Thermal characterization of different substrates under dried conditions for extensive green roofs

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Abstract

Extensive green roofs have been consolidated as good tools for passive energy saving~~s~~ systems in buildings, providing a more sustainable trend in the building field. However, as the growth of vegetation is variable depending on external factors such as weather conditions, disease, etc. the coverage of plants cannot ensure uniformity and consequently the “shadow effect” cannot be considered as a constant parameter. On the other hand, materials used in substrate and drainage layers should provide a constant “insulation effect” depending only on their physical properties and water content. In spite of this, the complexity of disaggregated materials used in internal layers of extensive green roofs implies a lack of real data about their thermal properties. The main objective of this study is to determine experimentally the physical properties of different disaggregated materials from the internal layers of extensive green roofs commonly used in Mediterranean climates. The experimentation presented in this paper allows to calculate the thermal transmittance in steady-state (U-value), the heat storage capacity (C*p*), and the dynamic thermal response under a daily thermal oscillation.

Keywords: Extensive green roofs; Substrates; Thermal properties; Passive system; Energy savings.

1 Introduction

In Europe the building sector represents 40% of the overall energy consumption and 36% of the overall CO_2 emissions [1]. Within the target to reduce the energy demand of buildings and preserve the environment, innovative technical solutions have to be proposed and adopted.

Among the systems available in the sustainable and bioclimatic architecture context, green roofs have an important role as it has been demonstrated in many cities with the increment of these features in new and refurbished building projects [2].

Green roofs have significant advantages. Considering from an energy and architectural point of view, green roofs offer an additional thermal insulation contributing to the reduction of energy consumptions. During summer, green roofs can control and mitigate the heat flux entering through the roof, by the evaporative effect and by reducing the total amount of solar energy absorbed by the building [3-5]. The benefits of green roofs are correlated to the shadow effect produced by the vegetation, the insulation effect and the thermal storage due to the substrate and drainage layers depending on their physical properties (density, thickness, thermal conductivity, and specific heat capacity) [6].

Previous studies highlight the importance of considering situations with low plant cover, where the plants provide scarce shade, and the thermal performance of the extensive green roof depends on the thermal characteristics of the lower layers, especially the substrate. This is a common situation in Mediterranean climates [7, 8].

Furthermore, green roofs protect the roof membranes from extreme temperatures during hot days [9] and avoid high thermal fluctuations decreasing thermal stress for the materials and improving the durability of the roof [10].

Another benefit is from a hydrologic point of view. Green roof substrates capture storm water altering the magnitude and timing of runoff peak [11]. By absorbing rainwater, green roofs delay the runoff and mitigate the impact of heavy rains [12]. Also, many more advantages from an environmental point of view can be highlighted. The evapotranspiration allows the humidification and the air cooling by reducing the heat island effect in urban areas. Additional green roof benefits include the generation of natural habitats and the aesthetic improvement for the cities [13].

The effect of implementing green roofs on buildings has been object of intense studies during the last decade. In particular, to evaluate their thermal performance many predictive models were proposed [14, 15]. However, the modelling of these systems is problematic because of the simultaneous phenomena of heat and mass transfer. For this reason, generally each model introduces simplifications concerning the evapotranspiration and the variability of the thermal properties of the substrate. The simplest modelling considers the green roof as a unique resistant layer whose thermal properties are constant and the thermal storage capacity is neglected.

More accurate formulations take into account the dynamic nature of the heat transfer through the green roofs [16, 17]. In this case an important role is associated to the substrate that influences the energy performance by means of the thermal resistance and the heat storage capacity.

Generally green roof substrates are composed of aggregates, sand and specific organic matter to ensure suitable living conditions for the vegetation planted on the roof. While detailed thermal property data for natural soils are available [18, 19], there is a lack of information in the scientific literature regarding the thermal properties of extensive green roof substrates, especially for those used in a Mediterranean climate. It is therefore difficult to deduce thermal properties of green roof substrates from data available for natural soils. Also, as there are many variations of growing media available and used in different geographical locations it is important to gather data regarding the thermal properties of a variety of different kinds of soil mix.

Few experimental studies to measure the thermal conductivity, heat capacity and thermal diffusivity of growing media have been conducted by researchers. To characterize the variability of these thermal properties in relation to the composition and the water content, Sailor et al. [20] and Sailor and Hagos [21] have measured the thermal properties of substrates with different compositions commonly used in western U.S.

Pianella et al. [22] studied the thermal conductivity values of three different green roof substrates with different moisture contents; dry, moist and wet in a south-eastern region of Australia. With the same target, Zhao et al. [23] analysed experimentally and numerically the thermal conductivity and specific heat capacity of green roofs selecting different plants and substrates for four different climate regions in the U.S. Finally, Ouldboukhitine et al. [24] characterized the thermal conductivity of five green roof substrate samples for different water content values.

The substrate thermal conductivity increased when the water content varies, ranged from 0.13 to 0.75 W/m·K [20]. Compared with concrete or rock wool in the dry state (0.92 W/m·K and 0.045 W/m·K, respectively), the insulating capacity of a substrate is more similar to that of rock wool; however, when the substrate is wet, the insulating capacity is less interesting.
For this reason, is crucial to study firstly the thermal properties of the substrates on dried conditions of the extensive green roofs. Moreover, it cannot be overemphasized that the paper is focused on characterize the thermal behaviour of five different substrates commonly used in dry Mediterranean continental climatic conditions, Spain. The average of annual rainfall is less than 250 mm/year according to the Meteorological Service of Catalonia, which means these areas have been considered as dry zones [25].

It is quite common that the composition of substrates indeed depends on the local availability of materials and it strongly varies according to national recommendations. A different composition is connected with different thermal properties of the substrate and, consequently, of the whole green roof system. For this reason is important to have accurate information about the growing media intended to be used, especially in the design phase, where heat transfer numerical models often require such information.

After a literature review, the most important components in the green roof, concerning the thermal performance, are plants and substrates [23]. Therefore, one of the main objectives of the present paper is to characterize five different green roofs substrates by providing thermo-physical parameters that can be used in numerical models and design processes of building components.

Moreover, only two important parameters, thermal conductivity (k) and specific heat capacity (C_p) were commonly studied, however, the daily thermal response of these materials was not experimentally evaluated and only was estimated by simulations. With this aim an experimental apparatus is used to determine the two main thermosphysical properties (*k* and C_p) and also provide an experimental dynamic thermal response of different substrate composition for extensive green roofs which have not been previously studied in the literature.

2 Materials and methodology

2.1 Experimental set-up

The apparatus created and assembled by GREA research group from the University of Lleida [26] that allows calculating the thermal transmittance in steady-state (U-value), the heat storage capacity and the dynamic thermal response under daily temperature oscillation, was adapted in order to conduct this new experimentation.

The equipment used to perform the experiments is based on a wooden structure with external dimensions of 32 cm x 28 cm x 61 cm. The exterior wooden panels are insulated with 35 mm of vacuum panels (RC- 0.14 $m^2 \cdot K/W$) and 20 mm of Pyrogel (k = 0.013 W/m·K). The internal space is divided into two cavities, which are used to simulate the inner and outer conditions of a building envelope (roofs). The tested samples have the dimensions of Ø 75 × 75 mm and are located between the both air cavities to force the heat flux to become one-dimensional through the sample (Figures 1a and 1b).

Both air cavities are connected to programmable water bath able to simulate different thermal conditions. The location of the sensors used is shown in Figure 1b. The cavity, surfaces and centre temperatures of the sample were measured using 0.5 mm thermocouples type T, with an error of ±0.75%. To measure ingoing and outgoing heat fluxes of the sample, two heat flux meters (Hukseflux HFP01) with accuracy of ±5% were fixed to the sample surfaces.

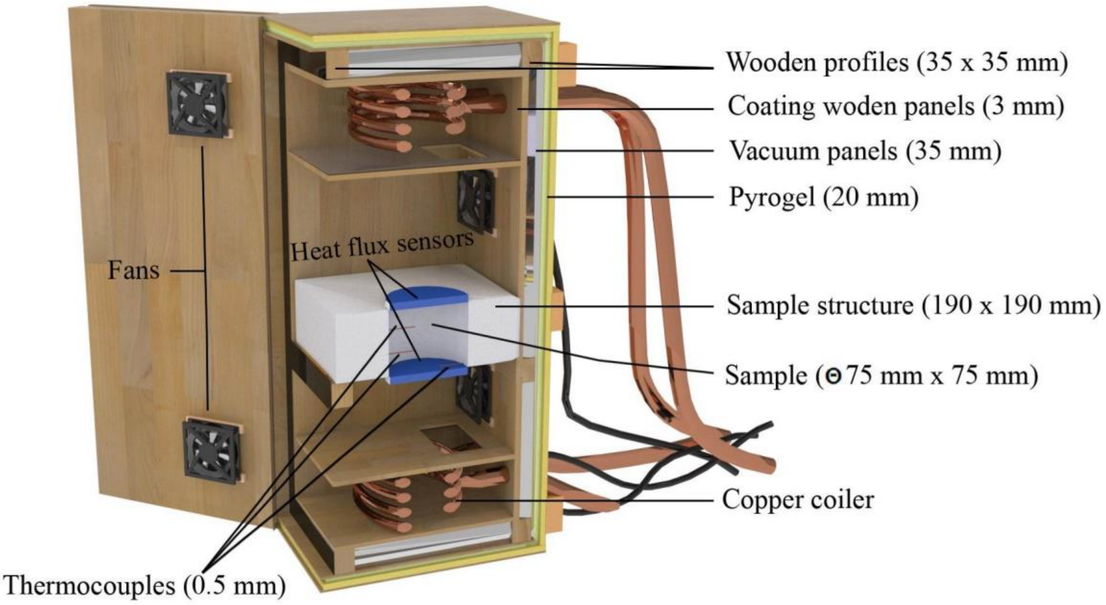
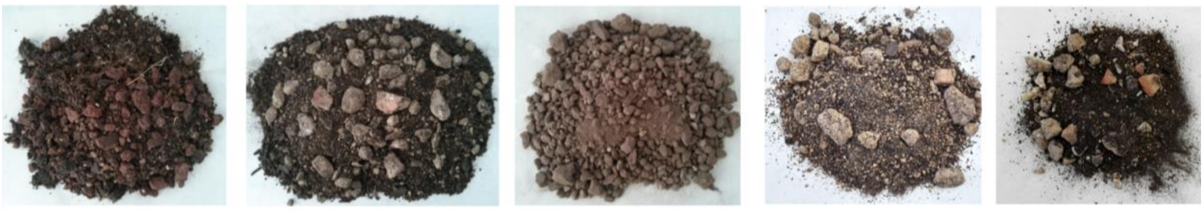


Figure1. Scheme design of the equipment.

2.2 Materials

The thermal response of five commercial substrates (Figure 2) with different composition (Table 1) used in green roofs under Mediterranean continental climate have been analysed under dry conditions. In agreement with the UNE 103:100 1995 [27], a laboratory stove at 40 ºC was used to remove the moisture content of the substrates.



Substrate 1 Substrate 2 Substrate 3 Substrate 4 Substrate 5

Figure2. Commercial analysed substrates

Table 1.Composition per cent by volume of green roof soils tested

Sample identifier	**Coco peat (%)**	**Compost (%)**	**Crushed building wastes (%)**	**Coarse grained sand (%)**	**Pozzolana (%)**	**Organic Content (%)***	**Density When dry* (g/cm^3)**	**Mass of samples (g)**	**Particle density (g/cm^3)**	**Total pore volume (%)**
Substrate 1	0	40	0	20	40	N/A	0.788	242.5	N/A	N/A
Substrate 2	25	25	40	10	0	6.77	0.923	261.4	2.5	63.22
Substrate 3	N/A	6	N/A	N/A	N/A	6	1.360	312.9	N/A	N/A
Substrate 4	25	40	30	5	0	14.12	0.546	336.4	2.27	77.01
Substrate 5	60	15	20	5	0	12.57	0.375	284.5	2.40	84.38
Density* (when dry) (g/cm^3)	0.07	0.240	0.494	0.457	N/A	-	-	-	-	-
Particle density (g/cm^3)*	1.517	1.92	2.60	1.45	N/A	-	-	-	-	-
Pore volume (%)*	95.28	87.52	81.06	68.53	N/A	-	-	-	-	-

*Given by the company

2.3 Methodology of experiments

Three different types of experiments were carried out to evaluate the thermal performances of the previously described samples. The first experiment allows to calculate the sample thermal transmittance in steady-state, also known as U-value. The heat storage capacity of the tested samples was measured in the second experiment. Finally, the third experiment was done to evaluate the dynamic thermal response under daily thermal oscillation that provides a step forward in evaluating experimentally the thermopysical properties.

2.3.1 Experiment 1 (U-value)

In this experiment the sample was placed in the equipment with an initial temperature of both water baths of 20 ºC until steady conditions were reached. Afterward a heating ramp was programmed using water bath B (from 20 ºC to 50 ºC); therefore the sample was heated from below, while water bath A was used to keep the upper section at a constant temperature (20 ºC). As it was previously mentioned, the U-value of the sample can be calculated from this experiment using the thermal gradient between surfaces in steady-state conditions.

$$U_{sample} = \frac{\dot{q}_{sample}}{A \cdot (T_{down} - T_{up})} \quad \text{(Eq.1)}$$

where $\dot{q}_{sample}$ is the rate of heat accumulation in the sample during the experiment, A is the area of the sample, and T_{down}, T_{up} are the temperatures from both surfaces of the sample.

2.3.2 Experiment 2 (heat storage capacity)

In the second experiment, the sample was placed as in the previous configuration and heated from an initial temperature of around 20 ºC (similar to the comfort temperature in the internal environment) to more than 40 ºC (peak of temperature in Mediterranean summer weather conditions) by programming heating ramps in both cavities. Note that the sample is kept in steady conditions (uniform temperatures) at the initial and final conditions; therefore an average heat storage capacity of the sample can be determined from this experiment since there is no temperature gradient in the sample at the end of the experiment. The heat fluxes per square meter passing through the top and bottom surfaces of the sample were measured; hence the amount of heat stored in the sample can be known at any time from the difference of these two fluxes. Since the sample temperature increases at all locations from T_i to T_f, the average heat capacity (Cp_{sample}), can be calculated as follows:

$$Cp_{sample} = \frac{q_{acc}}{(m_{sample}(T_f - T_i))} \quad \text{(Eq.2)}$$

where q_{acc} is the amount of heat accumulated in the sample during the experiment, and m_{sample} is the mass of the sample. This experiment was carried out three times for each sample to verify repeatability in the methodology of the average heat capacity calculation.

Moreover, the volumetric specific heat ($Cp_{.vol}$) is the product of the density (ρ) and specific heat (Cp_{sample}) of the analysed substrates.

2.3.3 Experiment 3 (dynamic thermal response)

The dynamic thermal response of the tested samples was evaluated in the third experiment. The temperature of the upper air cavity was driven by a programmable water bath which creates high thermal daily oscillation between 60 ºC and 15 ºC, to simulate summer conditions. In this case the upper bath simulates the temperatures generated on the roofs by the combined effect of external air and solar radiation. The water bath B (below) is not used during the experiment; hence the lower cavity remains under free floating conditions and the evolution of its temperature is registered and compared.

The thermal response of the sample was evaluated by analysing the delay between peaks of the inner and outer temperature, heat fluxes and by evaluating the dampening of the temperature wave (thermal stability coefficient [28]), which can be calculated as the ratio between the inner and outer thermal amplitudes. Surface temperatures were used to calculate this parameter.

3 Results and discussion

3.1 Experiment 1: (U-value)

From the measured quantities, steady state conditions could be assumed after 7 h from the beginning of the experiment for the five analysed substrates. From these measured values, thermal transmittance in steady state can be determined.

Table 2. Steady state conditions and parameters in experiment 1

	Substrate 1	**Substrate 2**	**Substrate 3**	**Substrate 4**	**Substrate 5**
$q_{top/A}$ [W/m^2]	26.04	26.07	36.25	35.82	31.93
$q_{bottom/A}$ [W/m^2]	27.98	27.93	36.00	36.98	32.00
K_{sample} [W/m·K]	0.138	0.145	0.196	0.199	0.158
U_{-value} [W/m^{2o}C]	1.83	1.91	2.60	2.63	2.09
σU_{-value}	0.01	0.01	0.03	0.04	0.01

Table 2 shows the heat fluxes on the top (q_{top}/A) and bottom (q_{bottom}/A), the calculated U-value and the thermal conductivity for the tested samples. In addition, the standard deviation (σ) of all repetitions of experiment 1 was provided for each substrate.
The sample of the substrate 4 shows the highest thermal transmittance with 2.63 W/m^2·ºC followed by substrate 3 with 2.59 W/m^2·ºC, substrate 2 with 1.90 W/m^2·ºC, and finally substrate 1 with 1.83 W/m^2.

These results are in agreement with those published by Shao et al [23], in which considering the mass of the analysed samples it can be confirmed that the higher the mass of a substrate sample, the higher the thermal conductivity. Thus, we can confirm that substrates 4 and 3, which have the heaviest samples, provide the lowest insulating capacity under dry conditions with 0.199 and 0.196 W/m·K, respectively. Otherwise, the mix of substrate 1 with 40 % of Pozzolana and the lightest sample provided the highest insulation capacity (0.138 W/m·K).

Moreover, recent research done by Pianella et al. [20] showed the thermal conductivity under dried conditions were between 0.1 W/m·K and 0.25 W/m·K, whilst the results obtained in the current study ranges between similar values (0.13 W/m·K and 0.19 W/m·K).

3.2 Experiment 2: heat storage capacity

The rates of heat accumulated during Experiment 2 by five different substrates are shown in Figure 3. The rates of heat accumulation of substrates show a different curve during the first hour, due to the different composition between them. The sample of substrate 3 shows the highest rate of heat accumulation followed by substrate 4, substrate 1 and finally substrates 5 and 2.

After an initial peak the samples started to lose part of the heat from the top surface while receiving heat from the bottom. The time needed to achieve steady state, and consequently the heat storage time, was around 13 h (when the rate of heat accumulation was almost zero) for the five analysed substrates.

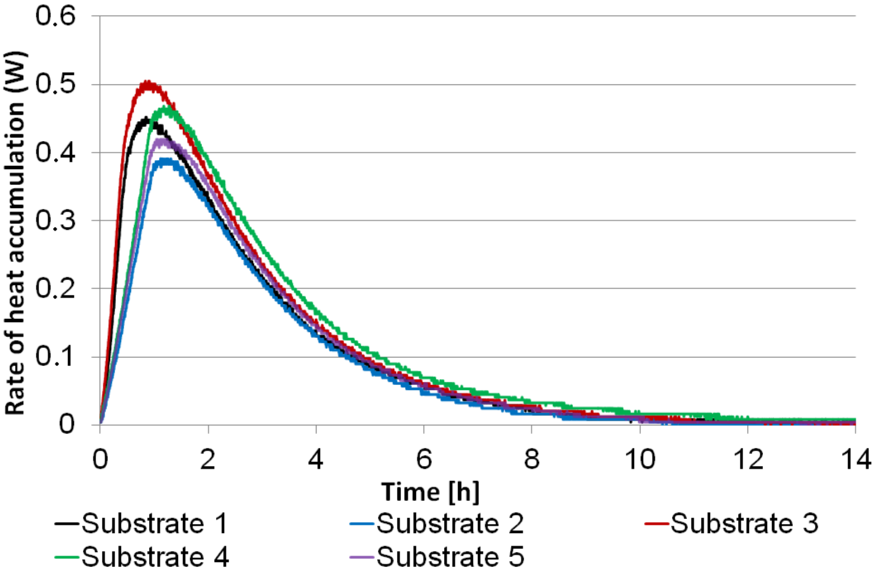


Figure 3. Rate of the heat accumulated for the five analysed substrates

Substrates 4 and 3 show the highest values of energy stored by the sample after 13 h of experiment equal to 5865 J and 5788 J, respectively, followed by substrate 1 with 11.5% less stored energy (5189 J). Substrate 5 presents 14.8% less stored energy (5000 J) and finally substrate 2 presents 24.2% less stored energy (4446 J) in comparison to substrate 4.

The measured parameters from Experiment 2 and the calculated heat storage capacity of the samples are presented in Table 3.

Table 3. Heat storage capacity of substrates

	Substrate 1	Substrate 2	Substrate 3	Substrate 4	Substrate 5
Cp_{sample} [J/kg·K]	873.2	759.6	772.7	748.4	724.0
Cp_{vol} [kJ/m^3·K]	688.08	701.11	1050.87	407.88	271.50
σ Cp_{sample}	6.74	16.87	3.05	6.01	5.59

The samples of substrates 3 and 2, which present the highest percentages of crushed building wastes, showed the higher volumetric heat capacity, followed by substrate 1 that is basically made by compost (40%). Finally, substrates that are mainly composed by coco peat and have higher values of organic content (substrates 5 and 4), showed lower heat storage capacities.

These results have a high impact on the thermal performance of a roof because depending on the total amount of a specific substrate used in a green roof system, the total energy that can be stored or released can vary a lot.

The volumetric heat capacity for the five analysed substrates, is also in agreement with those results recently published by Pianella et al. [22] for four different climate conditions in USA ranging from 600 to 1500 kJ/m^3·K and by Zhao et al. [23] for a south-eastern region of Australia ranging from 350 and 1600 kJ/m^3·K.

3.3 Experiment 3: dynamic thermal response

The dynamic thermal response of the samples under an outer daily oscillation between 60 ºC and 15 ºC was evaluated. The thermal evolution of the inner and outer temperatures of the tested samples is shown in Figure 4 and it allows calculating the thermal stability coefficients (TSC) from the five analysed substrates. The coefficients are reported in Table 4.

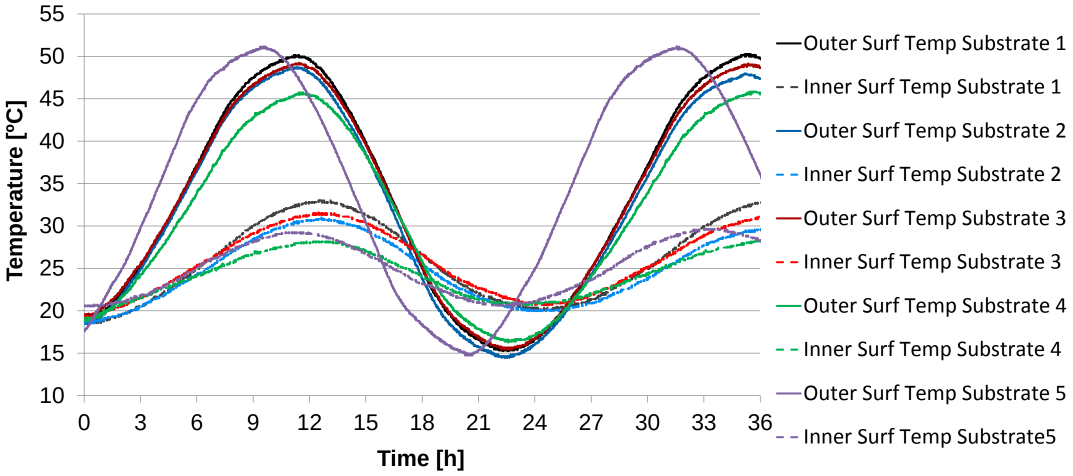


Figure 4. Dynamic thermal response of the surfaces temperatures

Instead of comparing the delay of inner and outer temperature peaks, the time lag between the outer temperature and the inner heat flux peaks (thermal lag) is evaluated. Figure 5 presents the thermal lag of the five samples under similar outer conditions. The different composition of substrates 3 and 4 lead to a 23% increase of the heat flux compared to substrate 2 and substrate 1 which did not show remarkable differences. Table 4 reports the time lag for the five analysed substrates.

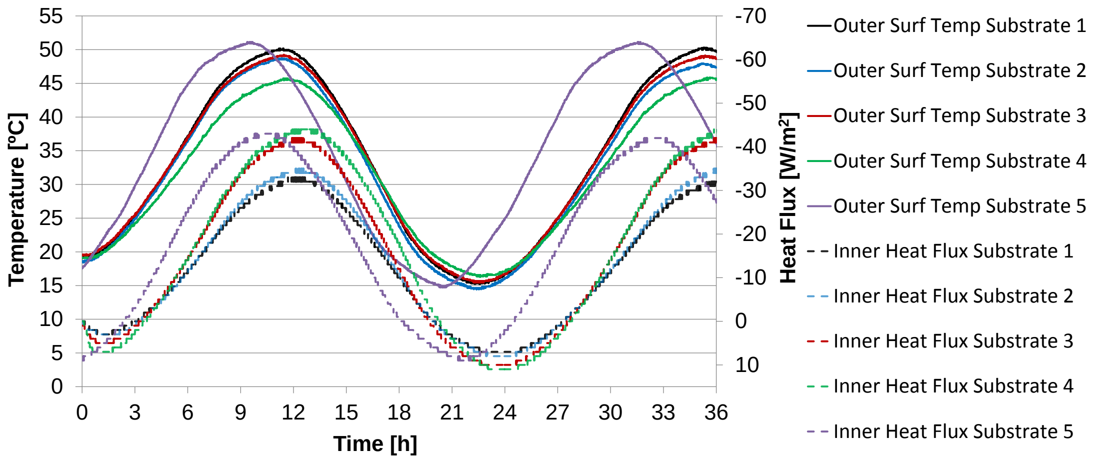


Figure 5. Thermal lag of the five analysed substrates

The calculated thermal stability coefficients were 0.37, 0.35, 0.32, 0.25 and 0.24 for substrate 1, substrate 2, substrate 3, substrate 4 and substrate 5 respectively. The substrates 4 and 5 proved to be more effective in dampening the temperature fluctuation, with the lowest TSC.

Regarding the time lag, two of the five analysed substrates showed similar values, 1.15 h for substrate 4, 1.18 h for substrates 5, that could be related to the lower volumetric heat capacity presented in the experiment 2. On the other hand, the substrates (1, 2, and 3) with high volumetric heat capacities have provided higher time lags 1.19 h, 1.21 h and 1.36 h, respectively. However, other physical properties of the substrate may affect this thermal parameter, so further investigations are required to understand this phenomenon.

Table 4. TSC and Time lag of the five substrates

	Substrate 1	**Substrate 2**	**Substrate 3**	**Substrate 4**	**Substrate 5**
TSC [-]	0.37	0.35	0.32	0.25	0.24
Time lag [h]	1.19	1.36	1.21	1.15	1.18

4 Conclusions

Focusing on five different typologies of substrates used in a dry Mediterranean climate, this study expands the thermo-physical data available in literature, by performing three different experiments. The results allow calculating the most common thermal properties and two experimental transient parameters.

Specific conclusions are:

- A specific equipment to measure the steady-state parameters, the dynamic thermal responses, and the heat storage capacity of different substrates is presented in this paper. Compared to traditional methods, the equipment allows testing the dynamic thermal response of a material subjected to daily temperature oscillations in a fully controlled environment.

- Representative differences were found for the calculated U-values and Thermal Stability Coefficients between the different analysed substrates, showing how the composition of these substrates can strongly affect the thermal performance of the whole roof system.
- The study reveals that thermal conductivity of samples is strongly related with their masses.
- Substrates with lower organic content (1, 2 and 3) showed the highest rates of volumetric heat storage capacity and also provide higher time lags.
- It is not accurate to assume equal properties for different kind of substrates considered as a general layer.
- Further research is needed to assess with more accuracy the thermal properties of green roof materials and his composition.

This study highlights the thermal performance of substrates under dry conditions across Mediterranean climate zone, for this reason further research will focus on analysing the thermal behaviour of substrates varying the water content. This is crucial information that should be implemented for green roofs energy simulation tools to provide more accurate results.

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