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Experimental measurements and numerical model for the summer performance assessment of extensive green roofs in a Mediterranean coastal climate

F. Olivieri [a,*], C. Di Perna [b], M. D'Orazio [c], L. Olivieri [d], J. Neila [a]

[a] Department of Construction and Technology in Architecture, Escuela Técnica Superior de Arquitectura, Universidad Politécnica de Madrid, Av. de Juan de Herrera 4, 28040 Madrid, Spain
[b] Industrial Engineering and Mathematical Sciences Department, Faculty of Engineering, Università Politecnica delle Marche, Via Brecce Bianche, 60131 Ancona, Italy
[c] Construction, Civil Engineering and Architecture Department, Faculty of Engineering, Università Politecnica delle Marche, Via Brecce Bianche, 60131 Ancona, Italy
[d] Instituto de Energía Solar, Universidad Politécnica de Madrid, Av. Complutense 30, 28040 Madrid, Spain

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ABSTRACT

This paper presents the results of an experimental study carried out on an extensive green roof situated in a Mediterranean coastal climate zone. The aim of the study is to analyze the thermal energy behavior of a green roof during the summer so as to evaluate the effect of vegetation density on the energy performance of the roof and to identify the characteristics of the plants and substrate that have the greatest impact. The paper describes the results of monitoring carried out during the summer in 2010, 2011 and 2012, the development of a numerical model for calculating the thermal resistance of the substrate and the vegetation and the procedure for validating the model using the experimental data. The results show that a green roof which has high vegetation density acts as a passive cooling system when the roof is highly insulated (U value = 0.24 W/(m^2 K)) and that in these conditions the incoming thermal gain is about 60% lower than when the roof has no vegetation.

1. Introduction

Although green roofs have been used for a very long time it is only during the last twenty years that there has been an increasing interest in their energy and environmental benefits, both for the urban area [1–7] as a whole and for the building itself [8–14]. In fact in recent years many studies have dealt with these aspects from both the qualitative and the quantitative point of view, even if the complexity of the phenomena associated with the thermo-physical behavior of green roofs has meant that no model for analysis which can easily be integrated in the building design process has yet been developed. For this reason, although green roof technology is well-established [15,16] and the cost of many extensive green roof solutions is competitive if compared with other types of roofing [17,18], in many countries green roofs have still not seen widespread use. Above all green surfaces integrated into architectural designs have not yet been regulated by legislation, and no incentives are available for these solutions [19–22]. Many studies concerning the energy effectiveness of green roofs are based on the development of complex mathematical models [23–26] which involve an understanding of the characteristics of the vegetation and the substrate [27–30]. Generally this goes beyond the know-how of most architects. Moreover, these studies analyze the instantaneous performance of the solution without focusing on its overall seasonal heat balance, although this factor is of great use when a green roof is proposed as an energy efficient solution. On the contrary, research which is based on the observation of monitoring data often refers to short periods of analysis and the results obtained, although of great interest for understanding the behavior of the type of roof analyzed, are difficult to extrapolate for other contexts and for other solutions. Furthermore, in most studies the green roof is considered as a single unit made up of plants and substrate and is always studied when there is the greatest density of vegetation, without bearing in mind that, unless it is a pre-vegetated green roof system, the vegetation takes time to develop after being installed and that the plants may die and the roof may have no vegetation for a certain period of time.

Therefore, the aims of this work are (a) to analyze the impact of vegetation density on the energy performance of a green roof

* Corresponding author. Tel.: +34 913364239; fax: +34 913366560.
E-mail addresses: francesca.olivieri@upm.es, francesca.olivieri.arch@gmail.com (F. Olivieri).

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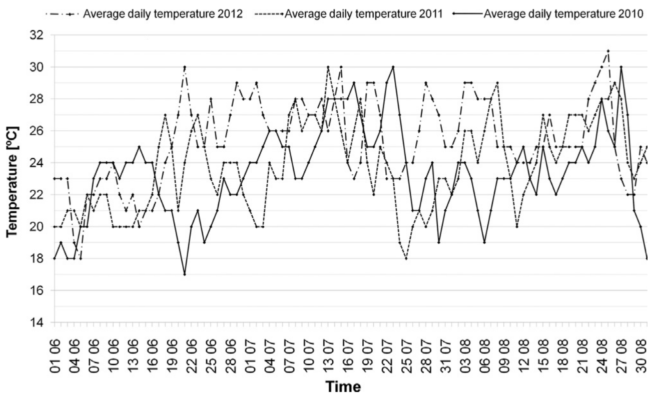

Fig. 1. Comparison between the summertime average daily temperatures in 2010, 2011 and 2012.

by monitoring the surface temperatures and the thermal fluxes through a roof in three periods of time characterized by similar climate conditions but by a different degree of vegetation density; (b) to develop a simplified numerical model which allows equivalent thermal resistance values to be obtained for the substrate and the vegetation and which is valid during the summer for extensive highly insulated green roofs situated in Mediterranean coastal climate zones. The model is based on a sensitivity analysis using the Eco roof routine of the Energy Plus software program developed by D.J. Sailor [31], which has proved to be valid in many experimental studies [31,32]; and (c) to validate the numerical model using the experimental data obtained by monitoring an extensive green roof [33] situated in a Mediterranean coastal climate zone.

2. Materials and methods

2.1. Local climate conditions

Monitoring was carried out on a real-scale experimental building in Agugliano, which is a town about 15 km south-west of Ancona. The three periods analyzed were the months of June, July and August in 2010, 2011 and 2012.

As shown in Table 1, the summer in 2012 was characterized by significantly higher temperatures than those recorded in 2011 and 2010. In 2012 on 63% of the days the average daily temperature was higher than 24 °C (297.15 K) and for 20% of the period was more than 28 °C (301.15 K); in 2011 and 2010 there were considerably fewer days with average temperatures of over 24 °C (297.15 K) (40% in 2011 and 31% in 2010), and in both years temperatures of over 28 °C (301.15 K) were recorded on only 5% of the days. In the latter summers the average temperature was lower than 22 °C (295.15 K) for about 25% of the period, while in 2012 this occurred only on 6% of the days (Fig. 1).

The maximum temperatures are higher than 30 °C (303.15 K) for 40% of the period in 2012, while the percentage goes down to 23% and to 16% in 2011 and 2010, respectively. During the latter summers the daily maximum temperature does not reach 26 °C on, respectively, 26 and 23% of the days. This happens on only 5% of the days in 2012.

The minimum daily temperatures found during the three summer periods are below 18 °C (291.15 K), on 43% of the days in 2010, on 34% of the days in 2011 and only on 23% of the days in 2012. During the summer in 2012 the minimum daily temperature does not go below 20 °C (293.15 K) on 40% of the days, with peaks of 26 °C (299.15 K) and 27 °C (300.15 K). The percentage goes down to 26% and 24% in 2011 and 2010, respectively.

The average daily relative humidity has a similar trend over the three years, normally varying between 40 and 80%. During the summer of 2010 higher values were recorded on average, reaching maximum values of 85–90% and never going below 45%. The summer of 2012 is characterized by the lowest values, on several occasions being around 30% and only rarely going above 80%.

As regards rainfall, the summer of 2012 was certainly the driest, with rain occurring only on 12 occasions, with long dry periods in between. The wettest year was 2010, when there were 24 rainy days, characterized in most cases by heavy showers or storms. In 2011 there were 18 rainy days in the early part of the summer, while the month of August was completely dry.

2.2. Description of the experimental building

A real-scale experimental building was constructed between September 2007 and January 2008 [33]. The one-storey building has a rectangular floor plan (8.20 m × 10.50 m) for a total floor area of 86.10 m^2 which is equivalent to about 250 m^3. The S/V ratio is 0.89. The roof has two slopes; the first faces south with a 17% pitch and is about 6.20 m long; the second is north-facing with a 30% pitch and a length of 2.25 m. The two slopes are connected by an east-west oriented ridge line.

The whole roof is divided into 6 parts of the same width (1.58 m); the six types of roof covering vary, being made of either brick or metal, with a slab in either pinewood or concrete and with or without under covering ventilation.

The six roof coverings are insulated with a double layer of expanded polystyrene for an overall thickness of 12 cm, with thermal conductivity 0.035 W/(m K). They all satisfy the *U*-value standard for zone D (U = 0.32 W/(m^2 K)) according to current national regulations on energy efficiency and savings.

The six types of covering used on the slope of the roof are listed below according to their layout, going from east to west as follows:

- 1 MNV-A_LR: non-ventilated metal roof on pinewood slab with copper sheeting; 1- MNV-A_GR: non-ventilated metal roof on pinewood slab with green roof;
- 2 MV6-A: ventilated metal roof with 6 cm under covering ventilation on pinewood slab;
- 3 LV3-A: ventilated brick roof with 3 cm under covering ventilation on pinewood slab;
- 4 LV6-A: ventilated brick roof with 6 cm under covering ventilation on pinewood slab;
- 5 LV6-L: ventilated brick roof with 6 cm under covering ventilation on concrete slab;
- 6 MV6-L: ventilated metal roof with 6 cm under covering ventilation on concrete slab.

The load bearing structure is made of a steel frame with HEA 120 pillars and IPE 180 beams with bolted joints. The external walls have a *U*-value of 0.20 W/(m^2 K) and are made of 10 cm multi-layer insulating panels, a ventilation space of 30 cm and internal OSB panels with a thickness of 2.2 cm.

Masonry irregularities were eliminated wherever possible in order to reduce to a minimum any thermal bridges. The floor slab was made with cast concrete, lightly reinforced with 5 cm thick rods. In order to reduce the *U*-value of this building component two layers of EPS panels with thermal conductivity 0.035 W/(m K), each 5 cm thick, were laid on top of the slab.

2.3. Description of the green roof system and the measurement equipment

The 1.58 m × 2.00 m portion of green roof was installed on the 1 MNV-A roofing. It is an extensive green roof characterized by low perennial vegetation (Fig. 2). It was laid without making any