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Attenuating heat stress through green roof and green wall retrofit

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ABSTRACT

The process of rapid urbanisation is becoming problematic due to the reduction in, and lack of compensation of, previously vegetated areas. With a combination of green roofs and green walls, adopted on a large scale, it is possible to attenuate the urban heat island effect and internal temperatures in buildings. Tall buildings are becoming a common housing type in many cities, and considering the role of external walls in heat gain, it is expected that the combination of green roofs and green walls have great potential to improve thermal performance. As only 1-2% is added to the total stock of buildings annually, the focus should be on the retrofit of existing buildings to deliver maximum thermal benefits. In the present work lightweight, modular vegetated systems were adopted for roofs and walls. Instead of considering only the temperature influence in heat stress, this research adopted the use of heat index that encompasses the combined effect of temperature and relative humidity. For this purpose, the thermal benefits of green roof and green wall retrofit is evaluated in two small scale experiments, where identical prototypes (vegetated and non-vegetated) are compared using block work and timber framed drywall structures for Rio de Janeiro, Brazil and Sydney, Australia, respectively. The results show a different understanding in heat stress evaluation regarding heat index rather than temperature itself, especially under high levels of relative humidity. This evidence demonstrates green roof and green wall retrofit offer a proven role in heat stress attenuation in residential buildings.

1. Introduction

Increased urbanisation has led to a worsening in the quality of life for many people in large cities, in respect of the urban heat island effect and increases of indoor temperatures in housing and other buildings. The total urban population is predicted to increase from 7.3 to 9.7 billion people by 2050 [1]. In terms of the concept of Urban Heat Islands (UHI), many suburban and urban areas experience elevated temperatures when compared to their outlying rural surroundings. The annual mean air temperature of a densely populated city can be between 1 and 3 °C warmer than the surrounding areas, and on a clear, calm night, this temperature difference can reach 12 °C [2]. As temperatures and populations increase, urban air quality worsens and the potential for increased health issues around heat stress grow, especially for older people. Despite rapid urbanisation and population growth, typically only 1–2% is added to the total stock of buildings annually, and therefore the focus for the maximum benefit for UHI mitigation lies with retrofitting existing buildings with vegetation applied to walls and roofs. These structures are known as green roofs and green walls. When building envelopes are covered with green roofs and green walls there is a great potential to attenuate the UHI effect [3–7]. According to Herreira-Gomes [8] and Yaghoobian and Srebric [4] green roofs are an alternative way to mitigate climate change effects.

Compared to traditional roof surfaces typically covered with bitumen, asphalt or steel sheeting which are directly exposed to the sun, retrofitted green roofs can attenuate housing temperature [9], and this is attributed to the reduction in thermal conductivity [10–13]. However, in residential external walls exposed to the sun and, especially in tall buildings, where wall areas are much greater than roof areas, it is expected the role of green walls in mitigating extreme temperatures is significant. Thus, the combination of green roofs and green walls is expected to promote better thermal performance in residential building envelopes. This research sought to explore to what extent this was the case, using a modular vegetated system as a retrofit covering for walls and roofs.

It is important to analyse the heat effect in terms of human impact, since heat stress may affect populations with adverse health consequences. According to Robinson [14], integration of meteorological elements must be used for the human evaluation of heat effects. The estimate of human heat exposure is based on environmental studies that use indices to capture the combination of several weather factors [15]. Steadman's apparent temperature [16–18] is one of the most popular

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indices for environmental health research. It combines air humidity and temperature into a single scale; adopting the same units as air temperature. The calculation of apparent temperature, based on original Steadman equations, requires the iteration of multiple equations that take into account heat and moisture transfer. Steadman [16] carried out this calculation for the combination of air temperature and moisture, expressed in terms of relative humidity (RH) or dew point temperature, summarised in table format. Further details on how the principles of physiological heat regulation are used to include the effects of humidity and temperature in determination of heat index (HI) values for a specific weather condition is presented in Steadman [16]. As an alternative to the use of Steadman's tables, Anderson [15] identified 21 algorithms that have been developed to reproduce HI values. One of these algorithms, based on Steadman's theory, is used by the United States (US) National Weather Service (NWS) to provide the base for heat warnings and is adopted in the present work.

The HI is a combination of RH and air temperature, which provides the apparent temperature in degrees Celsius or Fahrenheit. This index is used by the National Weather Service (NWS), an agency part of National Oceanic and Atmospheric Administration (NOAA) of the US government, responsible for providing weather forecasts and hazardous weather warnings. According to the Occupational Safety and Health Administration (OSHA), US Department of Labor, the HI can be used to indicate the risk of heat-related illness. Danger and Extreme Danger categories are associated with risk levels that vary from high to very high/extreme risk levels, whereas Caution and Extreme Caution represent low to moderate risks respectively.

This work evaluates the role of extensive, or shallow soil, green roof and green wall technologies in heat stress attenuation. As in previous studies [19–21], vegetation parameters such as substrate, foliage height and leaf area index (LAI) were not taken into account. However, the characteristics of the vegetation used in the experiments lie among previous works carried out by Pandey et al. [22]; Wong et al. [23]; Djedjig et al. [24]; Wong et al. [25] and Lazzarin et al. [26].

According to Pandey et al. [22] in experiments performed in prototypes, foliage height is related to the degree of shading of soil surface, and the lower the foliage height the higher the heat transfer. The combination of foliage height with the density of the vegetation is a crucial factor in thermal performance. As stated by Djedjig et al. [24], the shading effect of foliage decreases substantially the surface temperature of the building envelope. Additional studies corroborate a direct relationship between LAI and the thermal performance, showing a significant influence of foliage density on the thermal behaviour of green roofs [27–31].

In general, vegetation increases the thermal performance, quantified by the U-value of roofs and external walls. Also known as the overall heat transfer coefficient, this parameter indicates the heat transfer through a surface and higher values indicate low insulating levels. According to Wong et al. [25], when compared to a non-thermal insulating building, a roof covered by a 100 mm soil substrate, vegetated with turf reduces the U-value from 2.39 to 1.19 W/m^2K. In addition, for extensive green roofs with soil depths varying from 50 to 100 mm, Nichaou et al. [19], Alcazar & Bass [32] and Castleton [33], demonstrated the role of vegetation in reducing U-values. Castleton [33] stated that besides insulation, the vegetated surfaces provided by green roofs and green walls add thermal mass, which is the material capacity to store or absorb energy, providing inertia against temperature fluctuation that results in temperature peak delay in vegetated structures when compared to non-vegetated ones.

In addition to the role of affecting heat loss through the evapotranspiration process, the water content in soils influences their thermal conductivity and thermal mass. Alcazar and Bass [32], Castleton [33], Lazzarin et al. [26], Wong et al. [25], Lin et al. [34], Ouldboukhitine et al. [35] and Sun et al. [13] found that thermal performance worsens in wetter soils, as water is a better conductor of heat than air. In comparison to traditional roof design, Lazzarin et al. [26] stated that the thermal performance of green roofs under dry conditions reduces the influx of heat by 60%. However, when the soil is wet evapotranspiration plays an important role, acting as a heat sink [5,35–37]. The water content in vegetated structures seems to regulate the heat flux simultaneously by altering the conductivity condition of soils, and indirectly through evapotranspiration of the plants. According to Castleton [33], the water content regulates the heat outflow when the evapotranspiration process is considerable.

Considering that RH plays a relevant role in establishing HI values, any extra moisture supply provided by evapotranspiration, which may migrate into the vegetated structures, contributes to increase the RH levels, counteracting the internal temperature attenuation promoted by the plants.

The HI, also known as the apparent temperature, is the combination of what the temperature feels like to the human body when air moisture and temperature are combined. This has important considerations for human body comfort [15]. Rather than temperature itself, HI is used in the evaluation of heat stress in small-scale experiments, where identical prototypes (vegetated and non-vegetated) are compared using blockwork and timber-framed structures for Rio de Janeiro, Brazil and Sydney, Australia respectively.

Both countries are predicted to be affected severely by increased temperatures in the coming decades as climate change impacts. It will be necessary to retrofit many existing buildings, in a relatively short time frame. Furthermore, many developing countries will be severely affected by increased temperatures [38] and this research aimed to test lightweight, low-cost systems that could be used for retrofitting without the need for additional structural reinforcement to most existing wall and roof types. The research objective was to develop and test practical solutions that can be retrofitted quickly when needed. This paper sets out the rationale for the research design and the experimental setups, focussing on the implementation of low-cost, affordable technologies. The results of the experiments are presented, followed by a discussion of the datasets before conclusions are drawn.

This proposal focussed on affordability and low maintenance aspects. Low-income groups are far more vulnerable to heat stress, which also impacts on health and well-being. As a result, both experimental setups made use of simple technologies. In Rio de Janeiro, the materials came from recyclable resources, reusing vaccine boxes for the vegetated system on the walls. In Sydney, the use of document holders, available at stationery stores formed the vertical plant holders. For both sites, low-cost plastic trays were used for the vegetation on the roofs. The Sydney trays were fabricated using 3D printers. These materials were accessible, simple and affordable. Adoption of accessible, simple and affordable materials enables the application of these types of vegetated systems on a large scale and is not restricted to the service of specialised companies. He et al. [39] planted succulents in a modular rooftop system and found these plants to provide excellent insulation. Similar studies corroborate this [31,36,40,41]. Ease of and low maintenance were important criteria and succulent plants were used due to their drought-resistant characteristics, low risk of fire, and ability to grow in shallow substrates that do not require structural reinforcement to many typical existing roof and wall structures.

2. Research methodology and experimental design

This research adopted a quantitative experimental approach to data collection. The methodology comprises the use of adaptive building technologies to assist in mitigation of problems caused by increased urbanisation and climate change, such as the UHI effect and increased internal housing temperature.

Given that temperature increase and rapid urbanisation occur mainly in developing countries, low-cost techniques based on lightweight modular systems (modular containers) that enable off-site planting, cultivation and maintenance were adopted. Due to increasing building density in urban areas, envelopes may become more relevant