2 LITERATURE REVIEW

The aim of this study is to understand the effect of SWC on the thermal performance of green roofs; with the overall objective of determining the effectiveness of green roofs under various climatic conditions. This chapter defines green roof thermal performance for the purpose of this study; and reviews the soil thermal properties that may affect it. The effect of SWC on the latter is elaborated upon, with the aim of understanding its role in regulating the thermal properties of green roofs. A summary of research questions concludes this chapter.

2.1 Thermal performance of green roofs

In general, thermal performance of green roofs is either defined as the ability of green roofs to reduce energy consumption for winter heating and summer cooling (Sailor *et al*, 2008; Castleton *et al*, 2010); or the ability of green roofs to mitigate the UHI effect (Alexandri and Jones, 2007). In this study, the ability of a green roof to lower the cooling demands of a building is of interest; and is measured indirectly as its ability to reduce the average daily temperature (T_{ave}) incident on a roof, as well as its ability to reduce the amplitude (A) of daily temperature fluctuations incident on a roof.

Figure 2-1 is an artificial simulation of typical temperature time series data over a 24 hour period for the study area in summer. The data was simulated using a simple sine curve. It compares the behaviour of a normal roof to that of a green roof. T_{ave} and A are typically lower for green roofs. If one assumes that, at any point in time, air conditioner energy consumption is proportional to the difference between the temperature incident on the roof surface and the desired indoor temperature, then it can be shown that lower values for T_{ave} and A will result in lower energy demands. This effect is illustrated in Figure 2-2; and the reasoning follows below. Here, T_{ave} is expressed as ΔT, where ΔT is the difference between T_{ave} and the desired indoor temperature.

The human comfort zone ranges from 23.5-25.5 °C in summer (Olesen, 2004). The desired indoor temperature was therefore taken to be 24.5 °C for this exercise. Outdoor temperature (i.e. temperature incident on the roof surface) time series data was simulated for a range of scenarios with varying values of T_{ave} and A using simple sine curves. The period of oscillation was set to 24 hours. Energy consumption was calculated at hourly intervals, and summed over the 24 hour period. Energy consumption was artificially equated to |outdoor temperature - 24.5 °C| at any given hour. This is not an accurate expression of energy consumption in kWh, but rather aims to qualitatively illustrate the pattern of energy consumption as a function of A and ΔT (where $\Delta T = T_{ave}$ - 24.5 °C).

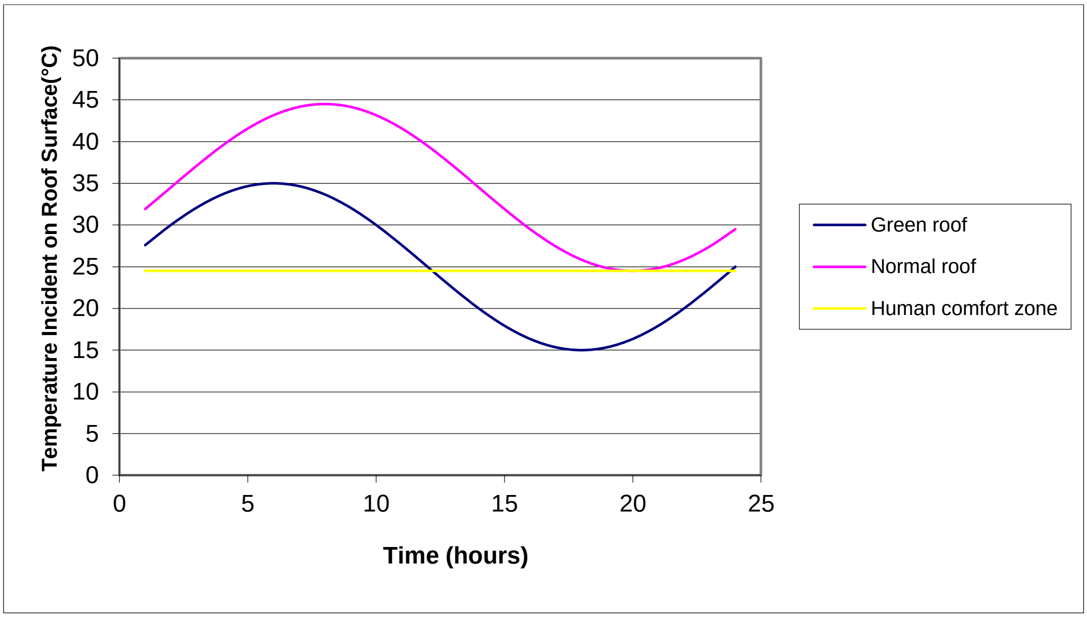

Figure 2-1: Typical temperature behaviour over a 24 hour period for the study area in summer. The data compares a normal roof to a green roof. T_{ave} and A are typically lower for green roofs. The data was artificially simulated using simple sine curves.

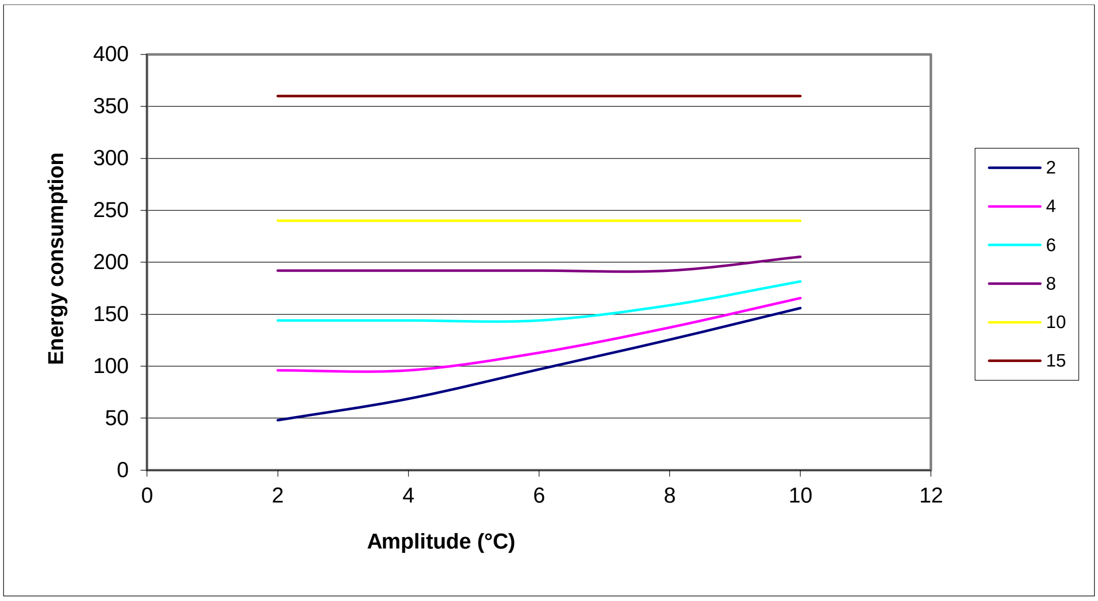

Figure 2-2: Energy consumption as a function of A and T_{ave}. Here, T_{ave} is expressed as ΔT, where ΔT is the difference between T_{ave} and the desired indoor temperature (chosen to be 24.5 °C). Energy consumption was artificially equated to |outdoor temperature - 24.5 °C| at any given hour, and summed over a 24 hour period. This was done for various temperature time series scenarios with differing values of A and T_{ave}. It can be seen from these simulations that energy consumption decreases with a decrease in A and/or ΔT.

2.2 Factors affecting the thermal performance of green roofs

Factors (Figure 1-5) identified as affecting the thermal performance of green roofs are evapotranspiration (Liu and Baskaran, 2005; Jim and Hongming He, 2010), shading (Liu and Baskaran, 2005), insulation (Del Bario, 1998; Liu and Baskaran, 2005) properties of the soil and foliage, and increased thermal mass (Liu and Baskaran, 2005).

Of interest here is the effect of SWC on thermal performance. Attention is therefore placed only on those factors directly influenced by SWC; namely evapotranspiration rates, insulation properties of the soil, and soil thermal mass. What follows is a review of the soil thermal properties that govern thermal performance, and how SWC in particular affects these thermal properties. The effect of SWC on evapotranspiration rates is also discussed.

2.2.1 Soil thermal properties and their effect on thermal performance

The transfer of heat within soil is governed by various thermal properties such as soil temperature, heat content, heat capacity (C), thermal conductivity (K_q) and thermal diffusivity (D_q). While K_q is used to quantify the steady state heat flow, D_q is used to present non-steady state heat flow phenomena in soil. D_q is expressed as the ratio of K_q and C_v (Hanks and Ashcroft, 1980):

$$\boldsymbol{D_q = K_q / C_v} \qquad \text{Equation 2-1}$$

Where C_v is the volumetric heat capacity.

Volumetric Heat capacity (C_v)

The C_v of soil is the amount of heat needed to increase the temperature of a unit volume of soil by one degree ($J.m^{-3}.\ ^oC^{-1}$). C_v depends on the constituents of the soil's solid phase (the mineral and organic components present), the soil's wetness, and the bulk density. Volumetric heat capacity can be expressed as (Hanks and Ashcroft, 1980):

$$\boldsymbol{C_v = 0.8 \times 10^3\ \rho_b\ + 4.2 \times 10^6\ \theta_v\ \frac{J}{m^3.℃}} \qquad \text{Equation 2-2}$$

Where ρ_b is the bulk density of soil and θ_v the volumetric water content (VWC) of the soil.

The volumetric heat capacity of water is $4.2 \times 10^6\ J.m^{-3}.^oC^{-1}$ and all other soil constituents have much lower heat capacities (Baver *et al.,* 1972). Table 2-1 displays C_v values of selected soil constituents.

Table 2-1: Volumetric heat capacities of soil constituents (at 10°C)

Constituent	**C_v (J.m^{-3}.°C^{-1})**
Sand (dry)	1.3×10^6
Sand (saturated)	2.6×10^6
Quartz	2.0×10^6
Other minerals (average)	2.0×10^6
Organic matter	2.5×10^6
Water (liquid)	4.2×10^6
Air	1.3×10^4

Sources: Hillel (1980); Hukseflux Thermal Sensors (1999)

Saturated sand, water and organic matter have relatively high C_v values. Since soils are mainly composed of mineral particles, organic matter and water, it is apparent from the table that these constituents will significantly affect the heat capacity (Hanks and Ashcroft, 1980).

The higher the heat capacity of the soil, the more heat is required to raise the temperature of the soil, and the longer the soil will take to lose its heat in cold conditions. Higher heat capacities therefore moderate T_{ave}; keeping soil cooler in summer, and warmer in winter. Higher heat capacities are also expected to lower A, by moderating extreme highs and lows in temperatures.

Since heat capacity increases with increasing SWC, it is expected that an increase in SWC will lead to a decrease in both T_{ave} and A.

Thermal conductivity (K_q)

The movement of heat in soil is strongly influenced by water content and temperature (Jim and Tsang, 2011). Some of the solar radiation from the sun passes through the soil profile through conduction. Conduction of heat is mostly affected by SWC. Heat readily moves from soil to water rather than from soil to air. Soil is composed of weathered rock particles, void spaces and water. The voids between soil particles contain either water or air. As the SWC increases, the air decreases (Brady, 1974). Being a liquid, water has more particle contact in the empty spaces connecting soil particles. Thus, it is an excellent thermal conductor. As the water content increases, its thermal conductivity also increases as there is sufficient water to link most of the soil particles (Evans, 2010).

Hillel (1980) defines thermal conductivity (K_q) as the quantity of heat transferred through a unit area in unit time under a unit temperature gradient:

$$\mathbf{K_q = - Q_q/(At \times \delta T/\delta z)} \qquad \text{Equation 2-3}$$

Where Q_q is the quantity of heat, A is the unit area, t is the unit time, and $\delta T/\delta z$ represents the temperature gradient.

As displayed in Table 2-2, K_q of particular soil constituents vary distinctly. Thus K_q is dependent on a soil's mineral composition, organic matter content, and in addition, the volume fractions of water and air. The K_q of air is very small compared to that of water and soil solids, hence a low SWC (or high air content) relates to low K_q values (Hillel, 1980). Furthermore, K_q changes with time since the fractions of SWC and air continuously fluctuate. As the soil depth increases, the composition of the soil constituents changes, so that K_q is also a function of depth.

Table 2-2: Thermal conductivities of soil constituents (at 10°C)

Component	**$J.s^{-1}.m^{-1}.^{o}C^{-1}$**
Sand (dry)	0.15-0.25
Sand (moist)	0.25-2.00
Sand (saturated)	2.00-4.00
Clay (dry to moist)	0.15-1.80
Clay (saturated)	0.60-2.50
Soil (with organic matter)	0.15-2.00
Quartz	8.8
Other minerals (average)	2.9
Organic matter	0.25
Water (liquid)	0.57
Air	0.025

Sources: Hillel (1980); The Engineering Toolbox (2011)

The same factors which affect C_v also affect K_q but the degree of change in K_q is larger than in C_v. In the field, C_v may change threefold while K_q changes a hundredfold or more (Hillel, 1980). This is explained by the fact that thermal conductivity is depended upon the volumetric proportions of the soil's solid, liquid and gaseous phases. The size, shapes, spatial arrangement of the soil solids and the boundary relationships between the liquid and solid phases further affect K_q.

The type of soils and their characteristic air porosity values likewise affect K_q with values in the order of peat < clay < loam < sand. These differences are due to the configuration in which soil particles are packed and the porosity of the specific soil type. Thermal conductivity decreases as the size of the particles decreases because there is a reduction in the surface contact among the particles across which heat will easily flow (Baver *et al.*, 1972). K_q can also be calculated as (Hanks and Ashcroft, 1980):

$$K_q = D_q \times C_v \quad (J.s^{-1}.m^{-1}.\,^{o}C^{-1}) \qquad \text{Equation 2-4}$$

Since thermal conductivity is the quantity of heat transferred through a unit area in unit time under a unit temperature gradient, an increase in K_q is expected to lead to an increase in T_{ave} and A, as the moderating effect of the soil will be reduced. K_q increases with increasing SWC, therefore increasing SWC will lead to an increase in T_{ave} and A.

2.2.2 Evapotranspiration and its effect on thermal performance

Evapotranspiration results in a rise in the activity of soil-water molecules. Heat absorption from the encompassing environment is enhanced and the corollary is a cooling effect of the soil (Brady, 1974). Research in China has shown that through evapotranspiration, 58% of heat can be lost from a green roof (Feng *et al*, 2010). Evapotranspiration, besides avoiding heat flow into the building, also acts as a docile cooler by eliminating heat from the building (Lazzarin *et al*, 2005).

SWC determines the quantity of heat used in the process of evapotranspiration by plants. In Italy it has been indicated that more than twice the amount of heat is lost through evapotranspiration in a wet soil than in a dry soil (Lazzarin *et al*, 2005). Since heat lost through evapotranspiration increases with SWC, it is expected that an increase in SWC will result in a decrease in T_{ave}.

2.3 Effect of SWC on thermal performance indicators

In summary, an increase in SWC is expected to lead to:

- an increase in C_v, and hence a decrease in T_{ave} and A;
- an increase in K_q, and hence an increase in T_{ave} and A; and
- an increase in heat lost through evapotranspiration, and hence a decrease in T_{ave}.

The effective influence of SWC on thermal performance is therefore not clear, as competing factors are at play; and their relative influence is unclear.

2.4 Research questions

1. *What* is the effect of SWC on the thermal performance of green roofs i.e. what is the effect of SWC on T_{ave} and A?
2. *How* does SWC alter the thermal performance of green roofs i.e. what is the effect of SWC on C_v, K_q and Evapotranspiration; and how do the various factors compare i.e. out of the three, which is the dominant factor affecting thermal performance of green roofs?
3. Are green roofs feasible under all climatic conditions? Specifically, are green roofs as effective in low summer rainfall areas as in high summer rainfall regions?
4. What factors can one adjust to optimize thermal performance in differing rainfall regions?
5. How important is SWC in terms of design and management of green roofs?