EXPERIMENTAL INVESTIGATION OF THE THERMAL AND OPTICAL BEHAVIOR OF AN INTENSIVE GREEN ROOF SYSTEM INSTALLED IN AN OFFICE BUILDING IN ATHENS

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ABSTRACT

The aim of this paper is to experimentally investigate and analyze the thermal and optical behavior of a Green Roof System (GRS) installed in the 10000 m^2 roof of a fully insulated, bioclimatic office building in Peania. More specifically, during the experimental procedure, measurements of the outdoor temperature and relative humidity have been performed, as well as of the air temperature inside the building and the surface temperature of the ceiling. Furthermore, the surface temperatures of the roof were measured using thermographic imaging, as well as the optical properties such as the albedo of the roof's covering materials. The GRS is an intensive green roof and it consists of almost 16000 indigenous plants of at least 14 different kinds which cover the largest part of the roof surface. The rest of the area is covered by a running truck of made by a bioclimatic stabilized ceramic floor. The ceramic material was found to be 5.1^{0}C – 7.2 ^{0}C cooler than the soil or other common materials and the planted area 10.1 ^{0}C - 16.1 ^{0}C cooler than the ceramic floor. The different species of plants were also studied and the conclusion that the density of the foliage plays a primary role was extracted, as there was a difference of 11.8 ^{0}C between a plant with and a plant without dense foliage. It was observed that the different surfaces present their maximum temperature at different hours. The ceramic floor, at 14:00 for the 46.7% of the time and at 15:00 for the 40 %, while the planted area at 14:00 for the 53.3 % of the days, at 13:00 for the 26.6% and, oppositely to the ceramic floor, never at 15:00.

KEYWORDS

Green roof, urban heat island

1. INTRODUCTION

Most of the Mediterranean cities suffer from a quite strong heat island phenomenon (Santamouris, 2007). In particular, in Athens, where its intensity causes important energy and environmental problems (Sfakianaki et al., 2009), mitigation techniques aim to balance the thermal budget by increasing thermal losses and decreasing the corresponding gains. Among the most important of the proposed techniques are those targeting to increase the albedo of the urban environment (Santamouris et al., 2011) and to expand the green spaces (Zoulia et al., 2009). Because of the lack of open spaces where green could be integrated and as the total surface of roofs constitutes over 20% of the total urban surfaces (Akbari et al., 2009), Green Roof strategy is one of these practices that not only provides heat island amelioration and thermal comfort but also reduces energy consumption of buildings (Saadatian et al., 2013).

There are two main available types of green roofs:

- Extensive roofs: light and covered by a thin layer of vegetation with soil thickness less than 10-15 cm where only small herbaceous species can survive, low maintenance requirement, no load consideration
- Intensive roofs: heavy constructions with soil thickness more than 15-20 cm that can support small trees and shrubs, large-scale plants and facilities (Sfakianaki et al., 2009,Kolokotsa et al., 2013, Jaffal et al., 2012, Lin et al. 2013)

There are several advantages associated to green roofs like:

They reduce the flux of heat through the planted area, the heating and cooling needs of buildings and the temperature fluctuation during the day resulting to decreased energy consumption (Santamouris et al., 2007), especially for the building's top floor. Evapotranspiration from the plants and convective losses to the ambient air may contribute to reduce the temperature in urban areas and mitigate heat island. They provide better air quality, absorb atmospheric pollutants and particulate matter, mitigate the greenhouse effect, filter pollutants (Sfakianaki et al., 2009) and they reduce a city's carbon footprint by converting carbon dioxide to oxygen through photosynthesis (Jaffal et al., 2012). They also reduce noise, help with the storm water runoff management, prevent erosion and increase the durability of the roof materials. (Santamouris, 2012). Major disadvantages associated with planted roofs are the additional load that the building has to support and the relatively high investment cost. (Sfakianaki et al., 2009)

The mitigation potential of green roofs depends on several parameters as summarized in (Santamouris, 2012):

(a) Climatic parameters: solar radiation, ambient temperature and humidity, wind speed and precipitation

(b) Optical Variables: albedo to solar radiation, emissivity of the roofing systems and absorptivity of the plants

(c) Thermal parameters: thermal capacity of the roofs and overall heat transfer coefficient, U value

(d) Hydrological variables: all parameters defining latent heat phenomena.

Several studies that have been performed for buildings in Athens analyze the thermal properties and the energy performance of green roofs. It has been shown that they reduce the cooling load at 6 – 49% for the whole building and 12 – 87% for the last floor (Santamouris et al., 2007). For non-insulated building, the temperature of the roof without planting is 42 - 48 ^{0}C while it is 28 - 40 ^{0}C with planting, ie occurs a decrease of 10 ^{0}C (Niachou et al., 2001). According to Sfakianaki et al., 2009, for a spring sunny day with ambient temperature 23.1 ^{0}C, the average temperature of the green roof was approximately 6.5 – 9.1 ^{0}C lower than that of a conventional roof. Furthermore, it was found that a green roof was able to effectively reduce the cooling load by approximately 11% for thermostatically controlled buildings and to improve heat comfort in summer with a maximum expected temperature drop of approximately 0.6 ^{0}C between the roof surface and the interior. A study on the energy-saving effectiveness of a green roof showed it reduced the electricity consumption for air conditioning in summer approximately 40%, however, the results showed no significant savings in heating (Spala et al., 2008).

2. DESCRIPTION OF THE BUILDING AND THE GREEN ROOF

Measurements have been performed in an office building located in the sparsely built industrial zone of Peania, an east suburb of the area of Athens. It is a three-storey building with three basements, equipped with a Green Roof System (GRS). It has a surface of almost 10000 m^2 per floor and 60000 m^2 in total while the elevation of each floor is equal to 3.60 m. The main axis of the building is northwest – southeast oriented and all external surfaces are exposed to solar radiation as it stands by itself and there is no shading from neighboring buildings.

Figure 1: The office building in Peania

The aspect ratio, which is the ratio of the building's height over its width, is equal to 0.07, as it is a very long building with only three floors, while the ratio of the surface covered by windows over the surface covered by wall is equal to 0.53.

It is fully insulated: the exterior walls consist of heavyweight reinforced concrete and insulation of extruded polystyrene, the floors are made of heavyweight reinforced concrete, a particle board and a linoleum coating, while the ceilings of a metal false ceiling and mineral wool. The whole façade is also covered by metal shades which have the ability to move.

The GRS is an intensive green roof installed on the 10000 m^2 roof of the building and it consists of almost 16000 indigenous plants of at least 14 different kinds which are listed in table 1.

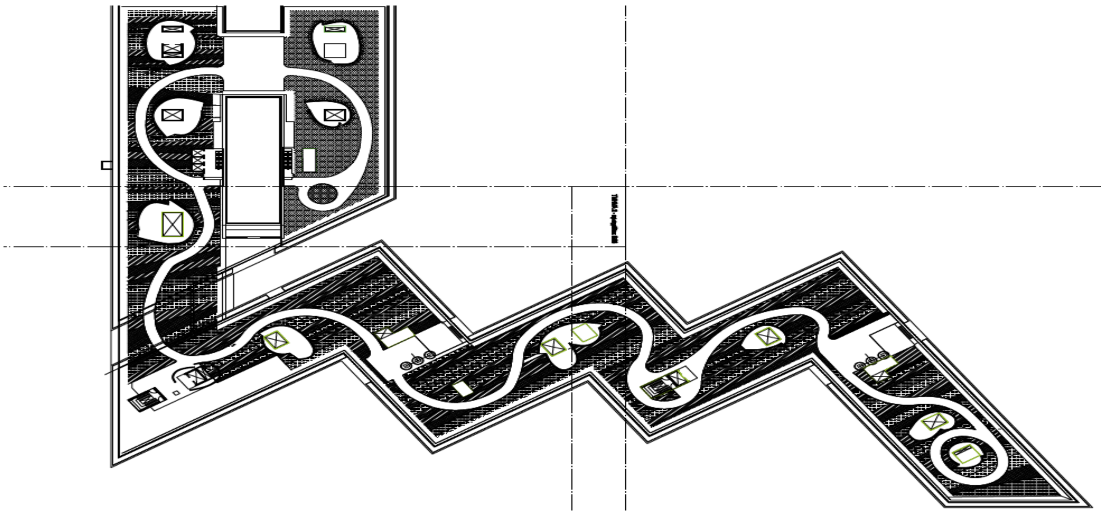


Figure 2: A plan view of the roof

Figure 3: A panoramic view of a part of the green roof

The rest of the area is covered by a running truck of 2000 m^2 made by stabilized ceramic floor. It is an ecological, bioclimatic and water permeable material which consists from ground tiles, mosaic, quartz, sand and pumice.

The materials and the structural elements of the GRS (the layers from outside to inside) are the following:

1. The plant level: local, dry – tolerant plants.
2. A mechanical substrate, a vegetation layer
3. A geotextile filter sheet from thermally strengthened polypropylene
4. A drainage system from thermoformed recycled polyethylene.

5. A moisture retention substrate from recycled fiber of polyester/polypropylene.
6. A waterproofing membrane – root barrier.
7. An elastomeric bitumen membrane.
8. A waterproofing bitumen membrane.
9. Lightweight concrete.
10. Polyethylene insulation
11. Extruded polystyrene insulation.
12. A vapor barrier (elastomeric, waterproofing, asphalt emulsion).
13. Heavyweight reinforced concrete.

Table 1: Kinds of different plants

Plant species	**Measured height (2/07/2013, cm)**	**Flowering season**
Artemisia ludoviciana	20	Summer - Autumn
Helichrysum italicum	32	Summer
Artemisia Alba	32	Autumn
Artemisia Absinthium	15	Summer
Satureja thymbra	40	Spring – Summer
Origanum dictamus	25	Summer
Origanum majorana	45	Summer – Autumn
Lavandula stoeches	30	Spring – Summer
Lavandula dentata green	60	Summer
Lavandula dentata		
Salvia fructicosa	25	Summer
Salvia farinacea	35	Spring – Summer
Salvia sclarea	60	Spring – Summer
Salvia of purpurea	65	Summer
	30	Summer

3. DESCRIPTION OF EQUIPEMENT AND EXPERIMENTAL MEASUREMENTS

The experimental investigation of the present study has been performed during the period 30/05/07/2013 – 30/07/2013 and consists of the following measurements:

- The outdoor and indoor temperature and relative humidity were measured with an interval of 5 minutes, with calibrated data loggers Tinytag Plus 2 placed in meteorological cages. The accuracy is $\pm 0.1^0$C, the temperature range is -40 to 85 ^{0}C and the humidity range 0-100. One sensor was installed on the roof and one in one of the top floor's offices.
- The solar and the reflected from the different roof surfaces radiation was measured every hour (10 am – 16 pm) with a double pyranometer in order to calculate the albedo of four different surfaces of the roof, as the ratio between the reflected from the roof radiation and the solar radiation.
- The top floor's ceiling's surface temperature was measured with a portable infrared thermometer with a laser pointer (range -22^{0}C–550^{0}C) and an infrared thermographic camera (Thermovision 570) in three spots (in an office, in the corridor and in the entrance) every hour.
- The surface temperature of the stabilized ceramic floor was measured hourly with an infrared thermometer and an infrared thermographic camera at two spots (in the sun and in the shade), as well as at the three spots situated exactly over those where the ceiling's temperature was measured.
- The illustration of the surface temperature of the different kinds of plants was performed with the infrared thermographic camera. There are hourly measurements for every different species of plants (Table 1) as well as for the whole vegetated area in order to study the differences between the different plants.

4. RESULTS AND ANALYSIS OF THE MEASUREMENTS

The experimental procedure took place for the time period of 30/05/2013 – 30/07/2013 during which the mean air temperature was 26.4 ^{0}C, while the maximum and the minimum values were 40.4 ^{0}C and 15.5 ^{0}C respectively. Figure 4 shows the fluctuation of the outdoor air temperature during this period, measured at a height of 1.80 m over the roof's surface.

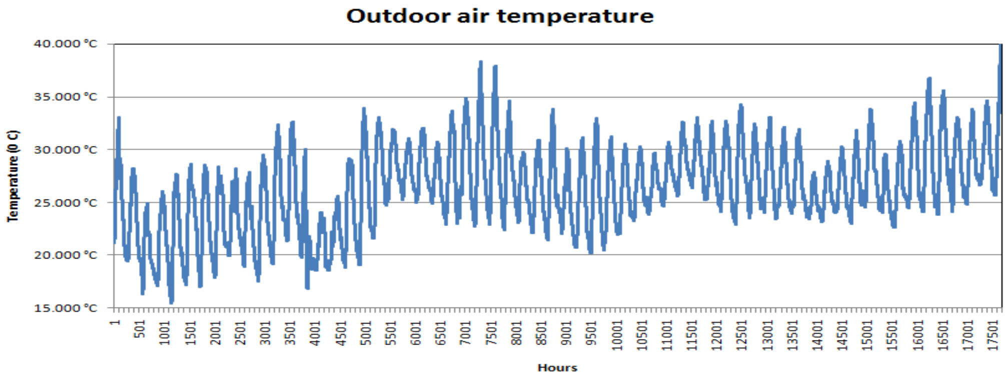


Figure 4: Variation of the outdoor air temperature for the whole measurements period

Several observations were made and the following conclusions were extracted for a typical summer (warm and sunny) day (25/07/2013):

The mean ambient temperature was 34.7 ^{0}C and the mean relative humidity 29.9%, while the respective maximum values were 36.8 ^{0}C and 34.7 %. The hourly mean variation of the air temperature on the roof is shown in figure 5.

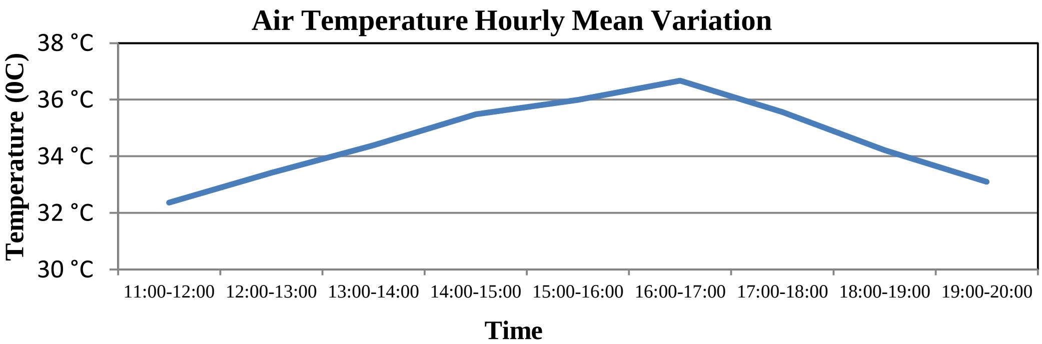
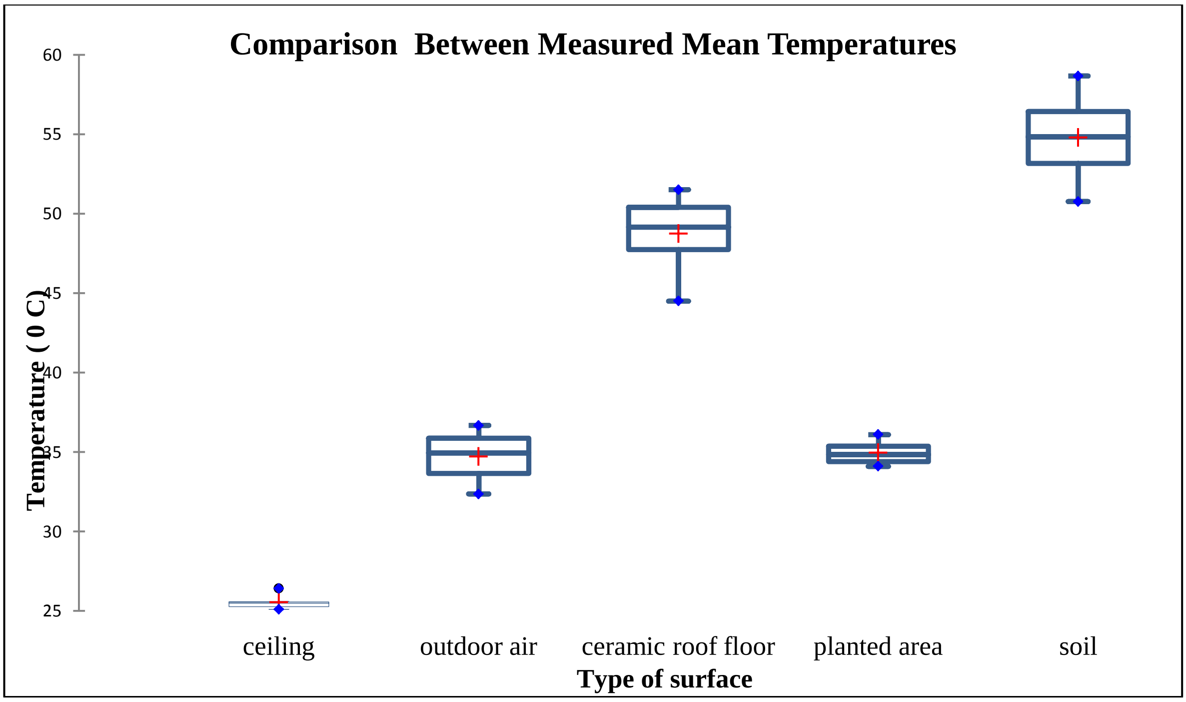
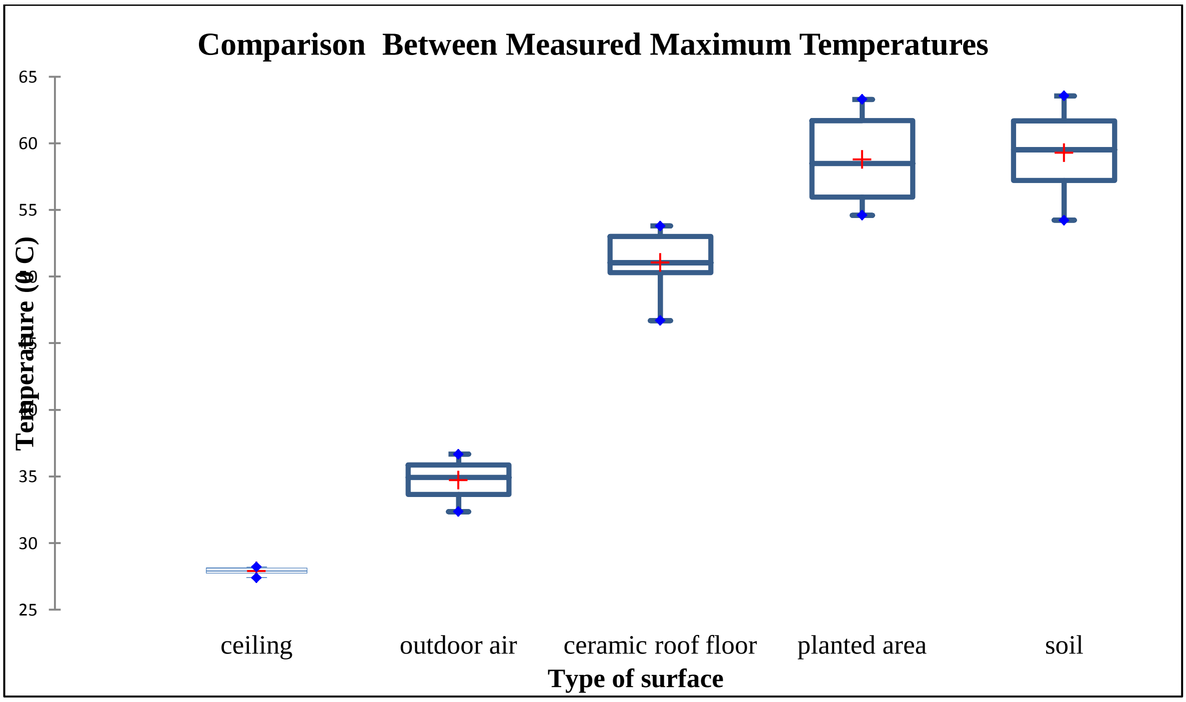


Figure 5: Hourly mean variation of the air temperature during the day 25/07/2013

In the following figure a comparison between the basic measured temperatures is presented. The mean surface temperature (Figure 6a) of the planted area is significantly lower than the ceramic floor's, with the temperature difference varying from 10.1 ^{0}C (at 11:00) to 16.1 ^{0}C (at 15:00). At the same time, the ceramic floor's mean surface temperature is from 5.1 ^{0}C (at 13:00) to 7.2 ^{0}C (at 13:00) lower than the soil's. The ceiling's surface temperature varies between 25.1 ^{0}C and 26.4 ^{0}C. The maximum value occurs at 15:00 for the ceramic roof floor and the soil while for the planted area at 14:00 and for the ambient air at 16:00. As far as maximum values are concerned (Figure 6b), the ceramic floor is also 6.6 ^{0}C (at 12:00) to 9.8 ^{0}C (at 15:00) cooler than the soil but, oppositely to the mean values, the maximum ones are higher for the planted area than for the ceramic floor since they correspond to spots of soil. The measurement is taken for the whole vegetated area which includes foliage and soil at the same time, and this is the reason the maximum values for the planted area and the soil are close. It is particularly interesting to examine separately and compare the temperatures of the foliage, the soil and the ceramic floor.



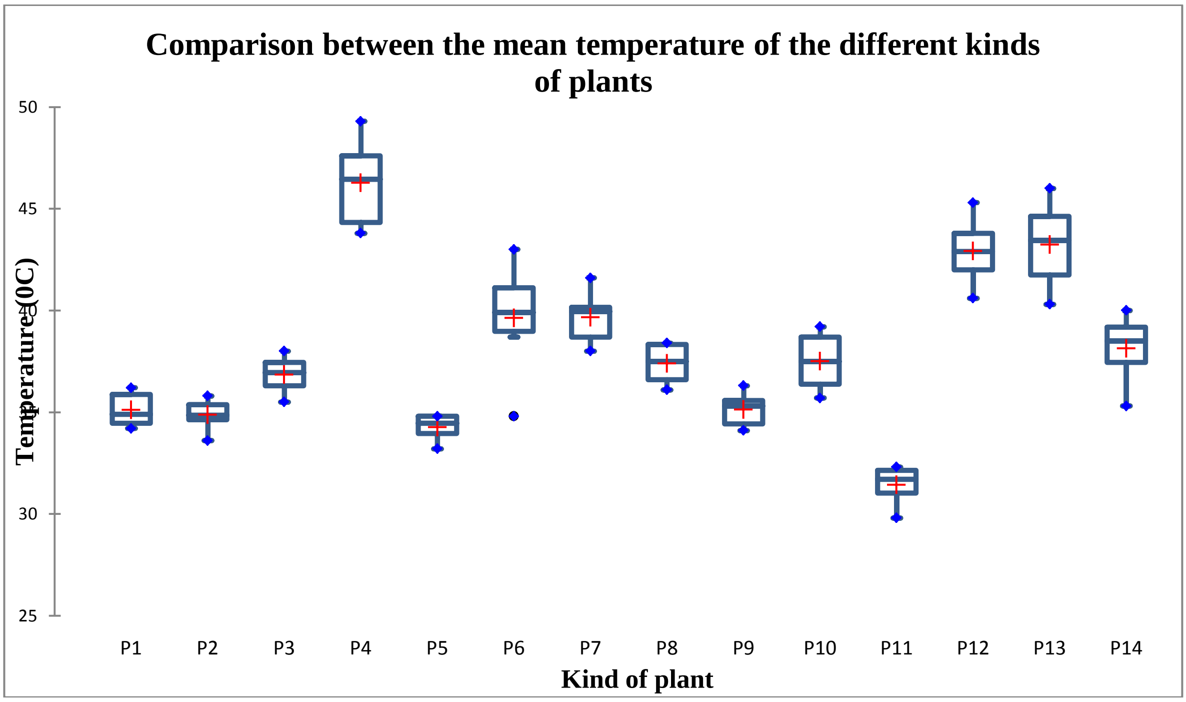
(a)



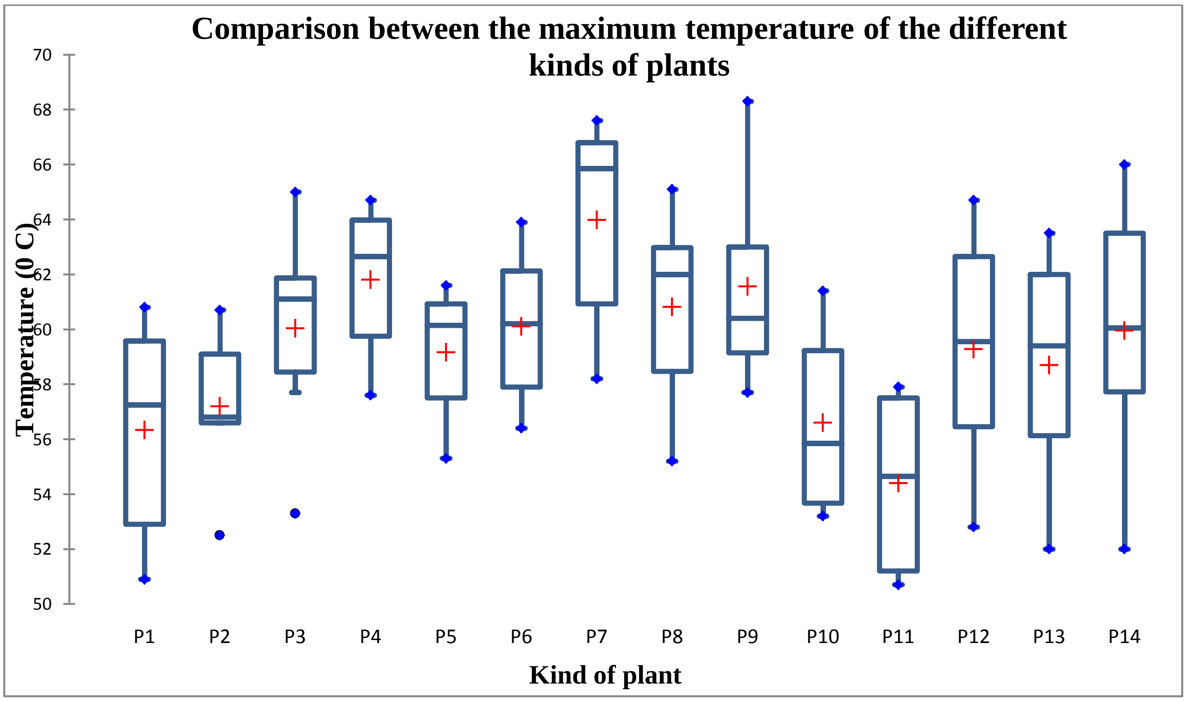
(b)

Figure 6: Comparison between the (a) mean and (b) maximum measured temperatures of the outdoor air, and the surface temperatures of the top floor's ceiling, the soil, the ceramic floor and the planted area

As it can be seen in a comparative graph that shows the variation of the mean temperature of all the different species of plants, the one which presented the lower mean surface temperature is plant 11 (Salvia fructicosa) because of its dense foliage and those with the highest are plants 12 (Salvia farinacea) and 13 (Salvia sclarea) because their foliage's low density lets a considerable area without leaves, covered only by soil. Plant 4, which also presents high temperatures, is ignored because its foliage had been dried.



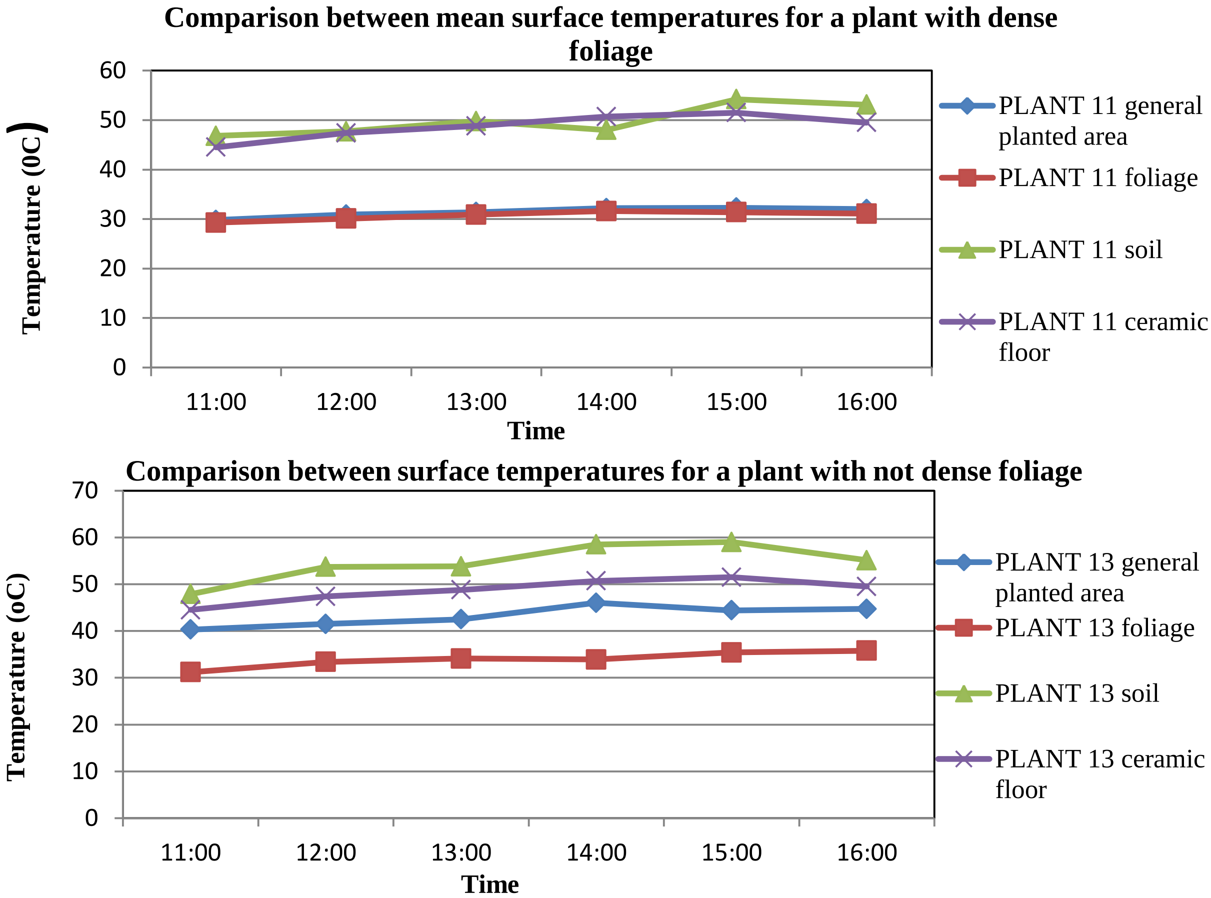
(a)



(b)

Figure 7: Comparison between the (a) mean and (b) maximum temperatures of the different kinds of plants

A comparison between the temperatures of the ceramic floor not only with the general planted area but with the foliage and the soil separately follows. Plants 11(dense foliage) and 13 (not dense foliage) were chosen because they presented the lowest and highest surface temperatures. The soil for plant 13 is presented 4.3 ^{0}C in average warmer than for plant 11 and the foliage itself is only 3.2 ^{0}C warmer for plant 13. At the same time, the whole planted area of plant 13 is 11.8 ^{0}C warmer than the one of plant 11. The curves for the foliage and the general planted area are similar and close for plant 11, while there is a greater temperature difference between the foliage and the general area for plant 13. More specifically, for plant 11 the average temperature difference between the foliage and the general planted area is 4.3 ^{0}C while for plant 13 it is 9.3 ^{0}C. All this illustrates strongly the importance of the foliage's density and the percentage of area covered by leaves. Finally, it can be remarked that the foliage of plant 11 is 18 ^{0}C cooler than the ceramic floor at the same time that the one of plant 13 is 14.8 ^{0}C cooler.



(b)

Figure 8: Comparison between the mean surface temperatures of the general planted area, the foliage, the soil and the ceramic floor for (a) a plant with high foliage density (plant 11: Salvia fructicosa) and (b) a plant with low foliage density (plant 13: Salvia sclarea)

A statistical analysis that corresponds to the entire set of measurements was also performed. In the figures that follow is given in boxplots the statistical distribution of the measured surface temperatures for every hour and for the ceramic floor, the soil and the whole planted area, where the median, the mean, the maximum and the minimum value, as well as the 25th and the 75th percentile are illustrated. Figure 10 shows the distribution of surface temperatures of the foliage only, of each different kind of plant for the measurements of 14:00, when the highest temperatures occurred.

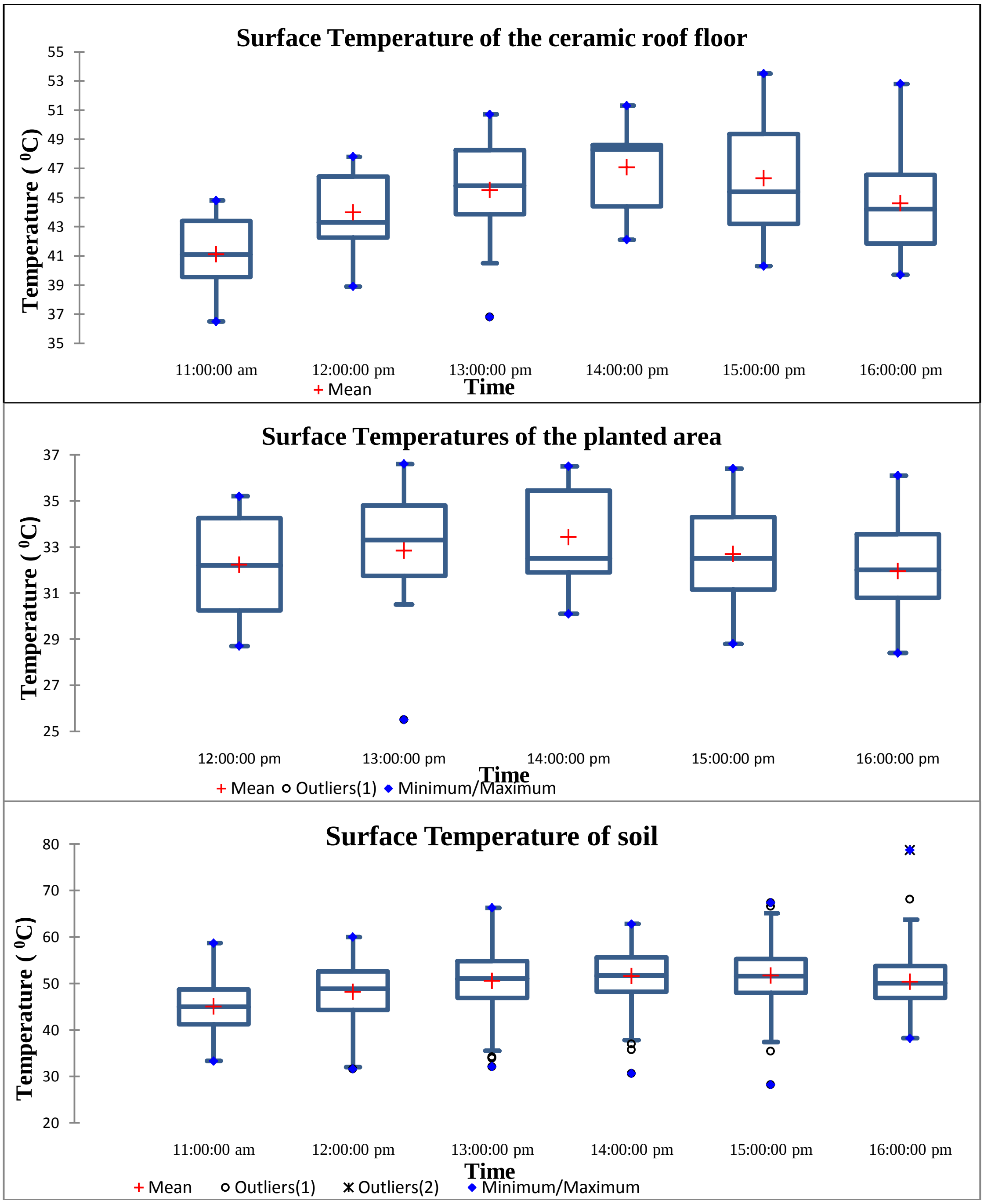


Figure 9: Comparison of the statistical distribution of the measured surface temperatures for every hour and for the ceramic floor, the planted area and the soil.

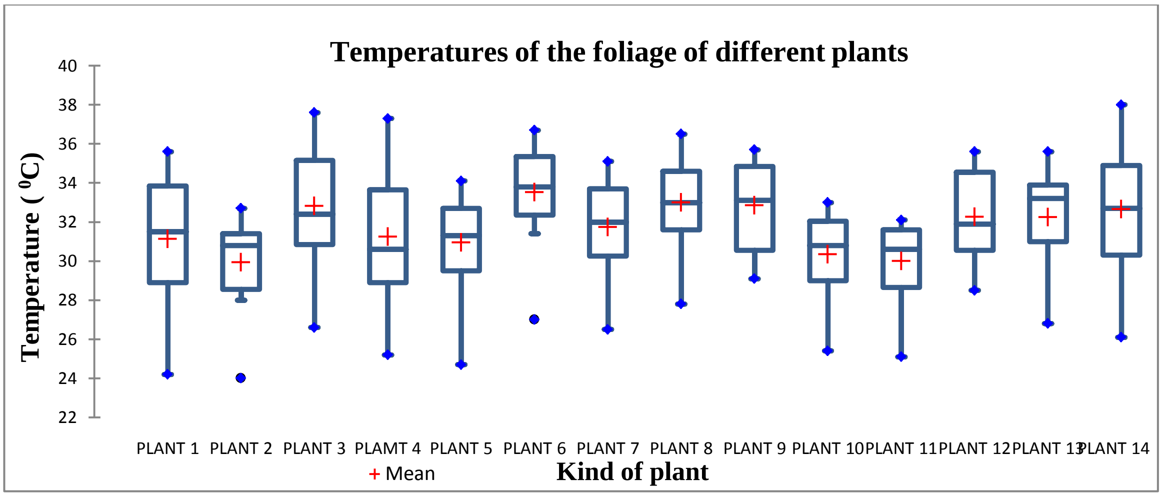


Figure 10: Distribution of surface temperatures of the foliage only of each different kind of plant for the measurements of 14:00, when the highest temperatures occurred

In Table 2 are presented the mean and the maximum values that appeared during the whole experimental period for every hour of measurements and for the ceramic floor, the planted area and the soil. The ceramic floor and the soil present the highest temperature at 15:00 (53.5 ^{0}C and 67.4 respectively)), while the planted area presents it at 13:00 and it is significantly lower (35.3 ^{0}C). Taking into account the mean values, it is concluded that the temperature difference between the planted area and the ceramic floor takes its greatest value at 14:00 when it is 13.66 ^{0}C and varies between 11.8 ^{0}C (at 12:00) and 13.6 (at 15:00). In Table 3 the frequencies of the hour that the maximum temperature appears are given. The result is that for the ceramic floor, the maximum occurred at 14:00 for the 46.7% of the time, at 15:00 for the 40 % and at 13:00 and 16:00 for 6.6% each. Concerning the planted area, the highest temperature appeared at 14:00 for the 53.3 % of the days, at 13:00 for the 26.6%, at 12:00 and 16:00 for 6.6% each and, oppositely to the ceramic floor, it never occurred at 15:00.

Table 2: Mean and maximum temperature for every hour and for different surfaces

	11:00		12:00		13:00		14:00		15:00		16:00	
	mean	max	mean	max	mean	max	mean	max	mean	max	mean	max
Ceramic floor	41.1	44.8	44	47.8	45.5	50.7	47.06	51.3	46.3	53.5	44.6	52.8
Soil	45	58.7	48.2	60	50.5	66.3	51.6	62.8	51.7	67.4	50.4	78.7
Planted area	31.6	35.3	32.2	35.2	32.8	36.6	33.4	36.5	32.7	36.4	32	36.1

Table 3: % Frequencies of the hour that the maximun temperature appears

Hour of appearance of max Temperatures (frequencies %)	**11:00**	**12:00**	**13:00**	**14:00**	**15:00**	**16:00**
Ceramic floor	0	0	6.6	46.7	40	6.6
Planted area	0	6.6	26.6	53.3	0	6.6

5. CONCLUSIONS

By conducting the experimental procedure and the present study, it was mainly concluded that the Green Roof System which is installed in the office building in Peania, is a particularly interesting case study and its thermal and optical behavior is greatly promising concerning its energy and environmental efficiency. The ceramic material that covers a part of the roof was found to be 5.1^{0}C – 7.2 ^{0}C cooler than the soil or other common materials and the planted area, which is the main surface cover for the roof, was 10.1 ^{0}C - 16.1 ^{0}C cooler than the ceramic floor. The different species of plants were also studied and the conclusion that the density of the foliage plays a primary role was extracted, as there was a difference of 11.8 ^{0}C between a plant with and a plant without dense foliage. A final difference that was observed is the fact that the different surfaces present their maximum temperature in different hours. The ceramic floor, at 14:00 for the 46.7% of the days and at 15:00 for the 40 %, while the planted area at 14:00 for the 53.3 % of the days, at 13:00 for the 26.6% and, oppositely to the ceramic floor, never at 15:00. The analysis of the experimental results is still in progress and a theoretical approach is also ongoing using the simulation programs Energy+ and EnviMet in order to extract some conclusions on the efficiency of the green roof and its contribution not only to the energy consumption of the building and the indoor thermal comfort, but also to the urban microclimate and the mitigation of the urban heat island phenomenon.

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