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Weather effect on thermal and energy performance of an extensive tropical green roof

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ABSTRACT

This study investigated the weather effect on thermal performance of a retrofitted extensive green roof on a railway station in humid-subtropical Hong Kong. Absolute and relative (reduction magnitude) ambient and surface temperatures recorded for two years were compared amongst antecedent bare roof, green roof, and control bare roof. The impacts of solar radiation, relative humidity, soil moisture and wind speed were explored. The holistic green-roof effect reduced daily maximum tile surface temperature by 5.2 °C and air temperature at 10 cm height by 0.7 °C, with no significant effect at 160 cm. Green-roof passive cooling was enhanced by high solar radiation and low relative humidity typical of sunny summer days. High soil moisture supplemented by irrigation lowered air and vegetation surface temperature, and dampened diurnal temperature fluctuations. High wind speed increased evapotranspiration cooling of green roof, but concurrently cooled bare roof. Heat flux through green roof was also weather-dependent, with less heat gain and more heat loss on sunny days, but notable decline in both attributes on cloudy days. On rainy days, green roof assumed the energy conservation role with slight increase instead of reduction in cooling load. Daily cooling load was 0.9 kWh m^{-2} and 0.57 kWh m^{-2}, respectively for sunny and cloudy summer days, with negligible effect on rainy days. The 484 m^2 green roof brought potential air-conditioning energy saving of 2.80×10^4 kWh each summer, equivalent to electricity tariff saving of HK\$$2.56 \times 10^4$ and upstream avoidance of CO_2 emission of 27.02 t at the power plant. The long-term environmental and energy benefits could justify the cost of green roof installation on public buildings.

Introduction

Green roofs can serve as surrogate green spaces in urban areas dominated by artificial structures and surfaces (Arnold and Gibbons, 1996). Many cities, especially the compact ones, have adopted this innovative way of extending urban greening into otherwise bare rooftops. Green roofs are well known for their wide range of environmental, ecological, social and economic benefits (Emilsson, 2006; Mentens et al., 2006; Oberndorfer et al., 2007). With rapid urbanization and aggravation of the urban heat island (UHI) effect in recent years, the thermal and energy performance of green roofs has attracted the attention of researchers, professionals, civil servants and citizens.

Many empirical and modelling studies of green roofs have been conducted in different climatic zones and cities of different sizes and development modes. The findings demonstrate notable green-roof contribution to lowering roof surface and ambient air temperature, reducing transmission of solar heat through the roof slab into indoor space, and trimming building cooling load (Takakura et al., 2000; Papadakis et al., 2001; Akbari, 2002; Wong et al., 2003a,b,c; Sonne, 2006; Santamouris et al., 2007; Wong et al., 2007a,b; Spala et al., 2008; Eumorfopoulou and Kontoleon, 2009; Teemusk and Mander, 2009; He and Jim, 2010; Jim and He, 2010; Williams et al., 2010). Cooling is attributed to the combined effect of evaporation from soil, transpiration from plants, shading by plants and substrate, and insulation by the soil and drainage layers with constituent moisture (Harazono, 1990/91). Summer cooling could range from 15 to 45 °C in daily peak surface temperature and 2–5 °C in peak air temperatures. Energy saving in air-conditioning electricity in summer could amount to 10–80% for individual buildings (Getter and Rowe, 2006).

Besides cooling, green roofs can bring environmental and social benefits. The living vegetation can filter or absorb air pollutants to improve air quality. The soft vegetation cushion, in conjunction with soil, can serve as a noise barrier. The soil and vegetation layers can clean and reduce stormwater discharged from buildings to improve water quality and abate flood hazard (DeNardo et al., 2003; Villarreal and Bengtsson, 2004; VanWoert et al., 2005). The vegetated roofs attract wildlife and flora to the above-ground habitats and stepping stone sites to enhance urban biodiversity (Brenneisen, 2004; Burgess, 2004). Buildings with well-designed and maintained green roofs can fetch higher rental and sale values.

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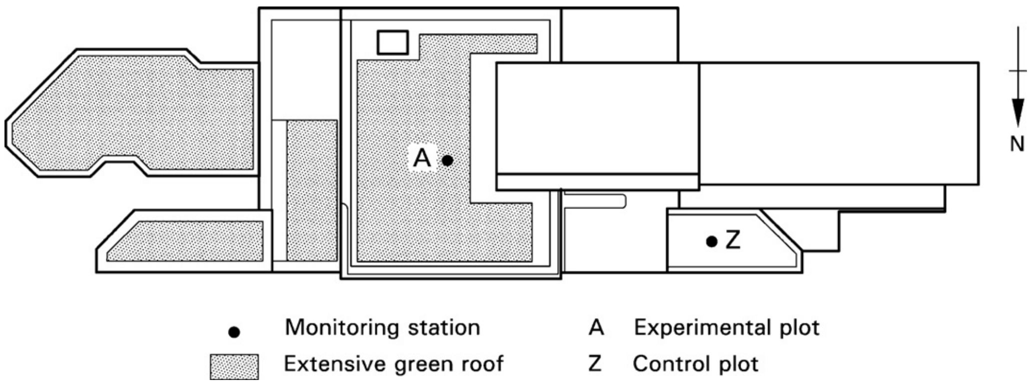

Fig. 1. Locations of the green roof experimental plot (*A*) and the bare control plot (*Z*) on the top of the Tai Po Railway Station.

The elevated green spaces provide recreational and amenity venues in semi-private or private grounds. Home-owners can enjoy outdoor life in a safe, clean, secluded and serene setting. Offices and factories with pleasant green roofs can attract and retain workers, who tend to be happy, healthy, productive and loyal. Due to multiple environmental, economic and social benefits, green roofs offer a promising, welcomed and cost-effective contemporary technology for buildings.

A modern green roof is composed of multiple layers of synthetic and natural materials installed in sequence from the bottom upwards: root barrier, drainage, filter, substrate, and vegetation. The first three layers are synthetic, manufactured and durable materials; the last two are natural. Two major types of green roofs, extensive and intensive, are distinguished by vegetation height and biomass structural complexity, which require different soil depth. The more common extensive green roof is usually covered by herbs, grasses or drought-tolerant succulent plants such as *Sedum* species. The intensive green roof embraces trees and shrubs often planted closely. The extensive green roof usually has 2–20 cm of substrate, and the intensive, over 20 cm (Oberndorfer et al., 2007).

Characterized by an exceptionally compact urban morphology, Hong Kong suffers from severe shortage of ground-level green spaces and intense UHI effect. The green-space deficit has degraded the quality of the urban environment and associated quality of life (Jim, 2004, 2008). Most of the 40,000 odd high-rise buildings mainly with flat reinforced-concrete rooftops have adequate load-bearing capacity to receive green roofs. Thus urban Hong Kong has a huge potential to embrace the green-roof innovation (Tsang and Jim, 2010). Empirical studies of thermal performance could throw light on underlying factors and processes, furnish hints to optimize design, and offer an objective basis to promote green roofs (Niachou et al., 2001; Köhler et al., 2002; Köhler, 2004). More local or regional studies in the humid-subtropical context could be attempted, as the results from other climatic zones may not be directly applicable.

The railway station at Tai Po covers a large area with significant demand on air-conditioning energy to cool the indoor space in summer. Installing a green roof could bring thermal and energy benefits, reduce cooling load and improve landscape and amenity values. This study focuses on the weather effect on green roof thermal and energy benefits with three specific objectives:

(1) Explore the impacts of the green roof on summer daily surface and air temperature;
(2) Evaluate the influence of meteorological variables on green-roof thermal behaviour; and
(3) Analyse green-roof thermal performance on the days representative of typical summer weather conditions.

Comparing with the literature, this study is different in two aspects:

(1) Evaluate green-roof thermal effect with reference to a comprehensive range of summer weather conditions covering sunny, cloudy and rainy days; in contrast, most studies concentrate on sunny days; and
(2) Acquire antecedent environmental monitoring of the experimental site for one year before green roof installation to permit longitudinal comparisons between before and after scenarios.

Study area and method

Study area

Hong Kong is situated at the south coast of China, at 22°N latitude and 114°E longitude with a typical humid-subtropical climate influenced by the dominating Asian monsoon climatic system. The summer is hot and humid with frequent showers and thunderstorms and occasional typhoons. It extends from late April to September, with August the hottest month often exceeding 33 °C. The rainy season largely covers summer with annual rainfall over 2000 mm. The winter is relatively short and mild, running from January to February with average temperature above 10 °C. The long-hot period vis-a-vis the relatively short-cool period indicate summer cooling as a priority in sustainable urban design to usher environment and human health.

An extensive green roof was retrofitted in July 2009 on the Tai Po railway station situated in a suburban new town in Hong Kong. The station is a one-to-two storey low-rise structure facing the platform and tracks. The large flat rooftop is composed of several parcels with different elevation and area (Figs. 1 and 2). This study enlists the largest plot (the experimental site with green roof) which is square in shape with 484 m^2. A nearby plot (the control site with original bare roof), with 106 m^2, provides a baseline for comparison.

Experimental design and environmental monitoring

The modern extensive green roof (Figs. 3 and 4) was installed on the reinforced-concrete flat-roof protected by a waterproofing membrane, screed and cement tiles. A proprietary multiple-layer green-roof system (Nophadrain, Kirkrade, the Netherlands) was laid directly on the tile surface with a 2% gradient to shed drainage water. From bottom to top, it contains five layers: plastic (polyethylene) root barrier, plastic (high impact polystyrene) drainage (2.5 cm), geotextile filter, rockwool water retention (5 cm), and growing medium (5 cm). The soil mix is composed of mineral soil (locally derived completely decomposed granite) mixed with 20% (v/v) mature compost. It has a sandy loam texture (with around 78% sand, 10% silt and 12% clay) and granular structure (Soil Survey Staff, 1999) to facilitate free drainage and aeration, with a water holding capacity of about 20% (v/v), and pH range of 5.5–5.8. It has been