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Dynamic *U*-value estimation and energy simulation for green roofs

G. Kotsiris [a,*], A. Androutsopoulos [b], E. Polychroni [b], P.A. Nektarios [a]

[a] *Laboratory of Floriculture and Landscape Architecture, Department of Crop Science, Agricultural University of Athens, Iera Odos 75, 118 55, Greece*
[b] *Buildings Department, Division of Energy Efficiency, Centre for Renewable Energy Sources & Saving (CRES), 19th km Marathonos Av., Pikermi 19009, Greece*

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ABSTRACT

Green roofs cooling and thermal insulating features have been demonstrated in many research projects. However, all efforts mostly have assessed green roof thermal properties under steady state conditions or by computational modeling. The present study evaluated green roof thermal performance in terms of the thermal transmittance coefficient, in real scale and under dynamic conditions. For the study's purposes, five semi-intensive green roof systems were constructed on the roof of an outdoor test cell. It was found that the green roof with 8 cm thick rock wool substrate with 2 cm sod on top had a very low *U*-value. For the same level of substrate moisture content, the other two green roof systems made of 8 cm deep coarse aggregate substrates with 2 cm sod on top provided higher *U*-values. In contrast, deeper amounts of same substrates (20 cm) reduced the *U*-value. The relation between the estimated thermal transmittance and the substrate moisture content was investigated and found to be linear. The green roof systems were also simulated for a single-storey residential building in order to quantify their possible energy savings. The results from the simulation showed that shallow substrates conserve building energy mainly during the summer period of the year. Rock wool and deeper substrates showed significant cooling and thermal insulating features.

1. Introduction

The energy benefits of green roofs are well-known from a general qualitative perspective [1–6]. However, a comprehensive assessment in quantitative terms is still a challenge [7]. To date, the thermal performance of green roofs is based on modeling simulation or numerical estimation using the involved parameters, which are collected experimentally or from data bases [8–13].

Therefore, the thermal transmittance coefficient (*U*-value) usually was estimated in steady state numerical approaches that utilised suitable data-loggers that used not only to store data but also as calculators. Wong et al. [2] utilised a BABUC-A (LSI-LASTEM) data logger, Onmura et al. [1] utilised a thermal conductivity meter and implemented a calculation of the *U*-value and Niachou et al. [14] estimated the *U*-values of a series of green roofs by using TRNSYS software, through the input of thermal conductivity coefficients for all the layers of each green roof component.

To maximise the usefulness of the models, several inputs should be utilised, thus increasing the inaccuracy of the models [9]. Moreover, computational models include many complicated mathematical or partial differential equations, which are difficult to solve directly. Therefore, these models should be improved for better accuracy and greater practicality [15]. Similarly a steady state numerical calculation of the thermal transmittance coefficient has a very restricted range of applicability. Lazzarin et al. [10] tuned their model in TRNSYS software to stress the significance of plant evapotranspiration. Sailor [13], in a sophisticated approach, coupled a model based on the Army Corps of Engineers [FASST] vegetations model [16] with the Energy Plus simulation program.

Recently, Feng [15] claimed that these models fail to account for every possible biological pathway, such as photosynthesis and plant respiration. He demonstrated a simplified model that calculated the instantaneous energy balance of a simplified extensive-type green roof system that was based on in situ measurements of eight parameters. However, all of these approaches considered the green roof as the sum of its partial materials instead of as a whole system. This approach leads to underestimates in the internal processes due to the air circulation, the trapped air and the additional quantities of water in the drainage membrane cavities and the effect of the root system on the physical properties of green roof component.

Therefore, the aims of the present study are: (a) the dynamic and real-scale determination of the thermal transmittance coefficient of semi-intensive green roof systems made from coarse aggregate materials or rock wool as an integrated system, (b) the comparison of the thermal transmittance coefficients of each of the green roof systems with a conventional and an advanced insulated roof construction, (c) the investigation of the relation between the estimated *U*-values and the substrate moisture content, and (d) the

* Corresponding author. Tel.: +30 210 5294554; fax: +30 210 5294553.
E-mail address: geokotsis@aua.gr (G. Kotsiris).

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quantified building energy savings from a one-storey residential building simulation by the use of TRNSYS software.

2. Green roof construction

The present study considered that the substrate composition depends on the materials available locally and can be formulated for the intended plant selection, climatic zone, and anticipated level of maintenance [17]. Additionally, the growing media must be chosen in accordance with the load-bearing capacity of the structure and the water requirements of the plant material.

Green roof substrates should be lightweight, chemically inert, and physically stable, and they should retain adequate amounts of water and minerals for sufficient plant growth and for fast draining to avoid substrate saturation [18]. Therefore, the majority of green roof substrates tend to be dominated by mineral-based components [19].

In the present trials, perlite, pumice and zeolite were selected as locally available, coarse aggregate materials to compose the substrate mixtures. Zeolite was utilised to improve plant growth by providing a slow release of N and K to the plants and to reduce NH_4^+ and K^+ leaching [20]. The organic matter of the substrate mixtures were peat moss or compost. The peat was a sphagnum peat moss with a pH of 3.75. Each material was selected based on their weight, water retention capacity, and contribution to plant growth sustainability and local availability. In addition, the substrate formulation using the selected materials aimed to comply with FLL specifications [21].

On the roof of the test cell, five different green roof systems – consisting from the same infrastructure and five different substrates – were consecutively constructed on a 1:1 scale. The infrastructure was as follows: each green roof system was installed on a 12 cm concrete slab that was placed on the top of the test cell. On the top of the slab a multiple course layering that was identical for all green roofs under investigation except for the drainage and substrate layers was applied. The first layer was a double-layered bitumen waterproofing membrane. Each layer was 4 mm thick, weighed 4 kg m^{-2} and consisted of refinery asphalt modified with thermoplastic polymers and an herbicide (Preventol B2) for enhanced membrane resistance to root penetration. In addition, the membrane included a polyester fiber that weighed 200 g m^{-2}. The first layer was applied by semi-thermal soldering on the top of the roof area after an application of extra asphalt varnish. The second layer was then applied under full thermal soldering on top of the first layer. The waterproof course was then protected by a PET (polyester) nonwoven geotextile 0.8 mm thickness and with a random fibrous structure and a weight of 150 g m^{-2}.

The drain course of the system was constructed by applying two layers of thickened HDPE drainage modules and filling their void volume with perlite to function as a water storage tank. The drainage course was separated from the substrate by a layer of nonwoven PET (polyester) geotextile 0.8 mm thickness and with a random fibrous structure and a weight of 150 g m^{-2}.

Above the common layering, five different green roof systems were built one after the other. More specifically, the roofs included three different substrates combined with two substrate depths (8–20 cm), except for in the case of the rock wool substrate, which was tested only in the depth of 10 cm. The five substrates were as follows: (1) 8 cm deep hydrophilic rock wool with a density of 150 kg m^3 with 2 cm tall fescue sod (*Festuca arundinacea*), (2) 8 cm deep sandy soil mixed with perlite and zeolite in volumetric proportions that are indicated by their subscript (S_{30}:Per_{65}:Z_5) with 2 cm tall fescue sod, (3) 8 cm deep pumice mixed with peat and zeolite (Pum_{65}:P_{30}:Z_5) with 2 cm tall fescue sod, (4) 20 cm deep pumice mixed with peat and zeolite (Pum_{65}:P_{30}:Z_5) planted with

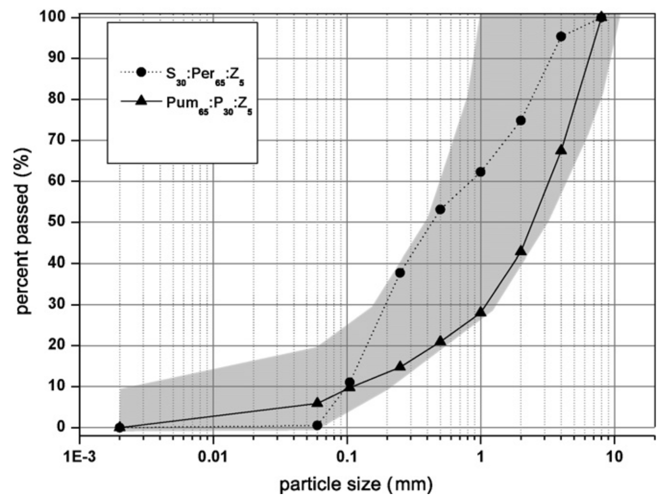

Fig. 1. The particle size distribution of the Pum_{65}:P_{30}:Z_5, Pum_{65}:C_{30}:Z_5 and S_{30}:Per_{65}:Z_5 substrates (Pum = Pumice, C = Compost, Z = Zeolite, S = Sandy loam soil and Per = Perlite). The grey area represents the appropriate substrate selection range for intensive green roofs following the FLL guidelines.

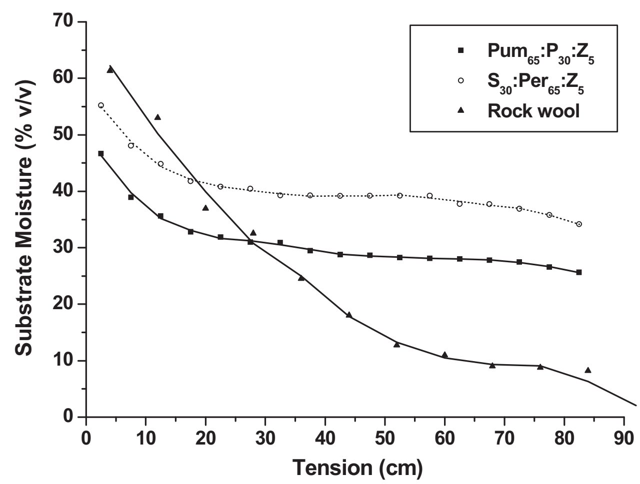

Fig. 2. Water retention curves of rock wool (d = 150 kg m^3), Per–S–Z mix and Pum–P–Z mix (Pum = pumice, Per = perlite, P = peat, S = sandy loam soil, Z = zeolite).

Lavandula angustifolia and (5) 20 cm deep sandy soil mixed with perlite (S_{30}:Per_{65}:Z_5) and planted with *L. angustifolia*. The grading of the aggregate materials were 1–8, 0.8–2.5, and 1–5 mm for the pumice (LAVA, Mining & Quarrying S.A.), the zeolite (S & B Industrial Minerals S.A.) and the perlite (Perloflor ISOCON S.A.), respectively.

The substrates were formulated based on preliminary studies of local materials with potential to serve as a green roof vegetation layer. The selection criteria of the substrates complied with FLL specifications [21] for particle size distribution (Fig. 1), physical properties and organic content (Table 1), except for the case of rock wool. The determination of organic matter was performed according to ASTM D 2974 [22] loss-on-ignition (LOI) method. Particle size distribution was performed according to ASTM D 422-63 [23]. In addition, the characteristic curves for each substrate were found by using a column of rings filled with the substrate [24] (Fig. 2).

It was found that rock wool retained higher water quantities close to and at the saturation zone (0–20 cm) compared to the other two substrates. The substrate with perlite in its composition retained increased moisture at all suction levels above 20 cm.

Green roof systems with 8 cm substrate were sodded with 2 cm thick *F. arundinacea* sod that contained five different grass varieties. The systems with 20 cm substrate were planted with