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An updated and expanded set of thermal property data for green roof growing media

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ABSTRACT

Vegetated (green) roofs alter the roof surface energy balance and hence affect both building energy consumption and the transport of heat into the environment. Quantitative evaluation of the energetics of green roof systems requires accurate knowledge of the moisture-dependent thermal properties of the growing media. To support this need for data and to supplement previously published data we conducted a laboratory study to measure thermal conductivity, volumetric heat capacity, and thermal diffusivity of 12 green roof soil samples of varying composition. The results indicate that thermal properties vary significantly as a function of growing media design. Growing media incorporating expanded slate as their aggregate had thermal conductivities that were two to three times those of media that used a porous silica-based aggregate. Media incorporating expanded clay as the aggregate had thermal conductivities roughly in the middle of these extremes. In general the thermal conductivity nearly tripled as the growing media moisture levels were increased from relatively dry to saturated. Also, it was found that compaction typical of green roof systems that have been installed for multiple seasons can increase thermal conductivity of moist soils by 30–40% over their uncompressed values.

1. Introduction

Vegetated (green) roofs offer a range of benefits including extended roof life [1,2], reduction in urban heat island effect [3], decrease in storm water runoff [4,5], and savings of building heating and cooling energy [6–8]. Building energy savings and urban heat island benefits of green roofs are both a result of the way in which the green roof alters the energy balance of the roof. Evaluation of the rooftop energy balance requires detailed information on both the vegetation and growing media. The study presented here focused on a laboratory evaluation of the thermal properties of the growing media (soil).

Green roof soils are composed of aggregate, sand and organic matter. Naturally occurring soils, on the other hand, are classified by their composition shape and texture as clay, sandy loam, silt, etc. Published data on thermal properties of natural soils vary widely depending on the type of soil [9,10]. Important parameters affecting thermal properties of soils include mineral composition, texture, and shape of the soil [11,12]. It is therefore difficult to infer thermal properties of green roof soils from data available for natural soils. Also, as there are many variations of growing media used in different geographical locations it is important to gather data regarding the thermal properties of a variety of different kinds of soil mixes.

Early efforts at modeling the building energy implications of green roofs commonly represented the green roof as a simple resistive layer whose thermal conductivity was essentially constant [13]. Sophisticated models of the green roof energy balance have been developed in recent years [14]. These models require input data for moisture-dependent thermal properties of green roof growing media. A preliminary study of green roof media thermal properties [15] provided such data for a small sample of eight different soils. This early study, while useful, was limited in that it focused on growing media types found mainly in the western US and also did not account for soil compaction that occurs naturally over time. The present study represents an extension of this earlier work to a much wider range of soils and also investigates the issue of soil compaction.

2. Materials and methods

Green roof soils need to be lightweight, permanent, and able to sustain plant health without leaching nutrients that may harm the environment. These soils usually contain light weight aggregate, sand, and organic matter. Actual soil mixes vary widely in terms of the volumetric ratios of each component, and many providers introduce additional soil amendments to enhance plant growth. Furthermore, the aggregate material – which typically makes up

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Table 1
Composition percent by volume of green roof soils tested and moisture holding capacity.

Sample identifier	Porous silica (%)	Expanded slate (%)	Expanded clay (%)	Compost (%)	Sand (%)	Dry density (kg/m^3)	Moisture capacity (m^3/m^3)
PS50C10	50	0	0	10	40	1.05	0.48
PS50C00	50	0	0	0	50	1.02	0.44
PS75C00	75	0	0	0	25	0.73	0.44
PS75C10	75	0	0	10	15	0.68	0.49
ES50C10	0	50	0	10	40	1.43	0.27
ES50C00	0	50	0	0	50	1.49	0.25
ES75C00	0	75	0	0	25	1.24	0.15
ES75C10	0	75	0	10	15	1.25	0.22
EC50C10	0	0	50	10	40	1.29	0.29
EC50C00	0	0	50	0	50	1.41	0.30
EC75C00	0	0	75	0	25	1.28	0.23
EC75C10	0	0	75	10	15	1.15	0.26

more than half of the growing media by volume – varies from region to region due to local availability and cost. So, in the present study we classify green roof soils based on aggregate material and nominal volume fractions (high or low) of aggregate and organic matter.

2.1. Growing media tested

In prior thermal property measurements we focused on green roof soils containing aggregates common in the western US – pumice and expanded shale [15]. In the current study we chose to test soils with expanded slate, porous silica, and expanded clay as the aggregates. Porous silica is the lightest of the aggregates tested and has the largest water absorbing potential. While porous silica is not commonly used in green roofs today its moisture holding capacity, light weight, and low thermal conductivity make it an interesting material for potential inclusion in green roof designs. Expanded slate is mostly used for green roofs in the eastern US while expanded clay is common in the mid-western and eastern US. Thus, in combination with our prior work, this new study provides a comprehensive resource for green roof thermal property data encompassing a wide range of growing media.

After the aggregate, sand is typically the next most abundant component in green roof soils, often comprising as much as 30–40% of the mix by volume. Organic matter can provide important nutrients to plants in a green roof system. Nevertheless, high levels of substrate organic matter are not recommended for green roof growing media because organic matter will decompose resulting in substrate shrinkage and can leach nutrients such as nitrogen and phosphorus in the runoff. Thus, organic matter usually constitutes less than 20%, and often less than 10% of the total volume of the growing media. Aged waste yard compost was used for this study in volume fractions of 0% and 10%.

Four growing media designs were tested for each of the three aggregate types. Two of these designs included 50% aggregate by volume and the other two included 75% aggregate by volume. For each level of aggregate volume one sample was created with 10% organic matter and the other contained no organic matter. Table 1 summarizes the composition of each test case. The first two letters in the case names correspond to the aggregate type: PS, ES, and EC for porous silica, expanded slate, and expanded clay, respectively. These two letters are followed by the volume fraction of the aggregate (either 50 or 75%) and then by the letter C for “compost” and two numbers signifying the percent composition of compost (either 0 or 10%). The soil dry densities ranged from 0.68 kg/m^3 for a porous silica mix to 1.49 kg/m^3 for an expanded slate mix. This represents a larger range of soil densities than previously tested. In the prior study the dry density of soils ranged from 0.76 kg/m^3 for a light weight pumice mix to 1.40 kg/m^3 for a mix containing expanded shale.

For each test case we created three samples and tested each at moisture levels ranging from dry to nearly saturated.

2.2. Thermal properties of soils

The present laboratory study used the same general methods used by Sailor et al. [15] to measure thermal properties. Specifically, we used a dual needle probe system based on the transient line heat source methods published in IEEE 442-1981 [16] and ASTM D5334 [17]. In this method one of the probe tips provides a line source of heat in a soil that is treated as a uniform semi-infinite medium. The heat pulse results in a temperature elevation measured at both probe locations as a function of time. The governing one-dimensional transient heat conduction equation can be solved with the resulting Bessel function solution that depends upon both thermal conductivity (k) and thermal diffusivity (D). For a needle probe with heat rate q, length $2b$ and radius a, the temperature at a radial distance r from the centerline is given by:

$$T(r,t) = T_o + \frac{q}{4\pi k}\int_{r^2/4Dt}^{\infty} R^{-1}\exp(-R)\exp\left[-\left(\frac{1}{r}\right)^2 R\right] \times I_o\left(\frac{2aR}{r}\right)\operatorname{erf}\left(\frac{b\sqrt{R}}{r}\right) dR \quad (1)$$

Here $I_o()$ is the zero order Bessel function and erf is the error function. The two measurement locations associated with the two probe system allow for simultaneous solution of both properties. The thermal diffusivity is then related to the specific heat capacity by:

$$C_p = \frac{k}{\rho D} \quad (2)$$

This method was implemented using a commercial system (KD2 Pro analyzer with 30-mm long SH-1 dual needle probe from Decagon) which automates the process of determining the thermal properties from a set of temperature measurements taken at 1 s intervals over a 30-s heating period and a 30-s recovery period. Specifically, a microcontroller approximates the solution to Eq. (1) by fitting measurements with exponential functions using a nonlinear least squares procedure. While these methods are capable of measuring thermal conductivity and specific heat capacity to within 5% [18], the natural variability in our green roof soil samples generally yields an uncertainty of ±10% in all thermal property measurements.

2.3. Water holding capacity of growing media

In the present study, three replicate samples (~700 ml each) for each green roof soil mix were tested for moisture holding capacity. These samples were oven-dried and tested for moisture holding capacity per ASTM D2216-05 [19]. The measurement averages are