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THERMAL CHARACTERIZATION OF DIFFERENT MATERIALS FOR EXTENSIVE GREEN ROOFS

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Abstract

Extensive green roofs have been consolidated as a good tool for passive energy savings system in buildings, providing a more sustainable trend in the building field. Given that working with living organisms, 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 its physical properties and water content. However, the complexity of disaggregated materials used in internal layers of extensive green roofs implies a lack of real data about its 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. The experimentation allows to calculate the thermal transmittance in steady-state (U-value), the heat storage capacity, and the dynamic thermal response under daily thermal oscillation.

1. Introduction

In Europe the building sector represents 40% of the overall energy consumption and 36% of the overall CO_2 emissions (Chen et al. 2011; Petersdorff et al. 2006). 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 (ecoroofs) have an important role as it has been demonstrated in many cities with the increment of these installations in new construction projects.

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 layer depending on their physical properties (density, thickness, thermal conductivity and specific heat capacity).

The advantages of green roofs can be categorized in three main typologies:

The first benefit can be considered from an energy and architectural point of view. In fact, green roofs offer an additional thermal insulation contributing to the reduction of energy consumptions. During the summer, green roofs can control and mitigate the heat flux through the roof, by evaporative effect and by reducing the overall solar energy absorbed by the building (Del Barrio, 1998; Wong et al. 2003). Furthermore, green roofs protect the roof membranes from extreme temperatures during hot days (Teemusk and Mander, 2009) and avoid high thermal fluctuations decreasing thermal stress for the materials and improving the durability of the roof (Kosareo and Ries, 2007).

The second benefit is from a hydrologic point of view. Green roof substrates capture storm water, altering the magnitude and timing of peak runoff (Fioretti et al. 2010). By absorbing rainwater, green roofs delay the

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runoff and mitigate the impact of heavy rains (Carter and Jackson, 2007), which affect urban areas with impermeable surfaces (Getter et al. 2007).

The third benefit can be noticed from an environmental point of view. The evapotranspiration allows the humidification and the air cooling by reducing the heat island effect in urban areas. Additional benefits of ecoroofs include the generation of natural habitats and the aesthetic improvement for the cities. (Zinzi and Agnoli 2008).

The effect of green roof installations on buildings has been object of intense studies during the last decade. In particular, in order to evaluate their thermal performance many predictive models were proposed. However, the modelling of ecoroofs 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 modeling considers the green roof as a unique resistant layer whose thermal properties are constant and the thermal capacity is neglected.

More accurate formulations take into account the dynamic nature of the heat transfer. 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, there is not enough information in the scientific literature regarding the thermal properties of green roof substrates. 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.

Some experimental studies to measure the thermal conductivity, heat capacity and thermal diffusivity of growing media have been conducted by researchers, in order to characterize the variability of these thermal properties in relation to the composition and the water content. Sailor et al. (2008) measured the thermal properties of substrates with different compositions (eight soil samples) commonly used in western U.S.

Ouldboukhitne et al. (2012) characterized the thermal conductivity of various green roof substrate samples for different water content values.

The substrate thermal conductivity increased when the water content varies, ranged from 0.05 to 0.7 W/m·K. 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 insulation power is less interesting.

The focus of the present paper is to characterize green roofs substrates by providing thermophysical parameters that can be used in numerical models. With this aim an experimental apparatus is used in order to determine the properties of different disaggregated materials for extensive green roofs. The apparatus was created and assembled by GREA Group from the University of Lleida (De Gracia et al. 2011a). It allows to calculate the thermal transmittance in steady-state (U-value), the heat storage capacity and the dynamic thermal response under daily temperature oscillation.

2. Materials and method

2.1 Experimental set-up

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 cavities to force the heat flux to become one-dimensional through the sample (Figures 1a and 1b).

Both 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 center 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.

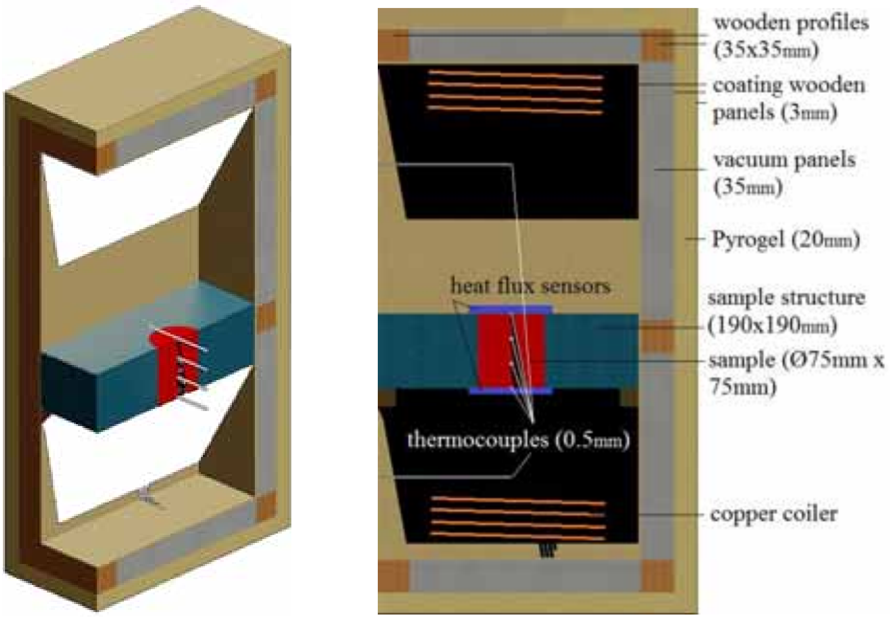

Fig. 1a and 1b: Sections of scheme design of the equipment.

2.2 Materials

The thermal responses of commercial substrates with different composition used for green roofs under Mediterranean climate have been analyzed. The three substrates were:

- Substrate 1 was used in the experimental set-up of Puigverd de Lleida (Spain). It has a density of 788 kg/m^3 under dry conditions and contains parts of coco peat, compost, crushed building wastes, coarse grained sand and organic content.
- The second one (GR-S2) is based on 25% coco peat, 25% compost, 40% crushed building wastes and 10% coarse grained sand. Density in dry conditions is 850 kg/m^3, and the organic content in volume is 6.77 %.
- Substrate 3 was used in an experimental installation located in the University of Calabria (Italy). This soil is mainly composed of lapillus with varied grain size and of a reduced content of pumice with a percentage of organic substance minor than 6%. The dry density is 960 kg/m^3 and the maximum water retention is 40%.

2.3 Methodology

Three different types of experiments were carried out to evaluate the thermal performances of the previously described samples. The first experiment allowed 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 and finally the third experiment was done to evaluate the dynamic thermal response under daily thermal oscillation.

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.

$$U_{sample} = \frac{q_{sample}}{A\,(T_{down} - T_{up})} \quad \text{(eq. 1)}$$

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 ($C_{p,sample}$), can be calculated as follows:

$$c_{p\,sample} = \frac{q_{acc}}{(m_{sample}(T_f - T_i))} \quad \text{(eq. 2)}$$

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 two times for each sample to verify repeatability in the methodology of the average heat capacity calculation.

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 will be in free floating conditions.

The thermal response of the sample was evaluated by analyzing the delay between peaks of the inner and outer temperature, heat fluxes and by evaluating the dampening of the temperature wave (thermal stability coefficient (De Gracia et al. 2011b), which can be calculated as the ratio between the inner and outer thermal amplitudes. Surface temperatures were used to calculate this parameter.

3. Results

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 three analyzed substrates. From these measured values, thermal transmittance in steady state can be determined.

Table 1 shows the surface temperatures ($T_{surface\_top}$, $T_{surface\_bot}$), the internal temperatures of the sample (T_{sample_top}, T_{sample_bot}), the heat fluxes on the top (q_{top}/A) and bottom (q_{bottom}/A) and the calculated U-value for the tested substrates. Also the air temperature in the upper and lower cavities is shown (T_{env_top}, T_{env_bot}). Substrate 3 shows the highest thermal transmittance with 2.59 $W/m^2\cdot{}^{o}C$ followed by Substrate 2 with 1.91 $W/m^2\cdot{}^{o}C$, and finally Substrate 1 with 1.84 $W/m^2\cdot{}^{o}C$.

Tab. 1: Steady state conditions and parameters in Experiment 1.

	1st measurement			**2nd measurement**		
	Substrate 1	**Substrate 2**	**Substrate 3**	**Substrate 1**	**Substrate 2**	**Substrate 3**
T_{env_top}	20.73 ºC	21.53 ºC	20.94 ºC	20.43 ºC	20.78 ºC	20.67 ºC
$T_{surface\_top}$	24.17 ºC	24.59 ºC	24.74 ºC	24.00 ºC	23.87 ºC	24.38 ºC
$T_{surface\_bot}$	38.87 ºC	38.70 ºC	38.67 ºC	39.00 ºC	37.83 ºC	38.45 ºC
T_{env_bot}	42.29 ºC	44.62 ºC	42.78 ºC	42.56 ºC	43.89 ºC	42.63 ºC
$q_{top/A}$	26.04 W/m^2	26.07 W/m^2	36.25 W/m^2	26.74 W/m^2	25.66 W/m^2	36.62 W/m^2
$q_{bottom/A}$	27.98 W/m^2	27.93 W/m^2	36 W/m^2	28.00 W/m^2	27.02 W/m^2	36 W/m^2
U_{-value}	1.84 $W/m^{2o}C$	1.91 $W/m^{2o}C$	2.59 $W/m^{2o}C$	1.82 $W/m^{2o}C$	1.89 $W/m^{2o}C$	2.58 $W/m^{2o}C$

3.2. Experiment 2: heat storage capacity

The rates of heat accumulated during Experiment 2 by three different substrates are shown in Figure 2. These powers of accumulation are calculated as the heat flux entering the sample minus the heat flux leaving the sample from both surfaces. The rate of heat accumulation of substrates shows a different curve during the first hour, due to the different composition between them. Substrate 3 shows the highest rate of heat accumulation followed by Substrate 1 and finally Substrate 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 13 h (when the rate of heat accumulation was almost zero) for the three analyzed substrates.

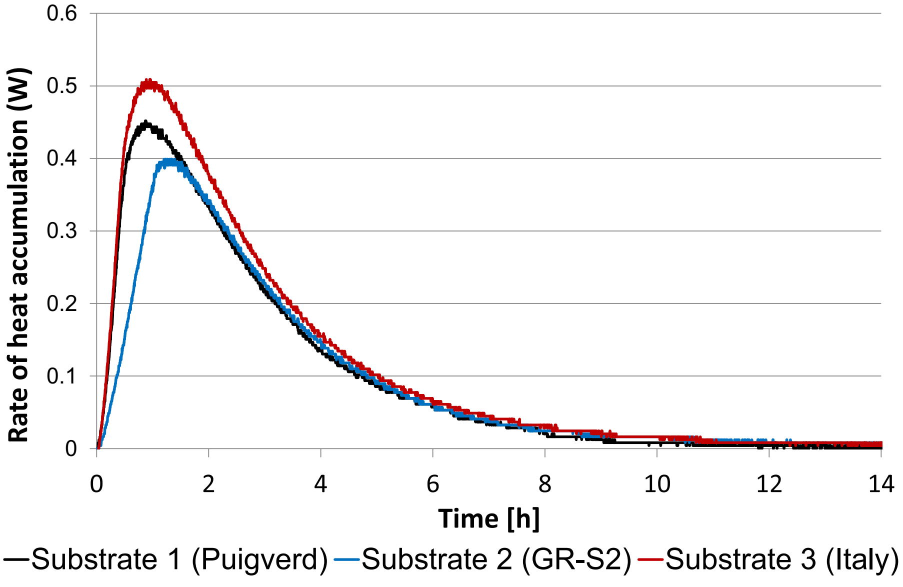

Fig. 2: Rate of the heat accumulated for the three analyzed substrates.

The measured parameters from Experiment 2 and the calculated heat storage capacity of the samples are presented in Table 2. The repetitions of the methodology, to calculate the average heat storage capacity of the substrates is also shown in Table 2. Deviations around 2.1%, 1.6% and less than 1% for Substrate 1, 2 and 3 respectively, have been found.

Substrate 3 shows the highest values of energy stored by the sample after 13 h of experiment equal to 6,063 J. Substrate 1 presents 14.5% less stored energy (5,181 J) and Substrate 2 presents 19.6% less stored energy (4,874 J) compared to Substrate 3.

Tab. 2: Heat storage capacity of substrates.

	1st measurement			2nd measurement		
	Substrate 1	**Substrate 2**	**Substrate 3**	**Substrate 1**	**Substrate 2**	**Substrate 3**
$T_{initial}$	19.08 ºC	19.01 ºC	18.78 ºC	18.96 ºC	18.15 ºC	19.29 ºC
T_{final}	43.26 ºC	42.11 ºC	42.96 ºC	43.26 ºC	42.73 ºC	43.00 ºC
AT_{sample}	24.18 ºC	23.1 ºC	24.18 ºC	24.31 ºC	24.58 ºC	23.71 ºC
q_{TOT}	5,181 J	4,874 J	6,063 J	5,316 J	5,108 J	6,002 J
Cp_{sample}	883.7 J/kg·K	807.3 J/kg·K	850.2 J/kg·K	902.1 J/kg·K	794.9 J/kg·K	858.4 J/kg·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 3 and it allows to calculate the thermal stability coefficients (TSC) from the three analyzed substrates. The coefficients are reported in Table3.

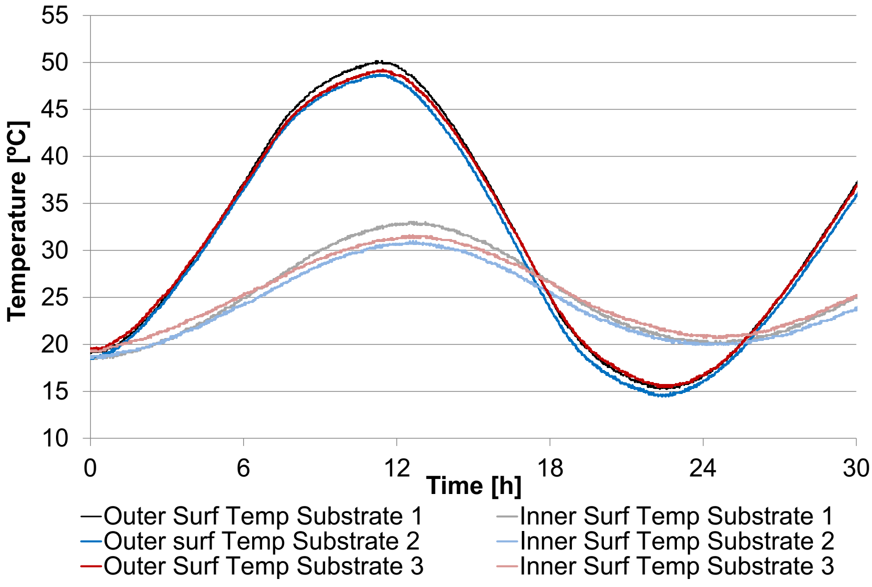

Fig. 3: Dynamic thermal response of the surfaces temperatures

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. Fig. 4 presents the thermal lag of the three samples under similar outer conditions. The different composition of Substrate 3 lead to a 23% increase of the heat flux compared to Substrate 2 and Substrate 1 which did not show remarkable differences. Table 3 reports the time lag for the three analyzed substrates.

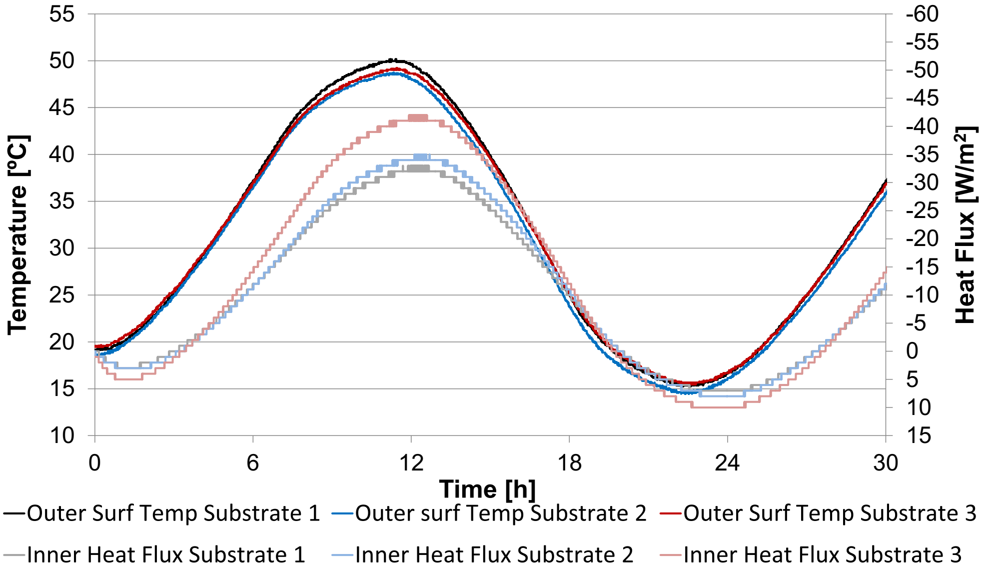

Fig. 4 Thermal lag of the three analyzed substrates

The calculated thermal stability coefficients were 0.43, 0.41 and 0.36 for Substrate 1, Substrate 2 and Substrate 3 respectively. The substrate 3 proved to be more effective in dampening the temperature fluctuation, with the lowest TSC. It also appear that greater density of growing media provide lower TSC. Regarding the time lag, all the three analyzed substrates showed similar thermal lag, 1.22 h for Substrate 1 and Substrate 3 whereas 1.33 h for Substrate 2. Other physical properties of the substrate may affect this thermal parameter, so further investigations are required to understand this phenomenon.

Table 3. TSC and Time lag of the three substrates

	Substrate 1	**Substrate 2**	**Substrate 3**
TSC [-]	0.43	0.41	0.36
Time lag [h]	1.22	1.33	1.22

4. Conclusions

Although some data about substrates used in green roofs can be found in the literature, no relevant information is available for substrates used in Mediterranean climate.

The composition of the substrate 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 it 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. Focusing on some kind of substrates used in Mediterranean climate, this study expands the thermo-physical data available in literature, by performing three different experiments. The results of the experiments allow to calculate the most common thermal properties and two experimental transient parameters.

- In this study, a specific apparatus design is used on purpose to carry out the experiments in a fully controlled environment. Compared to traditional methods, the apparatus presents an advantage: it permits to test the dynamic thermal response of a material subjected to daily temperature oscillations.
- An appreciable difference was found in the calculated U-value and Thermal Stability Coefficient between the different substrates, showing how the choice of this component can strongly affect the performances of the whole system.

- 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.

The next step will consist in analyzing the behavior of the substrates varying the water content. This is crucial information that should be provided to green roofs energy simulation tools in order to have more accurate results.

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