# 214: Cooling performance of green roofs

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**Abstract**

The present paper examines the green roofs. Green roofs are specially chosen as means for providing passive cooling to the buildings and the air that surrounds them. The paper investigates the factors that affect the cooling performance of green roofs, such as the climate of the location where installed, the foliage density of the plants used, the thickness of the implemented substrate as well as its water moisture content. These factors are evaluated by analyzing data from existing research. Apart from the parametrical analysis, an attempt was made to predict the green roofs' surface temperatures if the corresponding concrete ones are already known.

Keywords: green roofs, passive cooling, foliage density, substrate thickness, substrate moisture

## 1. Introduction

The existing global crisis regarding the increased energy consumption and the raised temperatures in the urban cores is making the application of sustainable strategies, especially in buildings, imperative. Green roofs can constitute a significant means of passive cooling the buildings and their surroundings. Green roofs have the potential to improve the thermal performance of a roofing system through shading, evapotranspiration, better insulation values and thermal mass, thus reducing a building's energy demand for space cooling [1].

Not until recently, had the thermal performance of green roofs been studied in detail by several researchers in several countries. Researchers conducted experiments and simulations regarding green roofs' cooling performance each one using its own parameters (plants, substrate thickness, climatic conditions and location). As a result, a variety of data was created but rather segmentally and not in a collective way. In addition, many researchers have constructed mathematical and simulation models regarding the prediction of green roofs' cooling performance. However, these models required the use of softwares which could be complicated and time consuming.

The main objectives of this study are the following:

- To gather and compare the existing experimental data results in order to discover and give the appropriate importance to the crucial factors such as climate, foliage density, soil thickness and moisture when designing a green roof
- to create predictive equations that could be used easily, as a first estimation of the applied green roofs' surface temperatures.

An attempt to assess the factors that affect green roofs' performance was made, by analyzing the data of several published papers. After the analysis, new figures were created in Microsoft Excel by combining and comparing the existing data. Predictive equations were also created in Microsoft Excel through the method of regression analysis.

## 2. Factors affecting the cooling performance of green roofs

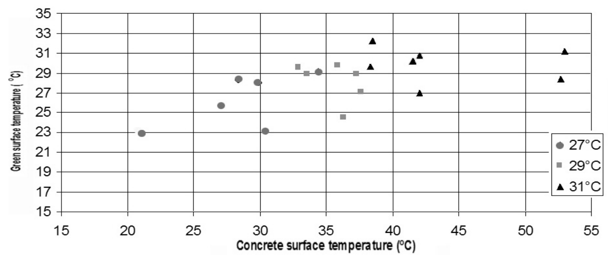
### 2.1 The effect of climate

In order to estimate the role of the climate in the cooling performance of green roofs[1], a comparison is made. The mean surface temperatures of green roofs are plotted against the mean surface temperatures of concrete ones under specific ambient air temperatures, unlike the previous works where the surface temperatures of green roofs were plotted against the ambient air temperatures and the surface temperatures of the concrete roofs against the same ambient air temperatures.

**Hot and humid climate**

**Daytime** (7:00-20:00):

Figure 1 shows the results of temperature measurements that took place in various cities[2] with hot and humid summer. The green surface temperatures are plotted against the ones of




concrete roofs, when the ambient air temperature is 27 °C, 29°C and 31°C.

Figure 1 Comparison of green roofs' surface temperatures against concrete roofs'

From the Figure 1 it can be noticed that the range of fluctuation in the green roofs' surface temperatures is much smaller than the one of

[1] All the data refer to green roofs with substrate thickness ranging from 100 to 200 mm, over non-insulated constructions. All the conventional roofs that green roofs were compared with are concrete and all the daytime measurements used in the figures refer to clear sky conditions.

[2] Kobe, Osaka, Tokyo (Japan), Singapore, Florida (USA), Porto Alegre (Brazil), Vicenza (Italy)

concrete roofs'. The surface temperatures of the green roof vary between 22.9 and 32.2°C, while the concrete surface temperatures range between 21 and 53°C.

Generally, it can be said that there is a substantial correlation between the ambient air temperatures and the surface temperatures of the green roof. The green roofs' surface temperatures follow closely the ambient ones, without reaching exceedingly high temperatures as in the case of concrete roofs. However their surface temperatures do not fall beneath the ambient ones. Consequently, the effect of the vegetation (grass) is quite significant: the surface temperatures of the green roofs compared to the concrete ones, are dramatically lower.

### 2.1.1. Relation between green and concrete surface temperatures at daytime (7:00-20:00)

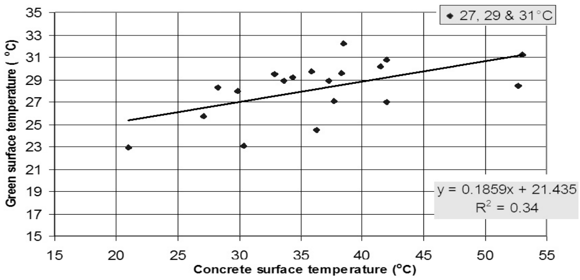



Figure 2 is similar to Figure 1 but the aim is different: to predict green roof surface temperatures if the concrete roofs' temperatures are already known.

Figure 2 Relation between green and concrete surface temperatures at daytime

The correlation coefficient (r) of the two variables is 0.59 which is characterised as "substantial to very strong relationship" [8]. Thus, their statistical relationship is accurate enough and as a result, it can be used to predict and give a brief idea of what the expected temperatures will be if concrete roofs are replaced with green in that specific type of climate.

**Nighttime (20:00- 7:00):**

Figure 3 shows the results of temperature measurements that took place in the examined cities at night. The green surface temperatures are plotted against the ones of concrete roofs, when the ambient air temperature is 25 °C, 26°C and 27°C.

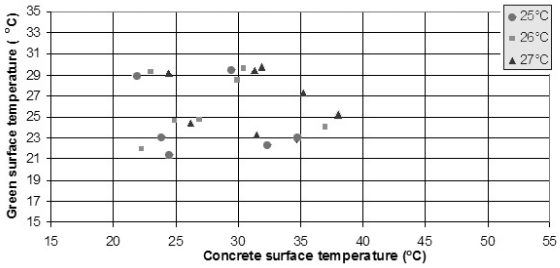



Figure 3 Comparison of green roofs' surface temperatures against concrete roofs'

Figure 3 shows that while the range of surface temperature fluctuation is almost the same for the green roofs at night, for the concrete roofs is dramatically reduced. Without solar radiation the temperatures at the concrete roof considerably decrease at night, whereas for the green roof remain at the same levels as daytime's.

### 2.1.2. Relation between green and concrete surface temperatures at nighttime (20:00-7:00)

Figure 4 expresses the relation among the green and the concrete surface temperatures during the nighttime.

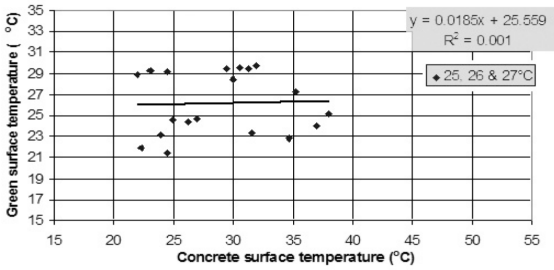



Figure 4 Relation between green and concrete surface temperatures at nighttime

The correlation coefficient (r) of the two variables is 0.03 which is characterised as "trivial relationship" [8]. Consequently, that the relationship between the two variables is tiny, practically zero. This might be due to the fact that the surface temperatures depend upon the rate of radiation from the roof to the sky, which in case of the nighttime period might be quite difficult to predict and generalise. In every case, more research and data is needed in order to draw conclusions.

**Hot and dry climate**

**Daytime** (7:00-20:00):

Figure 5 represents data gathered from simulated results [9] produced for Athens, Greece, while Figure 6 refers to field measurement data that were taken when the ambient temperature was 28°C at Loutraki, Greece [10].

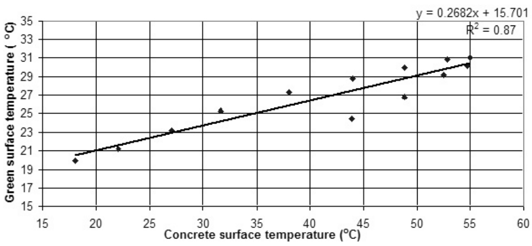



Figure 5. Comparison of green roof's surface temperatures against concrete's in Athens

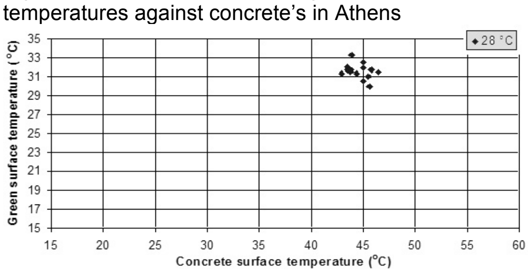



Figure 6. Comparison of green roof's surface temperatures against concrete's in Loutraki

From Figure 5 it is obvious that the temperature range of the green and the concrete roof is highly different. The surface temperatures of the green roof vary between 20 and 31°C whilst those of concrete roof vary between 18 and 55°C. In Figure 6 under 28°C of ambient air temperature, the green surface temperatures fluctuate between 30 and 33.3°C, while at the same time the concrete surface temperatures fluctuate between 43 and 46.4°C. The range of fluctuation of green roofs' surface temperatures is almost the same as in the hot and humid climate and much smaller than the one of concrete roofs. This may be attributed to the similar biological functions of plants and the way those semi extensive green roofs are constructed.

**2.2 The effect of different Leaf Area Index on the cooling performance of green roofs**

Afterwards the effect of plants' foliage density (LAI) on green roofs' cooling performance was investigated. For this purpose data from three cities (Athens, Yamuna Nagar and Singapore) was collected. Previous researchers had created figures where the canopy air temperature was plotted against time for several plants with different LAI. Here the canopy air temperature is directly plotted against LAI for each city under examination.

**Hot and dry: Athens**

Figures 7and 8 show the simulated data of an extensive green roof located in Athens, Greece.

**Daytime** (7:00-20:00):

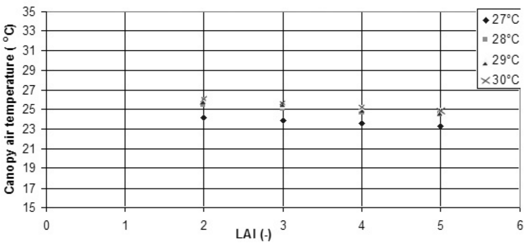



Figure 7. Effect of various LAI on canopy air temperature in daytime

Figure 7 shows the green canopy air temperatures which are plotted against plants with different LAI, when the ambient air temperature is 27°C, 28°C, 29°C and 30°C.

The effect of LAI can be easily perceived: increasing it from 2 to 5, a significant reduction of the transmitted solar radiation and hence, of the foliage temperature during the day, occurs. For instance, when the ambient air temperature is 27°C, the canopy air temperature of the plants with LAI = 2 is 24.2°C, whilst the canopy air temperature of the plant with LAI = 5 is 23.3°C. Similarly, when the ambient air temperature reaches 30 °C, the canopy air temperature of the plants with LAI = 2 is 26 °C, whilst the canopy air temperature of the plants with LAI = 5 is 24.8°C.

**Nighttime** (20:00- 7:00):

At night, the temperature differences between the plants with different LAI are reduced.

The canopy air temperatures seem to be alike, under the same ambient temperatures for different LAI. That is because the dense foliage's role is essential during the day, providing shadow and protection to the roof surface while it is not so important at night. In addition, the increased

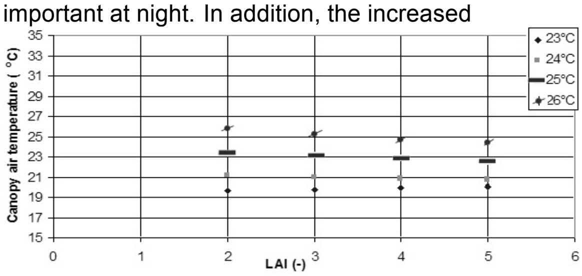



Figure 8 Effect of various LAI on canopy air temperature in nighttime

density of the foliage inhibits the long wave radiative heat loss from the surface and as a result night-time surface temperatures tend to be higher.

**Hot and humid: Yamuna Nagar**

The simulated data examined refer to a green roof located at Yamuna Nagar, India.

**Daytime** (7:00-20:00):

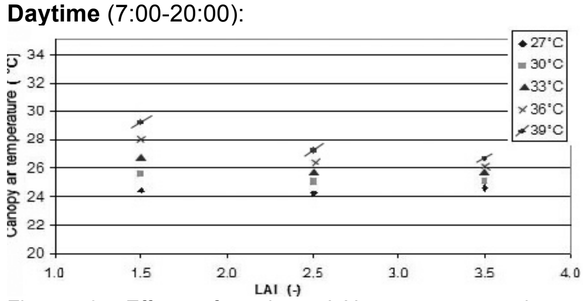



Figure 9. Effect of various LAI on canopy air temperature in daytime

From the Figure 9 it can be seen that for plants with denser foliages the temperature fluctuations of canopy air are smaller than for plants with less dense foliages. According to Kumar and Kaushik [11]: "larger LAI reduces the canopy air temperature, stabilises the fluctuating values and reduces the penetrating flux".

**Nighttime** (20:00- 7:00):

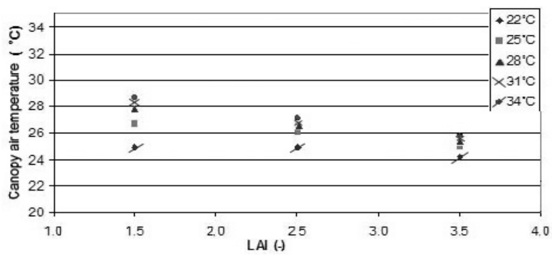



Figure 10. Effect of various LAI on canopy air temperature in nighttime.

During nighttime the same reduced fluctuation of canopy air temperatures that was previously observed for the dense foliage plants has remained. But this reduced temperature fluctuation at night was not the case for Athens and this might be due to the fact that climatic conditions or plants used were different for the two cities under examination.

**Hot and humid: Singapore**
The data examined in this section refer to field measurements on an intensive roof garden planted with different types of plants.

**Daytime** (7:00-20:00):

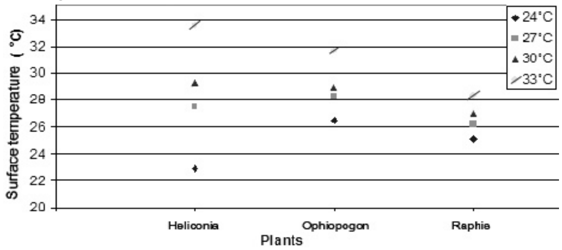
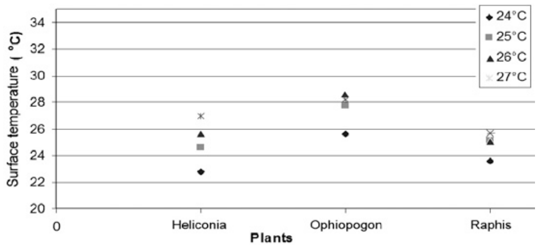



Figure 11. Effect of various LAI on surface temperature of green roof in daytime

Raphis, the dense shrub presented the lowest surface temperatures during the whole day. The dense foliage once again played its sun shading role for the surface beneath. Under sparse foliages higher temperatures were measured.




Hence the dependence of LAI on the shading effect became once again quite obvious.

**Nighttime** (20:00- 0:00 and 5:00-7:00)
Figure 12. Effect of various LAI on surface temperature of green roof in nighttime

At night, the surface temperatures decreased under all the types of plants. The lowest temperature was measured under Heliconia with the sparse foliage. Amongst the other two plants, Raphis would be expected to have the least temperature underneath its canopy because of its dense foliage, which prevents long wave radiation to escape. On the contrary, Ophiopogon with sparser foliage presented a lower minimum temperature. A possible explanation for this could be the high temperature that was measured under Ophiopogon during the day.

**2.3 The effect of soil moisture on the cooling performance of green roofs**
Then the effect of the soil moisture content on the surface temperatures of green roofs was sought. For this purpose data from several papers were put together in order to compare the performance of green roofs under wet and dry soil conditions. Most of the data collected refer to hot and humid climates, while data from only one paper [12] refers to hot and dry climates.

**Hot and humid climates**
The data analysed in this section refer to semi-extensive roof gardens planted with turf and shrubs. The soil's substrate thickness ranges from 100-200 mm.

**Daytime** (7:00-20:00)

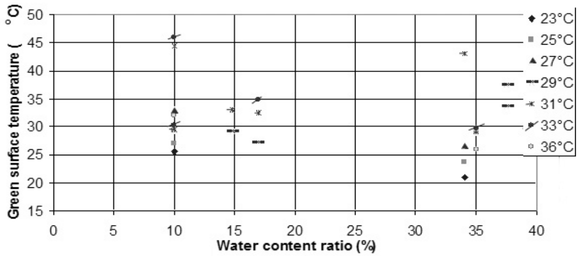



Figure 13. Green roofs' surface temperatures against moisture content in daytime

Figure 13 shows the effect of soil's water content on the green roofs' surface temperatures, for different ambient air temperatures. The effect is not so evident and this might be due to the fact that green roofs with different substrates were examined or to the already high green surface temperatures in some cases, that didn't manage to fall right after the soil was watered. In general, under the same ambient air conditions for wet and dry soil, it seems that green roof surface temperatures are 1-3 °C lower when the soil is wet.

**Nighttime** (20:00- 7:00)

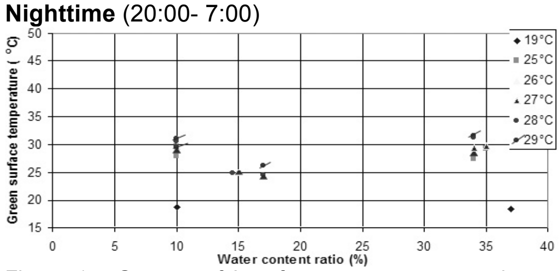



Figure 14. Green roofs' surface temperatures against moisture content in nighttime

At night, the variations in green surface temperatures because of the different soil water content are eliminated. As it can be observed, for the same ambient air temperatures the green roof surface temperatures are similar for different levels of soil moisture. This might be due to the fact that wet soils store more thermal energy in the day (because of their increased thermal capacity) which prevents them from immediate cooling at night. In contrast to the dry soils which exhibit higher daytime temperatures and lower nighttime temperatures, the wet soils present smaller daily fluctuations because of their high thermal diffusivity.

**Hot and dry climates**
The data cited below are slightly different from the ones examined above due to the lack of sufficient field measurements and simulation data.
The Figure15 refers to simulated data for the city of Athens and compares the heat flux that passes

through the roof for different soil volumetric moisture content.

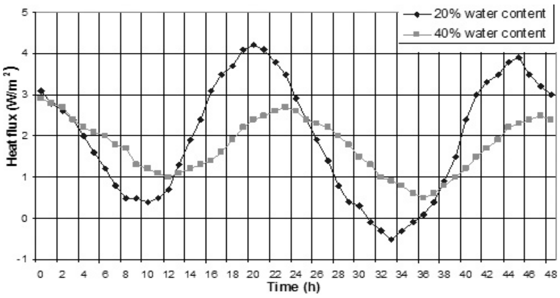



Figure 15. Heat flux through the green roof (redrawn from [12])

Figure 15 shows that when the water content ratio within the soil is larger, the heat entering the roof diminishes and the fluctuations of heat flux are reduced. While at the drier soil the temperature variations are more extreme, the wetter soil presents a more conservative curve with less variation.

Amongst the variations of soil with 20% moisture, there is a cooling effect between the 31st and 36th hour. That is because this soil has got a smaller thermal diffusivity than the wet one, therefore heats up mostly at the uppermost layers and consequently, cools down faster. On the other hand, in the case of the soil with 40% moisture, the heat flux entering the building through the roof apparently has got lower maximum values.

### 2.4 The effect of substrate thickness on the cooling performance of green roofs

Finally the role of substrate thickness on the cooling effect of green roofs during summer was assessed. The effect was investigated for "hot and humid" climates, where green roof surface temperatures are plotted against different substrate thicknesses and for "hot and dry" climates, where the heat flux transmitted through the green roofs is studied for different substrate thicknesses.

**Hot and humid climates**

The data examined in this section refer to roof gardens planted with turf and shrubs. Figures from where data have been extracted were providing green surface temperatures against time for a certain substrate thickness. Here an attempt was made to gather green surface temperatures for various substrate thicknesses and plot their mean values altogether not against time but against the parameter under examination.

**Daytime** (7:00-20:00)

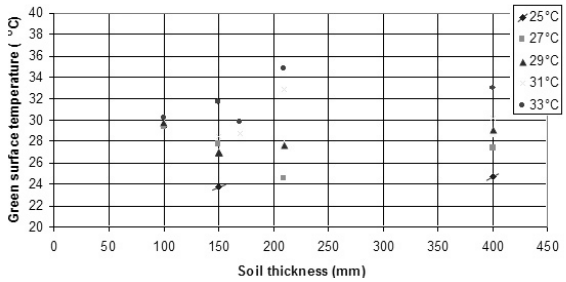
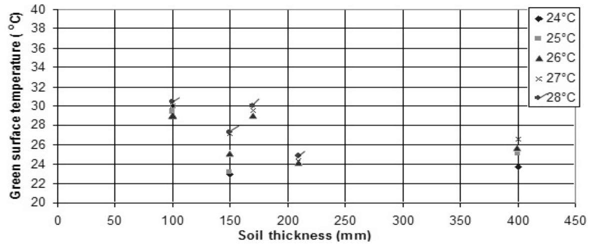



Figure 16. Green roofs' surface temperatures against various soil thicknesses

From the Figure 16 it can be observed that there is no great differentiation between the surface temperatures of the planted substrate of 100 mm and of 400 mm. Normally, thin layers of substrates, which represent low thermal capacity, result in higher surface temperatures than the thicker ones. However, this was not the case for




the thickest layer. The higher surface temperatures of the thickest layer might be due to the fact that the soil of 400 mm was possibly dry at the time of measurements or perhaps the foliage of the roof wasn't much developed as to provide efficient shading to the soil underneath.

**Nighttime** (20:00- 7:00)

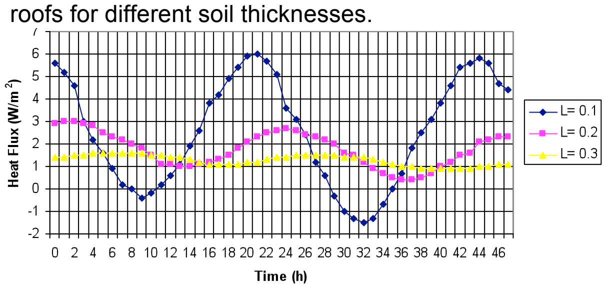
Figure 17. Green roofs' surface temperatures against various soil thicknesses

During nighttime it seems that the green roofs with the layer of 210 and 400 mm have got the best performance. This can be a little odd as substrates with low thermal capacity would be expected to cool down more easily and extract heat to the environment more quickly.

Possible reasons for this small dissimilarity might be for one more time the water content levels of green roofs' soil or some denser foliage that prevented the heat to escape. In any case, the differences were small and further research with thicker layer substrates needs to be effectuated.

**Hot and dry climates**

Due to the lack of sufficient data, the figures cited here instead of referring to green roofs' surface temperatures against various soil thicknesses, refer to the heat flux that passes through green roofs for different soil thicknesses.



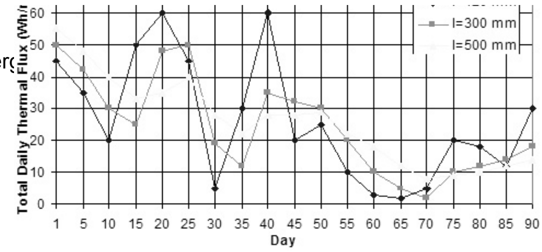



Figure 18. Heat flux through the roof for different soil layer thickness value (redrawn from [12])

For Figure 18 heat flux was considered positive when it was directed from the roof to the building (heating) but for Figure 19 heat flux was considered positive when it was directed from the building to the planted roof (cooling) and vice versa (heating).

These results show that the heat flux of the planted soil of 0.3 m can be distinguished from the noticeable time lag and the smaller variation of thermal flux. While the curve of L = 0.1 m presents a pick heat flux value of 6 W/m² at around 21:00, the curve of L = 0.3 m presents a pick heat flux value of 1.5 W/m² around 3:00. This time lag as well as the smaller heat flux variation of the thicker substrate is mainly due to the increased level of soil's inertia and the raised insulation level.

Similar comments can be made for Figure 19 as well. This Figure shows that the thinner layers were more capable of extracting heat to the environment than the thicker ones, but only during relatively cool days. This fact was due to

Figure 19 Heat flux through the roof for different soil layer thickness value (redrawn from [13])

the small thermal inertia of thin layers and hence to their ability to cool down quickly. On the contrary, during the hot days, when the need for cooling was intense their temperature increased quickly and a consequence their cooling effect decreased.

## 3. Conclusions

1. The climate, didn't seem to have a significant impact on the planted roofs' performance. All the green roofs examined, presented a similar picture regarding their summer surface temperatures both in "hot and humid" and "hot and dry" climates. The maximum temperature reductions, compared to the respective concrete roofs were of the magnitude of 21°C in the daytime and of 13°C in the nighttime for the 'hot and humid" climates. Similarly, for the "hot and dry" climates the maximum temperature decreases were of the magnitude of 24°C in the daytime and 14°C in the nighttime.
2. Equations were created with the aid of which green roofs surface temperatures could be predicted, if the respective concrete roofs' surface temperatures were known. With a satisfying level of accuracy, the equations $y = 0.1859 x + 21.435$ for the 'hot and humid" climates and $y = 0.2682 x + 15.701$ for the "hot and dry" climates could constitute a considerable means for a first estimation of the green roofs' surface temperatures.
3. Plants' Leaf Area Index (LAI) was found to be one of the most crucial ones regarding the reduction of green roofs' surface temperatures. The essential role of plants with high LAI values was detected to be the effective shading they provided to the roof. For instance, in Athens (hot and dry) green roofs with plants of LAI = 5, obtained during the day a maximum surface temperature of 24.8°C whereas roofs with plants of LAI = 2 obtained a maximum surface temperature of 26°C.
4. The role of moisture content of the green roofs' soil was investigated. After the respective figures' analysis it was found that the more humid the soil was, the lower the surface temperatures of the green roofs were. However, the green roofs' surface temperatures did not present a great fluctuation. The semi-extensive roofs that were examined, perhaps because of their restricted substrate thickness did not differentiated their surface temperatures whether their substrate layers were dry or wet.
5. Substrate thickness presented the least variation to the investigated surface temperatures. In the hot and dry climates, the thinner substrate layers were found to trap less heat and to be cooling down more easily at night. On the other hand, thicker substrate layers presented a noticeable time lag at reaching their highest surface temperatures, which occurred late in the afternoon when the high ambient air temperatures had already dropped. In the hot and humid climates, the performance of green roofs with different substrate layers was similar for all the studied thicknesses.

## 4. References

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