The thermal behaviour of extensive green roofs under low plant coverage conditions

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ABSTRACT

Green infrastructure for buildings, such as extensive green roofs, can improve the urban environment. Previous experimental studies confirm the benefits of these systems from different approaches; energy, hydraulics, materials, etc. But it is necessary to obtain data about its behaviour in real cases, where conditions could be very heterogeneous; different surface finish, low vegetation cover in first years, lack of maintenance, etc. In this article different aspects about this topic are discussed. Moreover, the results of monitoring a real extensive green roof during the first year after plantation in order to study the thermal behaviour are presented. In these conditions of low plant cover (10 %), the main conclusions refer to the substrate, which although it preserves cool near the base roof, it heated and cooled very quickly. This fact confirms the substrate limited thermal mass effect, due basically to its composition and small thickness. The material composition and the thickness of the substrate should be studied in depth because it can affect the thermal performance of the roof.

Keywords: Green infrastructure; extensive green roof; ecological roof; passive energy system; thermal behaviour; building.

1 Introduction

Green infrastructure can contribute significantly to improve the urban environment. In summer, absorption of heat by dark surfaces in urban areas, such as concrete rooftops and roads, contribute to the "urban heat island". Increasing vegetation cover within urban areas, for example, with green roofs and facades, can increase shading and the natural capacity of plants to cool the air by several degrees through evapotranspiration (European Commission Environment 2012).

At its most elemental, a green roof consists of introducing plants or seeds that grow in a medium on a roof (Snodgrass and Snodgrass, 2006). Everywhere in the world, examples of green roofs are becoming more and more frequent, usually on new and innovative buildings. New-style roof greening recognizes two main approaches, extensive and intensive systems (Dunnet and Kingsbury, 2008).

Extensive green roofs are not designed for public use and are mainly developed for aesthetic and ecological benefits. They are distinguished by being low cost, lightweight (50–150 kg/m2) and with thin mineral substrates of up to 100 mm. Minimal maintenance is required and inspection is performed 1–2 times per year. Plants selected tend to be of the low maintenance and self-generative type. Intensive green roofs are usually called 'roof gardens'. They involve a load of more than 150 kg/m2 and have more than 100 mm of substrate with a higher amount of organic material than extensive systems. They are developed so as to be accessible to people and are used as parks or building amenities. Hence, they usually incorporate areas of paving and seating. The added weight, higher capital cost, intensive planting, and higher maintenance requirements characterize intensive green roofs. Plant selection ranges from ornamental lawns, to shrubs, bushes and trees, consequently it affects the weight, build-up heights and costs of the roof garden. Moreover, further regular garden maintenance such as mowing, fertilizing, watering and weeding is required for intensive landscapes (Wong et al. 2007).

Both extensive and intensive green roofs require engineered systems to ensure proper functioning. Thus, while each green roof is unique, all share common components, including waterproofing, insulation, filtration, and drainage layers, some type of roof barrier, planting medium, and plant material. If any one of those elements is missing or fails, whether due to a roof leak or plant mortality caused by standing water, too little water, or inadequate medium, the green roof itself will ultimately fail (Snodgrass and Snodgrass, 2006).

Lately green roofs have been established all over the world as an important constructive solution that offers interesting advantages over conventional solutions, such as the reduction of surface runoff in large cities, the improvement of the urban environment, the support to biodiversity, the improvement of the durability of waterproofing materials, etc. This fact is especially important if its use as passive system for energy savings in buildings is taken into account. In this regard, it is know that green roofs can bring a cooling effect due to their capacity to provide shade and evapotranspiration by the plants, and moreover an insulation effect provided basically by the substrate layer.

Heat transmission through extensive green roofs or eco-roofs has been studied several times before, through experiments and through simulations. Experimental studies have included both field studies on working buildings and laboratory or special test buildings. Experiments, in general, use relatively short durations of data collection, typically less than 2 months. All studies, both experimental and simulation, have reported that eco-roofs reduce the heat transmission when compared to conventional roofs. The amount of energy reduction varies from a few percent to over 90%, indicating that performance depends on several factors, such as soil type, plant type, soil moisture, local climate, and season (Spolek, 2005).

Previous studies concluded that green roofs reduce the heat flow through the roof of the building, acting as insulation and by the cooling effect (Wong et al. 2007; Palomo del Barrio, 1998; Onmura et al. 2001; Theodosiou, 2001; Wong, 2003). Reviewing these studies, it can be noticed that the parameters that can influence this purpose can be grouped into three main areas corresponding to the layer of vegetation, to the substrate layer and, finally, to the climatic conditions. The most influential parameter on vegetation layer is the leaf area index (LAI), which depends basically on the foliage density, the foliage geometric characteristics and on the plant height. Thus, the most important contribution of the vegetation layer to the thermal behaviour is the shadow effect, both by the interception of solar radiation and reduction of roof surface temperatures. Regarding the substrate layer, it has been observed that the density and the thickness of this layer are two characteristics that influence the thermal behaviour. The substrate provides insulation capacity to the roof. Moreover, the moisture content of the substrate can influence the final thermal performance, both in terms of the transmission of heat through the substrate and the evapotranspiration potential from the substrate (cooling effect). Finally, the thermal behaviour of the green roof, particularly referring to the cooling effect, can be influenced by the climatic conditions, being the speed wind effect and the environment relative humidity the main parameters to consider. According to Jim and Peng (2012), cooling is attributed to the combined effect of evapotranspiration from soil and plants, shading by vegetation canopy, and thermal insulation by the substrate-drainage layers of the green roof system.

Among the parameters that influence the thermal performance of green roofs, it can be observed that those corresponding to the vegetation layer and climate conditions are highly variable, whereas those relating to the substrate layer are much more manageable from the design point of view, and moreover less variables along the roof whole life. So, vegetation cover (LAI) and consequently the ability to produce shade can become reduced in certain periods of the life of the extensive green roof, for example during the plant growth period, which can last up to two years, or in water shortage periods, disease, or even because the type of plants, etc. Also it is known that because the type of plants and the low maintenance levels, extensive green roofs hardly reach 100% of the vegetation cover.

For these reasons, special attention to the substrate layer thermal behaviour must be done in order to ensure the extensive good thermal operation under low plant cover situations. Regarding to this idea, some studies already have been conducted in order to study the improvement of the abiotic layers of green roofs (Jim and Tsang, 2011; Pérez et al. 2012; Vila et al. 2012). However, in these studies different types of substrates were used. The composition of growing medium or substrate will ensure good moisture retention capacity as well as aeration to the roots of the plants. But, there is not an universal composition and usually green roof companies supply their own substrate formulations, which may be tailored for different vegetation types, or for to be used on different types of green roofs (Dunnett and Kingsbury, 2008). This fact implies that the thermal behaviour of the green roof can vary for every different project.

On the other hand, some studies suggest that green roofs may have limited benefits in their role as a cooling device for the building. Results have shown that the contribution of green roofs to the cooling of buildings is due mainly to the shading of the roof provided by the plants and not necessarily to evaporation. This is because the process of transpiration takes place in the plants' leaves rather than in the soil, drawing energy from the environment and not directly from the soil-covered building. In addition, a thick layer of saturated air may form under the plant canopy, inhibiting evaporation from the soil substrate (Pearlmutter and Rosenfeld, 2008).

Fioretti et al. (2010) emphasizes the importance of working with full experimental case studies to complement the theoretical advances, often validated by scarce experimental data. These researches allow obtaining quantitative data on the operation of these construction systems and consequently to create a database, that can be useful for the future to move towards a more sustainable construction.

According to Theodosiu (2003), insulation layers strangle the heat flow and in consequence the cooling and insulation effects provided by green roofs. These insulation layers are required by law in real projects.

Another fact to take into account is that usually in real projects the roof surface is finished with different types of materials, therefore their thermal behaviour can vary in the different areas of the roof. For instance, there are lots of projects which include areas of transit and stay with one type of finish (gravel, tiles, etc.), and on the other hand, areas of vegetation that are not usually passable (sedum sp, delosperma sp, etc).

According to these considerations, in the present study an extensive green roof placed on an office building has been monitored during the first year after the roof construction, when plants were in the growth phase. This 2000 m^2 extensive green roof is a part of a renovation project located in the Gardeny Science and Technology Park in the city of Lleida (Spain) (Project. Agrifood Technological Science Center, Lleida 2009). This type of extensive green roof, commercial type "ecological roof" (Intemper) (Figure 1), was designed in 1994 by that company with the aim of adapting the concept of green roof to the climate of the Iberian Peninsula, which is characterized by low rainfall. There are two outstanding features of extensive green roofs, the first is the use of native species that are well adapted to local climatic conditions and the second is the low maintenance. The plants are aided by a cistern, which allows rainwater that falls on the roof to be collected, which is made available to the plants by capillary action using geotextile felt that hangs down into the cistern between the joints of the roof surface (Machado et al. 2001; Neila et al. 2008).

The main objective of this study is to obtain data about the whole thermal behaviour of an extensive green roof in real conditions, during the first year after its implementation, paying special attention to the substrate layer since it will be exposed due to the lack of plant coverage.

2 Methodology

The construction of this extensive green roof took place in 2009, during the renovation project of a building in the Gardeny Science and Technology Park in Lleida (Spain) (Project. Agrifood Technological Science Center, Lleida 2009).

The green roof consists of two different types of surfaces, not passable vegetation areas and pedestrian areas finished with gravel (Figure 2). In gravel areas, the vegetation and the substrate layers are replaced by a single gravel layer (8 cm).

Table 1 summarizes the parameters that were recorded at each area. Figure 3 and Figure 4 show the location of the different sensors in section for the two types of finish layer, with vegetation and with gravel.

Data were recorded every five minutes during the whole year 2010 for each parameter, from which the presented figures were drawn. Thus, in the graphics the evolution of every parameter throughout the year can be observed. As the studied parameters showed different thermal behaviour on summer in reference to winter period, but no differences were observed during each period, to show the results a representative week of the summer 2010 and one representative week of winter 2010 were selected. During the data collection indoor offices weren't operating, thus temperature and humidity indoors values reflect the true value without any conditioning (heating or air conditioning).

Species used in this project are sedum type, which are well adapted to the climate of the area. In percentage, the species planted were on one hand 40% Sedum album, Sedum rupestre, and Sedum moranense. On the other hand, the 60% remaining were a mixture of Sedum spurium atropurpureum, Sedum sediforme, Sedum acre, and Sedum album coral carpet. When data were recorded, vegetation cover was less than 10%, since the planting took place in 2009 and in 2010 and consequently plants were in the growth phase. The substrate used in this project was compounded by the mix of mulch, made from decomposition and fermentation of various plant materials, coconut fibres, and fine recycled particles of gravel. The percentage of organic matter was 40%, and 60% of mineral matter.

The area of study (Lleida, Spain) has a climate classified as Dry Mediterranean Continental, characterized by its great seasonal variations. It has low rainfall, that is divided in two seasons, spring and autumn and it has a thermometric regime with large differences between a long winter (between the spring and the last frost may take more than 160 days) and a very hot summer. The average annual rainfall is between 350-550 mm, and the mean annual temperatures oscillate between 12-14 ºC, with thermal amplitudes of 17-20 ºC. A special mention must be made to the fog, typical of the region in the months of November, December and January that can give a period of up to 55 days in the absence of sunlight.

3 Results and discussion

3.1 Temperatures

3.1.1 Summer conditions

Figure 5 shows the evolution of temperatures at 30 cm above the substrate surface for a representative week of summer 2010. During the whole summer, no significant differences between the temperatures at 30 cm height from the gravel area and the green area (10% plant cover) were observed.

This fact implies that extensive green roofs with low vegetation coverage will have a limited effect on the surrounding environment, and therefore on the heat island effect mitigation.

Figure 6 shows the temperatures evolution, at 5 cm above the roof surface, for the same summer week.

As it can be observed, these temperatures are slightly higher in the area of gravel, especially in the middle of the day. This behaviour stayed the same all summer long, possibly due to the evapotranspiration from the substrate and from plants. However, the low water content in the substrate and the low contribution from plants means that the cooling effect was very limited, and was not detected at 30 cm (Figure 5).

In Figure 7 the evolution of the temperatures at -2 cm depth below the surface in the green area is shown. Here the surface of the substrate gets very hot, reaching close to 60 °C. Also noteworthy the thermal behaviour of the substrate, which gains heat quickly during the morning, but then rapidly, loses this heat during the rest of the day.

Figure 8 shows the evolution of the temperature at -4 cm depth below the surface. It can be seen that the gravel area reaches higher temperatures at noon than green area (substrate). Moreover, the oscillation is large in the gravel area. These two facts mean that gravels store more heat than substrate and also that gravels release this heat more slowly into the atmosphere than substrate.

Finally, Figure 9 presents the temperatures at -8 cm depth. Although temperatures are slightly higher in the gravel area, this difference is lower than at -4 cm depth. This behaviour is the same throughout the summer. In addition substrate shows the same behaviour as before; it is heated and cooled more quickly than gravels.

Figure 10 summarizes the temperature evolution along the green area profile (substrate) during a summer week. Due to the position of the insulating layer just below the substrate layer, temperatures in lower positions remain very stable (cistern temperatures, indoor temperatures), therefore here only inside temperatures are shown. It must be taking into account that during the year 2010 the building was not operational and therefore, the indoor temperature was the temperature without conditioning. Two main facts can be pointed out from the results showed in Figure 10. First, the fact that even though the surface heats up high and rapid, because of the lower plant cover, it can be observed that such surface heating do not cause a considerable temperature rise under the substrate layers, so that substrate layer preserves coolness near the base roof. The same results were observed in previous experimental studies by Teemusk and Mander, (2010). The second interesting fact about the substrate behaviour is that substrate is heated and cooled very quickly which confirm its limited mass effect due to their composition and small thickness. This behaviour is similar than the found in similar to another research (Jim and Peng, 2012).

Due to this behaviour, the insulation ability of the substrate layer should be questioned. Consequently future studies, specially focused on substrate thickness and composition, must be done.

3.1.2 Winter conditions

Figure 11 and Figure 12 show the temperature evolution, at 30 cm and 5 cm above the roof surface, for a winter week of 2010. Similarly to what happened in summer (Figures 5 and 6), now winter air temperatures above the roof surface are between 1 ºC to 3 ºC lower in the green area (substrate) than in the gravel area, specially at 5 cm from roof surface. Thus, it can be confirmed that this behaviour is maintained for almost every month of the year. Given the low plant cover and considering the presence of constant soil moisture contend (see section 3.2. Water content of the substrate), those differences can only be explained by the effect of evaporation from the substrate. This results differ from the results of others experimental studies (Jim and Peng, 2012), in which it is stated that air temperature above the surface of the green roof shows little variation between different soil moisture states, and their correlations with substrate moisture are insignificant.

Figure 13 shows the temperature at -2 cm below the surface in the green area (substrate, 10% plant cover) which presents the same substrate behaviour as in summer, so that it heated rapidly and then lost temperature rapidly.

In Figures 14 and 15, the temperatures at -4 cm and at -8 cm depth below the surface for a representative week of winter 2010 are shown. As happens in summer, gravel reaches highest temperatures, being this fact more evident at -4 cm depth than at -8 cm depth.

Figure16 presents the temperature profile in the green area for a winter week 2010. Unlike in summer, now the substrate temperature is lower in all depths than the outside temperature (30 cm), being more uniform throughout the profile than in summer. Cistern temperatures and superficial indoor temperature are not shown here because the insulation layer intercepts the heat flux, and there is no remarkable change below this layer. However, indoor temperatures are shown. This temperature remains fairly stable. As at that time the office building was empty, this temperature shows the real temperature without heating.

In general it is found that the thermal behaviour at different heights was similar for summer and winter, although there were big differences for the temperature values reached. This behaviour is constant along the year because the substrate is constantly wet in this kind of green roof and, although the substrate moisture level is low, it is enough to keep fresh the bottom of the substrate layer, and to provide a slight evapotranspiration that result on lower temperatures at 5 cm above green areas than on gravel areas.

3.2 Water content of the substrate

Figure 17 and Figure 18 show the water content of the substrate (%) in a week in summer and winter, respectively. The volumetric water content of the substrate (%) was fairly stable throughout all year, ranging from 10% to 15% at -8 cm depth and from 8% to 13% at -4 cm position in winter. In summer, variations were from 5% to 6% at -8 cm depth and 4% to 5% at -4 cm depth. This percentage depends on the capacity of water to ascend to the substrate by capillary through the geotextile felt from the cistern, and of course on the availability of water in the cistern. In order to avoid long water scarcity periods in this roof, an automatic system which injects water into the cistern was installed by the maintenance company. This is the reason why the water content in the substrate remains more or less constant with time. However, according to technical recommendations the maximum water capacity of vegetation substrates for single layer construction extensive greening in their compacted or installed state must to be ≥ 20% vol. (FLL The Landscape Development and Landscaping Research Society 2008). Thus, the substrate water content could be higher in this case study, with the added advantages that it would mean. On the one hand, plants could have more water for growth, and on the other hand, the potential for evapotranspiration would also be higher and consequently the cooler effect as well.

In addition, although evapotranspiration from the substrate was not measured, it can be observed that there is a direct relationship between the low water contents with the high temperatures reached, especially in summer (Figure 10). Thus, having low plant cover (shadow effect) influences directly not only over the thermal behaviour of the substrate but the water content available for plants as well.

3.3 Relative humidity of the atmosphere

For the relative humidity of the atmosphere near the surface of the roof, no significant differences between the gravel area and the green area were found at 30 cm above the roof surface. At 5 cm above the roof a slight variations were found. In summer (Figure 19) the relative humidity at 5 cm above the surface was almost the same in both areas and only at noon was marginally bigger in the gravel area. In winter (Figure 20), at 5 cm, relative humidity daily fluctuations were lower (between 5 to 10 %) on the green area than on the gravel area, especially during the nigh period.

4 Conclusions

In this paper the need to obtain data on the behaviour of extensive green roofs in real cases where conditions could be very heterogeneous, such as different surface finish, low vegetation cover in first years, lack of maintenance, etc., is discussed. Moreover, a real extensive green roof with two different surface finish (gravel and green) has been monitored during the first year after the roof construction, in order to study the thermal behaviour (substrate layer specially) when the plants are in a growth phase (10 % plant surface cover).

The main conclusions of this research are:

- Air temperatures above the surface of the green area both, at 30 cm and 5 cm, were confirmed to be slightly lower than on the gravel area, through all the year. Given the low plant cover (10 %) this observation may be due to water evaporation from the substrate, this fact differs with similar studies (Pearlmutter and Rosenfeld, 2008) that stated insignificant correlation between substrate moisture and nearby air temperatures.

- Referring to the substrate behaviour, although it preserves a cool temperature near the base roof substrate, their quick heating and cooling confirm a limited mass effect due to its composition and small thickness. This fact is similar to previous studies.
- No significant differences for the relative humidity above the roof surface were found. Neither in green area nor in gravels area.

In general, it can be pointed that:

- Situations with low plant cover should be kept in mind. Where the plants provide little shade the thermal performance of the roof depends on the thermal characteristics of the lower layers, especially the substrate.
- In real projects the positive effect of green roofs can be masked by the insulation layer effect, mandatory by legislation. Therefore it is necessary to move towards more sustainable green roof constructive solutions that consider reducing insulating layers.

For further studies, the material composition and the thickness of the substrate should be studied in depth because it can affect the thermal performance of the roof, especially under low cover situations. Moreover, it would be of great interest to compare the extensive green roof thermal performance with different cover degrees.

5 Acknowledgements

The work was partially funded by the Spanish government (ENE2011-28269-C03-02 and ENE2011-28269-C03-03) and the European Union (COST Action COST TU0802), in collaboration with Gardeny Science and Technology Park in Lleida (Spain). The authors would like to thank the architect Josep Maria Puigdemasa his provision of information about the renovation project. The authors would like to thank the Catalan Government for the quality accreditation given to their research group (2009 SGR 534).

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Figure captions

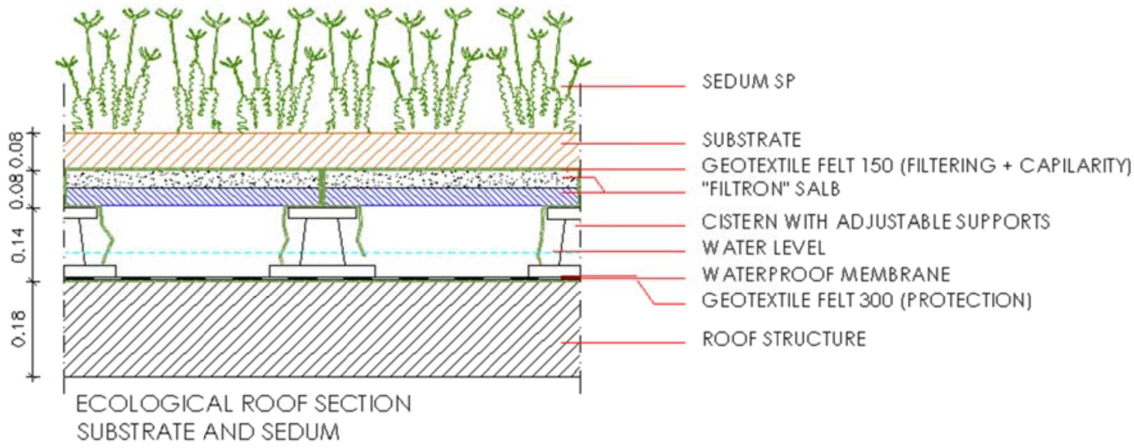

Fig.1 Green roof section in a vegetated area finish

Fig.2 Partial view of Gardeny extensive green roof. Green and gravel areas

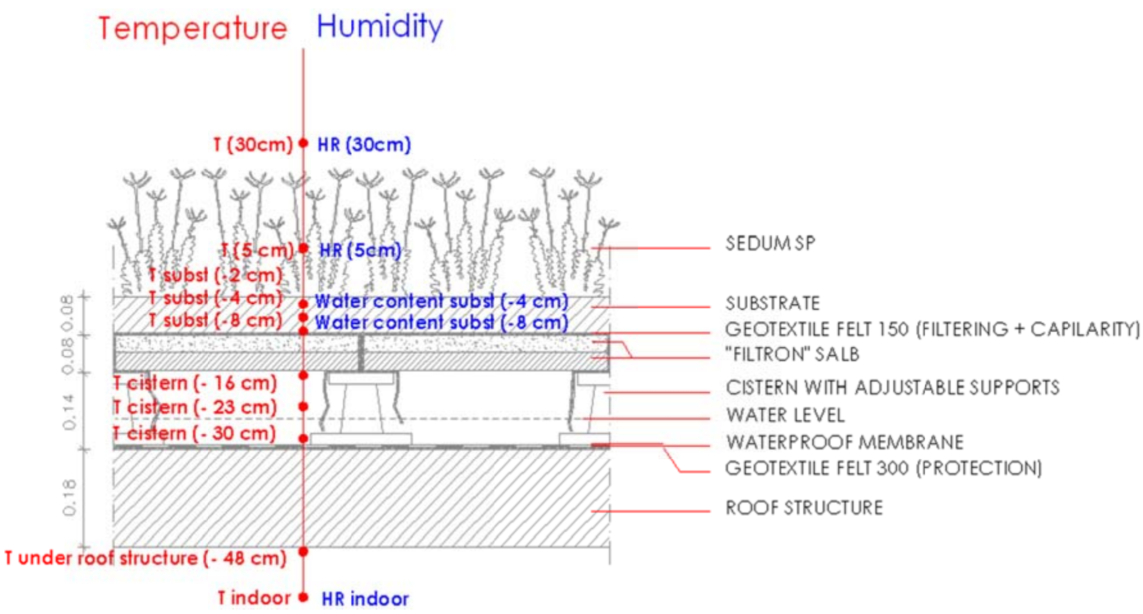

Fig.3 Recorded parameters in a green area

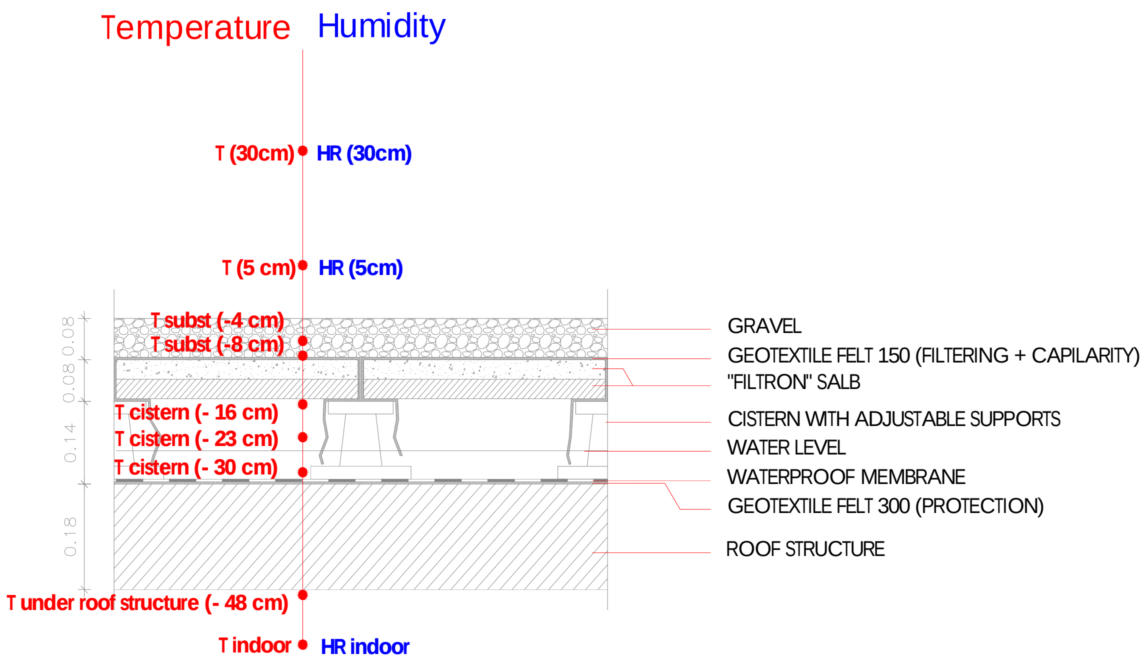

Fig.4 Recorded parameters in a gravel area

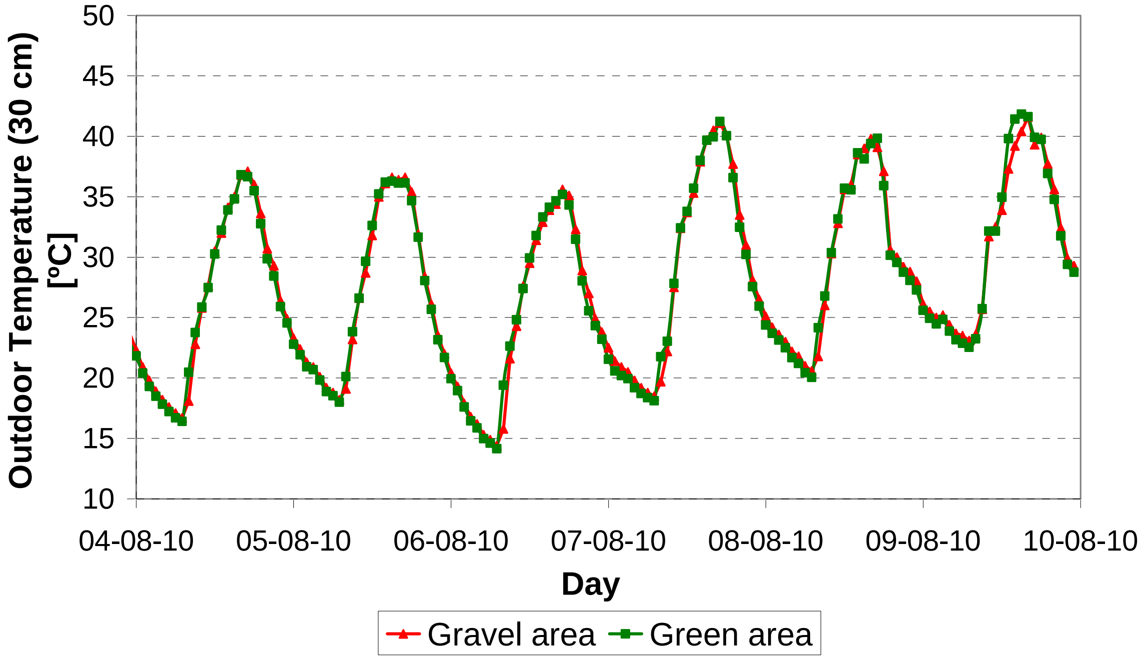

Fig.5 Outdoor temperature at 30 cm over the substrate surface. Summer time

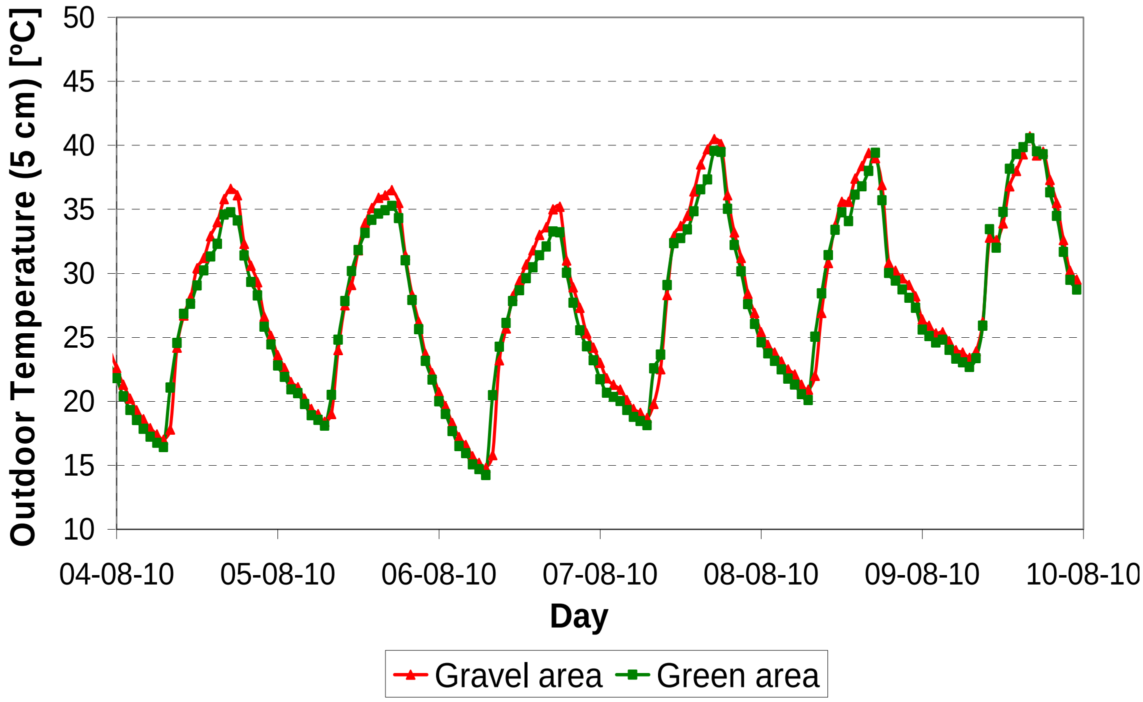

Fig.6 Outdoor temperature at 5 cm over the substrate surface. Summer time

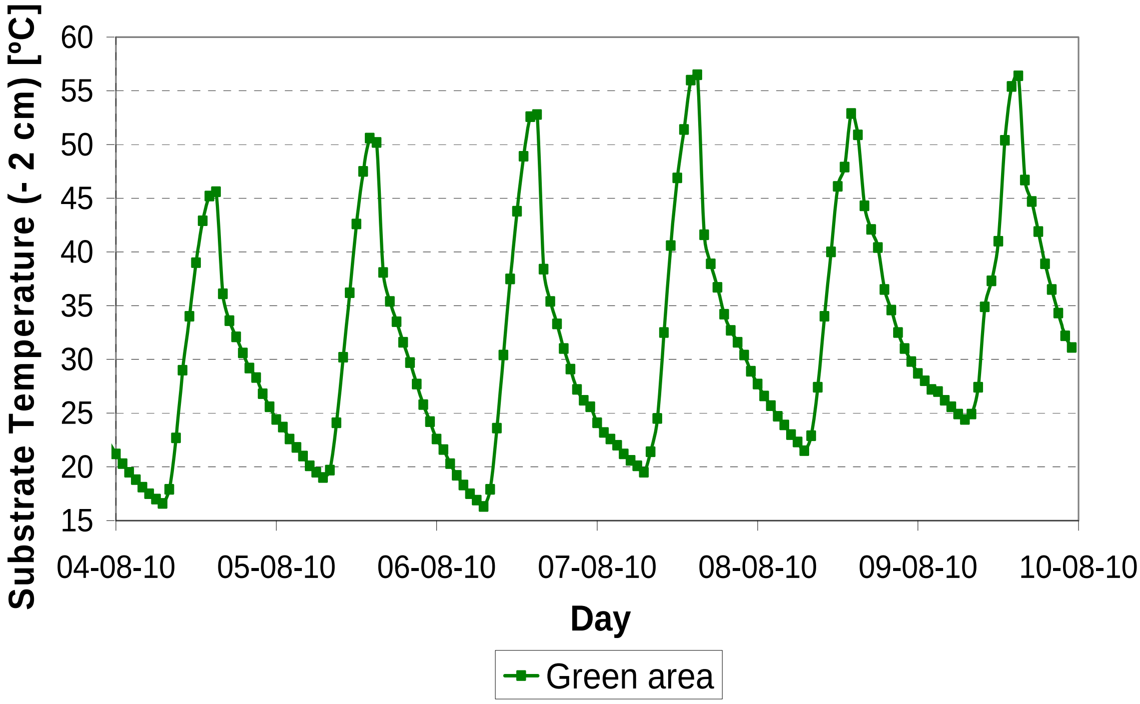

Fig.7 Substrate temperature at 2 cm below the substrate surface. Summer time

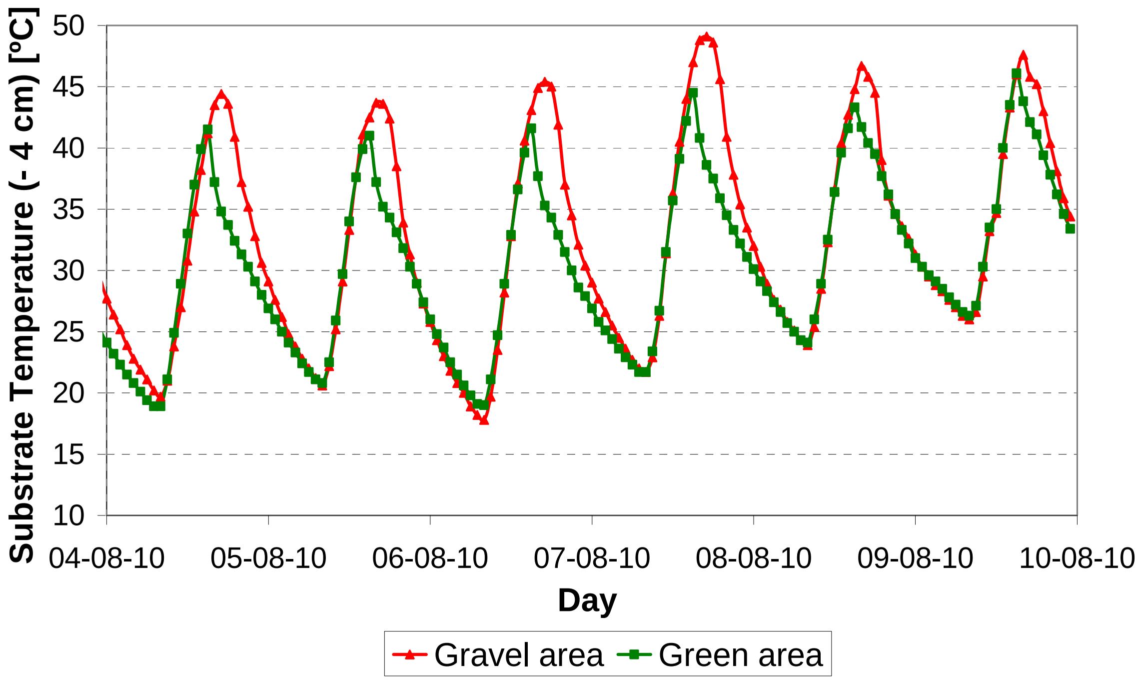

Fig.8 Substrate temperature at 4 cm below the substrate surface. Summer time

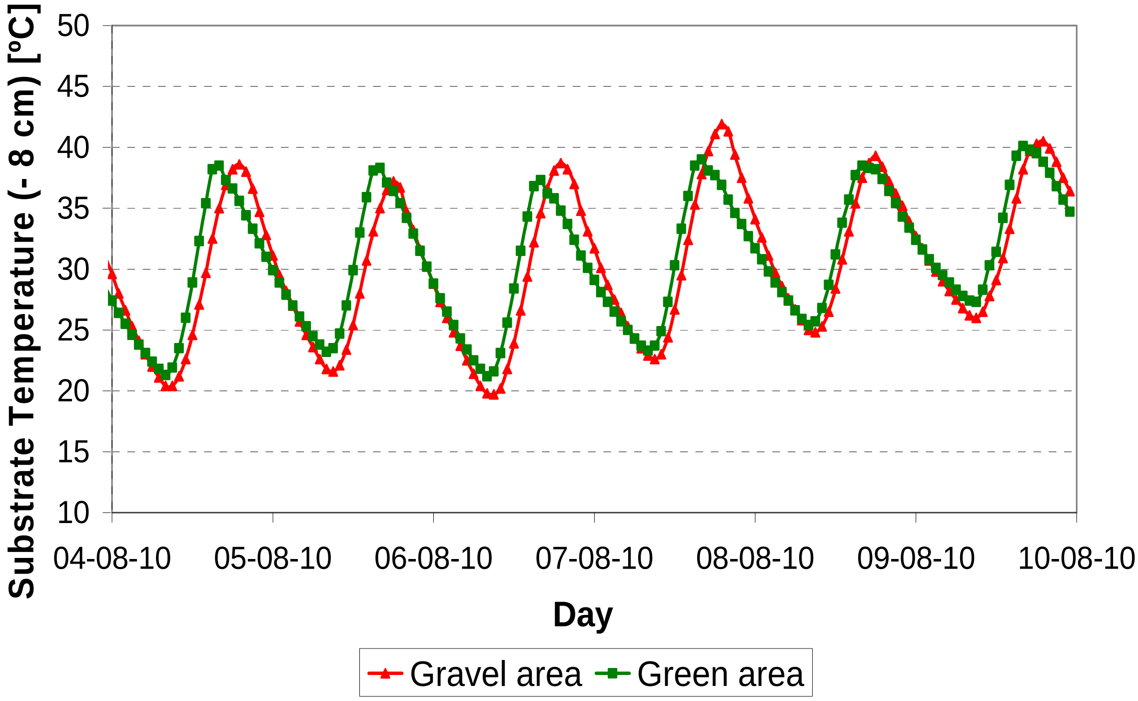

Fig.9 Substrate temperature at 8 cm below the substrate surface. Summer time

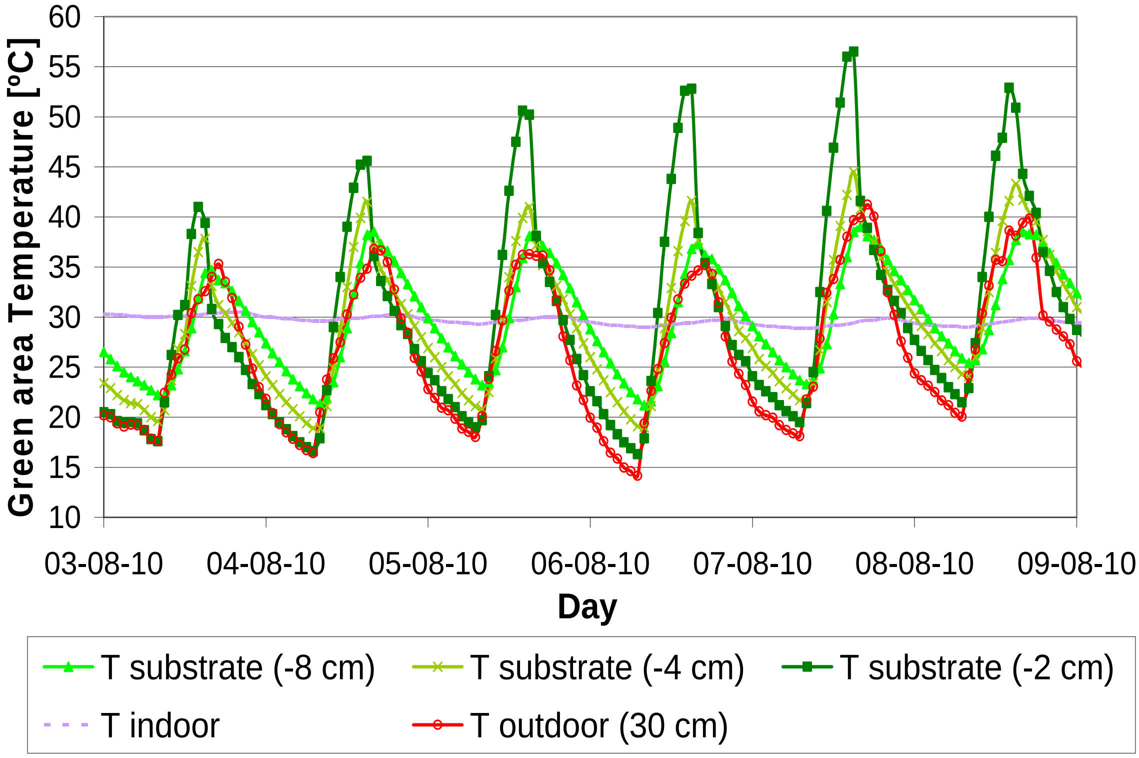

Fig.10 Green area temperatures. Summer time

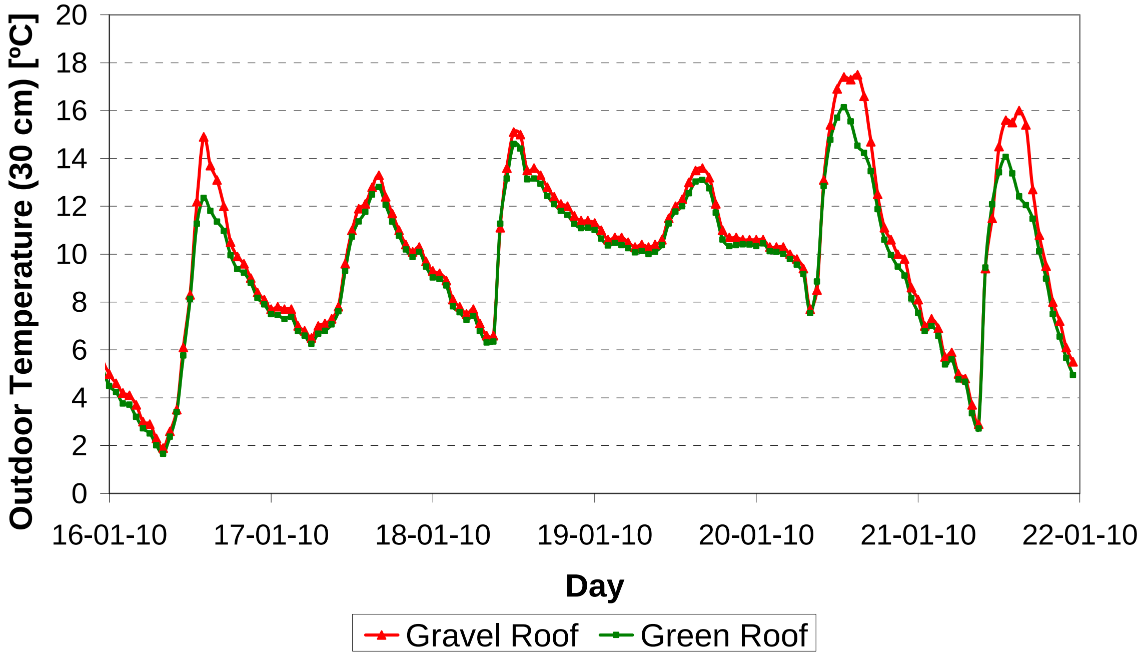

Fig.11 Outdoor temperature at 30 cm over the substrate surface. Winter time

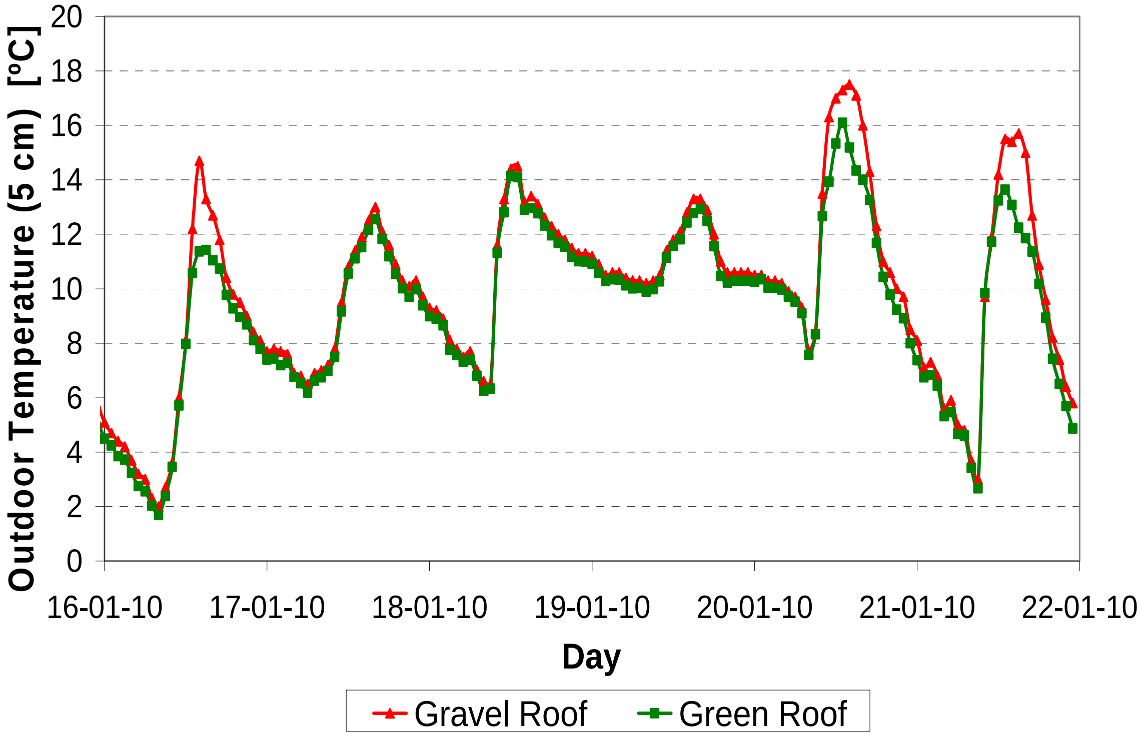

Fig.12 Outdoor temperature at 5 cm over the substrate surface. Winter time

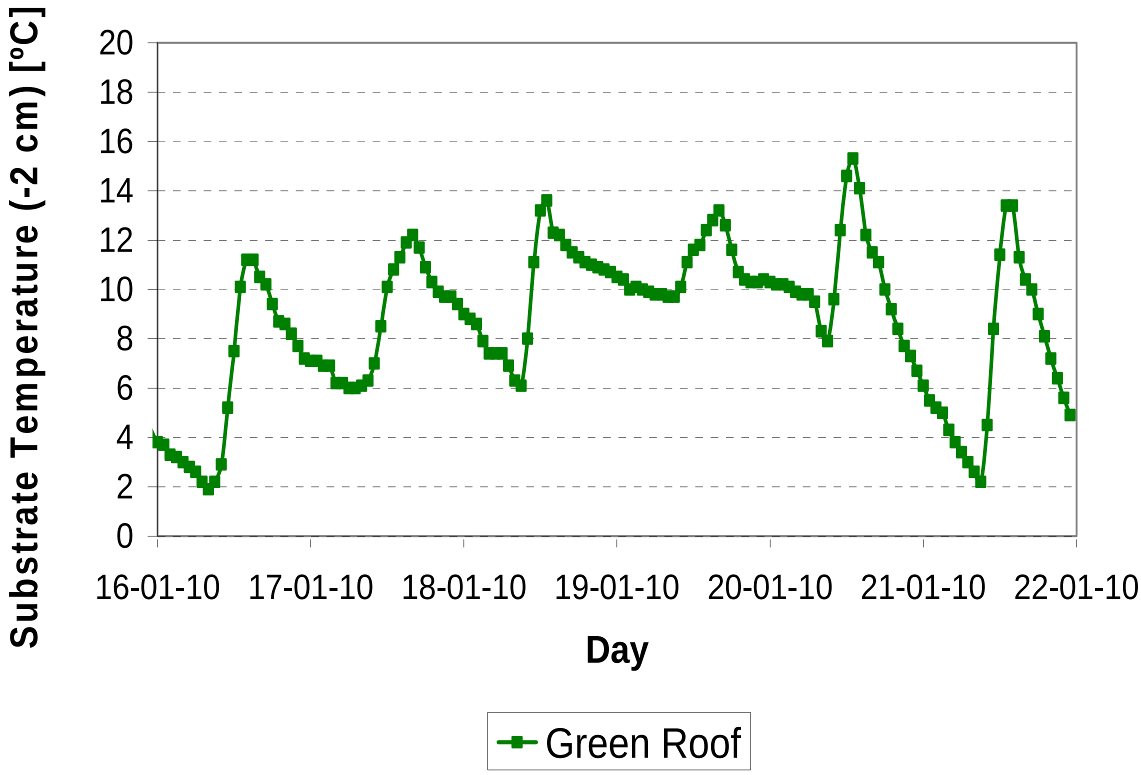

Fig.13 Substrate temperature at 2 cm below the substrate surface. Winter time

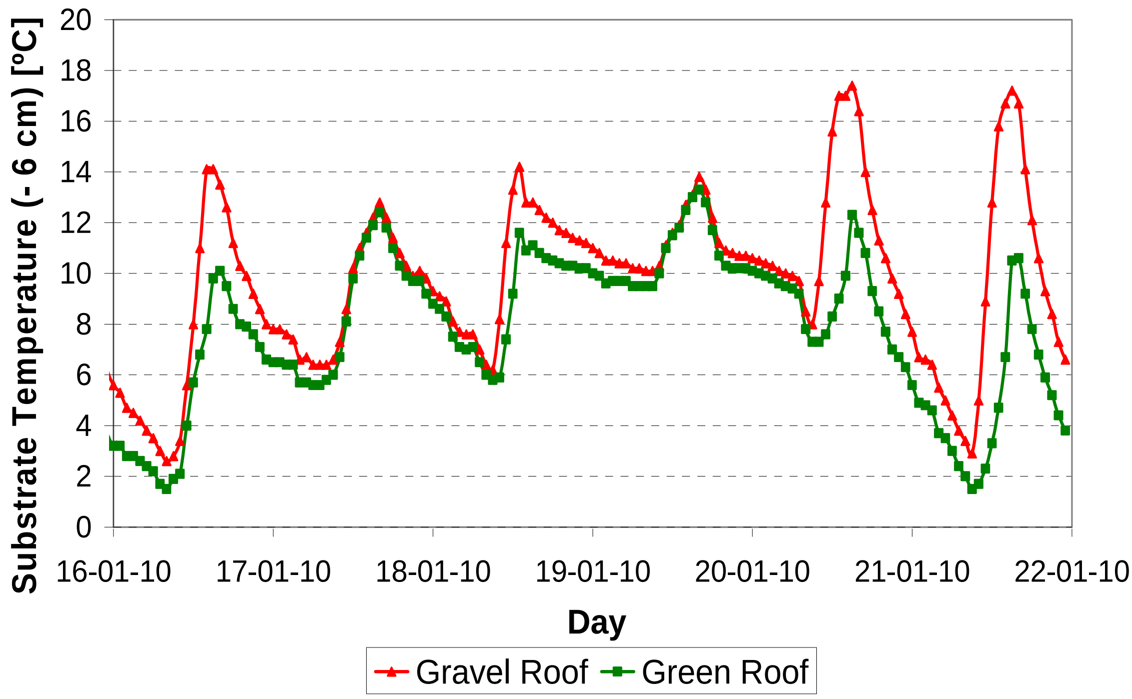

Fig.14 Substrate temperature at 4 cm below the substrate surface. Winter time

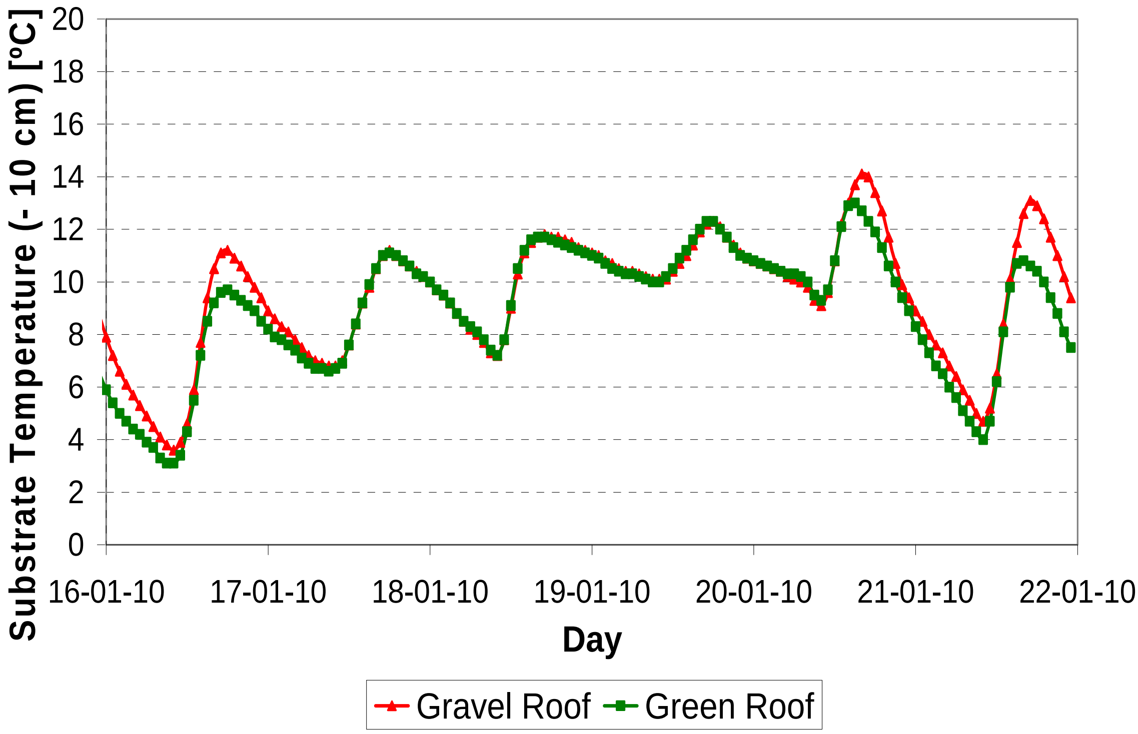

Fig.15 Substrate temperature at 8 cm below the substrate surface. Winter time

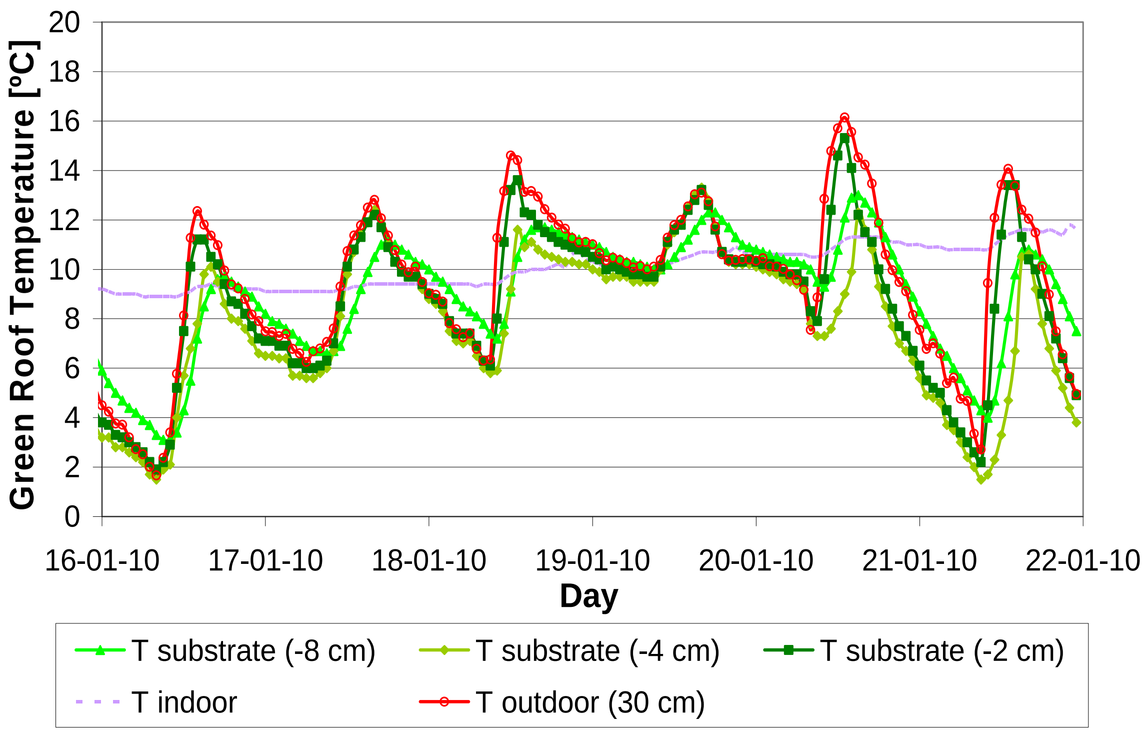

Fig.16 Green area temperatures. Winter time

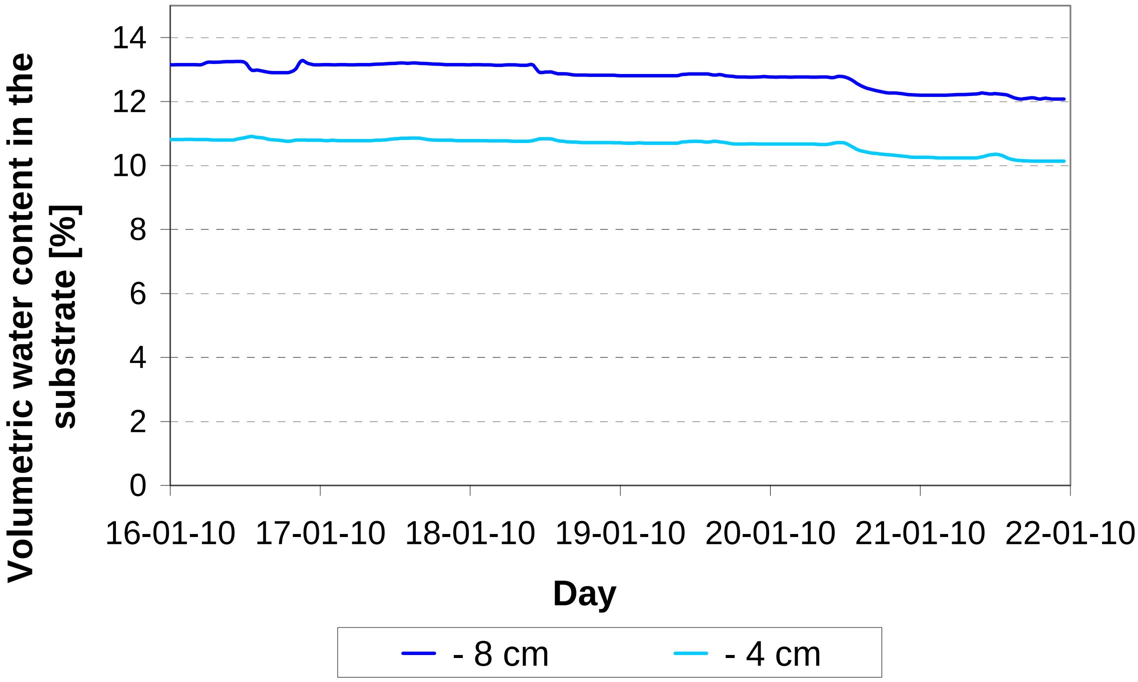

Fig.17 Volumetric water content in the substrate. Winter time

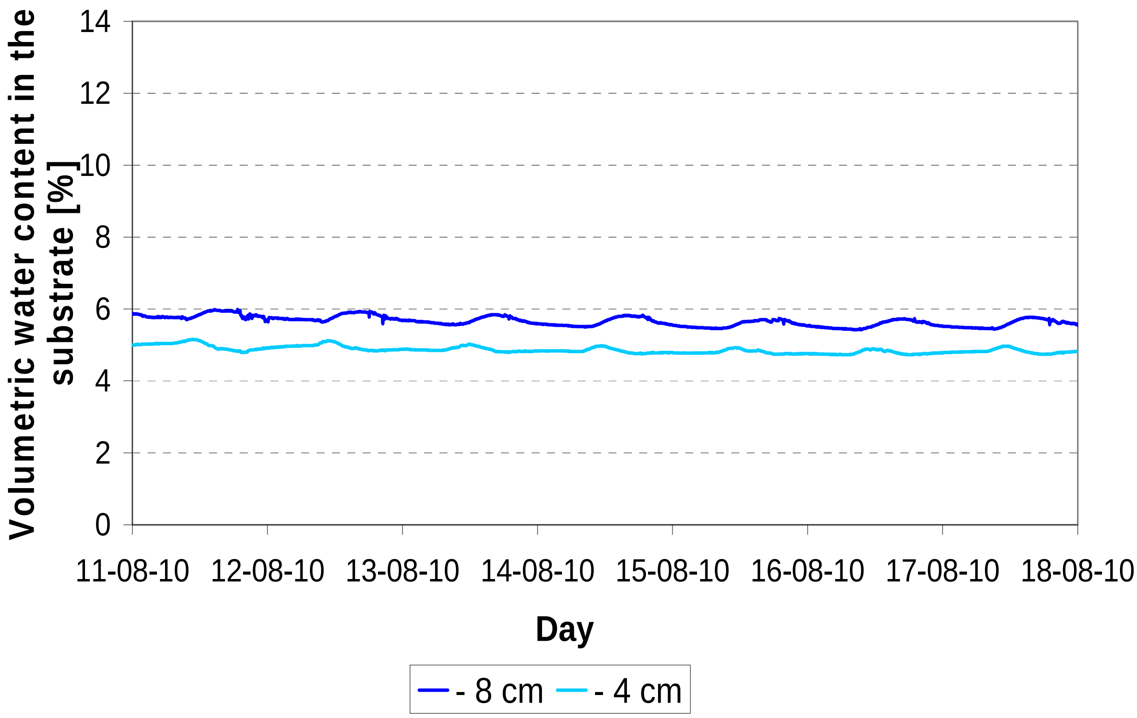

Fig.18 Volumetric water content in the substrate. Summer time

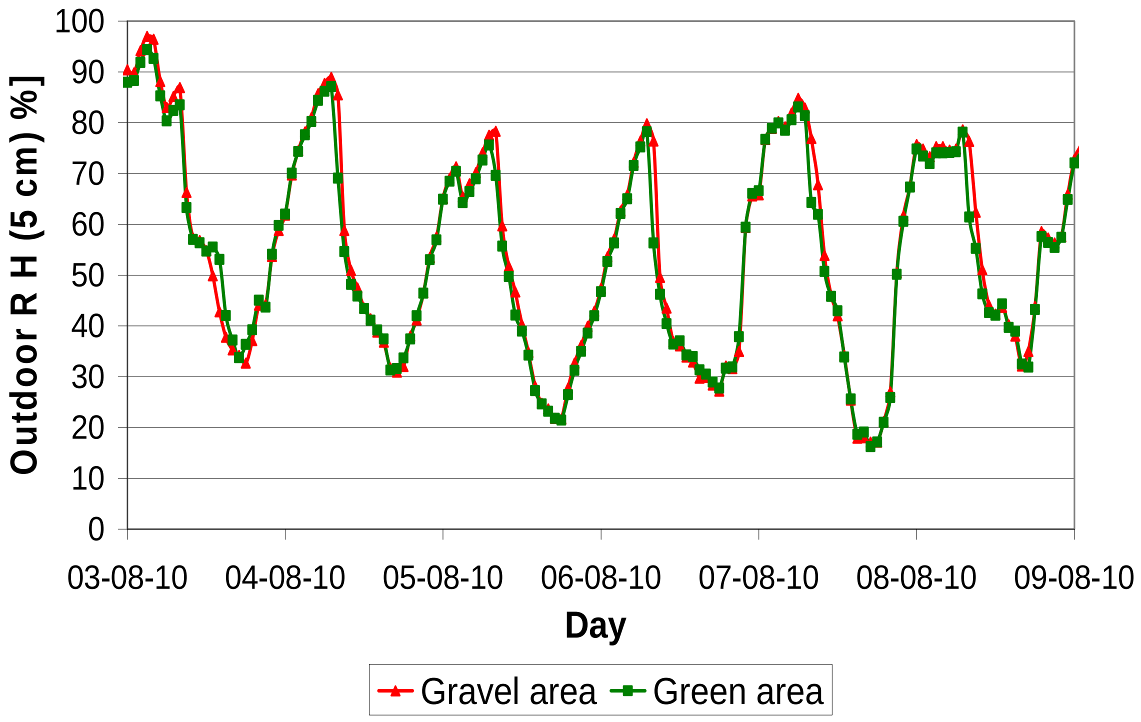

Fig.19 Outdoor relative humidity at 5 cm over the substrate surface. Summer time

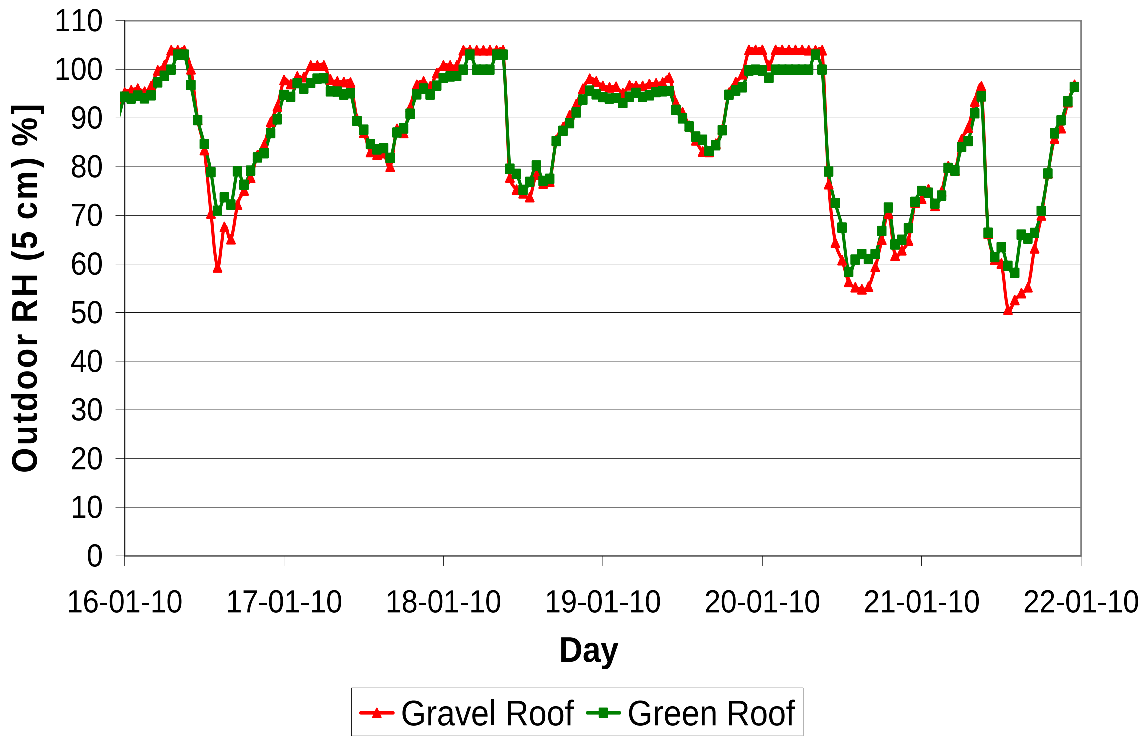

Fig.20 Outdoor relative humidity at 5 cm over the substrate surface. Winter time

Table captions

Table.1 Recorded parameters

Parameter	Unit	Instrumentation	Recording point	
			Green area	Gravel area
Outdoor temperature at 30 cm over the substrate surface	ºC	Testo 6651	Yes	Yes
Outdoor temperature at 5 cm over the substrate surface	ºC	Testo 6651	Yes	Yes
Substrate temperature at 2 cm below the substrate surface	ºC	Temperature sensor PT-100	Yes	No
Substrate temperature at 4 cm below the substrate surface	ºC	Temperature sensor PT-100	Yes	Yes
Substrate temperature at 8 cm below the substrate surface	ºC	Temperature sensor PT-100	Yes	Yes
Cistern temperature at 16 cm below the substrate surface	ºC	Temperature sensor PT-100	Yes	Yes
Cistern temperature at 23 cm below the substrate surface	ºC	Temperature sensor PT-100	Yes	Yes
Cistern temperature at 30 cm below the substrate surface	ºC	Temperature sensor PT-100	Yes	Yes
Under roof structure temperature at 48 cm below the substrate surface	ºC	Surface temperature sensor GE9020 0000 000004	Yes	Yes
Indoor temperature	ºC	Testo 6651	Yes	Yes
Relative Humidity 30 cm over the substrate surface	%	Testo 6651	Yes	Yes
Relative Humidity 5 cm over the substrate surface	%	Testo 6651	Yes	Yes
Indoor Relative Humidity	%	Testo 6651	Yes	Yes
Volumetric water content in the substrate at 4 cm below the substrate surface	%	Water soil content ECH2O EA-10	Yes	No
Volumetric water content in the substrate at 8 cm below the substrate surface	%	Water soil content ECH2O EA-10	Yes	No
Water level in the cistern	cm	Water level (buoy valve)	*	*

* The water level was installed in the gravel area because it was easier to install it there than in an vegetated area