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Characterization of green roof components: Measurements of thermal and hydrological properties

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A B S T R A C T

In this study, three of the main physical properties of green roofs were experimentally investigated to determine some of the key green roof modeling parameters. First, the thermo-physical properties of green roofs were characterized by correlating the thermal conductivity of the substrate with the water content for different substrates and maximum water capacities. Next, the moisture storage was characterized using the dynamic vapor sorption technique to determine both the sorption and desorption isotherms for three different temperatures as well as the moisture buffer capacity. Third, the micro-structural properties of green roof substrate were characterized using mercury intrusion porosimetry to measure the porosity range of the substrate and to compare this porosity range with different concrete porosities. In addition to these characterizations, the evapotranspiration term, which is very important in the water balance, was measured. The few studies found in literature provide the expression of the evapotranspiration term for a watered grass and vegetated areas on a large scale. In this study, this term is expressed for the experimentally studied green roof complex (substrate + vegetation). The ultimate objective of these experiments is to estimate the parameters used as input data in the developed green roof model to evaluate the energy performance of a building.

1. Introduction

Heating, ventilation, air-conditioning systems and heat produced by industries and services (computers…), as well as lights, water and elevators, all contribute to making buildings a significant source of greenhouse gas emissions and a leading energy consumer. In Europe, buildings represent 40% of the overall energy consumption and 36% of the overall CO_2 emissions [1,2]. Forty percent of the world's raw materials are used in buildings [3]. To protect the environment by reducing the energy consumption of buildings, various innovative construction solutions can be proposed. Among these solutions, green roof architecture has been increasingly used in new construction projects in major cities. Green roofs effectively contribute to the possible solutions of several environmental problems stemming from buildings and urban development.

Outside of aesthetic considerations, which only apply to landscape architects, green roofs have three key benefits. The first benefit is their thermal insulation contribution to the building within which they operate [4–6]. In the summer, green roofs play an efficient regulatory role in the heat flux through the roof, which constitutes a large proportion of the energy absorbed by the building, thereby enabling the energy consumption required for air conditioning and cooling to be significantly reduced. From a thermal point of view, green roofs protect the roof membranes from extreme temperatures during hot days and high temperature fluctuations by reducing thermal stress [7–12].

The surface temperature of conventional roofs can reach very high values in the summer; for example, a temperature of 90 °C has been recorded in Australia [13]. Green roofs can significantly reduce this temperature as a result of their green component characteristics (e.g., foliage shading soil, foliage soil thermal resistance, and evapotranspiration (ETP)). The conducted heat flux through the roof is thus affected, thereby modifying the building's energy demand and indoor thermal comfort level. The summer and winter temperatures on the roof support's exterior surface are less extreme, with smaller fluctuations than those on conventional roofs. Thus, the thermal stress on roof membranes is significantly reduced, which improves the durability of the roof [7–12].

The second benefit of green roofs is their role in the regulation of storm water. By absorbing rainwater in their substrate, green roofs delay the runoff and mitigate the impact of heavy rains, which affect urban areas with impermeable soils. Green roofs also decrease the risk of floods, duct overloading and water reprocessing [7,14–20].

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The third benefit of green roofs is that their presence allows for evapotranspiration, and the resultant humidification and air cooling will, in turn, reduce the heat island effect. In urban areas, this effect increases night temperatures in the heart of the city [9,21–24]. The heat island effect is due to the properties of concrete surfaces, which capture and store the heat received during the day and release it later during the night; the radiation trapped in the streets between high buildings with a small sky view factor; and the bad air circulation in the city, where buildings act as a windbreaker against natural air currents.

Several studies have analyzed the thermal impact of green roofs on building energy performance [7,17,25–27]. However, there is still a lack of characterized parametric data regarding coupled heat and mass behavior, which would render numerical results more precise. In this study, various experimental characterizations concerning the green roof substrate were performed because the green roof substrate is a medium with high porosity; therefore, the moisture transfer phenomenon has a very significant impact on thermal heat transfer [28–31]. The substrate used in a green roof construction has a specific organic matter composition to ensure suitable living conditions for the vegetation planted on the roof.

In order to evaluate the green roof performance, three experimental characterizations were conducted: thermo-physical, water transfer and micro-structural. In the first characterization, the thermal conductivity was measured for different water content values because water content changes in the substrate affect the heat transfer through the roof [32]. The thermal conductivity of the substrate was provided as a function of water content for different substrates with different maximum water capacities (MWCs, the maximum amount of water that the substrate can contain). Second, the moisture storage characterization was performed using the dynamic vapor sorption (DVS) technique to determine the sorption and desorption isotherms. The adsorption isotherms correspond to the amount of the absorbable substance stored by the porous material [33]. This experimental method allows the moisture buffer capacity for each material to be determined. Third, the micro-structural characterization was performed using mercury intrusion porosimetry both to measure the porosity range of the green roof substrate and to compare this porosity range with those of other conventional materials. This method has typically been used for building materials [34], and there are few data in the literature regarding its use in characterizing green roof substrates. Finally, an evaluation of evapotranspiration (ETP) was given by performing an experiment where the green roof components are taken on the same scale as those used in green roof construction. Through these experimental characterizations, the ultimate objective of this study was to use the characterized parameters as input data in a developed green roof numerical model.

2. Characterization

2.1. Aim of characterization

The various characterizations in this study were performed for the purpose of using the characterized parameters as input data in the developed green roof model to more precisely evaluate the impact of green roofs on building energy performance.

The developed model is a coupled heat and mass transfer model based on the work of Sailor [25] and Frankenstein [26]. The water balance equation was coupled in a previous study [32] to take the influence of water transfer on the thermal behavior of green roof into account. The thermal balance equations divide the energy balance analysis into an analysis of the leaf surface and an analysis of the soil surface. In these thermal balance equations, the radiative, sensible, latent and conducted heat fluxes are modeled.

The conducted heat flux depends on the green roof substrate's thermal conductivity, which depends on its water content. In the mass transfer model, the impact of mass transfer on the behavior of the green roof was taken into account through the Richard's equation. Thus, the mass transfer kinetics are related to the moisture buffer capacity C_m. The boundary conditions were defined through an evapotranspiration evaluation based on a corrected Penman-Monteith equation.

2.2. Thermo-physical characterization

Knowledge of substrate's thermal properties is needed to calibrate the proposed model, which describes the thermal behavior of green roofs with input data. Among these thermal properties, the thermal conductivity was determined in this study. This parameter varies depending on the amount of water present in the substrate and affects the ground heat flux [32]. The TP08 Hukseflux probe was used to measure the thermal conductivities of green roof substrates. This probe measures thermal conductivities between 0.1 and 6 $\text{Wm}^{-1}.\text{K}^{-1}$ with ±0.3% accuracy. The probe consists of a heating wire and a temperature sensor, which measures the source temperature. This method is described by the standards of the American Society for Testing and Materials (ASTM) and the Institute of Electrical and Electronics Engineers (IEEE). ASTM D 5334-00 and D 5930-97 as well as IEEE Std 442-1981 "Standard Test Methods" specify the use of non-steady-state probes (NSSP) in various applications. In general, an NSSP consists of a heating wire, which represents a perfect line source, and a temperature sensor capable of measuring the temperature at this source. After a short transient period, the temperature rise, ΔT, only depends on the heating power Q and the medium thermal conductivity K. This is reflected in the following heat transfer equation for cylindrical geometries:

$$\Delta T = \left(\frac{Q}{4\pi K}\right)(\ln t + B) \tag{1}$$

where ΔT is in Kelvin; Q is in Wm^{-1}; K is in $\text{Wm}^{-1}.\text{K}^{-1}$; t is the time in seconds and B is a constant. K can be calculated by measuring the heating power. Q, t and ΔT are all direct measurements of power, time, and temperature, respectively; thus, the measurement with the TP08 probe is absolute. The thermal conductivities of five substrates were measured for different water conditions, ranging from 0 to 100% of the maximum water capacity (MWC).

Previously, the MWC of the substrates was determined as the difference between the dry weight and the weight at saturation using a protocol given in the professional rules for conception and construction of green roofs published by ADIVET [35]. The results are presented in Table 1. The chemical and physical characterizations of these substrates were also performed [36], and the results are presented in Table 2.

There is a significant difference between the substrate properties, particularly for the water availabilities and the organic matter rates

Table 1
Maximum water capacity (MWC) of five types of substrates measured experimentally.

Sample substrate	CRITT Aquiland	Normal a quiland	Soprema M	Soprema X061	Siplat
Apparent density (20% moisture state) (kg/m^3)	955	931	1125	1119	1093
Apparent density (saturated state) (kg/m^3)	1229	1321	1275	1277	1412
Maximum water capacity (MWC) (kg water/m^3)	30	56	33	42	50