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Thermal conductivity of sandwich panels made with synthetic and vegetable fiber vacuum-infused honeycomb cores

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Abstract

Building, naval, and automotive industries have deep interest in eco-friendly, lightweight, stiff and strong materials. In addition, materials with low thermal conductivity are desirable in many applications where energy savings and thermal comfort are needed. In response to these requirements, sandwich panels were manufactured using glass and jute fiber composite skins bonded to different cores: balsa wood, Divinycell® and honeycombs. These honeycombs, as well as the skins, were manufactured by the vacuum infusion technique using polyester resin and jute, glass and carbon fiber fabrics. In this work, the thermal properties and density of the sandwich panels were measured and compared.

Keywords

Natural fiber composites, honeycomb, vacuum infusion, sandwich panels, thermal properties

Introduction

Nowadays, world oil reserves continue to decline and the consumption of fossil fuels has increased. Therefore, great effort is being made on the development of green energy that promotes sustainable development for the exploitation of energy

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resources. In addition, many countries have limited energy capacity, so energy efficiency is crucial to achieve sustainable development. Therefore, high performance materials that allow significant energy efficiency and low environmental impact have to be developed. The use of thermal insulation materials has many advantages [1]: environmental and economic benefits due to lower energy consumption, reduction of the reliance upon mechanical air-conditioning system, enhanced thermal comfort, improvement of building structural integrity since high temperature changes may cause undesirable thermal movements, and vapor condensation prevention.

Sandwich panels are widely used as a means to build high-performance lightweight structures [2,3] They consist of two thin and stiff face-sheets (or skins) bonded to a thick and light core. The face sheets provide the flexural stiffness and strength to the panel, while the role of the core is to transmit the shear between the face sheets. Typically, cores are made of polymer foams or balsa wood [4,5] or they are fabricated using corrugated, truss or honeycomb structures [6,7]. The most used materials in honeycomb fabrication are aluminum, polymers, and composites such as Nomex. Sandwich panels are usually good insulating components and widely used in many industries that require light and strong panels with low heat conductivity. Kawasaki et al. [8] manufactured low-density (0.3–0.5g/cm^3) sandwich panels of veneer-overlaid fiberboards of 12 mm thickness using an isocyanate compound resin adhesive and steam injection pressing method. The thermal diffusivity of these panels was 0.00040 and 0.00038 m^2/h at densities of 0.30 and 0.50 g/cm^3, respectively. These are only 0.03–0.20 times as much as those of fiberglass wool (0.012 m^2/h), polystyrene foam (0.0039 m^2/h), rigid polyurethane foam (0.0026 m^2/h), and rock wool (0.0019 m^2/h), and less than that of plywood (0.00049 m^2/h). Therefore, the authors concluded that the manufactured low-density sandwich panels were excellent materials for thermal insulators having also superior strength compared to that of common insulation materials such as fiberglass wool and polystyrene foam.

In another publication, Kawasaki and Kawai [9] measured the thermal insulation and warmth-keeping properties of thick plywood-faced sandwich panels with low-density fiberboard (plywood-faced sandwich, PSW), which were developed as wood-based structural insulation materials for walls and floors. The thermal conductivity for PSW panels with densities of 340 kg/m^3 and 410 kg/m^3 (PSW400) were 0.070 and 0.077 W/mK, respectively. Young-Sun Jeong et al. [10] measured the thermal conductivity of different materials commonly used as core for sandwich structures, expanded polystyrene (EPS), expanded polypropylene (EPP), ethylene-vinyl acetate copolymer (EVA), polyethylene (PE), and urethane foam. They found that thermal conductivity tended to decrease as apparent density of EPS and EPP increased, whereas in the case of EVA and PE, as the apparent density increased, thermal conductivity tended to increase as well.

Table 1 shows the thermal conductivity of some insulation materials commonly used in the building industry, measured in the temperature range of 20–21°C.

Table 1. Density and thermal conductivity of common insulator materials.

	ρ (kg/m³)	λ (W/m K)	References
Expanded Polystyrene 1	16	0,0364	[11]
Expanded Polystyrene 2	32	0,0322	[11]
Extruded Polystyrene 1	25.6	0.041	[9]
Extruded Polystyrene 2	29.2	0.041	[9]
Fiberglass wool	21.1	0.039	[9]
Polyurethane Foam	28.6	0.034	[12]
Epoxy Foam Rigid closed cell	80	0.04	[9]
Cellulose acetate Foam	96–128	0.04	[13]
Phenolic Foam	32–80	0.03–0.04	[13]
HRH-10 (Aramid fiber, 3.2 cell)	29–144	0.057–0.067	[14]

The main objective of the present work was to obtain lightweight and highly insulating components made from eco-friendly materials. Natural fibers present some advantages when compared to their synthetic counterparts: they are cheaper (about 50% of similar architecture glass fiber fabrics), they have lower specific gravity, biodegradable by nature, they do not produce skin irritation, and they provide good acoustic-insulating properties. Sandwich panels were manufactured using glass and jute fiber composite skins bonded to different cores: balsa wood, Divinycell®, and honeycombs made with jute, glass and carbon fiber composites. The thermal properties and the density of the sandwich panels were measured and compared. The mechanical performance of these materials was already reported in previous publications [15] These properties are summarized in Tables 2 and 3.

Petrone et al. [16,17] have also published some relevant scientific articles regarding the manufacturing and testing of natural fiber-filled honeycomb structures.

Theoretical background

Thermal conductivity (λ, [W/m K]) is a measure of the effectiveness of a material in conducting heat. It is defined as an intrinsic property that represents the amount of heat that is conducted per unit of time through a unit of area of a material when the temperature difference is set between its faces. Hence, knowledge of the thermal conductivity values allows quantitative comparison to be made between the effectiveness of different thermal insulation materials. Materials with low thermal conductivities are suitable to be used in situations where energy savings and thermal comfort are required. On the other hand, thermal resistance (R, [m^2K/W]) is a measure of the resistance of heat flow as a result of suppressing conduction, convection and radiation. Thermal conductance (C, [W/K m^2]) is similar to thermal conductivity except that it refers to a particular thickness of material.

Table 2. Tensile properties of manufactured skins.

		Fiber content (% vol)	Tensile modulus (MPa)	Tensile strength (MPa)
Skin laminates	Jute fiber/polyester resin	31	4255	32.25
	Glass fiber/polyester resin	42	16080	455

Table 3. Compressive properties of studied cores.

		Compressive modulus (MPa)	Compressive strength (MPa)
Cores	Balsa Wood	48	1.05
	Divinycell ®	115	3.4
	Jute fiber honeycomb	285	12.45
	Glass fiber honeycomb	355	14.2
	Carbon fiber honeycomb	400	11.3

When a body is introduced in a thermal gradient between a cold and a hot source, there is energy transference from the hot place to the cold one. The thermal energy is transferred by conduction and the rate of amount of energy per unit area is proportional to the temperature gradient. In other words, considering the proportionality constant λ, Fourier's law (1) is obtained as

$$Q = -\lambda . A . \frac{\partial T}{\partial x} \quad [W] \tag{1}$$

where Q is the heat transferred measured in Joules per second; λ is the thermal conductivity of the material; A is the contact area, and $\frac{\partial T}{\partial x}$ is temperature gradient normal to A. Figure 1 represents schematically the variation of temperature gradient across three different plates. Assuming that the system reached a steady, the heat flux can be calculated with equation (2)

$$Q = A.\lambda_1 . \frac{(T_1 - T_2)}{L_1} = A.\lambda_2 . \frac{(T_2 - T_3)}{L_2} = A.\lambda_3 . \frac{(T_3 - T_4)}{L_3} \quad [W]. \tag{2}$$

Therefore, the thermal conductivity of any "i-plate" is

$$\lambda_i = \frac{Q}{A} \cdot \frac{L_i}{(T_i - T_{i+1})} \left[\frac{W}{mK} \right]. \tag{3}$$

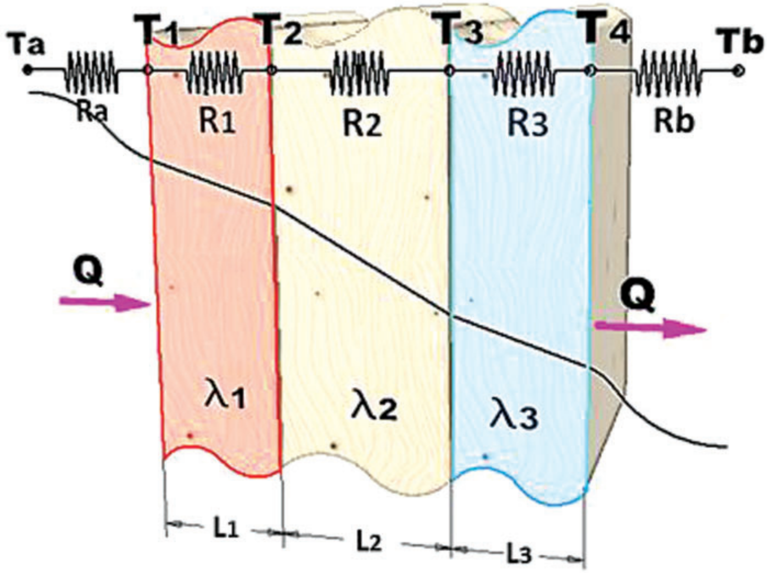

Figure 1. Thermal resistance to heat flux in one direction, across parallels plates with ideal contact.

Considering only the conductive terms, the conductive heat transference rate is defined as it follow

$$Q = \frac{(T_1 - T_4)}{R_{total}} \quad [W] \tag{4}$$

where the total thermal resistance is equal to the sum of all the thermal resistances, according to Figure 1. Consequently, thermal resistance is defined as

$$Ri = \frac{L_i}{A.\lambda_i} \quad \left[\frac{K}{W}\right]. \tag{5}$$

Methods for the determination of thermal conductivity for uniaxial heat flux

Methods to calculate thermal conductivity of materials can be classified in two types, absolute and comparative. Both consider steady state thermal transmission and uniaxial heat flux, which means that heat losses or gains must be minimized in the radial direction. This can be accomplished experimentally by using insulation materials around the sample.

Perhaps the most suitable and popular absolute method is the guarded-hot-plate apparatus, based on ASTM C177 [18]. A unidirectional heat flux should be produced between the top and bottom surfaces of the specimen in the one-sided mode in order to measure the thermal conductivity. It is necessary to measure all the parameters mentioned in equation (3) including the heat flux. This procedure was used as a template by Barrios et al. [19], who modified it to accommodate the other requirements that are needed for measuring the effective thermal conductivity of a spray-on foam insulation used on the Space Shuttle.

In the comparative methods, the measurement of thermal conductivity is done indirectly. One of the most widely used methods for axial thermal conductivity testing is based on ASTM E1225 [20], in which a sample with unknown thermal conductivity is sandwiched between two reference samples with known thermal conductivities. Then, a heat flux is imposed normal to these samples and the respective thermal gradients are compared, which are inversely proportional to the thermal conductivities of the samples. This set-up allows the system to be independent of heat flux according to equations (2) and (3). Another popular comparative test method is the one described in ASTM C518 [21], which involves the use of a heat flux transducer and is very similar to the ASTM E1225 method, but needs a larger number of testing instruments. These comparative methods need to be assembled with reference samples (subscript "M") having similar conductance as estimated for the subject sample (subscript "s") and shown in equation (6).

$$C = \frac{\lambda_M}{l_M} \approx \frac{\lambda_s}{l_s} \quad \left[\frac{W}{m^2 K}\right] \tag{6}$$

Experimental

Manufacturing of the sandwich panels

Composite skins were manufactured by vacuum infusion (VI) using bidirectional glass and jute-woven fiber fabrics (surface density of $165\,g/m^2$ and $300\,g/m^2$, respectively). Skins and honeycombs were made with a general purpose polyester resin (density of $1.2\,g/cm^3$) catalyzed with methyl ethyl ketone peroxide (MEKP) in the weight ratio of 1:0.03 and accelerated with cobalt naphthenate in the weight ratio of 1:0.01.

In order to obtain representative values for the thermal conductivity of the panels, the cores and skins thicknesses had to be the same in all the samples. However, the vacuum infusion technique does not allow controlling the thickness, since the compaction pressure is limited by the atmospheric pressure (1atm). The compaction behavior of the fabrics determines the number of layers that are needed for obtaining the desired thickness. Therefore, compaction tests were performed using an Instron Universal Testing Machine with a 30 KN load cell. Circular samples were cut out of the glass and jute fabrics and different number of layers were compressed at a constant speed (2 mm/min). Load vs. thickness data were recorded and the compaction pressure was estimated by dividing the load by the preform area. According to those results (Figure 2(a) and (b)), the number of layers needed to obtain 2 mm thick skins

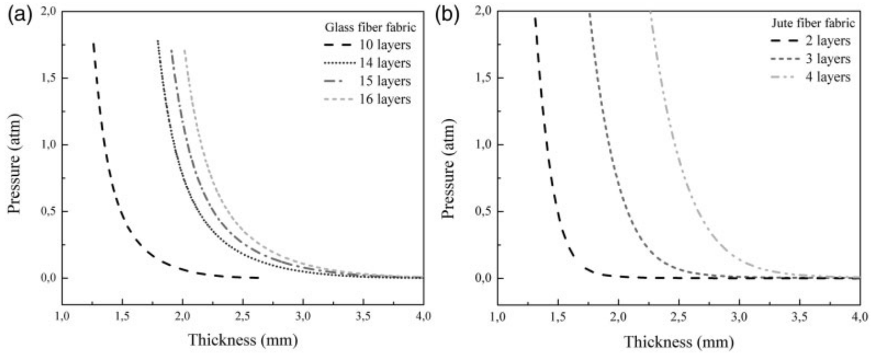

Figure 2. Compaction response of (a) glass and (b) jute fabrics.

by VI was 3 and 14 for jute and glass fiber fabrics, respectively. The real thickness of the final (cured) skins was 2.14 ± 0.05 mm and 2.03 ± 0.05 mm for glass and jute fiber skins, respectively. The fiber volume fractions were 0.42 and 0.31 for glass and jute fiber skins, as estimated with equation (7), where n is the number of reinforcement layers stacked in the preform, ζ the surface density (g/cm^2), ρ the fiber density (g/cm^3), and t is the preform thickness (cm).

$$Fiber\ Volume\ Fraction = \frac{n \cdot \zeta}{\rho \cdot t} \tag{7}$$

Honeycomb cores were manufactured by vacuum infusion using a polyethylene mold (to enhance demolding) for laying the jute, glass, and carbon (surface density of 220 g/m^2) fiber fabrics following the honeycomb shape. The mold dimensions were 230 mm in length (ribbon direction), 230 mm in width and 12 mm in height, and it contained an 18×15 array of 12 mm (cell size) hexagonal inserts. The clearance between the inserts, and thus the honeycomb wall thickness, was $t = 1 \pm 0.1$ mm. The walls and the inserts with the shape of the cells were kept in place by screwing them to the bottom plate following a zigzag pattern in the ribbon direction, as shown in Figure 3. Afterwards, the mold was wrapped with a vacuum bag and the same polyester resin used for the skins resin was infused. The honeycombs were left to cure at room temperature and then demolded by removing all the screws that held in place the inserts and then expulsing them out of the honeycomb. In addition, it is important to notice that as consequence of the manufacturing process, the average fiber-volume contents were different for the longitudinal and diagonal walls. Longitudinal walls contained two fabric layers leading to a volumetric fiber fraction of 0.42, while the diagonal walls had a single fabric layer leading to a fiber content of 0.21 approximately. Although this simple manufacturing method is labor intensive, it was intended for laboratory scale and some work towards larger scale production is currently being performed.

Figure 3. Plastic mold used for manufacturing the honeycombs.

In addition to the honeycombs, balsa wood (density of $154 \pm 40\,kg/m^3$) and commercial PVC foam core (Divinycell^{TM} H160, $160\,kg/m^3$) with the same thickness as the honeycombs (12 mm) were used as cores for comparison purposes. The cores and the skins were bonded together using the same polyester resin and a heated hydraulic press that allowed applying pressure during bonding stage. In addition, since the skins and cores were not fully cured, the heated press was used for the post curing stage of all the components comprising the panels altogether with the resin used as a glue. This method enhanced the bonding characteristics since polymerization occurred between skins and cores.

Figure 4 shows some of the samples used in this work. Figure 4(a) shows the composite skins, Figure 4(b) the honeycombs, and Figure 4(c) the sandwich panels made with jute fiber composite skins.

Heat flux measurements and thermal transmission properties

ASTM standards mentioned previously and ASTM C1045 [22] were used as templates and were modified to fulfill the requirements for testing flat samples composites as the ones we used in this study. Figure 5 shows the apparatus constructed for the thermal measurements. A single-sided guarded hot plate (an electrical hot plate set in 40°C) was used as the hot source and a water reservoir made with a plastic bag was used as the cold source (average temperature of 20°C), which had a water inlet and outlet for keeping the temperature constant. The temperature difference between the hot and cold sources was 20 K as recommended by ASTM C177 standard. The water flux was modified until a steady state was achieved. The sample was placed in between two reference plates (230 mm × 210 mm × 5 mm) of expanded polystyrene ($20\,kg/m^3$) and this stack was laid in the middle of the hot and cold sources. A thick aluminum plate was also placed between the hot source

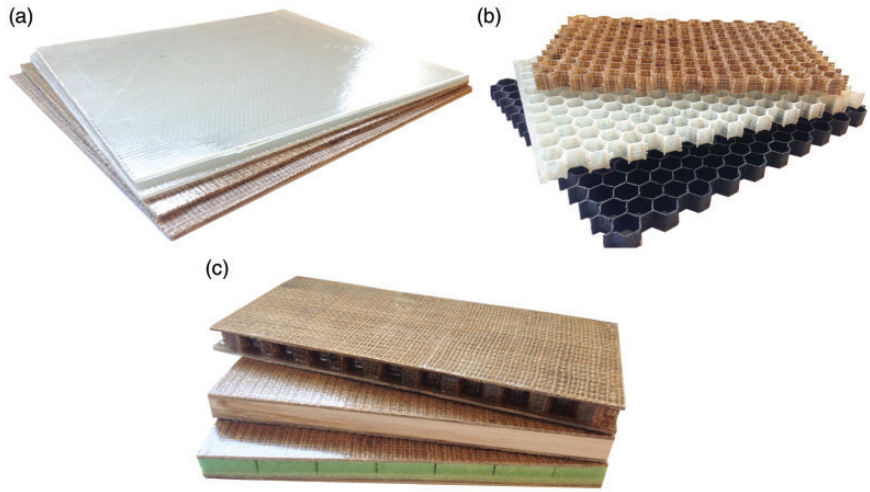

Figure 4. Skins (a), honeycombs (b), and sandwich panels (c).

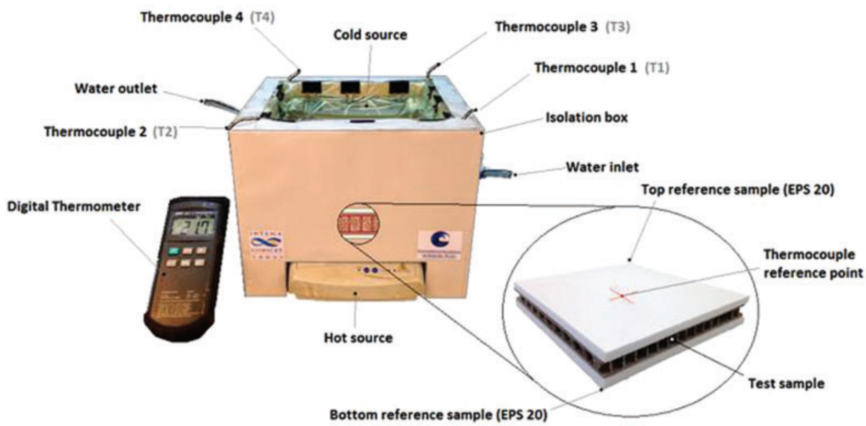

Figure 5. Device used for the experiments.

and the first reference plate, to assure a homogeneous heat transfer throughout its area. The weight of the water kept all the plates in contact. All these elements were cased in an insulation box made of wood and thick polyurethane foam. This method is a comparative one since it requires reference samples in order to calibrate the system and measure the thermal properties. Four thermocouples were set on the center and on both sides of each plate to measure the temperature, as shown schematically in Figure 6. With these temperatures, the thickness of the plates, and the known thermal conductivity of the reference plates, the thermal conductivity of

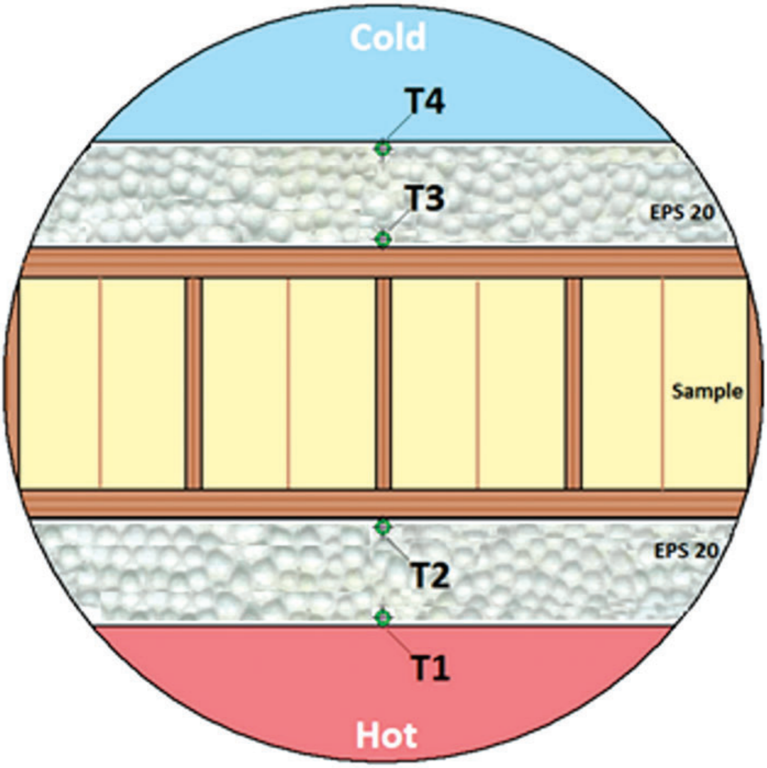

Figure 6. Test set-up and thermocouple locations.

the test sample could be calculated with equation (2), assuming perfect contact between plates and neglecting convective terms. Thermal conductivity of the sample was defined as the average between the ones calculated at the hot and cold sides. The "hot" thermal conductivity value (equation (8)) corresponds to the conductivity calculated at the hot side of the panel, i.e. pointing to the hot source. In the same way, the "cold" thermal conductivity value (equation (9)) corresponds to the conductivity calculated at the cold side of the panel, i.e. pointing to the cold source. These two values are similar, but not the same, since the thermal conductivity of all materials varies with the temperature. Therefore, the ASTM standard recommends reporting an average value between those "hot" and "cold" conductivities, as the "real" conductivity of the panel, as shown in equation (10).

$$\lambda_2^{hot} = \lambda_1 . \frac{(T_1 - T_2)}{(T_2 - T_3)} . \frac{L_2}{L_1} \tag{8}$$

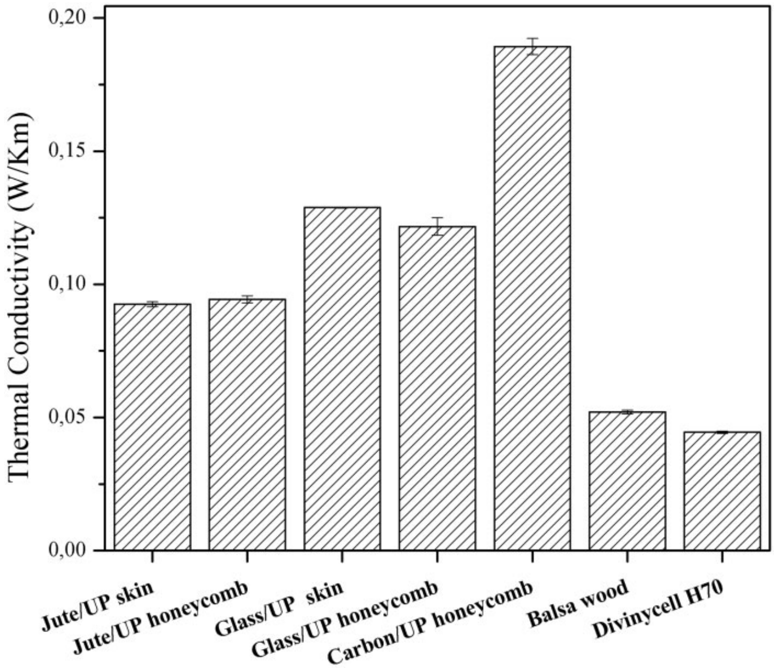

Figure 7. Thermal conductivity of skins and cores.

$$\lambda_2^{cold} = \lambda_3 . \frac{(T_3 - T_4)}{(T_2 - T_3)} . \frac{L_2}{L_3} \tag{9}$$

$$\lambda_2 = \frac{\lambda_2^{hot} + \lambda_2^{cold}}{2} \tag{10}$$

where L_1, L_2, and L_3 are the thicknesses (m) of the bottom reference plate, the test sample, and the top reference plate; T_1, T_2, T_3, and T_4 are the temperatures (K) measured with the thermocouples at the hot source–bottom reference plate interface, bottom reference plate–test sample interface, test sample–top reference plate interface, and top reference plate–cold source interface; and λ_1, λ_2, and λ_3 are the thermal conductivities (W/m K) of the bottom reference plate, test sample, and top reference plate, respectively. The thermal conductivities of the reference plates were 0.035 (W/Km) obtained from a polystyrene handbook [11]. In addition, the system accuracy was tested by calculating the thermal conductivity of expanded polystyrene plates of known thermal conductivities, and the error was lower to $\pm$ 6% in all the tests.

Three identical tests were carried out for each material. The reported results correspond to the average of the values obtained from these individual tests, and

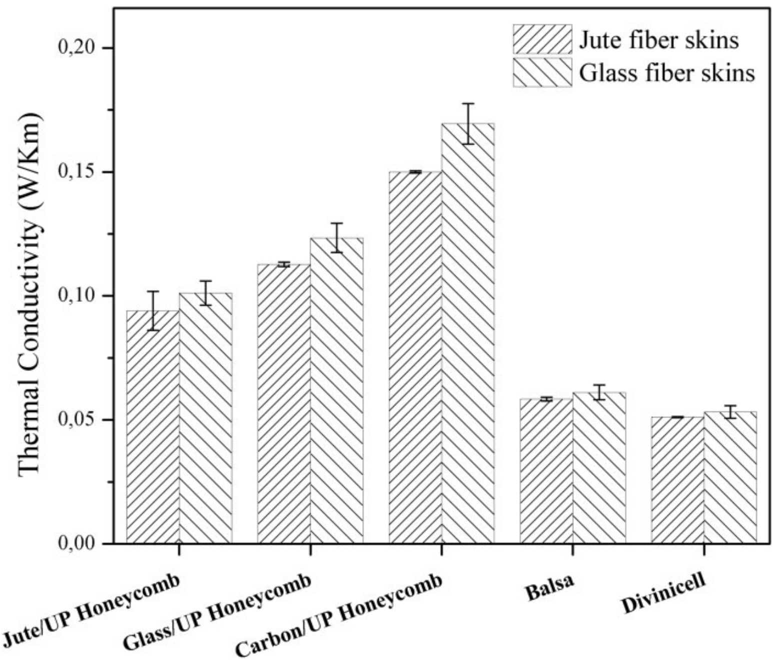

Figure 8. Thermal conductivity of sandwich panels.

the scatter bars were calculated using the standard deviation plus the 6% of error mentioned previously.

Results

Since thermal conductivity varies with temperature, the following results are useful for comparison purposes, but valid only at the test temperature.

The thermal conductivity of the skins and cores is shown in Figure 7. It can be seen that the skins and honeycombs made with jute have lower conductivity than the ones made with glass fibers. In addition, the commercial cores (balsa and Divinycell®) have similar conductivities, much lower than those of the jute and glass fiber honeycombs. The worst thermal insulation was displayed by the carbon fiber–polyester honeycomb.

Figure 8 shows the thermal conductivity data of all the sandwich panels tested. As expected, the core contributed dominantly to the values of thermal conductivity because the core thickness was approximately 75% of the total panel thickness. Therefore, the trend was very similar to the one observed for skins and cores, the best being the insulating materials, the ones made with balsa wood and Divinycell® cores and jute/polyester skins. Among the honeycomb-based panels, the one made with jute and polyester resin skins and core showed the best performance.

Table 4. Thermal properties for the skins and cores.

	ρ (kg/m^3)	λ^{hot} (W/m K)	λ^{cold} (W/m K)	λ (W/m K)	r (m K/W)	C (W/m^2 K)	R (m^2 K/W)
	Skins						
Glass fiber/polyester resin	1790	0.144	0.113	0.129	7.76	60.19	0.017
Jute fiber/polyester resin	992	0.105	0.08	0.092	10.81	45.57	0.022
	Cores						
Balsa wood	145	0.0597	0.044	0.052	19.23	4.33	0.231
Divinycell ®	70	0.050	0.038	0.044	22.48	3.71	0.270
Jute fiber honeycomb	150	0.113	0.075	0.094	10.60	7.87	0.127
Glass fiber honeycomb	236	0.143	0.100	0.122	8.22	10.14	0.099
Carbon fiber honeycomb	163	0.220	0.157	0.189	5.28	15.78	0.063

Table 5. Thermal properties for the sandwich panels.

		ρ (kg/m^3)	λ^{hot} (W/m K)	λ^{cold} (W/m K)	λ (W/m K)	λ_T (W/m K)	r (m K/W)	C (W/m^2 K)	R (m^2 K/W)
		Glass fiber skins							
C	Balsa Wood	652	0.0689	0.0528	0.061	0.061	16.36	3.82	0.262
O	Divinycell ®	619	0.0596	0.0466	0.053	0.053	18.80	3.32	0.301
R	Jute fiber honeycomb	691	0.1171	0.0847	0.101	0.101	9.89	6.32	0.158
E	Glass fiber honeycomb	721	0.1405	0.1047	0.123	0.124	8.10	7.71	0.130
S	Carbon fiber honeycomb	666	0.1926	0.1445	0.169	0.169	5.90	10.59	0.094
		Jute fiber skins							
C	Balsa Wood	388	0.0661	0.050	0.058	0.058	17.12	3.65	0.274
O	Divinycell ®	480	0.0591	0.0429	0.051	0.051	19.56	3.20	0.313
R	Jute fiber honeycomb	436	0.1115	0.0764	0.094	0.093	10.64	5.88	0.170
E	Glass fiber honeycomb	521	0.1366	0.090	0.113	0.113	8.87	7.04	0.142
S	Carbon fiber honeycomb	467	0.1802	0.1198	0.150	0.150	6.67	9.38	0.107

Table 4 summarizes all the properties obtained for the skins and cores, including density (ρ), thermal conductivity (λ), thermal resistivity (r), thermal conductance (C), and thermal resistance (R).

Table 5 shows the same properties obtained for the sandwich panels, and a new column was included with the theoretical value for λ (λ_T) calculated with the composite theory. According to this theory, the equivalent λ value for a sandwich panel can be calculated with equation (11) [9], where d_i and λ_i are the thickness and

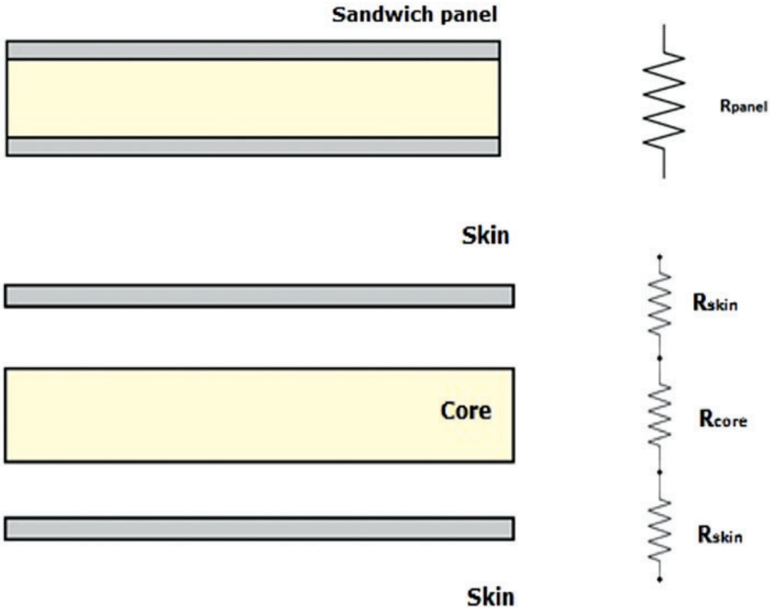

Figure 9. Thermal resistance of a sandwich panel as the sum of the thermal resistances of skins and core.

thermal conductivity of each layer comprising the panel.

$$\lambda = \sum d_i \Big/ \sum (d_i/\lambda_i) \tag{11}$$

It can be seen that the composite theory can be applied since the ratios of λ_T/λ (measured) are almost the same in all the panels. This means that separate measurements of skins and cores can be used for determining the thermal conductivity of sandwich panels made with any combination of those components, reducing dramatically the total amount of tests to be performed. In the same way, the thermal resistance of a sandwich panel could be estimated from the thermal resistances and dimensions of skins and cores according to equations (12) and (13) (schematized in Figure 9).

$$R_{panel} = R_{skin} + R_{core} + R_{skin} = 2.R_{skin} + R_{core} \tag{12}$$

$$R_{panel} = \frac{L_{skin}}{A.\lambda_{skin}}.2 + \frac{L_{core}}{A.\lambda_{core}} \tag{13}$$

where R_{panel}, R_{skin}, and R_{core} are the thermal resistances of the panel, skin, and core, respectively. The thermal conductivities of the skin and core are represented by λ_{skin} and λ_{core}. Finally, the variable A represents the area of measurement, used to avoid any border effects, considered in all the cases as 6400 mm^2.

This model was validated by obtaining the thermal resistance of sandwich panels in three different ways:

- using equation (13) (R_1).
- measuring λ of sandwich panels which skins were glued to the core (R_2).
- Measuring λ of sandwich panels which skins were put in contact but not glued to the core (R_3).

Table 6 shows the R_1, R_2, and R_3 values obtained for three different sandwich panels. It can be seen that the value of R_2 is always lower than the others because the resin improves contact between skins and core, enhancing thermal conductivity. However, the differences are not significant (lower than 5%) and therefore this model can be used to estimate the thermal conductivity of sandwich panels from the known thermal conductivities of skins and core.

Conclusions

In this work, sandwich panels were manufactured using glass and jute fiber composite skins and different cores: balsa wood, Divinycell®, and honeycombs made with jute, glass, and carbon fiber polyester composites. The thermal conductivity of the panels was measured and calculated with the composite theory from the λ values of skins and cores. These calculated values were almost the same as the measured ones. The panels made with balsa wood and Divinycell® showed the best thermal insulation properties. Among the honeycomb-based panels, the vegetable fiber-based panel (jute/UP skins and honeycomb core) showed a better performance than the synthetic fiber-based panels (glass and carbon). According to the Japanese Industrial Standard [23], a material can be considered as an appropriate thermal insulator if its thermal conductivity is 0.15 W/m K or less. From all the sandwich panels tested, only the ones made with carbon fiber honeycomb did not meet those requirements.

Table 6. Validation of the composite theory for the estimation of thermal resistance.

Skin/Core	R_1 $\left[\frac{K}{W}\right]$	R_2 $\left[\frac{K}{W}\right]$	R_3 $\left[\frac{K}{W}\right]$
Jute/Jute honeycomb	26.62	23.07	25.13
Jute/Divinycell	48.91	45.91	48.89
Jute/Balsa wood	42.81	41.01	39.75

In addition, the composite theory was used and probed to be accurate for the estimation of the thermal conductivity of sandwich panels. Therefore, separate measurements of skins and cores can be used for determining the thermal conductivity of sandwich panels made with any combination of those components, reducing dramatically the total amount of tests to be performed.

Declaration of conflicting interests

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