Experimental Investigation on Green Roofs’ Thermal Performance in Turin (Italy)

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Abstract: Green roofs can offer benefits in energy savings for both heating and cooling demand with positive effects on the energy performance of buildings especially during summertime; in particular, this technology can be considered as a passive cooling technique that attenuate the amount of incoming solar irradiation and cooling load. The purpose of the experimental analysis performed on green roofs is to evaluate the thermal performance of the entire technology in relation to its thickness, surface mass, thermal resistance, thermal inertia, moisture content in the same climatic condition. Many measurement campaigns on green roofs were carried out during heating and cooling seasons and different parameters were used to analyze their thermal behavior; some of these are measured and other are calculated and the measured parameters are closely tied to the climatic data in which measurement campaigns were carried out. Measured data have been calculated as function of calculated parameters and climatic data to assess the real thermal behavior of green roofs. With this research a mathematical model for the thermal behavior of green roofs and for the evaluation of temperatures in the soil has been identified.

Key words: Green roof, thermal behavior, model, linear regression, climatic data.

1. Introduction

The environmental benefits of green roofs are known by a qualitative perspective, but the overall assessment of their scientific potential in quantitative terms is still a challenge.

In Italy, few scientific studies and experiments assess the efficiency of green roofs as a tool for sustainable urban development and the classification of green roofs is based on qualitative aspects, while answers on thermal performance and benefits should be provided. Technology and employed materials, local climate and precipitation regime, orientation, slope and maintenance of the rooftop are certainly most of the influencing parameters that may affect the expected thermal performance of a green roof.

After an overview of legislation and the state of art about green roofs technologies, the case studies for the experimentation are presented with the results of measurement campaigns. Finally a model to evaluate thermal behavior of green roofs is proposed with a final discussion.

1.1 National and Local Legislation

The use of the green roof technology can get many credits in the U.S. Green Building Council’s LEED (Leadership in Energy and Environmental Design) rating system. Green roof technologies have many benefits: protection of the habitat, site improvement, heat island mitigation, stormwater control, water efficiency, energy performance, material reuse and recycle and finally use of regional materials. So, a green roof technology can strongly contribute to achieve a LEED-certified building.

In Italy, in the last years many laws on energy performance of buildings were presented; some of
them deal with green roofs as an energy saving technology. Article 6 of Italian Law n.10 of 2013 [1] promotes the increment of urban green spaces and measures of energy efficiency like the reduction of urban heat island through the use of green roofs and facades on buildings. The Decree of the President of Italian Republic n. 59 of 2009 [2], at article 4 states that the respect of the values of surface mass and periodic thermal transmittance can be reached with green roofs, which allow to reduce temperature fluctuations inside buildings especially during the cooling period.

At local level, the city of Bolzano has taken a concrete action, though introducing an indicator called RIE, as an index of the environmental quality used to certify the permeability of the soil, roof, paving materials, etc. The use of green technology for buildings’ roofs can provide water permeability even in a urban contest.

Moreover Bologna and Modena, respectively with the projects BLUE UP (http://www.blueap.eu/site/en/) and UHI (http://eu-uhi.eu/), promote the mitigation of the urban heat island phenomenon occurring in the metropolitan areas together with other strategies, in order to make the city more resilient and able to meet the climate change challenges.

1.2 Status of Research

Many scientific articles analyse green roofs under different points of view; for the purpose of this paper, only the researches on the thermal behavior of green roofs are considered.

Climatic conditions prove to play an important role in the performance of green roofs which has good thermal capabilities during both heating and cooling period [3, 4]. Literature shows several studies that focus on thermal analysis in the summer season, in which the green roof performance is more effective, especially for the Mediterranean area [5]. In hot climate, green roof constructions with shallow substrates composed of coarse aggregate materials are expected to save building energy especially during the cooling season [6].

Green roofs should work better under dry weather conditions; however a study in Florianopolis [7], with high levels of relative humidity, suggests that that this roof also works well in these climatic conditions, both in cooling and heating period. The efficiency of the green roof is probably due to compensation of lower evapotranspiration rates by other effects such as shading, insulation and thermal mass.

In winter, the subtropical intensive green roof triggers notable upward heat flow from the substrate to the ambient air. The warmer indoor air below the roof slab creates a temperature gradient which draws heat upwards into the substrate and hence dissipates in the air as sensible and latent heat [8].

In France, a model based on energy balance equations expressed for foliage and soil typology was proposed [9]. A parametric study was performed using the proposed model to classify green roofs. Results have shown the significant influence of foliage density on the thermal behavior of the green roof.

Green roof thermal insulation role was studied by many authors [10-13]. Green roofs could never replace the role of the insulating layer. In winter, the capacity of green roofs’ substrate to contain water, increases their thermal conductivity and thus reduces their thermal resistance [14]. But in summer, when the soil is wet, not only the entering flux is cancelled, but a slight outgoing flux is produced so that the green roof works as a passive cooler. In fact, the correlation between measured and modeled evapotranspiration is satisfactory when the green roof is in well-watered conditions [15].

In the UK, it is found that there is a strong potential for green roof retrofit, especially for old buildings with poor existing insulation [16].

The analysis conducted in this work starts from a previous research on the investigation on thermal performance of a wooden roof with a double layer of insulated material to improve roof thermal inertia [17].
In this study a methodology to evaluate dynamic thermal performances of building envelopes is described.

2. Materials and Methods

2.1 Green Roof Technology

Italian Standard on green roofs is the UNI 11235:2007 "Guidelines for the design, execution, monitoring and maintenance of green roofs". To develop an organic project, the designer can follow the procedure indicated in the standard UNI 11235.

In a green roof the different layers (vegetation, substrate, filtering, drainage and protection) are placed on the sealing element and on the thermal insulation (when it exists), forming together a single technology with functional and aesthetic aspects.

A green roof is a complex system and its behavior depends on many external factors, which must be taken into account in the design phases. On the other hand, a green roof can offer many benefits to the building and its surrounding environment; these include stormwater management, decrease of air pollution, thermal insulation, reduction of the urban heat island effect, acoustic insulation and ecological footprint.

Green roofs could be defined according to the following characteristics: accessibility (for maintenance, for people, for vehicles), slope, maintenance of the green system, water storage system, control of internal environmental conditions and environmental mitigation.

Maintenance of the green system provides a distinction in extensive and intensive systems. This distinction is of particular importance because the two solutions have different characteristics and fields of application related primarily to maintenance level and not on soil thickness and type of vegetation. The extensive green roof can be applied both on flat and inclined surfaces, but it is not a usable garden but just a green roof with effect on environmental mitigation and ecological compensation. The intensive roof, however, is the proper garden, complete with lawns, shrubs and trees. In most cases, for intensive roofs the construction and agronomic tasks do not influence the design requirements. The extensive roofs are more complex systems as performance in regime could be supplied after one year approximately at the end of the construction yard.

Substrate is an important element that provides anchorage, nutrients and space for the development of the roots. Usually substrates specifically produced for this purpose are used, while the use of normal topsoil can cause poor drainage of the surface and problems of management of stormwater.

2.2 Case Studies

The experimental analysis was conducted on three green roofs located in the city of Turin (northern part of Italy). This town has a temperate sub-continental climate, with cold winters and warm summers. Turin is a big town with more than 900 thousands of inhabitants and it’s affected by the phenomenon of the urban heat island, with higher temperatures in both summer and winter than in nearby rural areas.

The phenomenon is mainly due to greater absorption of solar energy by asphalt and concrete surfaces. In summer, in the sunny hours, the streets and the roofs of buildings can reach temperatures of 60-90 °C.

The average temperatures in Turin have increased in the last 24 years of about 1.6 °C in the heating period and of 0.9 °C in the cooling season due to the urbanization with concrete buildings and low albedo surfaces, compared to the period from 1970 to 1990 (although the number of inhabitants in the same period has decreased).

As seen in Fig. 1, there are three different types of roofs which were analyzed in the center of Turin:
- an extensive green roof, on the offices and the archive of Piedmont Region;
- a light intensive green roof, on the classrooms of Politecnico di Torino;
an intensive green roof, on the offices of Environment Park.

Extensive green roof of Piedmont Region has a vegetation consisting of a mixture of Sedum, that is a fleshy plant with erect or leaning stem in clumps. Leaves can be round, alternate, oval or vertical. 

The hardy species are cultivated outdoors in all of Italy. Sedum roof do not require irrigation system.

Light intensive green roof, on the classrooms of Politecnico di Torino, are lawns with a vegetation consisting of a mixture of Loliumperenne (60%), Poapratensis (20%) and Festucarubra (20%). These species require an irrigation system.

Intensive green roof on the offices of Environment Park, has a vegetation consisting of lawn and different type of shrubbery. Where measurement campaign was carried out, there are Cotoneaster horizontalis, deciduous shrubs with small, glossy, dark green, round or elliptical leaves and a short stem.

The aim of this work is to compare thermal behavior of a green roof taking into account the environmental conditions in which the roof is involved. In order to analyze the thermal behavior of the three green roofs, multiple measured and calculated parameters have been evaluated.

The measured parameters analyzed are:
- the thermal transmittance $U_{\text{mis}}$ (W m$^{-2}$ K$^{-1}$), measured according with the standard ISO 9869:1994;
- the decrement factor $f_{\text{mis}}$ (-);
- the time shift $\Delta t_{\text{mis}}$ (h).

The calculated parameters reflect the thermo-physical characteristics of the stratigraphy of the green roof and also the climatic conditions at the boundary. The following parameters were considered:
- thermal transmittance $U_{\text{calc}}$ (W m$^{-2}$ K$^{-1}$), determined by applying the procedure of the standard UNI EN ISO 6946:2008;
- the periodic thermal transmittance $Y_{12}$ (W m$^{-2}$ K$^{-1}$), as described in the UNI EN ISO 13786:2008;
- the decrement factor $f_{\text{calc}}$ determined by the ratio of the absolute value of the periodic thermal transmittance and $U_{\text{calc}}$, as provided in the UNI EN ISO 13786:2008;
- the time shift $\Delta t_{\text{calc}}$ (h), determined by the argument of periodic thermal transmittance;
- the mass per unit area $M_s$ (kg m$^{-2}$);
- the heat capacity $C_t$ (kJ m$^{-2}$ K$^{-1}$).

The climatic data were calculated by processing data collected mainly from the weather station at the Politecnico di Torino; in this work the following data were considered:
- $T_{\text{year}}$, $T_{\text{month}}$ and $T_{\text{day}}$ (°C), respectively the average temperatures of the year, month and day;
- $\text{Rad}_{\text{year}}$, $\text{Rad}_{\text{month}}$ and $\text{Rad}_{\text{day}}$ (MJ m$^{-2}$ day$^{-1}$), respectively the daily average cumulative global radiation of the year, month and day.

Green roof thermal performance is influenced by climatic data, especially solar irradiation and air temperature. In this study short and long term variables were considered because of the high thermal inertia of green roof. Relative humidity was neglected, because it is almost constant with average values.
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during the experimental campaign of 64% (June)-74% (October). The calculated parameters and the environmental conditions will be used as variables influencing measured data.

2.3 Green Roofs Analyzed

All experimental campaigns took place in Turin during the heating and cooling season.

The extensive green roof (mostly Sedum), is above the offices of Piedmont Region, made in 2002. The building consists in a old construction and the green roof is located in a courtyard surrounded by buildings. The roof does not present the thermal insulation layer and the irrigation system; Table 1 shows its stratigraphy.

The light intensive green roof is above the classrooms of the Politecnico di Torino. The green roof was completed in 2010 and it is equipped with an irrigation system; Table 2 shows its stratigraphy.

The intensive green roof is above the offices of Environment Park, a new construction completed in 2000. The vegetation is made up of lawn and shrubs of considerable size. The roof presents an irrigation system and Table 3 shows its stratigraphy.

In this work, the values of thermal conductivity used for the substrate are taken from literature [18] and technical brochure [19]: 0.141-2.326 (W m$^{-1}$ K$^{-1}$), depending on the humidity of the soil during the experimental campaigns. The values used were also compared with measured data: Table 4 summarizes the weather conditions and the presence of irrigation system influencing the thermal conductivity and the specific heat used.

A substrate thermal conductivity of 0.32 (W m$^{-1}$ K$^{-1}$) has been used for both measurement campaigns of cooling and heating periods carried out at Piedmont Region, because there was no irrigation system with a condition of very light rain during measurements in April 13-17th.

For the measurements carried out at Politecnico di Torino a conductivity of the substrate of 1.744 (W m$^{-1}$ K$^{-1}$) has been used because the irrigation system was

<table>
<thead>
<tr>
<th>Layer</th>
<th>Materials (from outside to inside)</th>
<th>Thickness (m)</th>
<th>Thermal conductivity (W m$^{-1}$ K$^{-1}$)</th>
<th>Density (kg m$^{-3}$)</th>
<th>Specific heat (J kg$^{-1}$ K$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Substrate</td>
<td>0.12</td>
<td>0.32</td>
<td>1070</td>
<td>800</td>
</tr>
<tr>
<td>2</td>
<td>Filter fabric</td>
<td>0.001</td>
<td>0.16</td>
<td>930</td>
<td>2010</td>
</tr>
<tr>
<td>3</td>
<td>Lapillo</td>
<td>0.05</td>
<td>0.16</td>
<td>850</td>
<td>840</td>
</tr>
<tr>
<td>4</td>
<td>Nonwoven fabric protective</td>
<td>0.001</td>
<td>0.16</td>
<td>930</td>
<td>2010</td>
</tr>
<tr>
<td>5</td>
<td>Anti-root membrane</td>
<td>0.004</td>
<td>0.53</td>
<td>920</td>
<td>2219</td>
</tr>
<tr>
<td>6</td>
<td>Insulated slab</td>
<td>0.30</td>
<td>0.406</td>
<td>1110</td>
<td>880</td>
</tr>
</tbody>
</table>

Table 2 Stratigraphy and thermal characteristics of the light intensive green roof at Politecnico di Torino (data from designers and producers).

<table>
<thead>
<tr>
<th>Layer</th>
<th>Materials (from outside to inside)</th>
<th>Thickness (m)</th>
<th>Thermal conductivity (W m$^{-1}$ K$^{-1}$)</th>
<th>Density (kg m$^{-3}$)</th>
<th>Specific heat (J kg$^{-1}$ K$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Substrate</td>
<td>0.20</td>
<td>1.74</td>
<td>1200</td>
<td>2000</td>
</tr>
<tr>
<td>2</td>
<td>Nonwoven geotextile filter</td>
<td>0.001</td>
<td>0.16</td>
<td>930</td>
<td>2010</td>
</tr>
<tr>
<td>3</td>
<td>Lapillo</td>
<td>0.15</td>
<td>0.16</td>
<td>850</td>
<td>840</td>
</tr>
<tr>
<td>4</td>
<td>Drainage panels</td>
<td>0.006</td>
<td>0.16</td>
<td>930</td>
<td>2010</td>
</tr>
<tr>
<td>5</td>
<td>Anti-root membrane</td>
<td>0.002</td>
<td>0.53</td>
<td>920</td>
<td>2219</td>
</tr>
<tr>
<td>6</td>
<td>Nonwoven separation</td>
<td>0.001</td>
<td>0.16</td>
<td>930</td>
<td>2010</td>
</tr>
<tr>
<td>7</td>
<td>Screed coat with polystyrene</td>
<td>0.10</td>
<td>0.30</td>
<td>300</td>
<td>840</td>
</tr>
<tr>
<td>8</td>
<td>Bituminous mantle</td>
<td>0.002</td>
<td>0.17</td>
<td>1700</td>
<td>1700</td>
</tr>
<tr>
<td>9</td>
<td>Screed slope</td>
<td>0.12</td>
<td>0.72</td>
<td>400</td>
<td>1000</td>
</tr>
<tr>
<td>10</td>
<td>Concrete slab</td>
<td>0.34</td>
<td>0.81</td>
<td>1110</td>
<td>880</td>
</tr>
</tbody>
</table>
Table 3  Stratigraphy and thermal characteristics of the intensive green roof at Environment Park (data from designers and producers).

<table>
<thead>
<tr>
<th>Layer</th>
<th>Materials (from outside to inside)</th>
<th>Thickness (m)</th>
<th>Thermal conductivity (W m⁻¹ K⁻¹)</th>
<th>Density (kg m⁻³)</th>
<th>Specific heat (J kg⁻¹ K⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Substrate</td>
<td>0.16</td>
<td>1.74</td>
<td>1200</td>
<td>2000</td>
</tr>
<tr>
<td>2</td>
<td>Polypropylene filter fabric</td>
<td>0.005</td>
<td>0.16</td>
<td>930</td>
<td>2010</td>
</tr>
<tr>
<td>3</td>
<td>Lapillo</td>
<td>0.05</td>
<td>0.13</td>
<td>850</td>
<td>840</td>
</tr>
<tr>
<td>4</td>
<td>Drainage layer</td>
<td>0.004</td>
<td>0.53</td>
<td>920</td>
<td>2219</td>
</tr>
<tr>
<td>5</td>
<td>Synthetic sheath</td>
<td>0.002</td>
<td>0.16</td>
<td>1400</td>
<td>900</td>
</tr>
<tr>
<td>6</td>
<td>Compensation layer non-woven fabric</td>
<td>0.003</td>
<td>0.16</td>
<td>930</td>
<td>2010</td>
</tr>
<tr>
<td>7</td>
<td>Expanded polystyrene</td>
<td>0.05</td>
<td>0.04</td>
<td>35</td>
<td>1400</td>
</tr>
<tr>
<td>8</td>
<td>Vapor barrier</td>
<td>0.001</td>
<td>0.53</td>
<td>920</td>
<td>2219</td>
</tr>
<tr>
<td>9</td>
<td>Concrete slab</td>
<td>0.30</td>
<td>1.16</td>
<td>1110</td>
<td>880</td>
</tr>
</tbody>
</table>

Table 4  Weather conditions and presence of irrigation system in measurement campaigns.

<table>
<thead>
<tr>
<th>Measurement campaigns</th>
<th>Rain</th>
<th>Irrigation system</th>
<th>Period of measure 2012</th>
<th>Number of measures</th>
<th>Time lag (min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Extensive green roof</td>
<td>light</td>
<td>no</td>
<td>April 13-17th</td>
<td>1206</td>
<td>5’</td>
</tr>
<tr>
<td>Extensive green roof</td>
<td>no</td>
<td>no</td>
<td>June 26th-July 2nd</td>
<td>1707</td>
<td>5’</td>
</tr>
<tr>
<td>Light intensive green roof</td>
<td>no</td>
<td>yes</td>
<td>September 18-24th</td>
<td>1760</td>
<td>5’</td>
</tr>
<tr>
<td>Light intensive green roof</td>
<td>no</td>
<td>yes</td>
<td>November 5-9th</td>
<td>1119</td>
<td>5’</td>
</tr>
<tr>
<td>Intensive green roof</td>
<td>yes</td>
<td>yes</td>
<td>June 11-15th</td>
<td>997</td>
<td>5’</td>
</tr>
<tr>
<td>Intensive green roof</td>
<td>yes</td>
<td>yes</td>
<td>October 29th-November 3rd</td>
<td>1632</td>
<td>5’</td>
</tr>
</tbody>
</table>

functioning during the measurement campaigns and so the substrate was wet. A value of conductivity of the substrate of 1.744 (W m⁻¹ K⁻¹) has been used for both measurement campaigns of cooling and heating periods carried out at Environment Park, because in both cases there were similar conditions of light rain.

2.4 Measurements

The purpose of the measurements was to compare the thermal behavior of the layers of the green roof systems with the calculated parameters during the heating and cooling seasons. Details about measurement campaigns are illustrated in Table 4.

To evaluate the thermal performances of the stratigraphy of the roof, measurement campaigns were carried out with the following sensors:
- a heat flow meter on the intrados of the insole;
- three thermocouples on the intrados of the insole;
- three external thermocouples positioned at two different depths in the soil and one on the surface of the soil;
- two probes for indoor temperature, positioned at two different heights from the floor.

The acquisition instrument adopted was the data-logger AHLBORN type ALMEMO 2890-9 with 9 channels. More information about instruments data can be found in [17].

3. Results and Discussion

The roof is certainly subject to variations of the boundary conditions created by the natural temperature fluctuation with a daily period of 24 hours and these conditions can be approximated to sinusoidal trends of both temperatures and heat flows as described in the standard UNI EN ISO 13786.

In the paragraphs 3.1, 3.2 and 3.3, the figures represent the temperature profiles and the thermal flux through the three green roofs with the following legend:
- Ti-average is the indoor air temperature, (°C);
- Tsup-i is the internal surface temperature of the insole, (°C);
- Txcm is the temperature recorded by the probe at x cm of depth in the soil, (°C);
- Tsup-e is the external surface temperature of the soil, (°C);
- Te-POLI is the temperature of external air recorded by the meteorological station of the Politecnico di
3.1 Extensive Green Roof of Piedmont Region

The results of the measurement campaigns carried out during the heating and cooling periods of the building are shown in the following Fig. 2.

In Fig. 2a, related to the heating period, it can be noted that the temperature of the probes at 4 and 8 cm of depth in the soil are very similar and this is due to the little difference of depth of the two probes. During the cooling period (Fig. 2b), it can be noted a similar temperature trend of the temperatures’ probes on the surface of the soil and at 8 and 12 cm of depth in the soil. This behavior probably depends on the absence of the insulation layer with a thin and dry substrate (this roof doesn’t have the irrigation system and the measurements were conducted in dry conditions).

3.2 Light Intensive Green Roof of Politecnico di Torino

The results of the measurement campaigns carried out during the heating and cooling periods of the building are shown in the following Fig. 3.

In Fig. 3 during the heating and cooling period, it can be noted that there are good attenuations and time delays, between the external and internal sensors’ temperatures. This is due to the thicker substrate with the presence of a insulation layer which attenuates thermal flux.
3.3 Intensive Green Roof of Environment Park

The results of the measurement campaigns carried out during the heating and cooling periods of the building are shown in Fig. 4.

In Fig. 4 of heating and cooling periods, good attenuations and time delays between the temperatures of the external and internal probes can be noted. This behavior is due to the presence on the insulation layer, a thick and wet substrate during raining conditions.

3.4 Comparison between Calculated and Measured Data

The numerical assessments resulting from the calculations were compared with the results of measurement campaigns.

To estimate the thermal transmittance $U_{\text{mis}}$ from the measurements it was adopted the progressive average method. Green roofs’ conductance $C$ was obtained by dividing the average heat flux ($q$) by the average difference between the temperature of the inside surface of the insole ($T_{\text{sup-i}}$) and the temperature of the outside surface of the substrate ($T_{\text{sup-e}}$). Repeated over a significant period of time, this method converges to an asymptotic value of conductance. Then knowing the internal and external surface thermal resistances, the thermal transmittance $U$ can be evaluated.

For dynamic parameters, in order to compare the measured data with calculations, it was adopted the procedure of standard UNI EN ISO 13786. The measures have been developed to calculate the sinusoidal trends of the temperatures (on the surface of the substrate, at different depths in the substrate and on the surface of the insole) as functions of time ($t$), through the following equation:

$$\bar{T}(t) = T + |\Delta T| \cdot \cos (\omega \cdot t + \psi)$$

Where:
- $T = \text{value of the average temperature of the layer (°C)}$;
- $|\Delta T| = \text{amplitude of the temperature, given by the difference between maximum and minimum value (°C)}$;
- $\omega = \text{angular frequency, in radians (2π/24 considering a time period of 24 hours)}$;
- $t = \text{time, in hours}$;
- $\psi = \text{phase, in hours}$.

Fig. 5 shows the sinusoidal curves which approximate temperatures profiles of the layers for the extensive green roof of Piedmont Region during the cooling period. The predictive equations represent the sinusoidal variation of the temperatures between different layers in the roof considering that its dynamic properties relate the external side of the roof to the internal one. From the amplitude and phase of the external and internal surface temperatures of the roof, the decrement factor $f$ and the time shifty have been evaluated.

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**Fig. 4** Temperature and heat flux measured on intensive green roof during the measurement campaign in the heating (a) and cooling (b) period.
Tables 5-7 show the comparison between measured and calculated parameters for all measurement campaigns on the three roofs.

### Table 5 Comparison between calculated and measured thermal transmittance U (W m⁻² K⁻¹).

<table>
<thead>
<tr>
<th>Measurements</th>
<th>Calculated U (W m⁻² K⁻¹)</th>
<th>Measured U (W m⁻² K⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Extensive green roof, April 13 to 17th</td>
<td>0.602</td>
<td>0.353</td>
</tr>
<tr>
<td>Extensive green roof, June 26th to July 2nd</td>
<td>0.578</td>
<td>0.554</td>
</tr>
<tr>
<td>Light intensive green roof, September 18 to 24th</td>
<td>0.406</td>
<td>0.356</td>
</tr>
<tr>
<td>Light intensive green roof, November 5 to 9th</td>
<td>0.418</td>
<td>0.454</td>
</tr>
<tr>
<td>Intensive green roof, June 11 to 15th</td>
<td>0.441</td>
<td>0.634</td>
</tr>
<tr>
<td>Intensive green roof, October 29th to November 3rd</td>
<td>0.455</td>
<td>0.596</td>
</tr>
</tbody>
</table>

The comparison between calculated and measured values shows high relative differences that can be explained with the different boundary conditions during the measurements. Variables like weather condition, state of maintenance of the roof, radiative heat exchanges of the foliage, shadow effect, evapotranspirative process of the plants, moisture content in the substrate, can seriously affect the variability of the measured values.

### 3.5 Conductivity of the Substrate

The conductivity of the soil was calculated using the progressive average method calculating the conductance of the substrate by using average values, calculated in all the previous instants, of thermal flux and inside and outside surfaces temperatures.

The data relating to the measures of conductivity of the substrate are summarized in Table 8. The data measured in September for the light intensive roof and in June for the intensive roof could not be significant because of the too high and low temperature respectively.

Fig. 6 shows the temperature profiles measured in the substrate of the three green roofs during the heating period and a thermal behavior of the substrate which does not change linearly with depth, as found in literature [7, 8]. After almost a half of depth, the temperature tends to stabilize and just in the first half of
Table 8  Comparison between measured conductivity and conductivity data from literature.

<table>
<thead>
<tr>
<th>Measurements</th>
<th>Probe max depth (m)</th>
<th>Thermal conductivity from literature (W m⁻² K⁻¹)</th>
<th>Thermal conductivity measured (W m⁻² K⁻¹)</th>
<th>Average external surface T (°C)</th>
<th>Halfway depth T (°C)</th>
<th>Deep depth probe T (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Extensive roof, April</td>
<td>0.08</td>
<td>0.32</td>
<td>0.33</td>
<td>11.79</td>
<td>12.59</td>
<td>12.63</td>
</tr>
<tr>
<td>Extensive roof, June</td>
<td>0.12</td>
<td>0.32</td>
<td>0.29</td>
<td>28.37</td>
<td>28.20</td>
<td>28.20</td>
</tr>
<tr>
<td>Light intensive roof, September</td>
<td>0.20</td>
<td>1.74</td>
<td>0.06</td>
<td>18.73</td>
<td>19.26</td>
<td>19.77</td>
</tr>
<tr>
<td>Light intensive roof, November</td>
<td>0.16</td>
<td>1.74</td>
<td>0.63</td>
<td>10.09</td>
<td>-</td>
<td>11.29</td>
</tr>
<tr>
<td>Intensive roof, June</td>
<td>0.16</td>
<td>1.74</td>
<td>1.34</td>
<td>20.85</td>
<td>20.53</td>
<td>20.56</td>
</tr>
<tr>
<td>Intensive roof, October</td>
<td>0.12</td>
<td>1.74</td>
<td>0.93</td>
<td>8.57</td>
<td>-</td>
<td>9.48</td>
</tr>
</tbody>
</table>

depth the temperature varies linearly. Considering the
depth using the percentage value of depth, in Fig. 7
the temperatures of the three green roof are compared.

In Fig. 7 measured and calculated values of
temperatures are related to the percentage of depth in
the soil. To calculate the temperature profiles (°C), the
following equation can be used:

\[ T_{calc} = 1.16 \cdot x + T_{sup \_e} \]  \( (2) \)

where, the angular coefficient is the average of the
three angular coefficients of the trend lines of the
measured values of temperature, the variable \( x \) is the
percentage values of depth of the probes (being 0% on
the outside surface of the substrates and 100% at the
total depth in the soil) and the constant term is the
temperature recorded on the outside surface of the
green roof \( T_{sup \_e} \), (°C).

The maximum percentage difference between
measured and calculated temperatures is of 3% and
this shows a common thermal behavior of the three
substrates.

3.6 Multiple Regression Analysis

In statistics, multiple regression is an approach to
modeling the relationship between a scalar dependent
variable \( y \) and more explanatory variables denoted \( x \).

In this work, three multiple regression models were
developed to estimate the expected values of the
measured parameters through the calculated variables.

From literature [20, 21] can be found that material
selection of green roof assemblies and climate data are
the more important variables that can influence the
thermal performance of a green roof. For the climatic
data short (day) and long (month and year) term
variables were considered.

![Fig. 6 The graphs show the trend of the temperature profiles measured in the substrate of the three green roofs of Piedmont Region for the heating period.](image)

![Fig. 7 Measured and calculated (calc) temperature profiles in the substrates of the three green roofs during the heating period.](image)
The predicted parameters processed in the model are: $U_{\text{mis}}$, $f_{\text{mis}}$, $\Delta t_{\text{mis}}$ and they are calculated through the variables: $Y_{12}$, $\Delta t_{\text{calc}}$, $f_{\text{calc}}$, $U_{\text{calc}}$, $M_s$, $C_t$, $T_{\text{year}}$, $T_{\text{month}}$, $T_{\text{day}}$, $\text{Rad}_{\text{year}}$, $\text{Rad}_{\text{month}}$, $\text{Rad}_{\text{day}}$, with the following equation:

$$U_{\text{mis}}, f_{\text{mis}}, \Delta t_{\text{mis}} = \alpha_0 + \alpha_1 Y_{12} + \alpha_2 \Delta t_{\text{calc}} + \alpha_3 f_{\text{calc}} + \alpha_4 M_s + \alpha_5 C_t + \alpha_6 T_{\text{year}} + \alpha_7 T_{\text{month}} + \alpha_8 T_{\text{day}} + \alpha_9 \text{Rad}_{\text{year}} + \alpha_{10} \text{Rad}_{\text{month}} + \alpha_{11} \text{Rad}_{\text{day}} \tag{3}$$

In the linear regression equations of $U_{\text{mis}}$, $f_{\text{mis}}$, $\Delta t_{\text{mis}}$, the variables are multiplied by the coefficients $\alpha$, shown in Table 9.

The coefficients $\alpha$ of the linear regression equations were evaluated choosing initials arbitrary values and then minimizing the difference between the predicted and measured parameters considering all the experimental campaigns during the heating and cooling season. The higher coefficients are evidenced in grey.

In order to determine which parameter has the greatest impact in the equations’ results, each coefficient $\alpha$ has been multiplied by the maximum value of each variable, as shown in Table 10.

Table 10 shows that the bigger contributions come from the surface mass $M_s$, the heat capacity $C_t$ and the solar irradiation data (in grey). These values have the same levels of magnitude but opposite signs, balancing the equation’s results.

In Fig. 8 the measured values are compared with the results of the Eq. (3) to determine $U_{\text{mis}}(a)$, $f_{\text{mis}}(b)$ and $\Delta t_{\text{mis}}(c)$. To evaluate how well the regression model approximates the real data, the $R^2$ coefficient of determination was used. The high values of the indexes of determination $R^2$ (near to the maximum value of 1) for the three regressions models indicate that the predicted values almost fit the measured data.

To simplify the Eq. (3), it was decided to reduce the number of variables maintaining high values of the indexes of determination $R^2$.

Analyzing the coefficients of correlation, climatic data were selected. The coefficients of correlation

<table>
<thead>
<tr>
<th>Coeff.</th>
<th>$Y_{12}$</th>
<th>$\Delta t_{\text{calc}}$</th>
<th>$f_{\text{calc}}$</th>
<th>$U_{\text{calc}}$</th>
<th>$M_s$</th>
<th>$C_t$</th>
<th>$T_{\text{year}}$</th>
<th>$T_{\text{month}}$</th>
<th>$T_{\text{day}}$</th>
<th>$\text{Rad}_{\text{year}}$</th>
<th>$\text{Rad}_{\text{month}}$</th>
<th>$\text{Rad}_{\text{day}}$</th>
<th>$R^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$U_{\text{mis}}$</td>
<td>0</td>
<td>0.100</td>
<td>-0.003</td>
<td>0.099</td>
<td>0.098</td>
<td>-0.003</td>
<td>0.002</td>
<td>0.046</td>
<td>-0.026</td>
<td>-0.011</td>
<td>0.048</td>
<td>-0.001</td>
<td>0.030</td>
</tr>
<tr>
<td>$f_{\text{mis}}$</td>
<td>0</td>
<td>0.100</td>
<td>-0.013</td>
<td>0.099</td>
<td>0.098</td>
<td>-0.001</td>
<td>0.001</td>
<td>0.040</td>
<td>-0.039</td>
<td>-0.028</td>
<td>0.041</td>
<td>-0.022</td>
<td>0.043</td>
</tr>
<tr>
<td>$\Delta t_{\text{mis}}$</td>
<td>0</td>
<td>0.102</td>
<td>0.502</td>
<td>0.104</td>
<td>0.107</td>
<td>0.018</td>
<td>-0.008</td>
<td>0.337</td>
<td>0.261</td>
<td>-0.042</td>
<td>0.301</td>
<td>-0.108</td>
<td>-0.145</td>
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</table>

<table>
<thead>
<tr>
<th>Max coeff. $\alpha$</th>
<th>$Y_{12}$</th>
<th>$\Delta t_{\text{calc}}$</th>
<th>$f_{\text{calc}}$</th>
<th>$U_{\text{calc}}$</th>
<th>$M_s$</th>
<th>$C_t$</th>
<th>$T_{\text{year}}$</th>
<th>$T_{\text{month}}$</th>
<th>$T_{\text{day}}$</th>
<th>$\text{Rad}_{\text{year}}$</th>
<th>$\text{Rad}_{\text{month}}$</th>
<th>$\text{Rad}_{\text{day}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>max $U_{\text{mis}}$</td>
<td>0.003</td>
<td>-0.056</td>
<td>0.008</td>
<td>0.059</td>
<td>-2.837</td>
<td>2.269</td>
<td>0.710</td>
<td>-0.633</td>
<td>-0.305</td>
<td>0.646</td>
<td>-0.021</td>
<td>0.983</td>
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<tr>
<td>max $f_{\text{mis}}$</td>
<td>0.003</td>
<td>-0.226</td>
<td>0.008</td>
<td>0.059</td>
<td>-1.200</td>
<td>1.306</td>
<td>0.615</td>
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<td>0.550</td>
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<td>0.008</td>
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<td>15.736</td>
<td>-9.061</td>
<td>5.211</td>
<td>6.240</td>
<td>-1.124</td>
<td>4.034</td>
<td>-2.188</td>
<td>-4.768</td>
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</tbody>
</table>
evaluate how strong is the relationship between the measured data ($U$, $f$ and $\Delta t$) and the calculated variables. In Table 11 the results of the model considering only the air temperatures and solar irradiations are represented.

Always with the aim to simplified the Eq. (3), the data about heating and cooling period were analyzed separately and only the variables with higher indexes of correlation were considered.

The calculated parameters that affect $U_{mis}$, $f_{mis}$ and $\Delta t_{mis}$ during the heating and cooling periods remain mostly the same as reported in the following Eq. (4):

$$U_{mis} = \alpha_4 U_{calc} + \alpha_7 T_{year} + \alpha_8 T_{month} + \alpha_9 T_{day} + \alpha_{11} \cdot Rad_{year}$$

$$f_{mis} = \alpha_3 f_{calc} + \alpha_7 T_{year} + \alpha_{10} \cdot Rad_{year}$$

$$\Delta t_{mis} = \alpha_2 \Delta t_{calc}$$

with the coefficients $\alpha$ and the indexes of determination $R^2$ of the linear regression equations reported in Table 12.

These correlations show a strong influence of climatic data on thermal behavior of green roof. This result was expected but not with this high influence. Thermal trasmittance as decrement factor and time shift, are strongly influenced by solar irradiation and air temperature, especially the long term variables.

4. Conclusions

The parameters that most affect the thermal behavior of green roofs are the density, the specific heat and therefore the thermal capacity stating the thermal heat storage property of the technology used. The high values of these parameters regulate the thermal behavior of the roof especially during the cooling period, ensuring greater time shift and attenuation of the thermal incoming flux.

A green roof should have an insulation layer to reduce heat dispersion during the winter and a thick substrate to accumulate heat and attenuate thermal flux especially during the summer.

Today, Standards do not consider the boundary conditions in which the green roof operates. The differences between calculated and measured parameters show that climatic data can strongly influence the thermal behavior of the roof, specifically air temperature and solar irradiation.

Considering only the substrate thermal behavior, the temperature has a not linear profile particularly in the deeper layer. These results are the same for all the three technologies considered: extensive, light intensive and intensive green roof.

Future studies will be performed to support these conclusions and to evaluate the thermal behavior of green roofs with different climatic data, typologies of foliage and shades of vegetation’s color.

Acknowledgments

A special thanks to Piedmont Region, Environmental Park and Politecnico di Torino for the precious collaboration during the experimental campaigns.

<table>
<thead>
<tr>
<th>Coeff.</th>
<th>$\alpha_7$</th>
<th>$\alpha_8$</th>
<th>$\alpha_9$</th>
<th>$\alpha_{10}$</th>
<th>$\alpha_{11}$</th>
<th>$\alpha_{12}$</th>
<th>$R^2$</th>
</tr>
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<tbody>
<tr>
<td>$U_{mis}$</td>
<td>0.046</td>
<td>0.044</td>
<td>-0.043</td>
<td>-0.045</td>
<td>0.002</td>
<td>0.015</td>
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<td>$f_{mis}$</td>
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<td>-0.010</td>
<td>-0.618</td>
<td>-0.003</td>
<td>0.011</td>
<td>0.9996</td>
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<tr>
<td>$\Delta t_{mis}$</td>
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<td>-0.129</td>
<td>2.883</td>
<td>-0.178</td>
<td>0.015</td>
<td>1</td>
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</table>

<table>
<thead>
<tr>
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<th>$\alpha_3$</th>
<th>$\alpha_4$</th>
<th>$\alpha_5$</th>
<th>$\alpha_6$</th>
<th>$\alpha_{10}$</th>
<th>$\alpha_{11}$</th>
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<tbody>
<tr>
<td>$U_{calc}$</td>
<td>-</td>
<td>-</td>
<td>1.080</td>
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<td>0.080</td>
<td>-0.042</td>
<td>-</td>
<td>-0.009</td>
</tr>
<tr>
<td>$f_{calc}$</td>
<td>-</td>
<td>1.571</td>
<td>-</td>
<td>0.700</td>
<td>-</td>
<td>-</td>
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<tr>
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<td>-</td>
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References


