THERMAL CHARACTERIZATION OF GLASS FIBRE REINFORCED POLYMER (GFRP) SANDWICH PANELS

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Abstract

Sandwich panels are being increasingly employed in civil engineering. Due to their lightweight, mechanical and insulation features, they can be used as floor and wall solution, either in new construction and building rehabilitation.

This work describes and analyses the thermal behaviour of sandwich panels made of glass fibre reinforced polymer (GFRP). In this approach four different types of cores were selected: 1) polypropylene (PP) honeycombs; 2) balsa wood; 3) polyethylene terephthalate foam (PET); and 4) rigid polyurethane foam (PUR). For this purpose, an experimental campaign was carried out in order to evaluate the thermal behaviour of such materials, depending on temperature and moisture content.

This study revealed that materials suffer a linear increase of their thermal conductivity as the temperature grows, and an exponential increase of their thermal conductivity as the moisture content grows. However, GFRP's thermal conductivity, which proved to be waterproof, is not affected by moisture content. Based on winter and summer temperatures, the total heat loss and the linear transmittance of the panels' junctions were obtained using THERM software. The results showed, from the thermal point of view, that depending on demands, different combinations of materials and thickness could be used as walls and floors (external and internal). From this study, it can also be concluded that linear transmittance is negligible for the sandwich panels' thermal design.

Keywords: GFRP, sandwich panels, experimental tests, temperature influence, moisture content influence, prediction models, thermal bridges

1 Introduction

The need of new constructions and building rehabilitation ensuring the demands imposed by human requirements led to major advances in materials science. These requirements, such as highly resistant but lightweight construction elements and appropriate thermal comfort, promoted an increasing use of composite materials, in which sandwich solutions are included. The sandwich panels are composed of two thin mechanically high performing material faces, separated by a core made from a low-density material [1]. This combination of materials gives rise to both high mechanical and thermal insulation properties of sandwich panels' applications, comprising floor and wall elements used in new constructions and building rehabilitation. The Directive 2010/32/EU policy [2], transposed for the Portuguese law through the Decree-Law 118/2013 [3], refers that any new construction or undergoing major rehabilitation shall present a net to zero energy balance. Consequently, GFRP sandwich panels' adoption provides, among traditional ones, a wide range of reliable solutions.

The present work describes and analyses the thermal behaviour of composite sandwich panels, made of glass fibre reinforced polymer (GFRP) laminates and a thermal insulation core. To evaluate this solution, several core materials were tested regarding their thermal insulation properties. As core materials four insulators were used: 1) polypropylene (PP) honeycombs; 2) balsa wood; 3) terephthalate foam (PET); and 4) rigid polyurethane foam (PUR). Materials' thermal behaviour, influenced by temperature and moisture content, were experimentally determined under both steady state and transient methods.

As far as the thermal conductivity value of each isolated material (GFRP and thermal insulation materials of the core) is known, the average U-value of different sandwich panels may be calculated. Furthermore, using the software THERM (from Berkeley Laboratory), the total U-value and the linear transmittance, Ψ-value, of each solution were also computed. Thus, heat losses originated from linear thermal bridges, in the connection zones between panels, may be estimated.

2 Thermal behaviour of sandwich panels

The thermal behaviour of a sandwich panel solution can be characterized by its thermal transmittance (U-value). The U-value is the overall heat transfer coefficient that describes the rate of heat through a square metre of a construction element. It measures the thermal transmittance originated by the mechanisms of heat transfer, which are conduction, convection and radiation. This means that the lower the U-value, the better the thermal performance of the element. The U-value can be obtained with Equation 1, and the corresponding heat flow through the element can be obtained using Equation 2.

$$U = \frac{1}{R_{si} + R_{se} + \sum \frac{e}{\lambda}} \quad (1)$$

where:
U - thermal transmittance coefficient (U-value) [W/m^2.°C];
R_{si} - interior surface thermal resistance [m^2.°C/W];
R_{se} - exterior surface thermal resistance [m^2.°C/W];
e - thickness of the material [m];
λ - thermal conductivity coefficient of the material [W/m.°C].

$$Q = U \times L \times \Delta T \quad (2)$$

where:
Q - heat flux through the element (W/m);
U - thermal transmittance coefficient (U-value) [W/m^2.°C];
L - length of the element [m];
ΔT - thermal gradient established in the element [°C].

When a construction element is not homogeneous along its length a phenomenon called thermal bridge occur. The heat flux through the element is no longer unidirectional and adopts the way of least resistance to its passage, causing a growth of the thermal transmittance. Thus, the heat flux is now two-dimensional or even three-dimensional. As a result, the connection zones of sandwich panels originate linear thermal bridges due to a change of material that forms the element. To evaluate the heat loss through a thermal bridge, like in the current zone, it is necessary to determine its transmittance coefficient, which in this case is called linear transmittance coefficient (Ψ-value). Since the determination of Ψ-value constitutes a hard problem to solve, software programs play an important role on its calculation. Accordingly, EN ISO 10211:2007 [4] indicates how to model thermal bridges using these programs. This way, Ψ-value can be computed with reduced effort and high precision compared to analytic calculations.
The average U-value is determined with Equation 3 and total U-value obtained using the software program, then, Ψ-value is determined with Equation 4.

$$U_{average} = \frac{\sum U_{zone} \times A_{zone}}{\sum A_{zone}} \quad (3)$$

where:
$U_{average}$ - area weighted average U-value [W/m^2.°C];
U_{zone} - U-value for each zone of the sandwich panel [W/m^2.°C];
A_{zone} - Area of each zone [m^2].

$$\Psi = \frac{Q_{software} - Q_{calc}}{\Delta T} \quad (4)$$

where:
Ψ - linear transmittance coefficient [W/m.°C];
$Q_{software}$ - heat flow obtained with software [W/m];
Q_{calc} - calculated heat flow [W/m];
ΔT - thermal gradient established in the element [°C].

3 Experimental tests

Thermal conductivity is the primary property of an insulation material. The most recommended way to determine its value, for a specific material, is to carry out an experimental setup and measuring a sample according to a standard method [5]. There are a number of methods for measuring the thermal conductivity that are broadly classified as steady state methods and transient methods [6].
Although these experimental measurements are, in general, highly time consuming they were used in the present task in order to obtain a comprehensive evaluation of heat transfer, involving the different GFRP sandwich panels' solutions.
In general, the effective thermal conductivity of materials depends on density, temperature, moisture content, as well as the constituents and voids present in their structures [7]. In fact, thermal conductivity of an insulation material does not only depend on its density, temperature and moisture content, but it also depends on the material atomic and molecular structure, porosity, anisotropy, structural faults and defects. Important differences in thermal conductivity values depend on aging effects and also upon manufacturing and storing conditions.
There is no single technique suitable for thermal conductivity measurements of all types of insulations, low conductivity materials and poor conductors, used in different conditions. The reliability of a specific method depends on various factors, such as the speed of operation, the required accuracy and execution under various environmental conditions, the physical nature of the material under investigation, and the size and shape of the available specimen [6].

3.1 Thermal conductivity obtained by a stationary method

Among the steady-state methods, the guarded hot plate and the heat flow meter methods can provide accurate results, with uncertainties as low as 3% for measurements in the dry state [5]. Although these methods have the potential to perform reasonably well, they suffer from some major drawbacks. For example, they require a long time to establish a steady-state temperature gradient across the sample and this gradient must be large [6].
In the present study, to acquire steady-state results, the heat flow meter method was applied (European EN ISO 8301:1991 [8], Portuguese NP EN 12667:2007 [9] and American ASTM C518-98 [10] Standards), using the

apparatus model Rapid-k from Holometrix (Figure 1). A schematic representation can be observed in Figure 2. The heat flow meter method consists on establishing a steady temperature gradient over a known thickness of a sample and on controlling the heat flow from one side to the other. The material is sandwiched between isothermal hot and cold plates. Once the steady state is achieved, the thermal conductivity of the sample can be determined from the one dimensional Fourier's Law (Equation 5). Therefore, the energy amount, supplied to the hot plate, needed to create a desired temperature gradient across the specimen is proportional to the thermal conductivity of the material [6]. Note that this method needs a previous measurement over a calibration sample, usually provided with the apparatus and a thermal conductivity value according to each temperature (in the present case a mineral wool sample). Thus, posterior measurements can be adjusted to obtain the normalized data. According to Rapid-k operation and maintenance manual [11], the device is capable of measuring thermal conductivities between 0,015 to 0,43 W/m°C with an associate error between 2 and 5%.

Figure 1 - Apparatus Model Rapid-k from Holometrix.

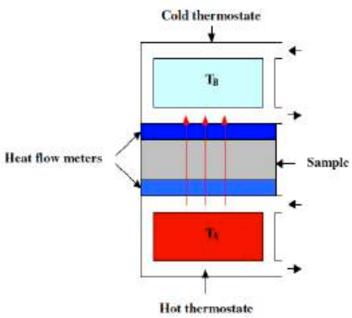

Figure 2 - Schematic of a Heat Flow Meter [6].

$$Q = \lambda \times \Delta T \frac{A}{L} \qquad (5)$$

where:

Q - amount of heat through the sample [W];

λ - thermal conductivity coefficient of the sample[W/m.°C];

ΔT - temperature gradient between sample's surfaces [°C];

L - thickness of the sample [m];

A - sample's area [m^2].

3.2 Thermal conductivity obtained by a transient method

While stationary methods measure a response from a constant flux across a sample, on the other hand, the transient methods measure a response to a signal that is sent out to create heat flux in the sample. Among transient methods, transient plane source (TPS), modified transient plane source (MTPS) and transient line source (TLS) are the most common, where the difference between them is the used probe. The TPS uses a double-sided surface probe, the MTPS uses a one-sided surface probe and the TLS uses a needle probe. These methods are distinguished, mainly, by the short time required to obtain the desired results, when compared to the stationary methods. The transient methods use a procedure where, firstly, the specimen is in thermal equilibrium with the surrounding atmosphere; then, a short heating pulse is given to one end of the specimen. During the process, the apparatus monitors the change in temperature so that thermal conductivity can be determined [6].

In the present work, the commercial TPS device ISOMET 2114 from Applied Precision, Ltd. (Figure 3 and schematically represented in Figure 4) was used, in order to obtain the thermal conductivity from a transient method. The measurement is based on the analysis of the temperature response of the tested material to heat flow impulses. The heat flow is induced by electrical heating using a resistor heater having a direct thermal contact with the surface of the sample [7]. According to Isomet 2114 manual [12], the used surface probe is capable of measuring thermal conductivities between 0,04 to 0,7 W/m.°C with an associate reading error of 5% plus 0,001W/m.°C, and between 0,7 to 6 W/m.°C with an associate reading error of 10%.

Figure 3 - Isomet from Applied Precision Ltd.

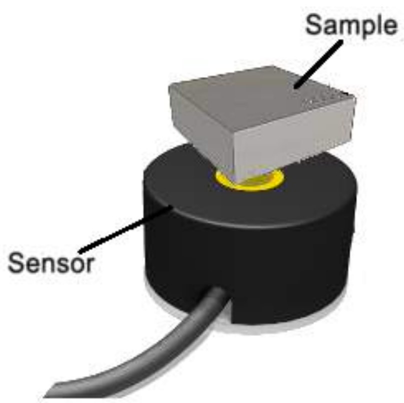

Figure 4 - Schematic of a Modified Transient Plane Source [13].

4 Experimental results

To evaluate the materials' thermal behaviour, influenced by temperature and moisture content, two experimental campaigns were conducted, using both steady state and transient methods. For the steady state apparatus Rapid-k was used, whereas Isomet 2114 device was used for the transient method. It must be pointed out that measurements with the Isomet 2114 use a base of another thermal insulator (with approximately 30 mm thickness) to avoid heat conduction between the sample and the stand. To determine the moisture content of the samples, and according to NP EN 1097-5:2002 [14], Equation 6 was used. The characteristics of the samples are presented in Table 1.

$$w = \frac{m_{wet} - m_{dry}}{m_{dry}} \quad (6)$$

where:
w - moisture content [%];
m_{wet} - wet sample weight [kg];
m_{dry} - dry sample weight [kg].

Table 1 - Samples characteristics.

Sample	Area (mm x mm)	Thickness (mm)	Weight (g)	Density (kg/m³)	w (%)
GFRP	299 x 299	8	1249,0	≈ 1750	0,1
PP honeycombs	301 x 299	92	876,5	≈ 110	0,3
Balsa	300 x 298	49	424,5	≈ 100	6,5
PET	300 x 300	24	209,4	≈ 100	0,9
PUR	298 x 296	92	573,0	≈ 70	1,0

4.1 Influence of temperature

To determine the influence of temperature on materials' thermal conductivity three temperature gradients of 10, 20 and 30 °C and two different temperatures were used in Rapid-k and Isomet 2114, respectively, to account for the effect of temperature on materials' thermal conductivity.

4.1.1 Thermal conductivity obtained with Rapid-k

The results obtained with Rapid-k are shown in Table 2 and Figure 5. By analyzing Table 2, it can be concluded that stipulated temperature gradients of 10, 20 and 30°C were almost achieved in all samples except in the GFRP sample. Due to the higher thermal conductivity and small thickness of this sample (less than 10 mm), compared to the other samples, the heat transfer was higher and the cold plate could not maintain the desired temperature to achieve the correct temperature gradient. As expected, in all five samples, the thermal conductivity grows with an increase of the mean temperature [15]. Trend lines on Figure 5 show that the thermal conductivity of all five samples varies almost linearly with temperature. Although it can be seen a slight difference between the trend line and the linear function, the coefficient of determination is higher than 90% for all samples. While PP honeycombs shows the higher thermal conductivities for the same mean temperatures, PET and PU show the lower values from among all samples.

Table 2 - Data acquired from measurements done with Rapid-k.

Sample	λ (W/m.°C)	Tmean (°C)	ΔT (°C)
GFRP	0,1581	38,5	3,8
	0,1618	46,5	7,6
	0,1688	54,9	11
PP honeycombs	0,1649	35,9	8,9
	0,1741	41,7	17,6
	0,1772	47,4	26,2
Balsa	0,0749	35,9	9,1
	0,0757	41,4	18,2
	0,0773	47,1	27
PET	0,0398	35,9	9,1
	0,0403	41,6	18
	0,0409	47,1	26,9
PUR	0,0243	35,5	10
	0,0261	40,7	19,7
	0,0269	45,7	29,7

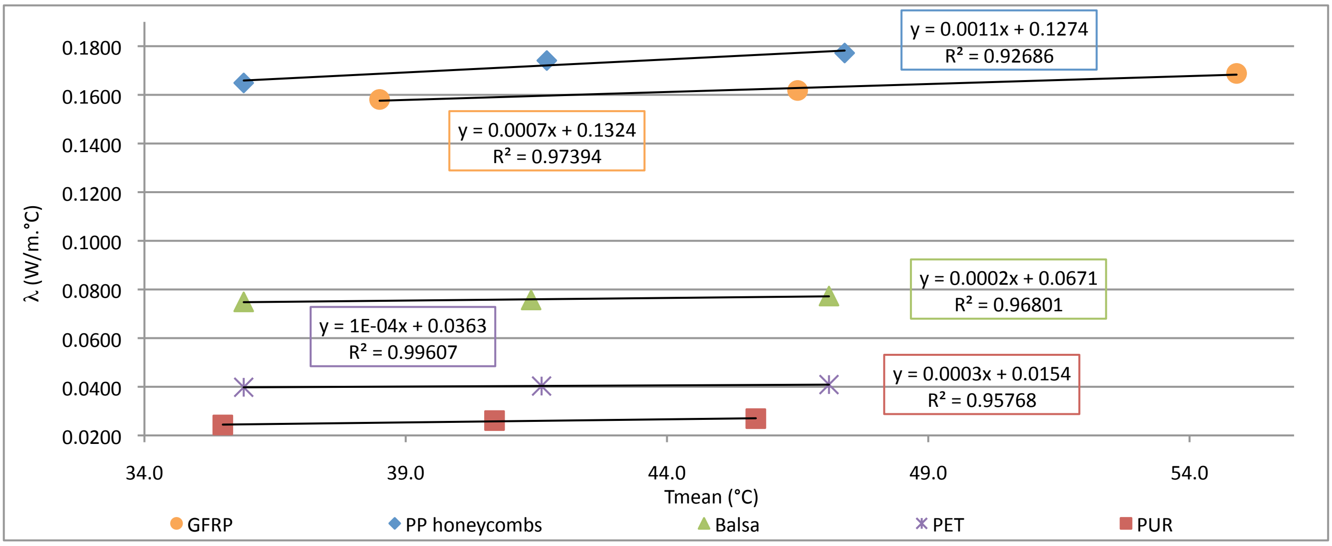

Figure 5 - Samples thermal conductivity measured with Rapid-k.

4.1.2 Thermal conductivity obtained with Isomet 2114

The results obtained with Isomet 2114 are shown in Table 3 and Figure 6. Since the mean temperature of the measurements depends on the surrounding atmosphere conditions, materials had to be tested at different times of the day. Table 3 and the graphic from Figure 6 show that materials have an increase of their thermal conductivity as the mean temperature rises. However, the PUR sample only shows a slight difference between mean temperatures and a slight decrease of the thermal conductivity for a higher temperature. Once the lowest thermal conductivity measurement range of the device is 0,04-0,3 w/m.°C, measurements of PUR should be taken with care, as the given values are smaller and the conditions at which measurements were made are similar. Figure 5 shows that PUR, PET, PP honeycombs and Balsa present lower thermal conductivities, whereas GFRP sample shows a higher value.

In this case, no trend lines were added, since only two measurements were made for each sample, what would lead to an exact trend line with no associated error.

Table 3 - Data acquired from measurements done with Isomet 2114.

Sample	*λ (W/m.°C*	*Tmean (°C)*	*ΔT (°C)*
GFRP	0,3084	28,8	9,43
	0,3161	29,4	9,42
PP honeycombs	0,0615	25,4	9,15
	0,0654	31,2	9,12
Balsa	0,0506	23,9	8,83
	0,0523	30,6	8,99
PET	0,0416	25,8	8,69
	0,0420	30,4	8,69
PUR	0,0364	26,9	8,63
	0,0360	27,0	8,67

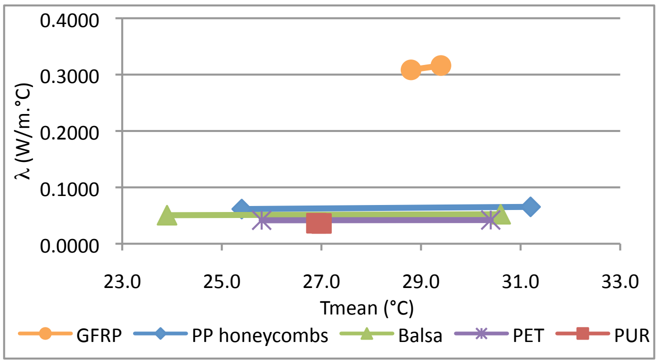

Figure 6 - Samples thermal conductivities measured with Isomet 2114.

4.1.3 Data comparison between Rapid-k and Isomet 2114

In order to compare data acquired from the two apparatus (Rapid-k and Isomet 2114), Table 4 and Figure 7 present the thermal conductivity obtained by the two methods, for a mean temperature of 30°C. This temperature was chosen based on the mean temperature of the samples, when tested with Isomet 2114. Since the Rapid-k measurements were done at higher mean temperatures, thermal conductivities were extrapolated from the samples' trend lines to 30°C.

The different values for the thermal conductivity of the GFRP sample, shown in Figure 7, can be explained by the fact that the surface probe used along with the Isomet 2114 is not the most accurate way to obtain its thermal conductivity. The probe evaluates a depth between 20 and 40 mm [12] and the sample only has 8 mm thickness. Although the desired temperature gradients could not be established in Rapid-k due to its small thickness, consistent thermal conductivity values, increased by a rise in the mean temperature were obtained. On the other hand, measurements done with Isomet 2114 for the GFRP sample show a significant difference on the thermal conductivity for almost the same mean temperature (see Figure 6), compared with the other samples. Even though Rapid-k and Isomet 2114 give similar thermal conductivities for PU at a mean temperature of 30ªC, it should be noted that the thermal conductivities acquired with the Isomet 2114 are below the minimum range of the surface probe (0,04 - 0,3 Wm.°C), and should be taken with care.

Table 4 - Samples' thermal conductivities at a mean temperature of 30°C obtained with the two methods.

Tmean 30°C	*Rapid-k λ (W/m.°C)*	*Isomet 2114 λ (W/m.°C)*
GFRP	0,1534	0,3228
PP honeycombs	0,1604	0,0654
Balsa	0,0731	0,0535
PET	0,0393	0,0421
PU	0,0244	0,0240

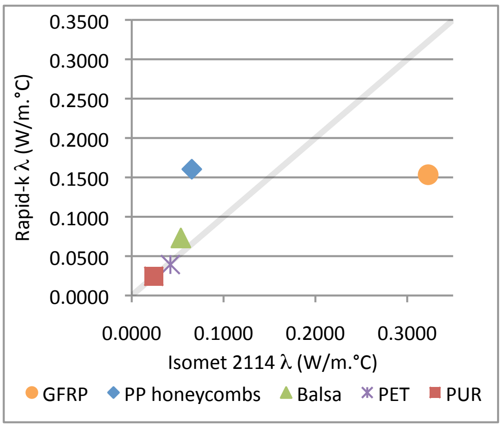

Figure 7 - Thermal conductivity comparison between Rapid-k and Isomet 2114 for a mean temperature of 30°C.

4.2 Influence of moisture content

To monitor the influence of moisture presence, 5 different moisture contents were used. The temperature gradient selected in Rapid-k was 20°C. It must be noted that the samples were wrapped with a cellophane film to avoid damage of devices and maintain the moisture content. The GFRP sample was not included in this study since it revealed to be waterproof.

4.2.1 Thermal conductivity obtained with Rapid-k

The results obtained with the Rapid-k are shown in Table 5 and Figures 8 - 11. Table 5 shows that every sample almost achieved the desired temperature gradient of 20°C, except Balsa sample. This can be explained by the large amount of water absorbed by Balsa that maintained the sample cooler than what was supposed to be. Observing the graphics on Figures 8 - 11, it is verified that the increase of moisture content in samples results in an exponential rise of thermal conductivity. In every material, except PUR, the moisture content increased thermal conductivity until a certain point at which it remained almost constant. On the other hand, the PUR sample's thermal conductivity increased until the saturation point. Figure 12 shows the influence of moisture content between dry and saturated samples. By analyzing Figure 12, it can be concluded that moisture content reveals almost unnoticeable increase in thermal conductivity of the PET and PUR materials while PP honeycombs reveal a slight increase and Balsa has its thermal conductivity increased almost five times when comparing saturated with dry state.

Table 5 -Data acquired from measurements with Rapid-k.

Sample	*w (%)*	*λ (W/m.°C)*	*Tmean (°C)*	*ΔT (°C)*
	0,0	0,1790	41,8	17,4
	7,3	0,2224	42,6	16,7
PP honeycombs	16,1	0,2217	42,4	16,7
	71,2	0,2219	42,6	16,7
	29,9	0,2219	42,6	16,5
	0,0	0,0722	41,7	18,0
	151,8	0,2095	43,2	15,2
Balsa	306,8	0,3054	44,1	13,7
	396,5	0,3506	44,4	13,0
	517,4	0,3565	44,3	13,0
	0,0	0,0422	41,9	18,0
	8,9	0,0477	42,1	17,5
PET	24,3	0,0485	42,2	17,5
	29,4	0,0491	42,1	17,4
	43,0	0,0482	42,1	17,6
	0,0	0,0277	40,8	19,7
	3,9	0,0274	41,0	19,6
PUR	7,6	0,0275	41,1	19,6
	11,0	0,0289	41,1	19,6
	15,6	0,0305	41,0	19,6

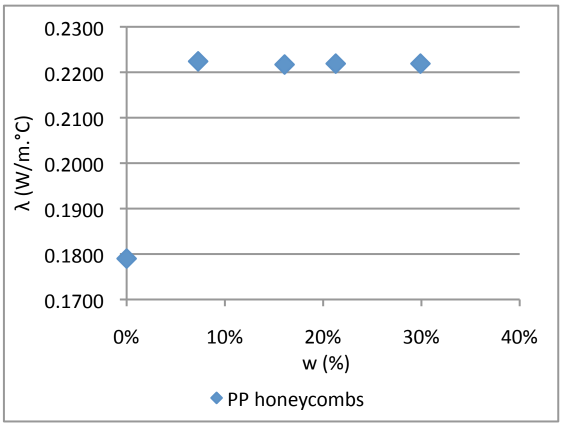

Figure 8 - Thermal conductivity of PP honeycombs influenced by moisture content and obtained with Rapid-k.

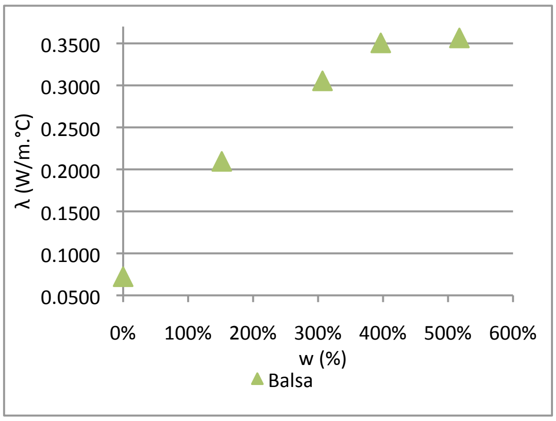

Figure 9 - Thermal conductivity of Balsa influenced by moisture content and obtained with Rapid-k.

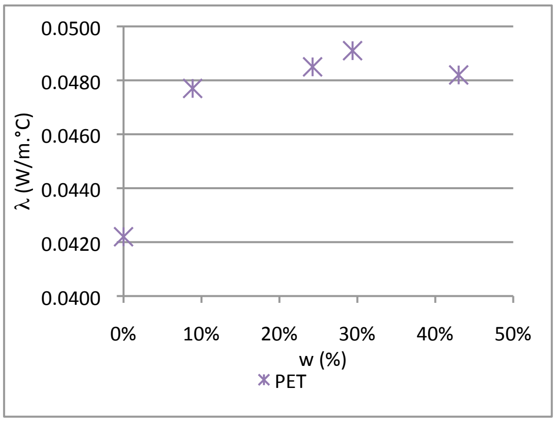

Figure 10 - Thermal conductivity of PET influenced by moisture content and obtained with Rapid-k.

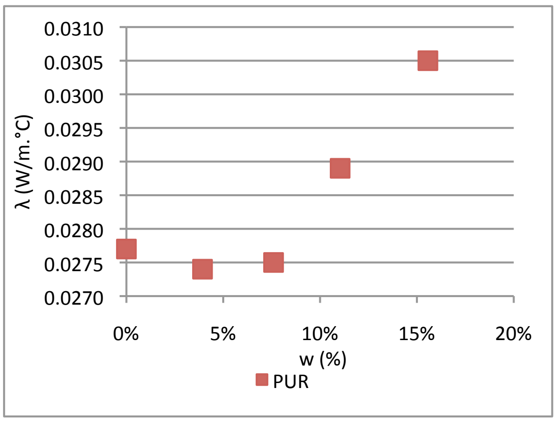

Figure 11 - Thermal conductivity of PUR influenced by moisture content and obtained with Rapid-k.

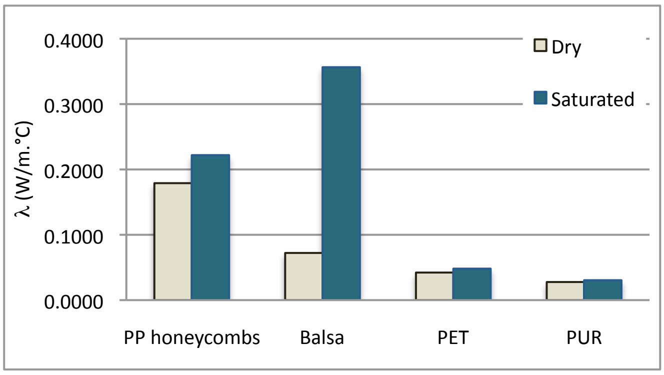

Figure 12 - Influence of moisture content in materials' thermal conductivity obtained with Rapid-k.

4.2.2 Thermal conductivity obtained with Isomet 2114

The results obtained with the Isomet 2114 are shown in Table 6 and Figures 13 - 16. Observing the graphics on Figures 13 - 16, the growth of moisture content on samples revealed an exponential increase on thermal conductivity. Every material, except PUR, revealed a trend line with a coefficient of determination higher than 90%, where PUR revealed a coefficient of determination higher that 80%. Figure 17 shows the influence of moisture content between dry and saturated samples. By analyzing Figure 17, it can be concluded that moisture content reveals a minimal increase in thermal conductivity of the PP honeycombs, PET and PUR materials, whereas Balsa has its thermal conductivity increased more than 8 times when comparing saturated with dry state.

Table 6 - Data acquired from measurements with Isomet 2114.

Sample	***w*** *(%)*	***λ*** *(W/m.°C)*	***Tmean*** *(°C)*	***ΔT*** *(°C)*
	0,0	0,0626	26,6	9,5
	7,3	0,0632	18,7	9,4
PP honeycombs	16,1	0,0651	20,0	9,0
	21,3	0,0656	18,1	8,7
	29,9	0,0691	21,1	9,0
	0,0	0,0474	24,8	9,1
	151,8	0,0774	18,0	9,4
Balsa	306,8	0,1504	20,2	9,7
	396,5	0,2034	18,2	9,2
	517,4	0,4074	20,0	8,7
	0,0	0,0406	23,7	8,8
	8,9	0,0424	18,7	8,6
PET	24,3	0,0485	20,1	8,1
	29,4	0,0495	17,5	7,9
	43,0	0,0557	17,9	7,9
	0,0	0,0362	27,1	8,7
	3,9	0,0363	20,3	8,6
PUR	7,6	0,0368	17,8	8,7
	11,0	0,0386	18,8	8,1
	15,6	0,0429	18,4	8,0

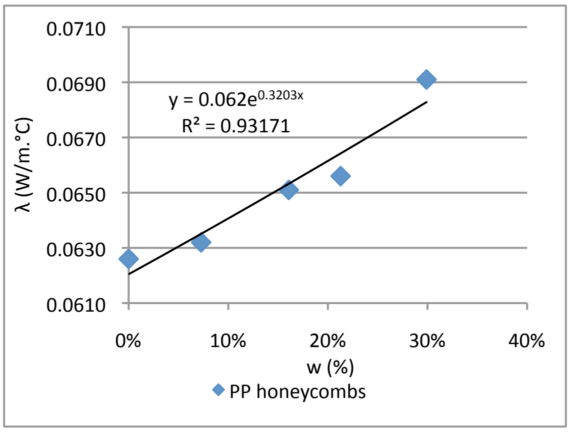

Figure 13 - Thermal conductivity of PP honeycombs influenced by moisture content and obtained with Isomet 2114.

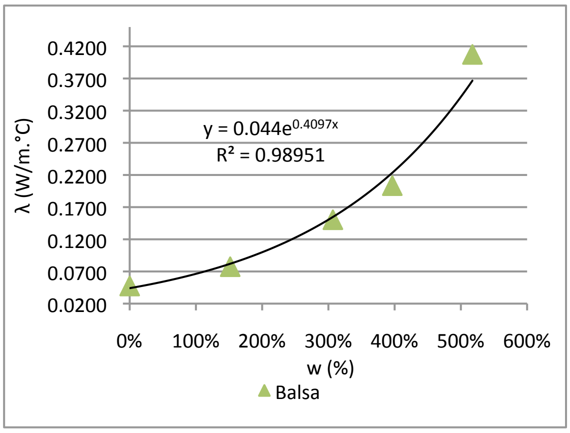

Figure 14 - Thermal conductivity of Balsa influenced by moisture content and obtained with Isomet 2114.

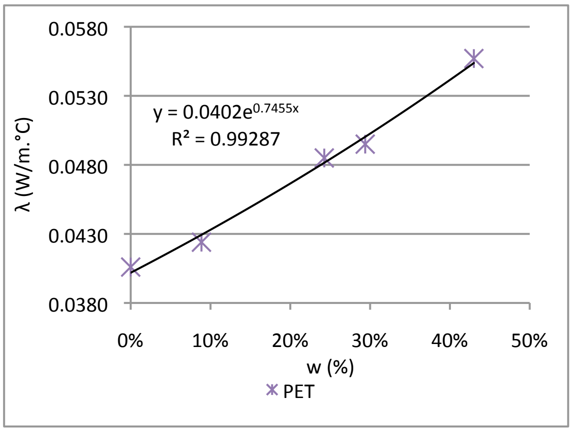

Figure 15 - Thermal conductivity of PET influenced by moisture content and obtained with Isomet 2114.

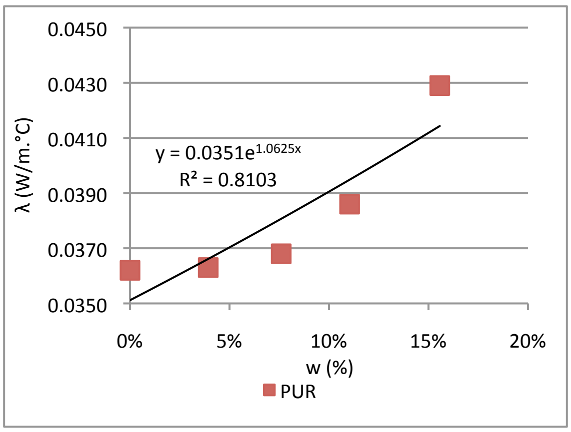

Figure 16 - Thermal conductivity of PUR influenced by moisture content and obtained with Isomet 2114.

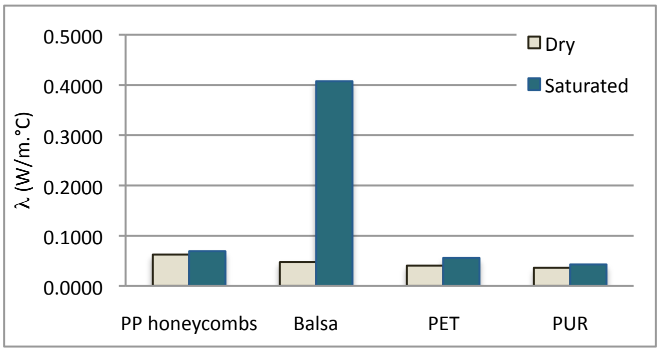

Figure 17 - Influence of moisture content in materials' thermal conductivity obtained with Isomet 2114.

4.2.3 Data comparison between Rapid-k and Isomet 2114

In order to compare data acquired from the two devices, Table 7 and Figure 18 present the thermal conductivity obtained with the two methods, for the same moisture contents. Observing Figure 18, it can be seen that the two methods give similar results for PET and PUR samples. On the other hand, Balsa and PP honeycombs show higher thermal conductivities with Rapid-k, except for Balsa when saturated. The fact that Rapid-k is more suitable for dry samples and as both Rapid-k and Isomet 2114 are more suitable for homogeneous and solid materials can explain the difference on the results between the two methods. However, both methods show that PP honeycombs has the higher thermal conductivity, followed by Balsa, PET and PUR until approximately 25% of saturation (around 160% moisture content), where Balsa becomes the most conductive material.

Table 7 - Samples' thermal conductivities obtained with the two methods for the same moisture contents.

Sample	*w* (%)	*Isomet 2114 λ* (W/m.°C)	*Rapid-k λ* (W/m.°C)
PP honeycombs	0,0	0,0626	0,1790
	7,3	0,0632	0,2224
	16,1	0,0651	0,2217
	21,3	0,0656	0,2219
	29,9	0,0691	0,2219
Balsa	0,0	0,0474	0,0722
	151,8	0,0774	0,2095
	306,8	0,1504	0,3054
	396,5	0,2034	0,3506
	517,4	0,4074	0,3565
PET	0,0	0,0406	0,0422
	8,9	0,0424	0,0477
	24,3	0,0485	0,0485
	29,4	0,0495	0,0491
	43,0	0,0557	0,0482
PUR	0,0	0,0362	0,0277
	3,9	0,0363	0,0274
	7,6	0,0368	0,0275
	11,0	0,0386	0,0289
	15,6	0,0429	0,0305

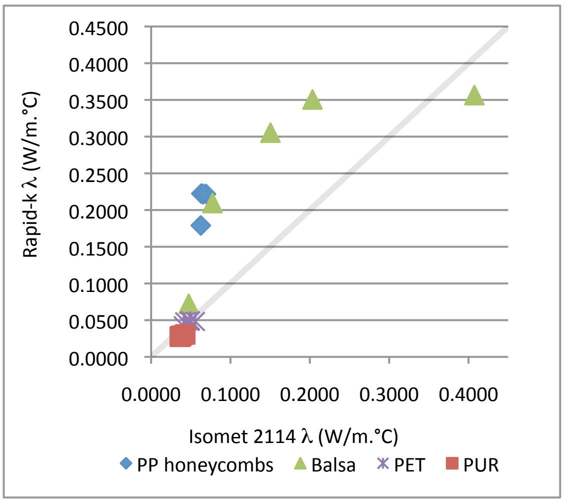

Figure 18 - Thermal conductivity comparison between Rapid-k and Isomet 2114 influenced by moisture content.

5 Prediction models

After measuring and determining the thermal conductivity of each material independently, a study was carried out to estimate the total heat loss through each sandwich panel solution, when used as wall or slab elements. This section presents the methodology to analyze the sandwich panels' thermal behaviour taking different scenarios into account.

5.1 Model development

The geometry characteristics of the sandwich panels are determined by the mechanical properties of the composing layers, consisting of a 8 mm GFRP outer layer and a 120 mm insulation layer forming the core, as illustrated in Figure 19. As shown in Figure 19, the sandwich panel has not a uniform thermal resistance because of the junction zones between panels, where a thermal bridging effect occurs. The linear thermal bridges were estimated using the software THERM (Berkeley Laboratory) [16] and, in order to set the best thermal configuration for the sandwich panels, different core materials and thicknesses were studied. The model was developed according to ISO 10211:2007 [4], where the current zone was extended until it does not suffer from the thermal bridge effect. The model goes from the middle of a panel to the adjacent panel's middle with a junction in-between made of epoxy resin with 1 mm of thickness. The model is 509 mm wide, where the junction represents 9 mm of the total length. The model is divided into 3 different zones: current; contact; and junction (Figure 20). Since no measurements were made for determining the resin's thermal conductivity, this has been considered the same of the GFRP material, which is mainly composed of a similar resin. For all the other materials (GFRP, PP honeycombs, Balsa, PET and PU) the experimentally obtained thermal conductivities from Rapid-k were adopted. Note that for the THERM simulations, 2 adiabatic surfaces that represent continuation of the panels and 2 isothermal surfaces in contact with the external and internal environments were considered.

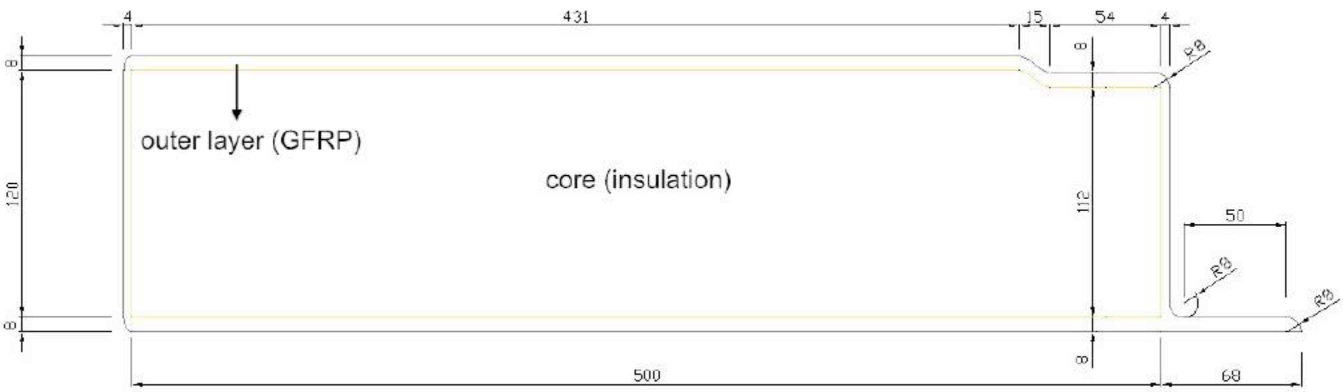

Figure 19 - Schematic of the sandwich panel solution cross-section.

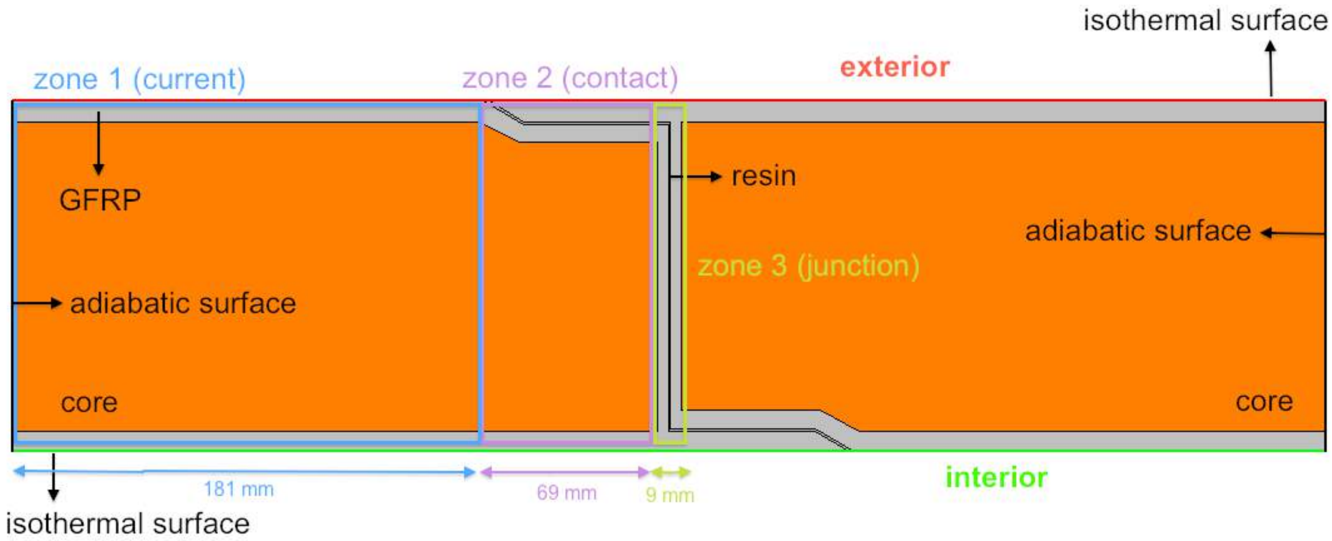

Figure 20 - Sandwich panel model's cross-section.

5.2 Studied scenarios

Only the worst-case scenario is referred to in the present document, with respect to the roof element, due to lower U-values and higher requirements to be assessed. Even though winter scenario is the most conditioning case, when constant thermal conductivity is considered, this study will present both winter and summer scenarios, varying the materials' thermal conductivity with the mean reference temperatures. Therefore, to determine the thermal behaviour of the sandwich panels Table 8 - 11 present relevant data to be taken into account.

Table 8 - Reference temperatures [17].

	Reference Temperatures	
	winter	*summer*
Tin (°C)	20	25
Tout (°C)	0	30
Tmean (°C)	10	27,5
ΔT (°C)	20	5

Table 9 - Surface thermal resistances [18].

	Direction of heat flow	
	Upwards	*Downwards*
Rsi (m^2.°C/W)	0,10	0,17
Rse (m^2.°C/W)	0,04	0,04

Table 10 - Material's thermal conductivity for reference temperatures.

	winter	*summer*
	Tmean = 10°C	*Tmean = 27,5°C*
Sample	*λ (W/m.°C)*	*λ (W/m.°C)*
GFRP	0,1394	0,1517
PP honeycombs	0,1384	0,1577
Balsa	0,0691	0,0726
PET	0,0373	0,0391
PUR	0,0184	0,0237

Table 11 - U-values recommendations from different European building thermal legislation [19,20].

		Recommendations	
		U-value *(W/m^2.°C)*	
Country	*ISO 3166-1 Coutry Code*	*Roof*	
		Low	*High*
Bulgaria	**BGR**	0,30	0,30
Denmark	**DNK**	0,15	0,25
France	**FRA**	0,20	0,25
Germany	**DEU**	0,20	0,20
Portugal	**PRT**	0,30	0,40
United Kingdom	**GBR**	0,13	0,20

5.3 Calculation of average U-value and one dimensional heat flow, total U-value and heat flow using THERM software and Ψ-value for each solution

Firstly, the U-value was calculated for each of the separate zones represented in Figure 20 (zone 1 - current zone; zone 2 - contact zone; zone 3 - junction zone), using Equation 1. After calculating the U-value of each of the separate zones, the average U-value of the three zones considering one dimensional heat flow was determined using Equation 3. Finally, the total U-value of the sandwich panel (including the linear thermal bridges) and the linear transmittance Ψ-value were determined using THERM and Equation 4. Calculations and simulations were made, considering the model of two panels with a junction illustrated in Figure 20.

5.3.1 Roof in winter scenario

The results obtained of the average and total U-values and Ψ-values for roofs on winter scenario are presented in Table 12. Figure 21 shows the comparison between total U-values and different countries from Europe recommendations and, in Figure 22 is presented the linear transmittance for each solution.

Table 12 - Average U-value, total U-value and Ψ-value for roofs in winter.

Core	*Core thickness* (mm)	U_{avg} ($W/m^2.°C$)	U_{tot} ($W/m^2.°C$)	*Ψ* (W/m.°C)
PP honeycombs	80	1,2010	1,2010	0,0000
	100	1,0234	1,0234	0,0000
	120	0,8916	0,8916	0,0000
	140	0,7898	0,7899	0,0000
	160	0,7089	0,7089	0,0000
Balsa	80	0,7251	0,7260	0,0002
	100	0,6010	0,6018	0,0002
	120	0,5132	0,5139	0,0002
	140	0,4479	0,4484	0,0001
	160	0,3972	0,3976	0,0001
PET	80	0,4386	0,4421	0,0009
	100	0,3580	0,3606	0,0007
	120	0,3025	0,3044	0,0005
	140	0,2619	0,2635	0,0004
	160	0,2309	0,2321	0,0003
PUR	80	0,2400	0,2459	0,0015
	100	0,1942	0,1985	0,0011
	120	0,1632	0,1663	0,0008
	140	0,1407	0,1431	0,0006
	160	0,1237	0,1256	0,0005

Observing Figure 21, it can be stated that U-values decrease with the increase of the core thickness and higher thermal conductive materials show the higher U-values. The PP honeycombs and Balsa solutions do not reach any recommendations from all the chosen countries. PET solutions, with 120 mm core thickness or higher, comply with recommendations of Bulgaria and Portugal. On the other hand, the PUR solutions, with 80 mm or thicker cores, are in accordance with Bulgaria and Portugal recommendations. The PUR solutions also meet recommendations in Denmark's case, with a thickness of 100 mm, and in France and Germany, with 140 mm and 160 mm core thickness, respectively.

Observing Table 12 and Figure 22, it can be concluded that linear transmittance is very low in every solution, and even zero in all solutions of PP honeycombs, due to the similarity of both materials' thermal conductivity. Observing Figures 23 and 25 for PUR and PP honeycombs solutions, respectively, the temperature gradient varies linearly across the panel thickness. Although the PUR solution, as shown in Figure 24, present different heat fluxes through the sample, PP honeycombs in the other hand, show no difference in heat fluxes, as it can be observer in Figure 26.

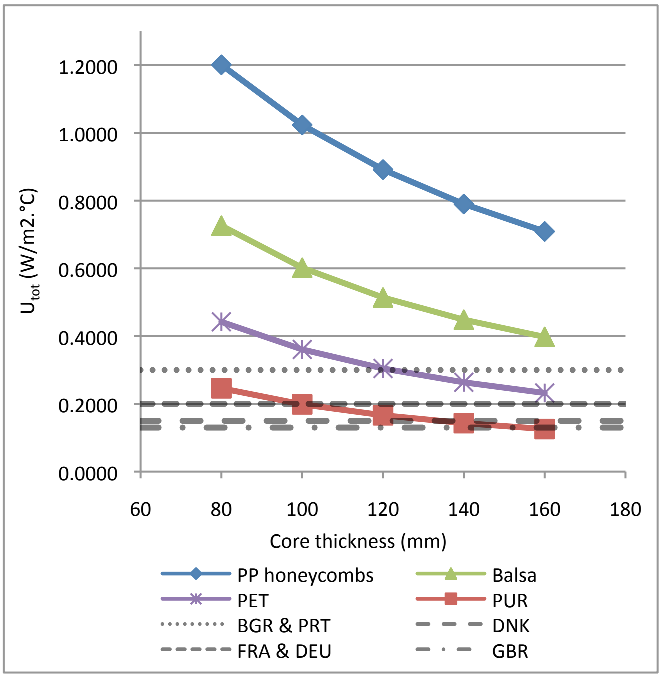

Figure 21 - Comparison between total U-values and recommended U-values for roofs in the winter scenario.

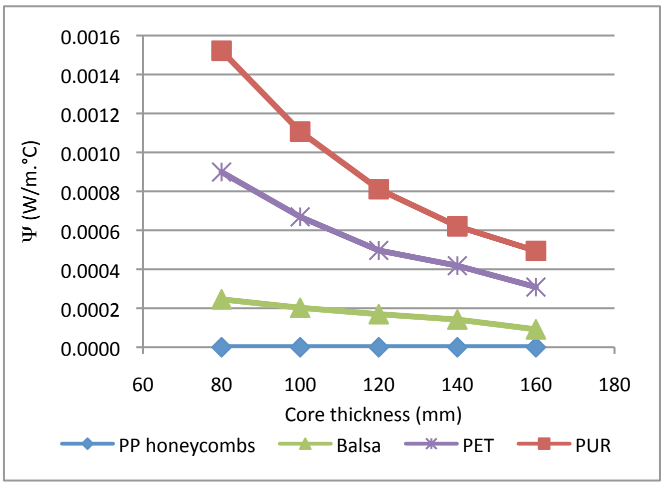

Figure 22 - Ψ-value for roofs in the winter scenario.

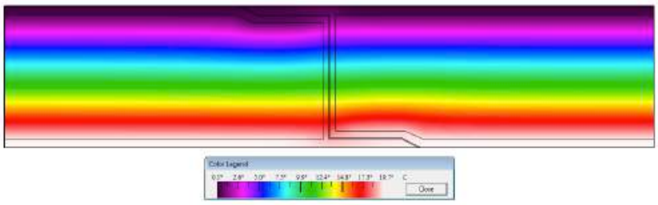

Figure 23 - Temperatures through the 120 mm PUR core solution for winter conditions obtained from THERM.

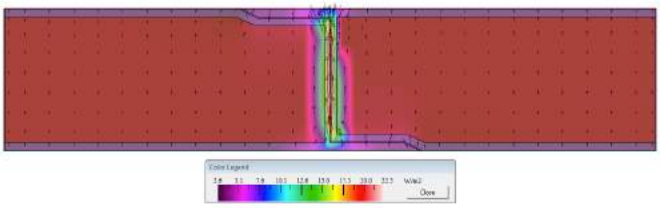

Figure 24 - Heat flux through the 120 mm PUR core solution for winter conditions obtained from THERM.

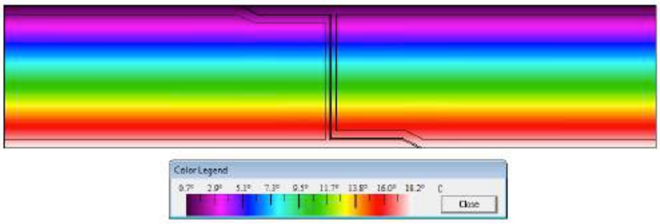

Figure 25 - Temperatures through the 120 mm PP honeycombs core solution for winter conditions obtained from THERM.

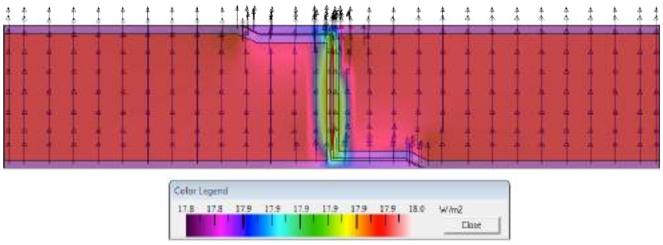

Figure 26 - Heat flux through the 120 mm PP honeycombs core solution for winter conditions obtained from THERM.

5.3.2 Roof in summer scenario

The results obtained of the average and total U-values and Ψ-values for roofs on summer scenario are presented in Table 13. Figure 27 shows the comparison between total U-values and different European's recommendations and, in Figure 28 is presented the linear transmittance for each solution. Observing Table 13, in the summer scenario, U-values are higher than in the winter scenario. This fact can be explained by the increase of materials' thermal conductivity, originated by a rise in the mean temperature. Even though U-value decreases with a higher interior surface thermal resistance, promoted by a downward heat flow, the increase in thermal conductivity counteracts this decrease, increasing the U-value when comparing to the winter scenario. However, heat fluxes will be higher in the winter scenario due to a higher temperature gradient.

Observing Figure 27, it can be stated that the increase of the U-values changes the possibilities of the studied solutions to be applied as roof elements. Even though the studied PUR solutions still comply with all the Bulgarian and Portuguese recommendations, Denmark's recommendations are only assured by a 160 mm or thicker core. For this scenario, United Kingdom's recommendations are not assured by any of the studied solutions. On the other hand, the 120 mm PET solution is close to Bulgarian and Portuguese recommendations, whereas 140 mm solution satisfies them. Table 13 and Figure 28 show that linear transmittance values are higher, when comparing to the winter scenario, nevertheless, remain close to zero and may be negligible for the total heat exchanges.

Table 13 - Average U-value, total U-value and Ψ-value for roofs in summer.

Core	*Core thickness (mm)*	*U_{avg} ($W/m^2.°C$)*	*U_{tot} ($W/m^2.°C$)*	*Ψ (W/m.°C)*
PP honeycombs	80	1,2138	1,2141	0,0001
	100	1,0517	1,0520	0,0001
	120	0,9279	0,9281	0,0001
	140	0,8301	0,8304	0,0001
	160	0,7510	0,7512	0,0001
Balsa	80	0,7221	0,7234	0,0007
	100	0,6040	0,6051	0,0006
	120	0,5192	0,5200	0,0004
	140	0,4552	0,4560	0,0004
	160	0,4053	0,4059	0,0003
PET	80	0,4444	0,4492	0,0025
	100	0,3649	0,3683	0,0017
	120	0,3096	0,3125	0,0015
	140	0,2689	0,2713	0,0012
	160	0,2377	0,2396	0,0010
PUR	80	0,2927	0,2998	0,0036
	100	0,2383	0,2436	0,0027
	120	0,2011	0,2051	0,0021
	140	0,1739	0,1772	0,0017
	160	0,1532	0,1559	0,0014

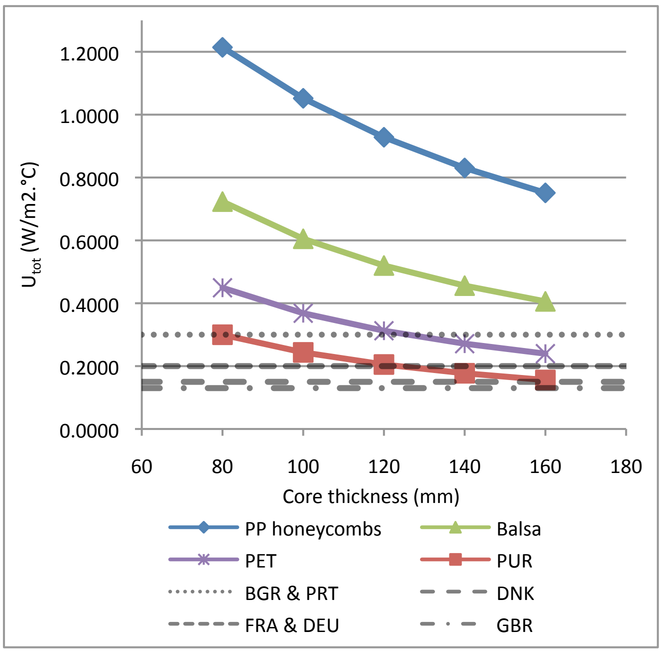

Figure 27 - Comparison between total U-values and recommended U-values for roofs in the summer scenario.

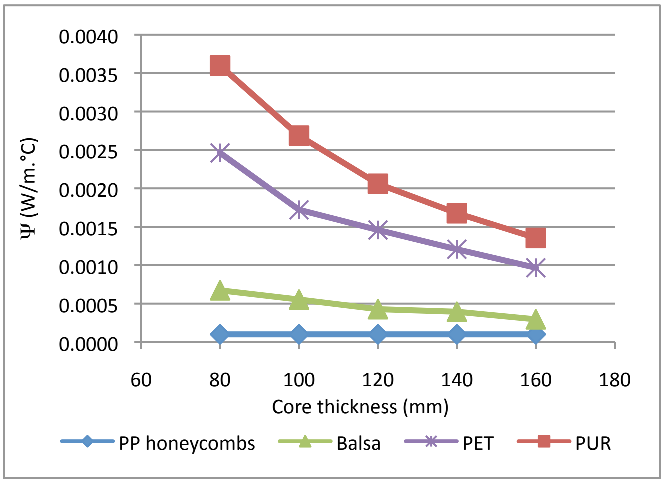

Figure 28 - Ψ-value for roofs in the summer scenario.

6 Conclusions

The thermal efficiency of a building depends, among other factors, on the thermal characteristics of the envelope components and corresponding constituent materials. Thermal conductivity is the material property from which the thermal insulation of a building component depends on. The lower the thermal conductivity is, the lower are the heat losses and the larger are the energy savings to maintain the thermal comfort inside a building. Therefore, thermal insulators, characterized by having a low thermal conductivity, are currently used to increase the thermal performance of the building elements, thus playing a very important role in the energy efficiency of the buildings.

In order to determine the thermal behaviour of the GFRP sandwich panels' solutions (with cores made of Balsa, PET, PP honeycombs and PU), influenced by temperature and moisture content, two distinct experimental methods were used, a steady state method with Rapid-k apparatus from Holometrix, and a transient method with Isomet 2114 apparatus from Applied Precision Ltd. The use of these experimental tests and a modelling program (THERM software from Berkeley Laboratory), were crucial for accurately predicting the total heat loss of the solutions, as well as thermal bridges, and linear thermal transmittances. Even though materials' thermal behaviour is influenced by moisture content, calculations were only made for a scenario of temperature change since the GFRP laminate revealed to be waterproof, maintaining the cores in dry state, as expected. However, breaks in the GFRP laminates can origin water absorption, leading to higher thermal conductivities in the solution.

The steady state method, performed with Rapid-k, revealed to be the most adequate apparatus to measure the thermal conductivity of the evaluated materials, influenced by temperature, whereas Isomet 2114 revealed to be the most adequate apparatus to measure the thermal conductivity of the evaluated materials, influenced by moisture content.

Experimental tests revealed that materials suffer a linear increase in their thermal conductivity with a rise in temperature, and an exponential increase in their thermal conductivity is expected with a rise in moisture content.

With the increase of materials' thermal conductivity influenced by higher temperatures, instead of constant values, the U-values are higher in summer than in winter.

Six countries from distinct areas of Europe were chosen to analyze how the studied solutions accomplish the recommendations and to evaluate the maximum heat flow regarding construction elements. It can be noticed that the chosen solution, a sandwich panel with 120 mm thermal insulation as core, does not meet all the recommendations for U-values in the studied European countries. Thus, some of these solutions are away from the desired thermal efficiency performance. The solutions made with PP honeycombs and Balsa are the less efficient, whereas PU and PET give better performances. It was concluded that a 180 mm PU core solution meets the recommendations for all the chosen countries in the winter scenario, but none of them comply with United Kingdom's U-values recommendations in the summer scenario. Even though the 120 mm core solution, which is the determined solution by the mechanical properties, does not satisfy all the thermal recommendations by all materials, they also may be used. For this purpose, solutions will have to comply other energy requirements, assisted with standard calculation methods.

The estimation of the total heat loss and the linear transmittance shows that additional heat flow through linear thermal bridges plays an insignificant role on the total heat flow through the panel, and can be negligible to thermal design. The small dimension of the panel's junction can explain this fact, since it is only 9 mm wide. As a result, average U-value revealed to be a good and easily obtainable parameter that indicates the GFRP sandwich panels' thermal behaviour.

As a final remark, it should be noticed that the solution being build up can have added materials, as finishing surface layers, which can provide a better thermal performance to the element as a whole.

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