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Impact of water content on the thermal conductivity of soils used in green roofs

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ABSTRACT: Green covers are used in many geotechnical applications, being made with soils having roots and other organic materials. The application of such green covers in roofs (green roofs) is becoming increasingly widespread in urban environments because of their environmental and landscape benefits. In addition, green covers can be used as a sustainable solution for thermal insulation of roof structures, however their thermal properties must be characterized for design purposes. Because green roofs are exposed to outdoor climatic actions and irrigation systems are predicted, it is important to have studies to assess the dependence between the thermal conductivity of the soil and its water content or degree of saturation. In this study, an experimental campaign was performed to assess this dependence. To this end, the thermal conductivity and corresponding suction and water content were measured on samples prepared with two types of soil used in such covers: a universal organic-based substrate and a sandy substrate for high-drainage applications. Although the variability of the results, mainly due to the presence of the roots, relationships were defined that can be used for improving the thermal design of green roofs.

Keywords: Green roofs; root; thermal conductivity; permeability

1 INTRODUCTION

Green covers are used in many geotechnical applications, such as green roofs on buildings or vegetation on slopes to prevent erosion, being made with soils having roots and other organic materials. The application of such green covers in roofs (green roofs) is becoming increasingly widespread in urban environments due to their environmental and landscape benefits. Indeed, green roofs offer several environmental, economic, and social benefits, including mitigation of the urban heat island effect, improved stormwater management, and enhanced building energy performance (Brandle, 2006; BuGG, 2025). Some of the benefits are illustrated in Figure 1. Recent European directives (EU/2024/1275 - EPBD, 2024) on building energy performance have emphasized reducing fossil fuel emissions and promoting materials with lower embodied carbon, thereby reinforcing the relevance of green roof systems.

The thermal properties of green roofs must be characterized for thermal insulation design of roof structures. Because these systems are exposed to outdoor climatic actions and irrigation systems are predicted, it is important to have studies to assess the dependence between the thermal conductivity of the soil and its water content. This dependence was investigated in this study. Then, the values found were used to investigate the impact of such knowledge on the determination of the thermal conductivity of a simple example of a roof with a basic green cover system.

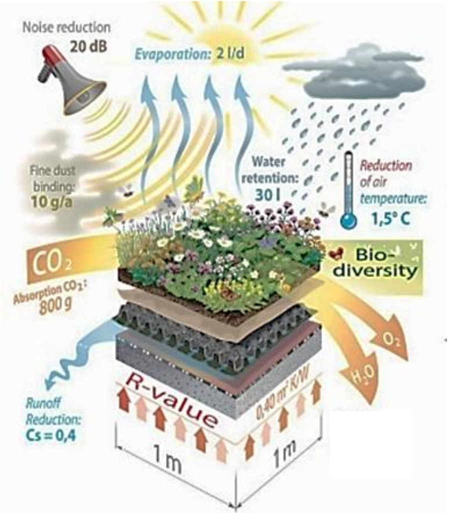

Figure 1. Advantages of green roof systems (BuGG, 2025).

2 THERMAL CONDUCTIVITY OF SOILS

Thermal conductivity represents the ability of a material to conduct heat. In soils, heat flows through the solid, liquid and gas phases, and therefore soil's thermal conductivity depends on the amount and proportion of each phase present. For reference, the solid thermal conductivity varies between 1.4 to 3 W/m/K, for distilled water is around 0.591 W/m/K and for dry air is around 0.024 W/m/K, all values for 20ºC and 1 atmosphere (Farouki, 1981).

Fixing porosity, several expressions can be found in the literature to relate thermal conductivity λ with the degree of saturation S_r, assuming parallel, series or geometric average arrangements for the different phases (Farouki, 1981). Nevertheless, other alternatives are based on the saturated and dry thermal conductivity values, such as the equation (1) proposed by Johansen and adopted in this work:

$$\lambda = \lambda_{dry} + {S_r}^m(\lambda_{sat} - \lambda_{dry}) \qquad (1)$$

where λ_{dry} and λ_{sat} are the soil's thermal conductivity when dry or fully saturated, respectively, S_r is the degree of saturation, and m is an empirical exponent typically taken between 0.5 and 1 (Farouki, 1981).

The degree of saturation can easily be related with water content w by using equation (2):

$$S_r = \frac{G_s}{e} w \qquad (2)$$

where e is voids ratio and G_s is the relative density of the solid particles. In this work it was assumed constant volume (constant e) for all measurements.

3 MATERIALS AND METHODS

3.1 *Materials*

The thermal conductivity for different water contents was measured on samples prepared with two types of soils typically used in green covers (Figure 2): a universal organic-based substrate (SIRO Plant Silver); and a sandy substrate (SIRO Cactus). The saturated permeability was measured as well.

Figure 2. Soils used

SIRO Plant Silver is rich in roots and other organic matter (>85% by dry weight), has more than 85% of particles smaller than 10 mm and the average volumetric weight of the solid particles is 4.70 kN/m³ (G_s=0.47).

SIRO Cactus has less quantity of roots than SIRO Plant Silver (about 50% by dry weight). This soil has more than 95% of particles smaller than 10 mm and less than 15% of fines (particles smaller than 0,075 mm). The mineral particles presented are mainly silica and the average volumetric weight of the solid particles is 5.20 kN/m³ (G_s=0.52).

3.2 *Samples preparation*

To simulate realistic conditions observed in green roof systems, the samples of each soil were prepared with two different dry volumetric weights γ_d: 3.5 kN/m³ and 4.0 kN/m³. Each soil was compacted into PVC cylinders (7 cm diameter × 14 cm height) using manual compaction, with gravimetric water content w=30%. The soils were dried at 60°C for 24h before preparing the samples, to avoid organic combustion that would occur if drying would be done in the oven (105ºC). This temperature allowed removing free water and control the mass of solids in each sample, knowing that it is very difficult to work with materials rich in organic matter. Further details can be found in Garcia (2025).

Four different water contents were tested for each volumetric weight and each type of soil, using two replicates per condition. Besides full saturation (by immersion in tap water for 24h), three different water contents were applied: water content after compaction, achieved after vapour equilibrium under the relative humidity of 75% (saturated solution prepared with NaCl, following Romero (2004), see Fig 3a) and dried under 60ºC after compaction. The water content was measured after final drying under 60ºC for 24h.

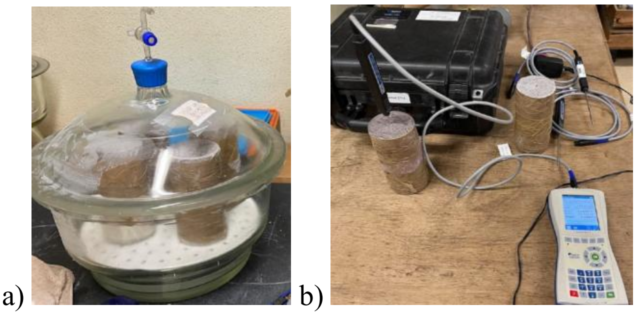

Figure 3. a) Vapour equilibrium; b) ISOMET equipment

3.3 *Saturated hydraulic conductivity*

Saturated permeability was measured in samples prepared specially for this purpose (8 cm diameter × 5 cm height), one for each soil and dry volumetric weight. Equipment KSAT was used, from METER (2021), performing a constant water head test.

3.4 *Thermal conductivity*

ISOMET device was used to measure thermal conductivity (Fig 3c), with thermal probes to perform measurements covering different ranges of values. Measurements were done using the needle probe method, based on ASTM D5334-22 (2022). This technique uses a needle probe with an internal resistive wire and temperature sensor to analyse heat dissipation in the soil.

The probe is a steel needle 10 cm long and 2.3 mm diameter inserted into the soil. Especial care was taken to ensure uniform contact between it and the soil, particularly for the SIRO Plant Silver soil, as it showed variable thermal behaviour due to high organic content and root inclusions.

4 RESULTS

4.1 Saturated Permeability

The saturated permeabilities measured for the two soils are presented in Table 1. The values are typical of silty soils and decrease with increasing dry volumetric weight, as expected. The differences are less marked for soil SIRO Catus, possibly because this soil exhibits large collapse when saturated. In addition, it has smaller number of roots than the other soil. The presence of roots may interfere with voids geometry, creating gaps between the root fibbers through which water can flow easily. The presence of roots may also increase compressibility, and therefore void ratio reduces with compaction, also reducing permeability.

Table 1. Saturated permeability measured (m/s).

SOIL	γ_d=3.5 kN/m³	γ_d=4.0 kN/m³
SIRO Plant Silver	3.86×10^{-5}	1.34×10^{-5}
SIRO Cactus	2.73×10^{-5}	2.18×10^{-5}

4.2 Thermal conductivity

The thermal conductivities measured for all the unsaturated samples of the two soils is presented in Figure 4. This figure also presents the fitting curves using Equation 1, adjusted to minimize quadratic error, fixing m=0.5 for simplification. The void ratio and fitting parameters for each case are in Table 2.

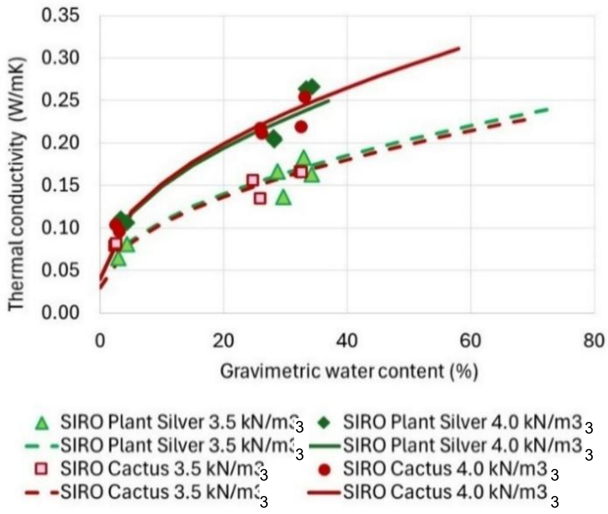

Figure 4. Thermal conductivity vs water content

As expected, thermal conductivity (λ) increases with increasing water content. It is higher when dry volumetric weight is 4.0 kN/m³ because it is when void ratio (e) is the smallest, and therefore the contribution of the solid phase is the largest. The contribution of the solid phase explains the largest values observed for SIRO Cactus soil as well. The void ratios (e) for this soil are smaller than those of the other soil because of the largest volumetric weigh of the solid particles. In SIRO Cactus soil there are more mineral particles and less organic matter than in the other soil.

Considering curve fitting, although the water content was measured following the standard method, the dry density when preparing the samples was determined considering the samples dry at 60ºC and not 105ºC, therefore affecting void ratio and consequently of the degree of saturation.

The contribution of the solid phase also explains the smallest valued of λ_{dry} estimated for the denser samples of the two soils. This value increases naturally in the presence of water, explaining the larger values of λ_{sat} when compared with λ_{dry}.

Table 2. Calibration parameters (voids ratio e, thermal conductivity λ, and empirical exponent m)

SOIL		γ_d=3.5 kN/m³	γ_d=4.0 kN/m³
SIRO Plant Silver	e	0.343	0.175
	λ_{sat} (W/mK)	0.24	0.25
	λ_{dry} (W/mK)	0.03	0.04
	m	0.5	0.5
SIRO Cactus	e	0.486	0.300
	λ_{sat} (W/mK)	0.26	0.31
	λ_{dry} (W/mK)	0.03	0.04
	m	0.5	0.5

The thermal conductivities measured in the saturated samples are presented in Table 3. These samples were disturbed by the thermal probe before being saturated, because they were the samples with the compaction water content where this parameter was measured.

Table 3. Saturated thermal conductivities (λ_{sat} in W/mK)

SOIL	γ_d=3.5 kN/m³	γ_d=4.0 kN/m³
SIRO Plant Silver	0.476	0.576
SIRO Cactus	0.454	0.490

Although the same features were observed when the saturated soils are compared with the unsaturated ones, i.e., the values increase with increasing dry volumetric weight or decreasing void ratio, the values measured for SIRO Cactus are smaller than those measured for SIRO Silver Plant. This may be explained by experimental error and collapse caused by saturation, being collapse more marked for SIRO Silver Plant soil. In addition, all samples had lost soil during immersion. The values were not included in Figure 4 because of these errors

Finally, it is worth to note that the saturated values measured and estimated by curve fitting are small when compared with the values expected for solids, being closest to those of water (around 0.6 W/mK). This is explained by the presence of roots and other organic matter, which have large amount of water in their composition.

5 IMPACT ON ROOFS

The relationship between the saturated and dry thermal conductivities fitted numerically varied between 5 and 10 (Table 2). Their impact on realistic configurations of green roofs was evaluated in the analysis of the standard cross section of a green roof presented in Figure 5, in which several materials can be identified. The impact of the water content on the thermal transmittance of the green roof, U, can be computed using equation 3:

$$U = \frac{1}{Rsi+\sum\frac{d_i}{\lambda_i}+RSe} \qquad (3)$$

where λ_i are the thermal conductivities of the different materials, d_i is their thickness, and Rsi (0.10 m^2K/W) and Rse (0.04 m^2K/W) are the thermal resistances of the interior and exterior surfaces, respectively. The values adopted are presented in Table 4. For the soil, it was assumed the largest and smallest thermal conductivities found in the numerical adjustment of the experimental values measured for the two soils (Table 3).

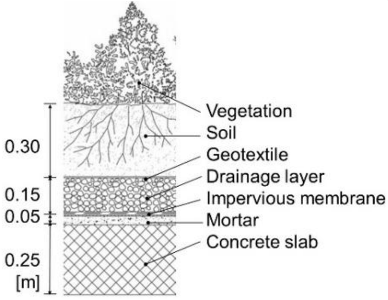

Figure 5. Standard cross section of a green roof

Table 4. Values adopted for the calculations of U (Brandle, 2006; Farouki, 1981)

Material	d (m)	λ_{dry} min (W/mK)	λ_{sat} max (W/mK)
Soil	0.30	0.030	0.320
Drain	0.15	0.200	2.000
Geotextile (wool)	0.01	0.020	
Impervious layer (asphalt)	0.01	0.170	
Mortar (thermal insulator)	0.05	0.200	
Reinforced concrete	0.25	1.700	
XPS Insulation	0.15	0.033	

The value of U varies from 0.084 W/Km^2 to 0.468 $W/K\ m^2$ (average value is 0,276 W/Km^2) when the soil is dry and full saturated, respectively. Such difference confirms the impact on this physical property of the degree of saturation of the soil (and drain).

For comparison purposes, U is equal to 1.678 W/Km^2 if only the concrete slab, the mortar and the impervious asphalt would be considered, which is very high. This value reduces to 0.195 W/Km^2 if an insulation material, such as EPS, is placed above the concrete slab, mortar and impervious membrane. If a green cover is adopted instead of the EPS thermal insulator the values found for U improve the performance of the roof, independently from the degree of saturation of the soil. However, the green cover solution is only better than EPS thermal insulator when the soil is dry, therefore a proper drainage is necessary for the soil.

6 CONCLUSIONS

The experimental study performed allowed defining an empirical relationship for the thermal conductivity of two soils used in green roofs with different dry volumetric weights. The results confirm the importance of considering the degree of saturation in the design of green roof solutions, because the relationship between the saturated and dry thermal conductivities varied between 5 to 10. They were consistent despite some intrinsic experimental error, associated to the difficulty of preparing samples of soils with a significant percentage of roots and organic matter. The exercise done to study the impact of such knowledge on a standard roof section showed that green covers improve the thermal performance of unprotected roofs independently from the degree of saturation of the soil, however the solution is only better than adopting a thermal insulator material when the soil is dry. Nevertheless, although green covers may be less effective than the adoption of thermal insulator materials, they offer several environmental, economic, and social benefits, including mitigation of the urban heat island effect, improved stormwater management, and enhanced building energy performance.

7 ACKNOWLEDGEMENTS

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