Available online at www.sciencedirect.com

ScienceDirect

Energy Procedia 78 (2015) 1177 – 1182

Energy Procedia

6th International Building Physics Conference, IBPC 2015

Impact of the properties of a green roof substrate on its hydraulic and thermal behavior

V. Sandoval[1,2], F. Suárez[1,2,*], S. Vera[2,3], C. Pinto[2,3], F. Victorero[3], C. Bonilla[1,2], J. Gironás[1,2], W. Bustamante[2,4], V. Rojas[5], P. Pastén[1,2]

[1] Department of Hydraulic and Environmental Engineering, Pontificia Universidad Católica de Chile
[2] Center for Sustainable Urban Development (CEDEUS), Pontificia Universidad Católica de Chile
[3] Department of Construction Engineering and Management, School of Engineering, Pontificia Universidad Católica de Chile
[4] School of Architecture, Pontificia Universidad Católica de Chile
[5] VR+ARQ, Chile

Abstract

Green roofs integrate vegetation into infrastructures to reach benefits that minimize negative impacts of the urbanization. Green roofs use artificial soils (substrates) that have an improved performance compared to natural soils. In this work, we characterized four substrates in terms of their hydraulic and thermal properties, and performed numerical simulations of heat and fluid flow to study the effect of these properties on green roof performance. Simulation results show that the green roof behavior strongly depends on substrate properties and on moisture content prior to a rainstorm, highlighting the need of dynamic biophysical models for design/maintenance of green roofs.

© 2015 The Authors. Published by Elsevier Ltd. This is an open access article under the CC BY-NC-ND license (http://creativecommons.org/licenses/by-nc-nd/4.0/).
Peer-review under responsibility of the CENTRO CONGRESSI INTERNAZIONALE SRL

Keywords: green roof substrate; water retention curve; hydraulic conductivity; thermal conductivity.

1. Introduction

Due to public concern towards sustainable development, greenhouse gas emissions and energy efficiency, the use of green roofs in buildings have increased quickly in the last years [1-4]. Green roofs are technological solutions that

* Corresponding author. Tel.: +56-2-2354-4227; fax: +56-2-2354-4227.
E-mail address: fsuarez@ing.puc.cl

1876-6102 © 2015 The Authors. Published by Elsevier Ltd. This is an open access article under the CC BY-NC-ND license (http://creativecommons.org/licenses/by-nc-nd/4.0/).
Peer-review under responsibility of the CENTRO CONGRESSI INTERNAZIONALE SRL
doi:10.1016/j.egypro.2015.11.097

integrate vegetation into infrastructures to reach additional benefits, which minimize negative impacts of the urbanization [2]. For instance, a correctly designed green roof can reduce environmental pollution, noise levels, energetic requirements, and surface runoff. At the same time, it can increase the urbanization biodiversity [3].

The proper performance of green roofs depends on the operation of each component of the system, and on environmental conditions. The substrate and the vegetation layers are the most important components of a green roof [1]. The substrate is an artificial media that has an improved performance compared to natural soils [4], and is one layer of interest because it provides critical resources for vegetation survival: water, nutrients, and a growing media [5]. In this work, we hypothesize that a correct characterization of the substrate, combined with numerical modelling, allows understanding the effect of substrate properties on the behavior of a green roof. The general objective of this work is to investigate how the thermal and hydraulic properties affect the behavior of a green roof. The specific objectives are to: 1) characterize a set of organic and mineral green roof substrates in terms of their hydraulic and thermal properties: hydraulic conductivity, water retention curve, thermal conductivity, thermal diffusivity, and specific heat capacity; 2) evaluate the impacts of the previous properties on green roof performance using numerical simulations of heat and fluid flow.

2. Materials and methods

2.1. Theory of fluid and heat transport in green roof substrates

Liquid water and vapor flow in a green roof substrate can be described using Darcy’s Law [6], which requires knowledge of the soil water retention curve and the hydraulic conductivity curve. These curves are the most important parameters to model fluid flow in an unsaturated porous medium. The water retention curve is the relationship between pressure head, h, and water content, θ, and represents the capacity of the porous media to hold water. In this work, the water retention curve is described using the van Genuchten model [7]:

$$S_e = \frac{\theta - \theta_r}{\theta_s - \theta_r} = \frac{1}{\left(1 + |\alpha h|^n\right)^m} \tag{1}$$

where S_e is the effective saturation, θ_r and θ_s are the residual and saturated volumetric water content, respectively; α is the inverse of the air-entry pressure; and n and m are empirical parameters. The hydraulic conductivity curve, $K(h)$, represents the ease with which the water moves through the pore spaces of the medium, i.e., the substrate. Here, $K(h)$ was estimated using the van Genuchten-Mualem model [7,8], which requires knowledge of the saturated hydraulic conductivity, K_s. The K_s is typically estimated using a constant- or variable-head permeameter [8].

Heat flow in a porous medium can be described by the energy conservation equation [6]:

$$C_p \frac{\partial T}{\partial t} + L_0 \frac{\partial \theta_v}{\partial z} = \frac{\partial}{\partial z}\left[\lambda(\theta)\frac{\partial T}{\partial z}\right] - C_w q_l \frac{\partial T}{\partial z} - L_0 \frac{\partial q_v}{\partial z} - C_v \frac{\partial}{\partial z}\left[q_v T\right] \tag{2}$$

where T is temperature; C_p, C_w and C_v are the volumetric heat capacities of the moist soil, liquid water, and water vapor, respectively; q_l and q_v are the liquid and vapor flux densities, respectively; L_0 is the volumetric latent heat of vaporization; and $\lambda(\theta)$ is the soil apparent thermal conductivity:

$$\lambda(\theta) = \lambda_0(\theta) + \beta_t C_w |q_l| = \left(b_1 + b_2\theta + b_3\theta^{0.5}\right) + \beta_t C_w |q_l| \tag{3}$$

where β_t is the thermal dispersivity, and $\lambda_0(\theta)$ is the thermal conductivity in absence of fluid flow. $\lambda_0(\theta)$ has been described by the Chung and Horton model [9], in which b_1, b_2 and b_3 are empirical parameters.

2.2. Substrates

The substrates investigated in this work are commonly found in green roofs and are presented in Fig. 1. The S1 substrate has a similar texture than a sandy loam soil; the S2 substrate is comprised by perlite and peat; the S3 substrate has crushed bricks (clay); and the S4 substrate is a mixture of topsoil and a mineral soil.

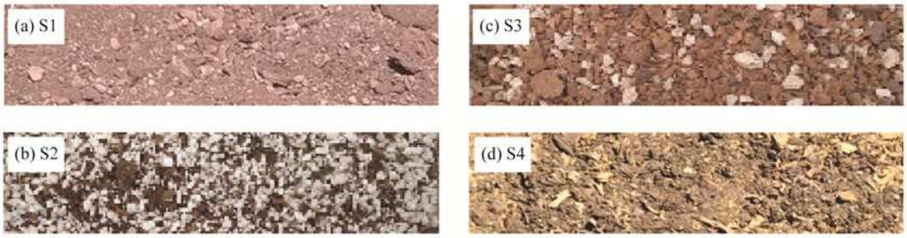


Fig. 1. Substrates used in this investigation. (a) S1; (b) S2; (c) S3; (d) S4.

2.3. Determination of hydraulic and thermal properties of the substrates

The water retention curve was estimated in the laboratory using a pressure plate extractor (1600 5-bar, Soilmoisture Equipment Corp., Santa Barbara, CA) under drying conditions. The experimental data were then used to estimate the water retention parameters by the least squares method [7]. The saturated hydraulic conductivity was determined using a constant head permeameter (Soil Measurement System, Tucson, AZ).

The thermal properties of the substrates (conductivity, diffusivity and volumetric heat capacity) were obtained using the dual-probe heat-pulse technique [10,11]. The thermal properties were obtained for different moisture levels, which were measured using a time domain reflectometry probe (GS3, Decagon Devices, Pullman, WA).

2.4. Impacts of green roof properties on its performance using numerical simulations

Figure 2 shows the conceptual model utilized to evaluate the impacts of the green roof properties on its performance. We selected a 15-cm thickness substrate above a 20-cm concrete roof, and solved the fluid and heat transport equations using the Hydrus 1D software [12]. The hydraulic and thermal properties of the concrete were obtained from the literature [13].

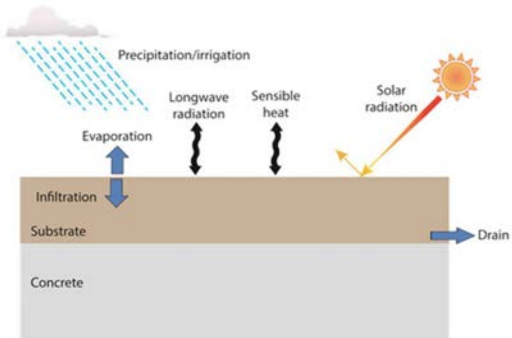


Fig. 2. Conceptual model of the Green roof.

The following surface energy balance was used as the boundary condition at the top of the domain for the heat transport equation [12]:

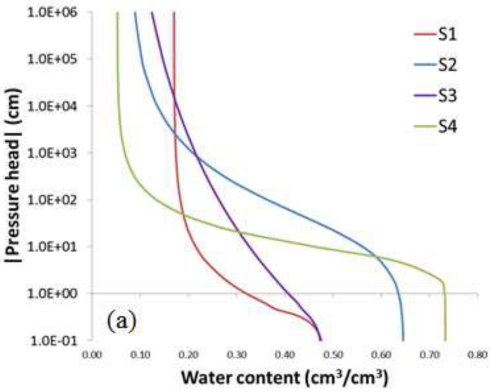
$$R_n = H + L_0 E + G \tag{4}$$

where R_n is the net radiation, H is the sensible heat flux, E is the evaporation rate and G is the soil heat flux. Precipitation, irrigation and evaporation are also used as boundary condition for flow at the substrate surface. The previous boundary conditions were estimated from the meteorological conditions of Santiago, Chile, and allow coupling fluid and heat transport in the domain. At the bottom of the substrate, a seepage face boundary condition was used for fluid flow [12]. This boundary condition assumes that the flux will remain zero as long as the pressure head is negative. However, when the bottom of the substrate becomes saturated, a zero pressure head is imposed and water exits the roof. In the concrete below the substrate only heat is allowed to flow. At the bottom, a zero gradient boundary condition was selected as the lower boundary condition for heat transport [12]. A uniform water content of 0.3 $m^3\ m^{-3}$ was utilized as initial condition in the substrate, and a uniform temperature of 20 °C was used as initial condition in the entire domain.

3. Results and discussion

3.1. Hydraulic and thermal properties of the substrates

Figure 3 show the hydraulic and thermal properties of the substrates used in this investigation. The four substrates present a relatively large saturated hydraulic conductivity (between 2 and 26 m/d), meaning that water can move easily through the saturated media and thus, under saturated conditions a green roof would not have the potential to mitigate storm-water runoff unless a thick substrate layer is used, e.g., such as the thickness of an intensive green roofs [14,15]. Nonetheless, under unsaturated conditions the substrates will be able to store water, providing a retention time that could mitigate the runoff generated in the green roof. This storage volume will be proportional to the difference between the saturated and residual water contents. Thus, substrates such as S1 and S3 will have less storage volume than substrates S2 and S4. It is also interesting to observe that substrate S2 is able to retain more water than substrate S4 at suctions higher than 10 cm. As a consequence, substrate S2 should be more efficient than the other substrates when trying to retain storm water and to minimize the roofs runoff.



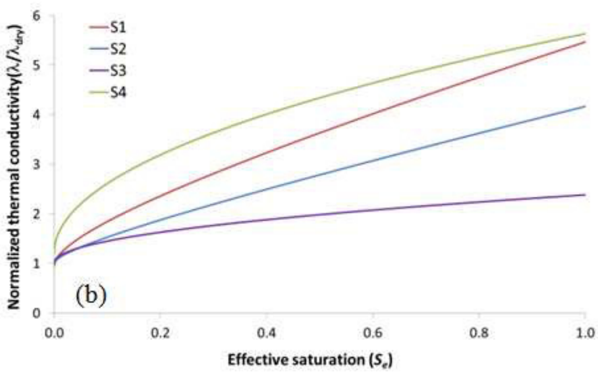


Fig. 3. Properties of the four substrates used in this research: (a) water retention curve. (b) Normalized thermal conductivity. λ_{dry} is the thermal conductivity of the dry substrate.

The thermal properties of the substrates are on the same order than those found in the literature [5,16]. As shown in Fig. 3 (b), the S3 substrate has the smallest increase in thermal conductivity as moisture increases. The thermal conductivity of this substrate increases approximately two times its dry thermal conductivity. Therefore, a green roof with the S3 substrate will provide more thermal resistance than the other substrates, being more efficient to dissipate the thermal daily fluctuations produced by environmental conditions. On the other hand, the S4 substrate increases its thermal conductivity to about 5-6 times from its driest to its moistest state. This significant increase in thermal conductivity creates larger thermal fluctuations in the green roof.

The previous results suggest that a single substrate may not be able to simultaneously minimize roofs runoff and the buildings energetic requirements. Thus, for design purposes, it is important to define in advance the benefits that a green roof should target. For instance, if decreasing roofs runoff is an important goal of a green roof, substrates S2 or S4 may be more appropriate than substrates S1 or S3. If reducing the energetic requirements is a second aim, then substrate S2 should be selected for the green roof since it has a smaller thermal conductivity than substrate S4. In other words, if the substrate is selected only by analyzing its thermal conductivity curve, i.e., using the data from Fig. 3(b), one may be tempted to choose the S3 substrate. However, as shown in Fig. 3 (a), the S3 substrate is the second worst in terms of its capacity to retain water. These results highlight the need of simulation tools to help in the green roof design process. The next section provides more insights on how numerical models can be used to understand the effects of green roof properties on its performance.

3.2. Impacts of green roof properties on green roof performance using numerical simulations

Figure 4 shows the results of numerical simulations of fluid and heat flow in a green roof. In these simulations, meteorological data of November 2014 was utilized. Fig. 4 (a) presents the cumulative water fluxes obtained when the roof was irrigated two times per day, for the S1 substrate under two initial moisture levels (0.20 and 0.45 cm^3/cm^3). The cumulative infiltration (green line) shows the irrigation scheme, and the cumulative drainage (red and blue lines) represents the water flow that exits the bottom of the green roof. The main conclusion that can be drawn from these results is that a green roof that is near its saturated state will not be able to mitigate the runoff generated in the green roof. When the green roof is at a moisture level higher than its field capacity, water will drain even if the roof is not irrigated [5]. This is depicted in Fig. 4 (a), where after three days of simulation more than 45 mm of water have been drained through the green roof, even when only 25 mm of water infiltrated into the soil. The difference between these two cumulative fluxes corresponds to the water that was initially within the substrate. On the other hand, if the substrate has a moisture level below the field capacity, water will be retained in the substrate until irrigation drives the fluid flow in the system. For instance, as shown in Fig. 4 (a), when the S1 substrate is initially at 0.20 cm^3/cm^3, the water breakthrough at the drainage occurs after 1.5 days. The other substrates (S2, S3 and S4) will also have different breakthrough times (data now shown). For example, the breakthrough in the S2 substrate occurs after 3 days when the water content prior to irrigation is 0.45 cm^3/cm^3. Even more, for the conditions used in these simulations, the S2 substrate is able to retain water for more than one day for initial moisture levels as high as 0.58 cm^3/cm^3. Hence, the hydraulic behavior of a green roof strongly depends on the moisture content prior to irrigation (or rainstorm) and on its hydraulic properties. This aspect must be taken into account when designing a green roof because it also affects water quality problems due to storm-water runoff [15]. These results highlight the need of dynamic biophysical models for green roof design.

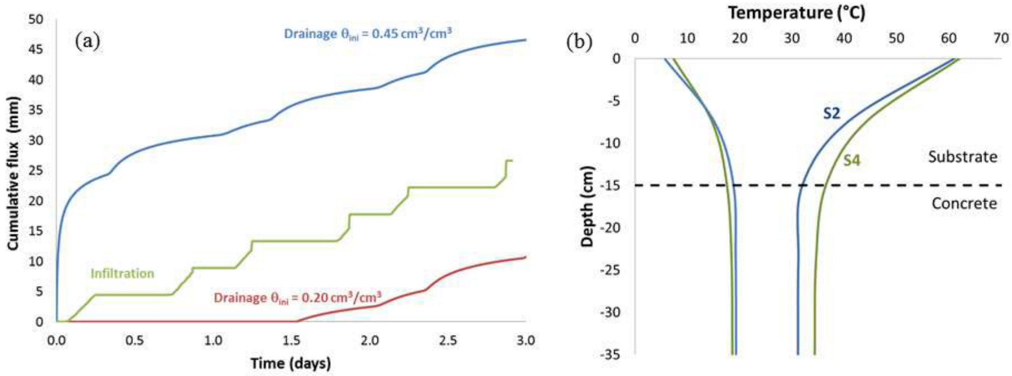


Fig. 4. (a) Cumulative fluxes in a green roof comprised by S1 substrate. (b) Temperature envelopes in the green roof for S2 and S4 substrates.

Figure 4 (b) presents the temperature envelope of the S2 and S4 substrates for the 1-month simulations that used meteorological data of November 2014. In these results, no irrigation was performed. For clarity, the temperature envelopes of the other substrates are not shown since they fall within those shown in Fig. 4 (b). At the surface of the S2 substrate, a daily thermal fluctuation of 55°C is observed, while the thermal oscillation at the bottom of the concrete is of 12°C (80% of reduction in the thermal amplitude). In the S4 substrate, a 72% of reduction in the thermal amplitude is obtained. Note that this thermal reduction should be improved when including the vegetation layer (not analyzed here because it is out of the scope of this paper). It is also interesting to observe that the S2 substrate is the one that attenuates more the thermal signal that comes from the environment, even when it has a larger thermal conductivity than substrate S3. These results suggest that the thermal behavior of the green roof not only depends on the thermal properties but also on properties related to its hydraulic behavior. Therefore, this coupling must be accounted for when defining what substrate will be used in a green roof.

4. Conclusions

In this work, the effects of the properties of green roof substrates on its performance were investigated. The hydraulic and thermal properties of the substrates were determined experimentally and then used to drive numerical simulations to understand how these properties impact green roof behavior. Experimental results showed that two of the substrates (S2 and S4) have more capacity to retain water and thus to reduce storm-water runoff. The thermal properties of the substrates under investigation were on the same order of magnitude than those of other substrates presented in the literature, with an increase in the thermal conductivity as moisture increases. Simulation results showed that the green roof behavior strongly depends on its hydraulic and thermal properties. In particular, simulations highlighted the importance of using dynamic biophysical modeling for design because of the complex interactions between the hydraulic and thermal processes that occur in these systems.

Acknowledgements

The authors acknowledge funding from the following projects: INNOVA-CORFO 12IDL2-13630; Fondecyt N°1150675; Fondecyt N°1131131, Fondecyt N°1130522 (CONICYT, Chile); and the Centro de Desarrollo Urbano Sustentable (CEDEUS - CONICYT/FONDAP/15110020).

References

[1] Saadatian O, Sopian K, Salleh E, Lim CH, Riffat S, Saadatian E, Toudeshki A, Sulaiman MY. A review of energy aspects of green roofs. Renew Sust Energ Rev 2013; 23:155–168.
[2] La Roche P, Berardi U. Comfort and energy savings with active green roofs. Energ Buildings 2014, 82: 492–504.
[3] Xiao M, Lin Y, Han J, Zhang G. A review of green roof research and development in China. Renew Sust Energ Rev 2014, 40: 633–648.
[4] Berndtsson JC. Green roof performance towards management of runoff water quantity and quality: A review. Ecol Eng 2010;36:351-360.
[5] Campbell GS, Norman J. An introduction to environmental biophysics. 2nd ed. New York: Springer; 2013.
[6] Saito H, Simunek J, Mohanty BP. Numerical analysis of coupled water, vapor, and heat transport in the vadose zone. Vadose Zone J 2006; 5:784-800.
[7] van Genuchten MTh. A closed-form equation for predicting the hydraulic conductivity of unsaturated soils. Soil Sci Soc Am J 1980; 44:892-898.
[8] Mualem Y. A new model for predicting the hydraulic conductivity of unsaturated porous media. Water Resour Res 1976; 12:513-522.
[9] Chung S-O, Horton R. Soil heat and water flow with a partial surface mulch. Water Resour Res 1987; 23:2175-2186.
[10] Li M, Barbour SL, Si BC. Measuring solid percentage of oil sands mature fine tailings using the dual probe heat pulse method. J Environ Qual 2014; doi:10.2134/jeq2014.06.0262.
[11] Bristow KL, White RD, Kluitenberg GJ. Comparison of single and dual probes for measuring soil thermal properties with transient heating. Aust J Soil Res 1994;32:447-64.
[12] Šimůnek J., van Genuchten MTh, Šejna M. Development and applications of the HYDRUS and STANMOD software packages, and related codes. Vadose Zone J 2008;7:587-600.
[13] Schneider S, Mallants D, Jacques D. Determining hydraulic properties of concrete and mortar by inverse modelling. Mater Res Soc Symp Proc 2012;1475:367-372.
[14] Brown RA, Hunt WF. Impacts of Media Depth on Effluent Water Quality and Hydrologic Performance of Undersized Bioretention Cells. J Irrig Drain Eng 2011;137:132-143.
[15] Pitt R, Clark SE. Integrated Storm-Water Management for Watershed Sustainability. J Irrig Drain Eng 2008;134:548-555.
[16] Sailor D, Hagos M. An updated and expanded set of thermal property data for green roof growing media. Energ Buildings 2011;43:2298-2303.