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Experimental investigation of the thermal performances of an extensive green roof in the Mediterranean area

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ABSTRACT

Nowadays green roofs are a well-consolidated technology used in several countries since these systems can be employed both to generate considerable energy savings and to improve the thermal performances of buildings. This paper deals with an experimental analysis of an extensive green roof, installed on a building of the University of Calabria (Italy, Lat. 39.3° N). The thermal performances of different layering solutions are analysed under typical Mediterranean climate conditions with reference to a traditional roof system. The analysis showed that the green roof is able to reduce the temperature at the interface with the structural roof, on average, by 12 °C with respect to a black bituminous roof in summer and to maintain, on average, a value that is 4 °C higher in winter. The measured temperatures allowed to calculate the transferred heat through the building roof, showing negative heat fluxes for the whole period and a reduction of the thermal energy entering the indoor environment of 100% in summer, proving the passive cooling effect of the green roof, and a reduction between 30% and 37% of the thermal energy exiting the indoor environment in winter. The experimental data have been employed also to conduct a dynamic characterization of the different vegetated solutions, showing that the different green roofs solutions are able to generate values of decrement factor varying between 0.135 and 0.193 and a time lag between 3.1 h and 4.8 h, which can substantially improve the dynamic properties of traditional roof structures, especially in the case of roofs with limited dynamic performances.

1. Introduction

In recent decades, the increasing awareness of the indefensibility of the actual model of economic growth has led to new concepts of sustainable development. In the building sector, which is responsible for a relevant demand of primary energy, the trend in the quest of adequate technical solutions is continuously increasing. Many systems have been investigated to evaluate performances in terms of environmental, economic and energy benefits. Passive systems such as green roofs, also named eco-roofs, living roofs or roof gardens [1], belong to the studied systems. Nowadays green roofs are a well-consolidated technology used in several countries around the world as an innovative roofing solution. Vegetated roofs have been used since ancient times with the most famous example being the Babylonian gardens in Mesopotamia [2], but more recent examples can be found especially in Northern European countries. Indeed this technology has historically proven validity in the improvement of the building envelope insulation in cold climates and in the improvement of stormwater management. Nevertheless, these systems allow the achievement of several other benefits, such as the reduction of rainwater runoff [3–5], the mitigation of urban heat island effect (UHI) [6,7], the improvement of membrane durability and extension of roof life [8,9] and the reduction of heating and cooling demands for the buildings air-conditioning [10–15].

Finally, green roofs sequester carbon dioxide and reduce localized air pollution [16–19], increase the water runoff quality [20], create habitat for wildlife and recreational opportunities [21–24] and decrease urban noise pollution [25,26]. Therefore, green roofs actually represent an innovative construction system that can increase the sustainability of buildings and cities.

Vegetated roofs are categorised as intensive, simple intensive (or semi-intensive) and extensive greenings according to the level of maintenance required, but often only the extensive and intensive categories are considered. Intensive roofs are deep, heavy, require a high level of maintenance and, usually, they are designed for complete accessibility. This type of roof is usually applied to new buildings in which the extra weight is kept in consideration during the design of the structural components. The extensive ones, instead, are characterized by lightweight growing media of reduced depth; they require low maintenance and are less

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likely to be designed for frequent human access. Typical extensive green roofs are equipped with self-sustaining and native species of plants, therefore they require low irrigation since the vegetation is well adapted to local climatic conditions [27–29]. The plants represent a necessary element to realize the evapotranspiration process in the substrate layer, crucial for the achievement of cooling effects [30]. Moreover, the reduced system weight makes them suitable for installation on existing buildings. A typical extensive green roof layering, together with the materials generally employed, can be found in [31–34]. Different constructive solutions are nowadays available, that are often not standardized and may be composed of different types of layers, materials, thicknesses and vegetation. Consequently a more comprehensive datasets to report quantitative information about the performance for the different technologies adopted is required [29].

From an energetic point of view, as the surface of the roof increases, in relation to external walls surface, the heat flux through the building cover assumes a more relevant contribution in the energy requirements of the building upper floor air-conditioning [35]. In this regard, the physical phenomena involved in the energy balance of the several layers of an extensive green, such as vegetation, substrate and drainage roof, lead to the reduction of the thermal loads of the indoor environment, both in summer and winter. Regarding the vegetation layer, the heat fluxes with the outdoor environment involve absorption of solar radiation, long-wave radiative exchange with the sky, convective exchange with external air, precipitation and evapotranspiration processes. Similar physical phenomena are involved in the thermal balance of the soil, with the addition of the conductive heat flux and the sensible heat stored in the structure. The theoretical investigation of these systems is very difficult due also to the strong variation of the thermo-physical properties of the soil and drainage layer with the water content (WC) [36]. In summer, the shading effect of vegetation, the increased thermal mass of the system and evapotranspiration phenomena, permit the reduction of heat fluxes entering the building through the roof. In winter, the green roof offers additional insulation to reduce heat losses from indoor spaces to the outdoor environment.

In the recent literature many researchers focused their studies on the mathematical modelling of the heat and mass transfer in a green roof in order to be able to assess the resulting benefits [36–42]. Such topic, given the complexity of the physical phenomena involved, is still under development. Consequently many authors addressed the problem by using mathematical model solved with a numerical approach; however the results obtained provide only a qualitative accuracy. Niachou et al. [43] estimated the impact of a green roof on the total energy consumption of buildings with various types of roofs, with and without insulations, through a simplified mathematical approach, simulating the presence of the vegetated roof by properly modifying the thermal conductance of the building cover. They observed that the greatest yearly energy saving, in the case of non-insulated buildings, was of 37%. Spala et al. [44], using the dynamic simulation program TRNSYS, calculated the energy consumption of a two-storey building in Athens. They observed a remarkable reduction in the cooling load with a maximum of 39% for the whole building, and of 58% for the last floor. Moreover, they observed a maximum decrement of heating loads of 8% for the whole building, and 17% for the last floor. However, not many details were given about the mathematical approach used. Another group of researchers, by using a more detailed green roof model based on the numerical procedure implemented in EnergyPlus, calculated the energy performances of an office building with various typologies of green roof and a high reflective coating, in different European climate conditions [45]. They concluded that in warm climates green roofs are suitable for reducing the energy demand for the space cooling, without penalizing the scarce heating demand, and in cold climates they are useful for reducing the thermal losses in winter. However the thermal transmittance value in the study was not varied, since they considered as a case study a well-insulated building.

Other researchers have evaluated the performance of green roofs through experimental analysis. The results obtained by Liu and Minor [9] in the city of Toronto showed that green roofs are effective in reducing heat fluxes through the roofing system, thus lowering the energy demand for space conditioning in the building. The additional green roof systems, compared to the reference roof consisting of steel deck, gypsum board, vapor retarder, thermal insulation, fibreboard and modified bituminous membrane, reduced the heat fluxes through the roof by 70–90% in summer and 10–30% in winter. The green roofs also reduced the roof membrane maximum temperature in summer by more than 20 °C and daily temperature fluctuations experienced by the roof membranes by about 30 °C. Their results refer to a humid continental climate locality, and in the study the temperature inside the building was kept constant so that any heat flow between the building and its environment created energy demand for space conditioning. Therefore, the energy demand due to the roof was estimated by the sum of the heat entering and leaving through the roof. In similar climatic conditions another study, conducted by Teemusk and Mandar in Estonia, compared experimentally the temperature regime of a lightweight aggregates based roof garden with a modified bituminous membrane roof in different season [8]. The results of their study revealed that the roof garden can decrease the temperature fluctuations significantly in summer, protecting roof membrane from rapid cooling and freezing in autumn and spring, and provide effective thermal insulation in winter. In a Midwestern U.S. climate Getter et al. [46] quantified the thermal properties of an inverted 325 m^2 extensive green roof installed over a traditional gravel insulated roof, taken as reference. Their results demonstrated how an extensive green roof influences temperatures and heat fluxes in the roof during different seasons of the year, with a reduction of heat fluxes, through the building envelope, by an average percentage of 13% in winter and 167% in summer. In terms of maximum and minimum temperature, the monthly average values over the course of the year were consistently higher for the gravel-ballasted roof than the green roof, with values up to 20 °C warmer during summer. The study reported in [47], regarding five typical days, showed that a green roof test bed in Singapore (China), can reduce the internal air temperature by an average value of 0.5 °C if compared with a bare roof.

Even though many examples of experimental analysis can be found in the literature, most of the available researches on green roofs rely on simulated data. Furthermore one of the main factors affecting the performance of a green roof is the climatic conditions, therefore generalizable results are difficult to assess. In this regard the performance of green roofs in winter period is still a matter of debate where some scientists claimed it as a medium to save energy and some viewed it as a cause of more energy consumption [1].

Other experimental studies have been conducted in Mediterranean climate conditions. Coma et al. [48] evaluated the energy consumption and thermal behaviour of three identical house-like cubicles located in Puigverd de Lleida (Spain): two of them were equipped with extensive green systems with different drainage layer materials, pozzolana and rubber crumbs, installed on a traditional non insulated flat roof, and one with a traditional insulated roof. They measured the electrical energy consumption of a heat pump system for more than one year. Their results indicated that both extensive green roof cubicles generated less energy consumption (16.7% and 2.2%, respectively) than the reference one during warm periods, whereas higher energy consumption (6.1% and 11.1%, respectively) during heating periods were detected. D'Orazio et al. [49] assessed the yearly thermal performance of