTAL

Skin/Core Materials and Manufacturing

Skin Materials and Manufacturing. In this study, Flax and Jute yarns were used in weaving the two fabrics to be used in the skin layers. The Flax and Jute fabrics were produced in a local weaving company. Fabrics construction and specifications are given in Table II.

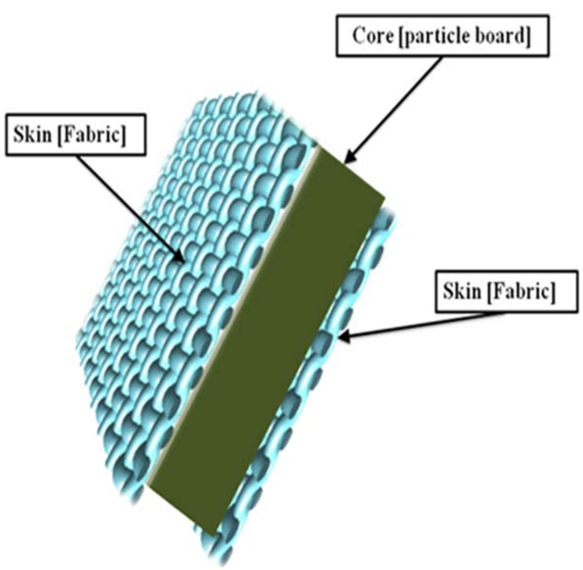

Figure 1. Sandwich composite structure [Skin/Core]. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

Core Materials and Manufacturing. Poplar veneer wastes were obtained from local factory for plywood manufacturing at Bourg El-Arab district, west of Alexandria, Egypt. A laboratory hammer mill was used for converting the veneer residues to wood particles which, consequently, screened on a vibratory screen shaker using 60 mesh size (250 micron openings). After screening, the particles were then oven dried to approximate moisture content of 3% based on oven dry weight. Manufacturing of single layer particleboards were carried out using poplar wood particles. The urea formaldehyde (UF) adhesive (60% of solid content) was used as a binding agent at 7% based on wood oven dry weight, 1% (W/W) of ammonium chloride was used as a hardener agent. The mixture was then blended using a laboratory blender for 10 min at room temperature (20–22°C). The panels produced with dimension of 300 × 300 × 7 mm at 0.60 g/cm3 fixed target density. The mat was then hot pressed for 2 min in a hydraulic laboratory press at a temperature of 160°C and a pressure of 2.5 MPa. The finished panels were conditioned for a week at 65% relative humidity and temperature of 25°C.

Sandwich Structure Assembly and Manufacturing. VARTM technique was used to manufacture the sandwich structures and attach the skin and core of the composite together. Figure 2 shows a diagram representing the mechanism of VARTM technique and Table III defines the construction specifications of the experimental composite samples. In this manufacturing technique, unsaturated polyester resin was used as the polymeric matrix and Methylethylketone peroxide (1% wt) was used as the curing agent. The amount of resin infused through the samples was adjusted to achieve around 50% fiber volume fraction. Figure 3 illustrates a real particle board during the infusion process. After infusion process the samples were left for 24 h under vacuum for completing the curing process.

Characterization of Composite Structure

Mechanical Tests. The mechanical characterization of the experimental samples was carried out at the laboratories of the Polymer and Fiber Engineering, Auburn University, USA. The flexural test was performed by using a computer controlled Instron® universal testing machine model 5565 equipped with a 10 kN load cell. The European standard EN 310 test method[23] was followed to determine the apparent MOE in flatwise bending and MOR of wood-based panels [Figure 4(a,b)]. At least

Table II. Construction and Specifications of Skin Fabrics

Skin	Structure	Warp material	Weft material	Warp count (Tex)	Weft count (Tex)	Warp density (thread/inch)	Weft density (thread/inch)
Jute fabric	Plain ft/1	Cotton/Polyester	Jute	58	386	24	22
Flax fabric	Plain ft/1	Cotton/Polyester	Flax	58	445	24	22

five specimens of each sample were used and reported the average values.

Dimensional Stability Tests. Water absorption (WA) and thickness swelling (TS) were evaluated from oven dry condition to water soak condition after immersion in water for 2 and 24 h and carried out as specified by ASTM D-1037.[24] The test specimens were immersed in a water bath at room temperature for 2 h, then were taken out and weighed. The samples were then soaked again to complete 24 h immersion time. The results of WA and TS after 2 and 24 h were expressed as a percentage of the original state. Before the WA test, density of the produced composites was determined based on the oven-dry weight and volume.

Biological Durability Tests. Laboratory decay tests using mini block specimens (10×10×10 mm) were prepared to assess biological resistance of the control and composites. Prior to biological testing with basidiomycetes, volatile inhibitory components such as formaldehyde were removed; otherwise will cause unrepresentatively high durability ratings to be determined for laboratory tests. The specimens were placed in a vacuum oven and heated to 40 ± 2°C at 10 mbar pressure for 3 days. The oven was vented for 1, 2, and 3 days by slowly releasing the vacuum and waiting for the temperature to return to 40°C.[25] Sterile culture medium (20 mL), prepared from malt (40 g), and agar (20 g) in distilled water (1 L), was placed in a Glass jar inoculated with a small piece of mycelium of a freshly grown culture of *Poria placenta* as a brown rot fungus and *Coriolus versicolor* as a white rot fungus. The cultures were incubated for 2 weeks at 22°C and 70% RH to allow full colonization of the medium by the mycelium. Samples were supported on sterile plastic mesh to prevent contact with the agar and incubated. All samples, previously oven dried at 105°C to constant weight, were sterilized with radiation and three blocks (two treated and one control) were placed in each Glass jar under sterile conditions, and all treatments were duplicated. Incubation was carried out for 12 weeks at 22°C under controlled humidity conditions of 70% RH in a climatic chamber WTB BINDER TYP KBF 240. At the end of the test period (12 weeks), mycelia were removed, and all specimens were oven-dried to constant mass at 103°C and weighed. Mass loss (ML) was expressed as a percentage of the initial oven-dried weight of composite samples according to the formula:

$$ML = \frac{M_0 - M_f}{M_0} \times 100 \quad (1)$$

where M_0 is mass of oven-dried sample prior to the test and M_f is mass of oven-dried sample after the test.

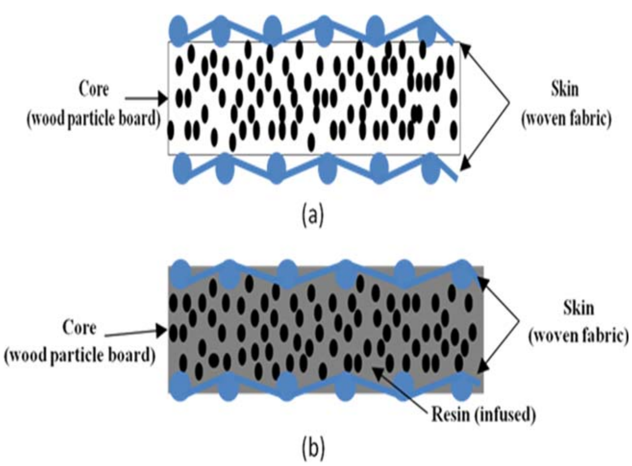

Figure 2. Schematic diagram for sandwich sample (a) before VARTM and (b) after VARTM. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

RESULTS AND DISCUSSION

Effect of Skin-Core Structure and VARTM Process on Mechanical Properties

The mechanical behavior in weft direction and areal density for the both tested skin fabrics were summarized in Table IV, it can be noticed that the skin fabrics construction specifications and tensile properties seem to be nearly similar for Jute and Flax fabrics. The low density and good mechanical performance for these fabrics are attractive parameters in manufacturing light weight material.

It was found interesting to see the effect of using polyester resin by applying the VARTM technique in manufacturing the wood based composites without skin. From Figure 5, it can be noticed that using VARTM in consolidation of the wood particleboard instead of just using UF alone, has a significant effect on MOR and MOE of wood particleboard. This can be attributed to the infusion of polyester (PET) resin through the whole structure of wood particle board which increases the bonding between particles, which consequently enhanced the mechanical properties. The effect of PET infusion can be very obvious in Figure 6 which clearly showing the presence of polyester resin in the void spaces in the modified composite structures.

On the other hand, the sandwich structure mechanical performance can be seen in Figures 7 and 8. The skin/core modified composites were found to have a significant enhancement in its MOR and MOE when compared to No-skin particleboard panels. Figure 7 show significant differences between MOR values of No-skin and sandwich structure either with Jute or Flax fabric skin. MOR value for No-skin sample is 37.6 MPa while

Table III. Materials and Construction of Samples

Sample	Core material	Skin material	Binder	Process	Structure
Control	Ground popular waste	no	Urea formaldehyde	Hot press	–
No-skin	Ground popular waste	no	Urea formaldehyde/ Polyester resin	Hot press/VARTM	–
Flax-skin	Ground popular waste	Woven flax fabric	Urea formaldehyde/ Polyester resin	Hot press/VARTM	Sandwich
Jute-skin	Ground popular waste	Woven flax fabric	Urea formaldehyde/ Polyester resin	Hot press/VARTM	Sandwich

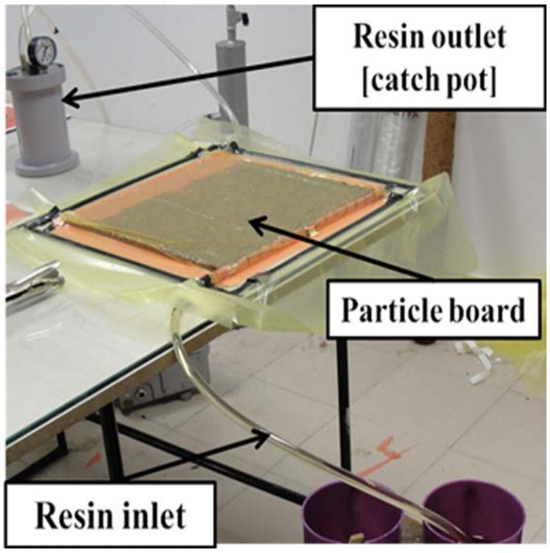

Figure 3. Sample during VARTM process. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

MOR values for Jute-skin and Flax-skin particleboards are 82.33 MPa and 78.1 MPa, respectively. Contrary to the expected outcome, Figure 8 shows a little difference between the MOE values of different modified composite structures (with and without skins). It is also shown the higher disperse in the No-skin composites compared to the fabric-skinned ones. This can be explained by the sandwich structure acts as an I-beam structure in which the skins, during bending, carry compression, and tension loads as the flanges do. On the other hand, the core carry the shear stress as the core does in the I-beam structure, which leads to high bending stiffness.[26] These findings lead us to an important fact that sandwich wood particle board structure will be more efficient in such applications that need high bending stiffness more than tensile. To exclude any effect of composite density or weight from the results, Specific Modulus of Rupture (SMOR) was calculated by normalizing all the MOR (MPa) values to the density (g/m^3) as shown in Figure 9. This normalization came in the favor of control samples but the main findings stay the same.

Failure mechanisms for a sandwich structure under flexure test can be basically summarized in three cases: (a) skin failure (top skin under compressing, lower skin under tension), (b) core failure, and (c) skin-core delamination. Normally, combinations from the previous cases could occur at the same time.[27–29] In our case, as it can be seen from Figure 10, the dominating failure mechanisms were skin failure, especially the lower skin under tension mode, and core failure. Delamination between skin and core has not been noticed in our samples, which indicates that an excellent bonding between skin and core was achieved. This strong bonding between skin and core can be attributed to VARTM which leads to construct an integrated sandwich structure between skin and core. This compatibility

Figure 4. 3-point bending test: (a) test specimens and (b) 3-point bending test set up. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

Table IV. Skin Fabrics Construction Specifications and Tensile Properties of Skin Fabric in Weft Direction

Skin	Structure	Weft material	Weft count (Tex)	Weft density (thread/inch)	Areal density (g/m^2)	Fabric Max. load (N)	Fabric elongation at max. load (%)
Jute fabric	Plain 1/1	Jute	386	22	362	957	389
Flax fabric	Plain 1/1	Flax	445	22	413	1300	451

and solidarity between the principle elements of sandwich structure (skins and core) lead to higher bending stiffens.

The required values of mechanical properties standardized by ANSI A 208.1 (American National Standard)[30] for high density exterior industrial grade particleboards (above 0.8 g/cm^3) are 23.5 MPa for MOR and 2.75 GPa for MOE, which were overstepped in current study by even resin infused particleboard No-skin sample (37.6 MPa for MOR and 4.05 GPa for MOE). By comparing the mechanical results, MOR, and MOE, of this study to the other values in the current literature and the standard requirements of EN312:2010 and ANSI, it can be clearly noticed that the developed particleboard in this work represents major and drastic achievements in the enactment of mechanical properties of particleboards which can create new fields of applications for particleboards industry.

Effect of Skin-Core Structure and VARTM Process on Dimension Stability and Density

The panel density, WA, and swelling properties results of modified and non-modified particleboard that were submerged in water bath at room temperature for 2 and 24 h are illustrated in Table V. It was observed that the panel density increased significantly in the modified panels compared to the traditional particleboard panels. This can be directly contributed to the infusion of PET resin through the internal structure of particle board and fills in most of the voids between the wood particles.[31,32] Meanwhile, water uptake and TS values decreased. However, the results indicated that the lowest WA, which was judged based on 24 h immersion, was observed with Jute skin panels (1.09%) compared with 160.1% in non-modified panels. The recorded TS values after the 24 h of water immersion showed a great improvement in dimensional stability in the particleboard/polyester composites. The swelling properties strongly decreased from 71.9% in control panels to about 2% in the sandwich structure panels after 24 h of water submerging due to the modification, which is likely associated with a reduction of water uptake.[33] Consequently, it seems that the novel wood based/ polyester composites has high potential to be used in the outdoor construction applications.

Effect of Skin-Core Structure and VARTM Process on Biological Durability

Decay resistance of mini blocks samples obtained from the modified and non-modified composites panels against *Poria placenta* and *Coriolus versicolor* is reported in Figure 11. After 12 weeks of fungal exposure, the results clearly demonstrate that the fungal activity of the test decay fungi was high enough under the test conditions, and this allowed us to compare the decay resistance (mean percent ML) for the novel manufactured composites particleboard panels. The ML caused by both tested fungi species were drastically decreased when compared with the control specimens. Slight ML of $<3\%$ was recorded with the modified composites against the brown rot fungus *Poria placenta* while the percentage of ML in the control samples recorded 20.9%. It was found that the modified composites (No-skin, Flax skin, and Jute skin) performed well against *Coriolus versicolor* and sustained a ML of $\leq 2.5\%$ meanwhile the control specimens suffered a ML of 18.6%. The present results strongly indicate that the modified composites using VARTM technique exhibited a significant improvement in the decay-resistance when compared with the non-modified composites. This can be attributed to the water repellent effect of the used resin (PET) which play an important role in preventing the wood based modified composites from absorbing moisture

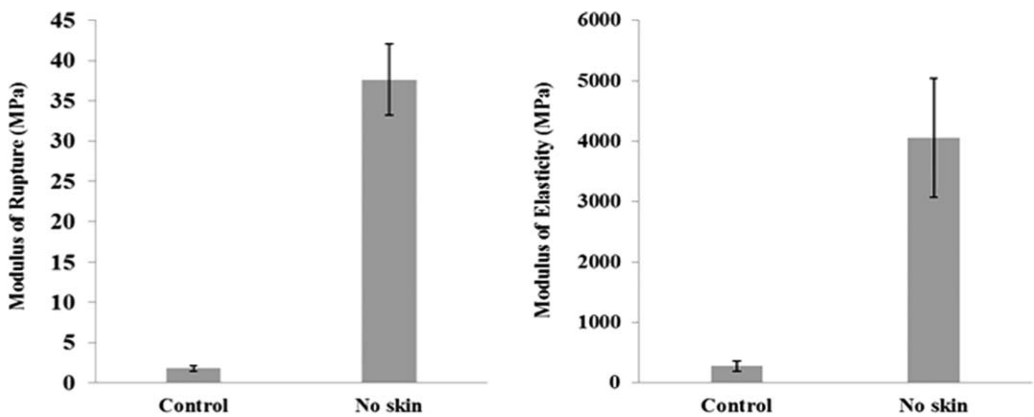

Figure 5. MOR and MOE of control and No skin particleboard.

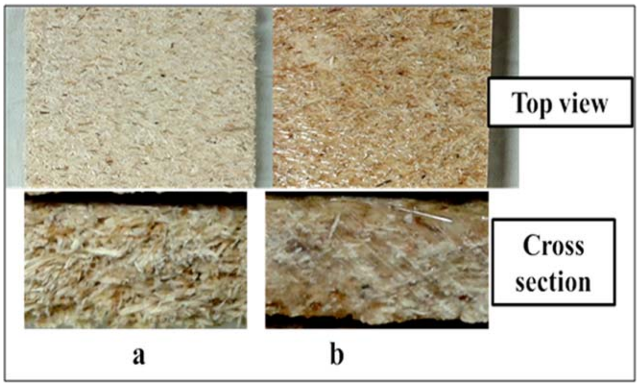

Figure 6. Cross section and top view images for samples: (a) before VARTM (control) and (b) after VARTM. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

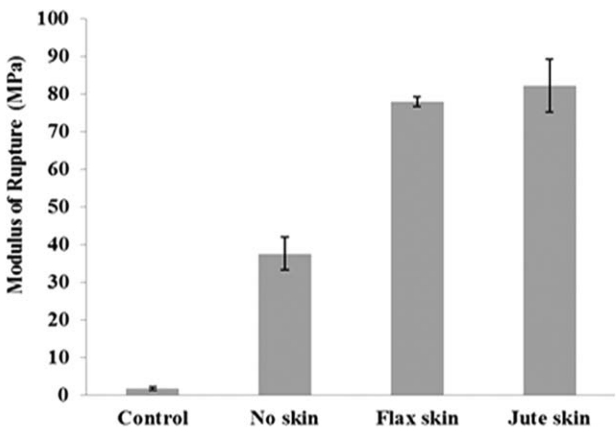

Figure 7. Modulus of Rupture (MOR) of different composites samples.

during fungal exposure leading to un-appropriate conditions for fungal decay.

CONCLUSION

This study aimed to develop high performance particleboard using lingocellulosic residues. In this context, traditional particleboards which produced using poplar veneer residues were developed as composites structures in form of skin/core or sandwich structures using Flax, and Jute fabrics as skin. VARTM

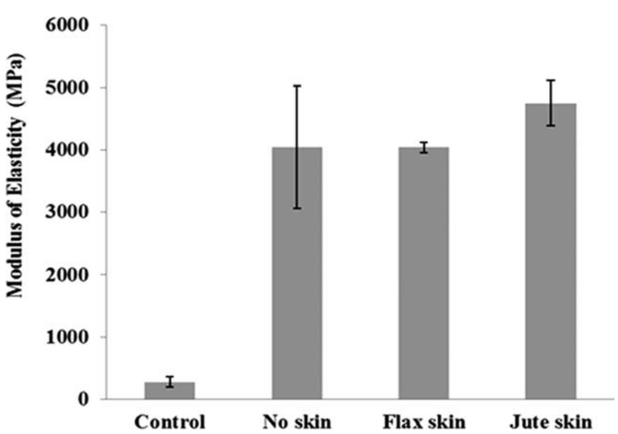

Figure 8. Modulus of Elasticity (MOE) of different composites samples.

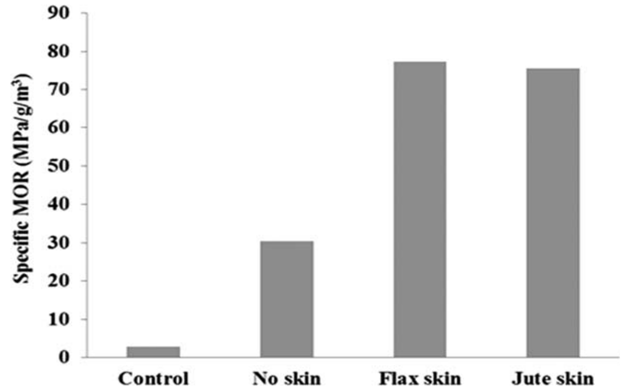

Figure 9. Specific modulus of rupture (SMOR) for different composites structure.

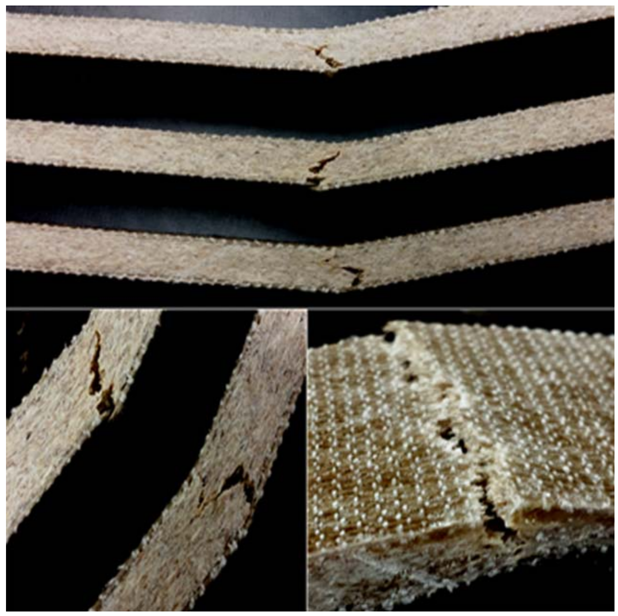

Figure 10. Flexural modes of sandwich composites during 3-point bending test. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

Table V. Water Absorption, Thickness Swelling, and Density of Control and Sandwich Structure Panels

Panel type	Density (g/cm^3)	Water absorption (%)		Thickness swelling (%)	
		2 h	24 h	2 h	24 h
Control	0.51	23.69	160.10	52.28	71.89
	(0.02[a])	(1.73)	(13.20)	(15.81)	(16.79)
No-skin	1.24	0.40	1.53	0	1.10
	(0.06)	(0.08)	(0.29)	(0)	(0)
Flax-skin	1.01	1.3	4.42	0	2.36
	(0.07)	(0.22)	(0.40)	(0)	(2.76)
Jute-skin	1.09	0.34	1.09	0.54	2.10
	(0.08)	(0.04)	(0.11)	(0.62)	(1.79)

[a] Values are average of five replicates and values in parentheses are standard deviations.

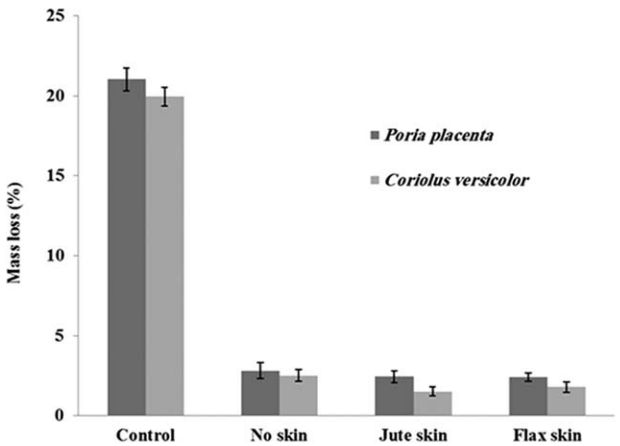

Figure 11. Decay resistance of the modified and non-modified composites against *Poria placenta* and *Coriolus versicolor*.

technique used to consolidate the sandwich structure. Mechanical, physical, and biological properties for these sandwich composite structures were evaluated. The following conclusions could be drawn:

- Using VARTM in consolidation of the wood particleboard instead of just using UF alone, has a significant effect on mechanical, physical, and biological properties of wood particleboard.
- The novel sandwich composites exhibited a high strength and stiffness properties with MOR values of 78.1 and 82.3 MPa for Flax skin and Jute skin sandwich structures, respectively. Meanwhile, the MOE values for both sandwich composites with Flax and Jute were 4039 and 4753 MPa, respectively.
- Moisture absorption and TS properties of the modified composites decreased drastically which reflected a good dimensional stability for the engineered composite structures when compared with the control non-modified composites.
- The new ameliorating composite structures revealed a significant biological resistance against the tested white and brown rot fungi in the same time, the control non-modified composites suffer a severe deterioration after 12 weeks of fungal exposure.
- The good mechanical, physical, and biological properties for the new developed composites in this study can certainly have an edge over conventional panel products which can open new fields of application for the particleboard industry.

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