International Journal of the Physical Sciences Vol. 6(1), pp. 65-73, 4 January, 2011
Available online at http://www.academicjournals.org/IJPS
DOI: 10.5897/IJPS10.664

Full Length Research Paper

Study on rooftop outdoor thermal environment and slab insulation performance of grass planted roof

Han-Hsi Liang[1] and Kuo-Tsang Huang[2]*

[1]Department of Architecture, National United University, No. 1, Lien-Da, Miaoli 36003, Taiwan.
[2]Department of Landscape Architecture, National Chiayi University, No. 300 University Rd., Chiayi City 60004, Taiwan.

Accepted 31 December, 2010

The benefits of rooftop greening are ascertained in thermal perspective. It effectively reduces the near surface ambient temperature and the reflected irradiation from the rooftop slab, thus increasing the thermal comfort environment above the lawn and reduces the heat transferred through the rooftop slab. The former effect enables the potential usage of the rooftop spaces for human activity and helps to alleviate the urban heat island effect while the latter is able to reduce the interior space cooling load especially in subtropical climate. A field experiment was carried out in the subtropical central Taiwan to quantify these two performances. Indices of Mean Radiant Temperature (MRT), Wet Bulb Globe Temperature (WBGT), and heat flux rate were used to explain and discuss the performance of thermal comfort and heat flux of the rooftop lawn. The results confirmed that rooftop lawn contributes benefits both on its outdoor surrounding environment and the indoor energy beneath.

Key words: Grass planted roof, thermal environment, slab thermal insulation.

INTRODUCTION

Taiwan which central is located right on the Tropic of Cancer is a fast developed and over populated island. The climate here is of subtropical climate characteristic. High concentration of buildings is commonly seen in many urban districts, which result in various urban environmental issues, such as lacking enough recreation areas, low urban greenery cover ratios, and moreover, the urban Heat Island Effect (UHI). Green roofs (or planted roofs) as an extension of urban green areas and recreational open spaces not only provide visual aesthetic, they also contributes to the thermal benefits in buildings and their surrounding environments.

There are direct and indirect effects of green roof from thermal perspective. The direct effects of green roof are their thermal benefits in reducing surface temperatures of roofs and heat transfer into the rooms underneath. It will directly contribute to improving the indoor thermal environment and thermal performance of buildings.

Indirect effects of green roofs refer to its potential thermal impacts on surrounding environment. It will contribute to creating better outdoor thermal environment and mitigating the UHI effect (Wong et al., 2003).

Besides, because most of the rooftop zones are private estate, low maintenance is usually required to sustain a rooftop garden. Extensive roof greening style such as lawn or turf greening is a much favorable and feasible solution due to its lower maintenance and lower initial cost benefits. Incentives from the government were recently also proposed to encourage rooftop greening in Taiwan. This is why the lawn planted rooftop is therefore chosen for studying in this research. Although several studies on green roofs regarding its thermal impacts on the environment have been carried out worldwide (Niachou et al., 2001; Theodosiou 2003; Wong et al., 2003; Kumar and Kaushik, 2005; Lazzarin et al., 2005; Wong and Li, 2007; Wong et al., 2007; Dvorak and Volder, 2010; Jim and He, 2010; Teemusk and Mander, 2010), they are limited to certain locations, climate and planting types. These data are not directly applicable to the subtropical environment.

The objectives of the research are as follows:

*Corresponding author. E-mail: keith@mail.ncyu.edu.tw. Tel: +886-5-2717636. Fax: +886-5-2717634.

Figure 1. A five meter square lawn planted area with 13 cm substrates underneath were created at the centre of a building's rooftop.

1. To investigate the environment thermal comfort enhancement over the rooftop lawn greening.
2. To understand thermal insulation performance of the rooftop lawn greening which contributes to the reduction of interior heat gain.

The first subject intend to quantified the reduction of ambient temperature and the surrounding long-wave radiation due to the rooftop lawn, which is essentially the two key factors that affect the people's willingness of using rooftop for recreational purpose. The second subject attempts to quantify the interior heat gain reduction amount on its insulation perspective.

METHODOLOGY

An experiment field of lawn greening were established on top of a four-story student center building located in National Chiayi University at Chiayi City, Central Taiwan, where its latitude is of 23.6°N. Five meter square lawn planted area with 10 cm growing medium was created at the center of the rooftop to avoid any rooftop object shading overlaid (as shown in Figure 1). The surface material of the rooftop exposed slab is grey concrete tile which is a very common material used for flat roofs' surface construction in Taiwan. Material layers that comprise the original rooftop construction from top to down are 5 cm concrete tile, 2 cm polystyrene insulation, 1 cm polyurethane membrane, and 18 cm reinforced concrete. The overall thermal conductivity (U-value) of the original rooftop slab is estimated 0.99 W/m²K with horizontal outdoor and indoor near-surface air-film resistance included. Space underneath the rooftop experiment field is a public unconditioned corridor.

Cynodon dactylon was chosen as the rooftop lawn to plant over the 10 cm-thick Finland KEKKILÄ peat moss studied herein, because of its drought and heat enduring as well as fast growing features. Furthermore, an additional 3 cm perlite layer for drainage was placed below the growing medium separated by a thin nonwoven layer. Therefore a minimum of 13 cm thick lawn grass layer paved over the original concrete rooftop was constructed. Manual irrigation was performed consecutively in the past one week when there was no natural precipitation to wet the grass.

The experiment last for over a year and was carried out from 8th September, 2008 to 9th October, 2009. The comparative set (that is, control set) of the experiment without rooftop greening located about five meters away from the lawn planted field was also carried out simultaneously (Figure 2).

Deployment of instruments

The experiments in the research comprises two sections, one is for studying outdoor thermal comfort and another is for understanding the effect of indoor heat flux reduction.

For experiment of outdoor thermal comfort, two sets of instruments were placed above the lawn and the exposed slab respectively. Each set includes sensors for measuring globe temperature (T_g), dry-bulb temperature (that is, ambient temperature)(T_a), relative humidity, wind velocity (W_V) and naturally ventilated wet-bulb temperature (T_{nwb}). All the sensors were horizontally aligned at one meter height above the ground surface, as shown in Figure 3. Instruments used herein includes calibrated T-type thermocouples placed in the white louver shelters for measuring ambient temperature, black globe thermometers for measuring Tg, omnidirectional hotwire air speed transmitters for measuring wind velocity. Naturally ventilated wet bulb temperature could be obtained via placing cotton-wrapped Pt100 sensor within

Figure 2. The comparative set of the experiment.

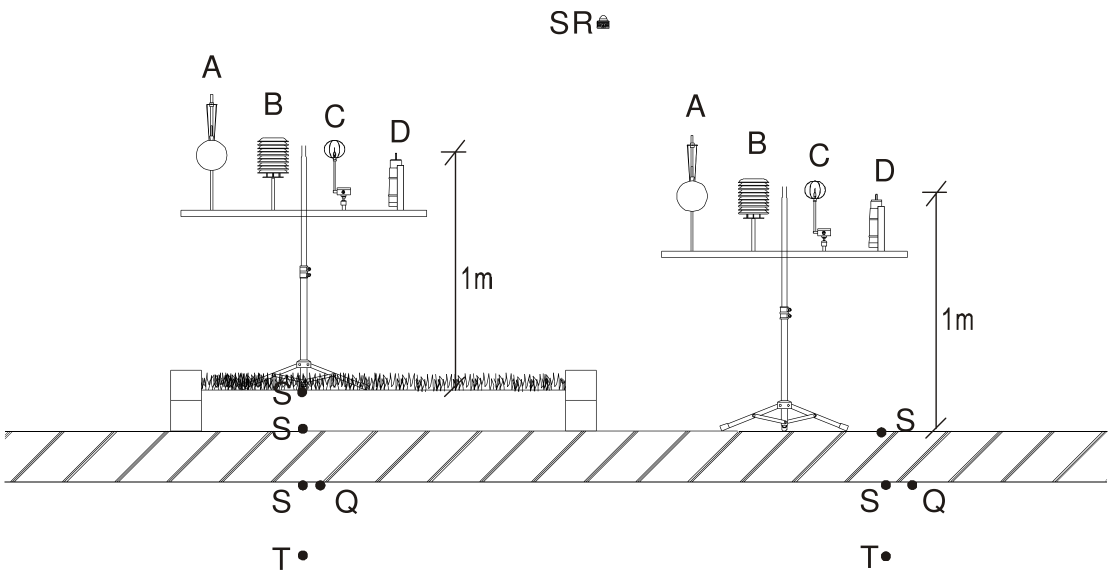

Figure 3. Sensors used and their deployment in the field. (A: globe temperature, B: ambient temperature and relative humidity, C: wind velocity, D: naturally ventilated wet bulb temperature, S: surface temperature, Q: heat flux, SR: solar radiation).

two third water filled vacuum stainless bottles. Moreover, pyranometer was installed to record the incident total horizontal solar radiation that reaches to the experiment field. All the measured values from the above instruments were simultaneously recorded at an interval of 10 s by a Delta GL-800 data logger.

For experiment of indoor heat flux, another two sets of instruments were deployed above and under the floor slab both with and without lawn conditions. Thin heat flux sensors were seamlessly attached beneath the floor slab with aluminum foil cover over it to prevent heat intervention from the corridor making sure the measured values only accounts for heats that transferred through/from the floor slab. Moreover, to further understand the fluctuations of the surface temperature of the slab due to lawn greening, several T-type thermocouple wires were placed above and beneath the floor to fetch values of their surface temperature, as shown in Figure 3. The indoor ambient temperatures were also taken measured by hanging thermocouples five centimeters under the floor slab ceiling.

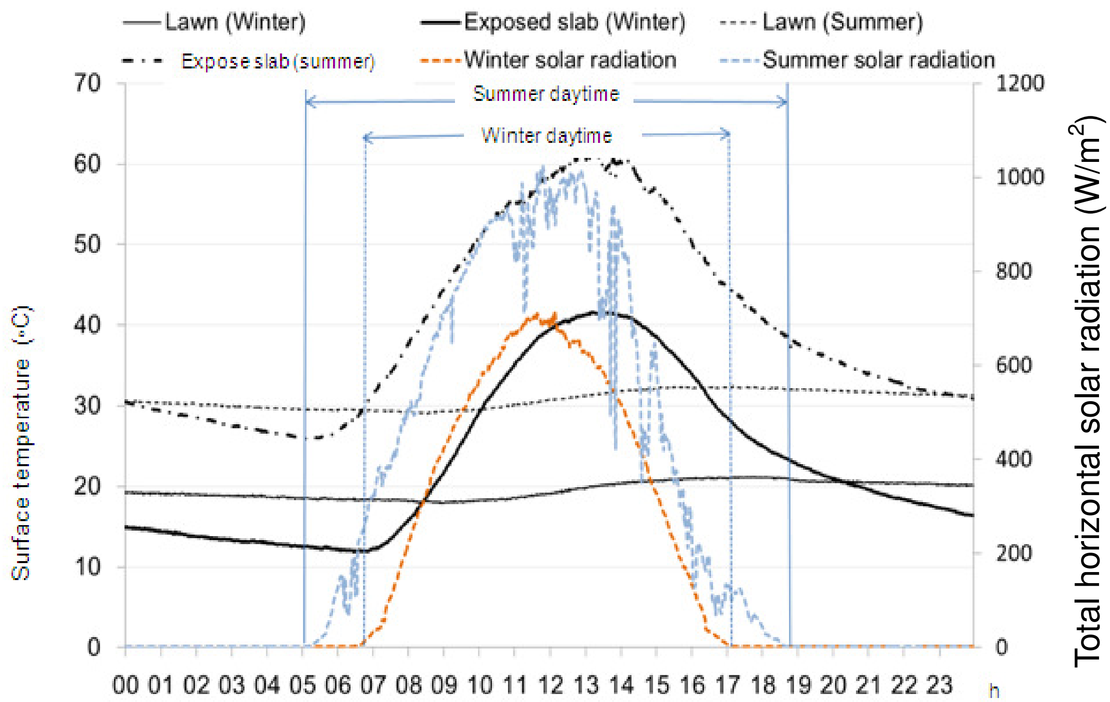

Figure 4. Surface temperature variation above slab in different seasons.

Indices for interpreting thermal comfort

There were two indices used to describe thermal environment. The mean radiant temperature (MRT) is a key variable in thermal calculations for the human body. It is the uniform temperature of an imaginary enclosure in which radiant heat transfer from the human body equals the radiant heat transfer in the actual non-uniform enclosure (ASHRAE, 2005). The simplified calculation method of MRT can be easily obtainable using several physical measured parameters as described in Equation1. The MRT index is closely related to parameters including T_g, T_a and W_v. It can efficiently responses the long-wave radiation from surrounding environment enclosure, which is considered the most influential factor to human comfort sensation. Furthermore, the energy balance of one's body is highly responsive to changes in MRT and is more suitable and direct for describing human's thermal sensation.

$$MRT=T_g+0.237\times(W_v)^{0.5}\times(T_g-T_a) \tag{1}$$

The wet bulb globe temperature (WBGT) index is widely used for estimating the heat stress potential of industrial environments concerning activity status. It is a composite temperature used to estimate the overall effect of temperature, humidity, and solar radiation on humans. Parameters of T_a, T_{nwb}, and T_g are each multiplied by a corresponding weighted values to calculate WBGT index as in Equation 2 (Dukes-Dobos and Henschel, 1973; ISO 7243, 1989).

$$WBGT=0.7\times T_{nwb}+0.2\times T_g+0.1\times T_a \tag{2}$$

RESULTS AND DISCUSSION

Although the experiment lasts for one year, it is rather difficult to process such a huge amount of data; therefore, typical day was selected for analysis. The day in which ten days before it was without precipitation or cold draft or other exceptional weather conditions is considered a typical day to rule out unusual weather influences. Moreover, the daily averaged differences of dry-bulb temperature, wind velocity and total horizontal solar radiation of the typical day should all fall between 1% margin compare to long-term recorded seasonal data. According to the above criteria, 10th December, 2008 and 10th June, 2009 were selected as typical days for further analysis each representing winter and summer respectively.

Surface temperature variation

The slab surface diurnal temperature variation of the typical days selected for winter and summer were plotted as shown in Figure 4. The daily averaged total horizontal solar radiation intensity were 176.1 (W/m²) and 288.4 (W/m²) for winter and summer cases. It showed that the variation patterns from the two seasons, either with or without lawn, were of similar shape. The major difference was its absolute values. By comparing the surface temperature drop in winter, temperature decreased more on the exposed slab surface than on the lawn soil surface. With the similar variation pattern observed from Figure 4, therefore, for the discussion, only the selected typical day of summer was discussed afterward.

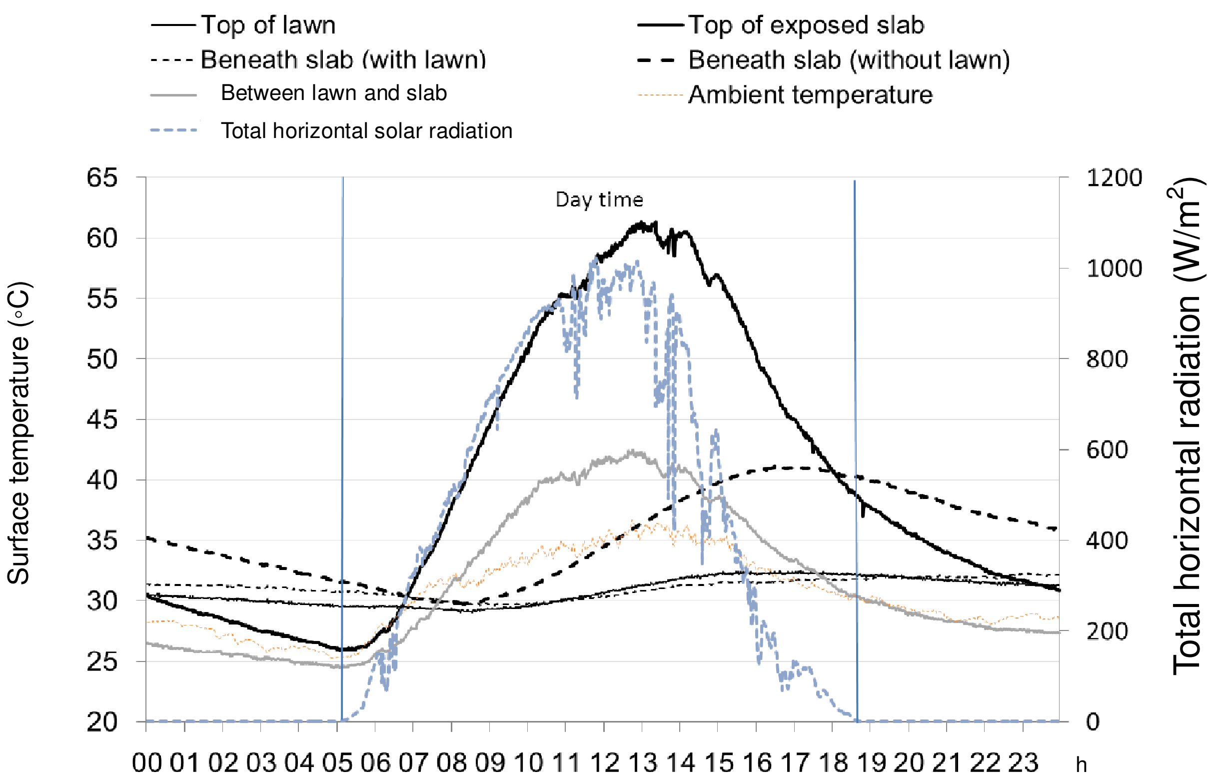

Figure 5. Diurnal surface temperature variation in summer.

Figure 5 revealed that while without lawn greening, the maximum temperature of the exposed slab surface could reach 61.3℃ which occurred at seven minute later when solar radiation was at its daily high of 1015 W/m² at 12:52. The maximum daily variation of surface temperature was 35.4℃. For lawn planted area, the surface temperature measured during daytime was not as high as that of the exposed slab surface. The maximum surface temperature of lawn field was around 32.4℃ and the maximum daily variation of surface temperature was only 3.5℃ which was much lower than those measured on the exposed slab surface. The reason could be due to the combination effect from the grass leaf shading and the evaporation of moisture in the soil.

As for the surface temperature beneath the exposed floor slab, maximum surface temperature of 41.1℃ occur at 17:06, at which time it was delayed for about four hours when its top surface temperature reaches its maximum value. For lawn planted area, maximum surface temperature of 32.3℃ occurs at 23:04, at which time it was delayed for around 10 h in comparison to that of the exposed slab. It indicates that with a 13 cm substrate layered lawn greening on top of the roof could extend the time lag of sub-surface temperature to around six hours. With this effect it could also alleviate the daytime indoor heat gain by delaying heat transfer into space.

Outdoor thermal comfort performance

On the discussion of outdoor thermal comfort of spaces between above lawn and above exposed concrete slab, T_g, MRT index, WBGT index, ambient temperature and relative humidity measured at one meter height above both conditions were compared. The daily averaged ambient temperature above the lawn was 0.24℃ lower than the exposed slab condition. After sunset there was significant reduction of ambient temperature above the lawn planted area and lasted till the next day sunrise. It indicated that the lawn constantly lowered the ambient temperature during non-solar-radiation period. Maximum difference of 2℃ was observed at around 7:00.

The comparison of relative humidity measured at one meter height above exposed slab surface and lawn planted area is shown in Figure 6. When at night time, lower relative humidity was observed above the lawn planted area with a maximum difference value of 10.48% in comparison to that of the exposed slab. But when in daytime it was a bit higher by around 5%, it could be due to the grass vigorous transpiration in daytime that slightly moisturize the surrounding air.

Based on the T_a, T_g, and W_V measured at one meter height, the MRT above the exposed slab surface and lawn area were calculated. The T_g represents the integrated effects of radiation and wind. The measured T_g

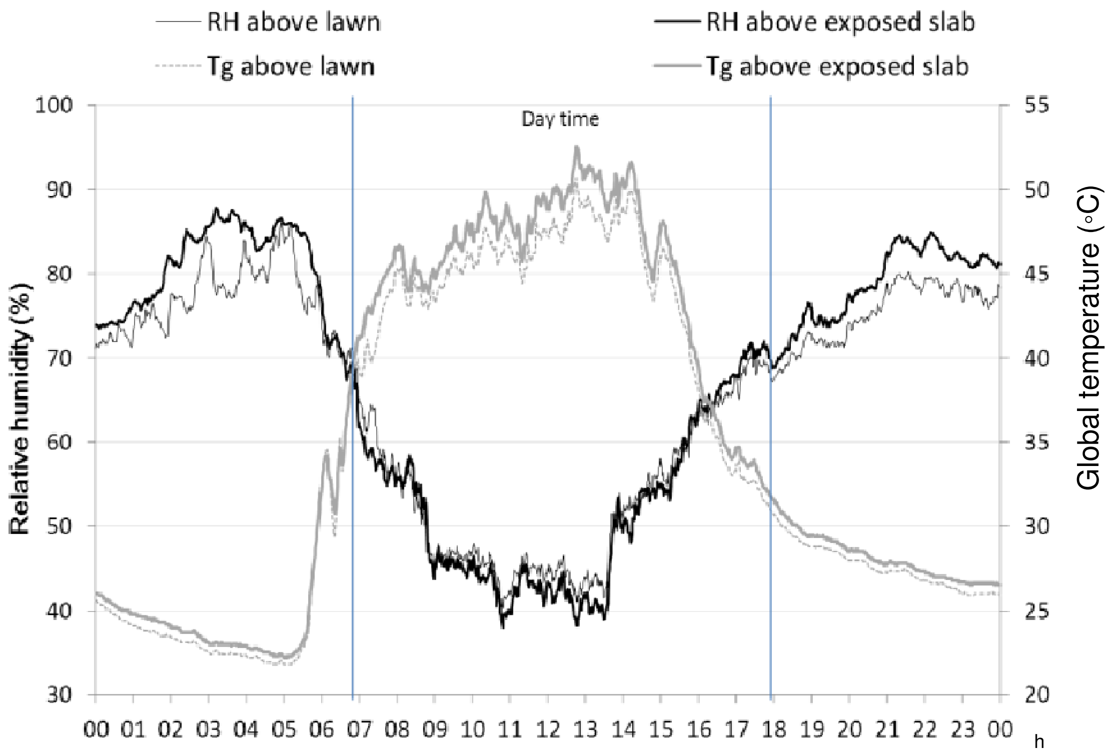

Figure 6. Diurnal relative humidity and globe temperature variation in summer.

and calculated MRT were plotted in Figures 6 and 7 respectively. There were obvious differences in T_g and MRT between both conditions. Maximum differences of T_g and MRT, 2.6℃ and 3.19℃, occurred at 13:18 when the solar radiation was the strongest. It was due to the fact that surface temperature on the exposed slab was relatively higher than that of the lawn planted surface, thus it caused long-wave radiation to be emitted a lot more from the exposed slab surface resulting in higher T_g and MRT. This indicated that lawn planted field was able to provide more comfortable environment for outdoor activities than with exposed slab conditions during daytime.

On the other side, during night time, heat dissipation was more quickly on the exposed slab surface than on the lawn planted area, which led to drastic surface temperature drop on the exposed slab surface. Without solar radiation, the radiation part of T_g and MRT mainly depended on the amount of long-wave radiation emitted from surrounding surfaces. When in early morning, around 6:00, surface temperature on the exposed slab surface reached to a maximum difference of 3℃ lower than the lawn planted area, and subsequently resulted in 0.7℃ of T_g and 0.87℃ of MRT lower than that of planted area.

WBGT was also studied in this research, providing more overall view on the heat stress issue that relates to thermal comfort. The calculated WBGT was drawn in Figure 7 together with MRT overlaid. According to regulations from Taiwan Council of Labour Affairs, maximum WBGT of 30.6℃ for continuously light work load activity is recommended. With the above criteria, from sieving the calculated WBGT during working hours (that is, from 8:00 to 18:00), there was 52.3% for planted condition and 63.5% for exposed slab conditions that would fell out of the criteria. That is, there was 11.2% higher probability unable to meet the criteria on above exposed slab surface than on above lawn planted area.

Furthermore, according to Hwang and Lin (2007), a research of defining semi-outdoor thermal environment comfort zone for Taiwan, the result reveals that while MRT is between 21 to 47℃ is considered comfortable. From this point of view, there was a probability that of 24.79% the MRT within a day above the lawn would fall out the comfort zone. When compared to the MRT above the exposed slab, there was 31.74% probable of falling out the comfort zone, which is 6.95% higher. All the fell-out period was between 8:00 to 16:00.

Indoor heat flux fluctuation

On indoor heat flux, a considerable rate of heat flux was observed under the floor slab with exposed slab on top. The maximum heat flux, 48.5 W/m², was found at 17:07, which was five hours later when daily maximum total

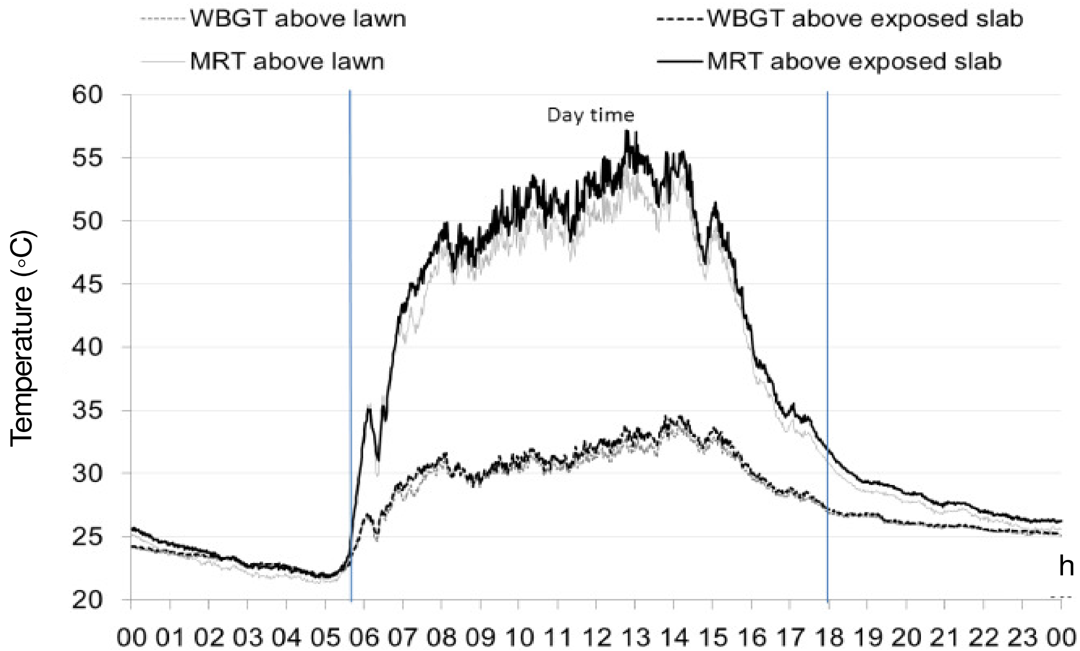

Figure 7. Calculated MRT and WBGT variation on a summer day at the height of 1 m.

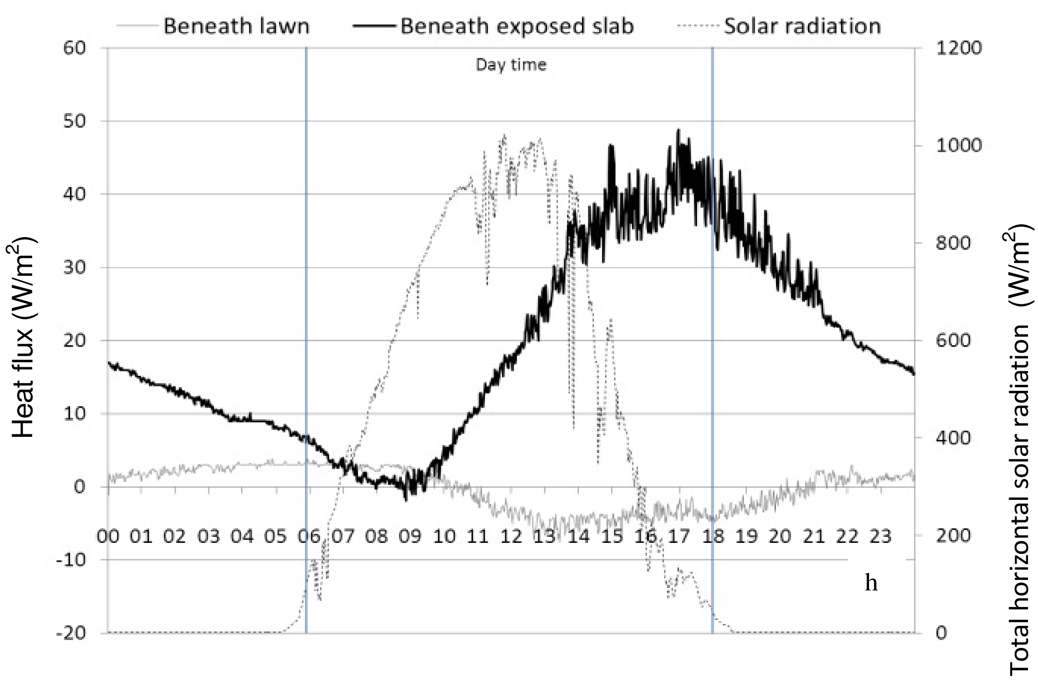

Figure 8. Diurnal heat flux variation comparison.

horizontal solar radiation occurred. Heat gain was observed nearly all day long, except there was around five minute periods at 8:50, in which heat loss was encountered. Diurnal heat flux variation range could reach up to 50.7 W/m², as indicated in Figure 8.

For the area with lawn planted condition, most heat flux observed underneath the floor slab during daytime was of negative values, that is, the space was encountering heat loss. The heat loss began at approximate 10:00 and continued till around 21:00 at night, which had positive

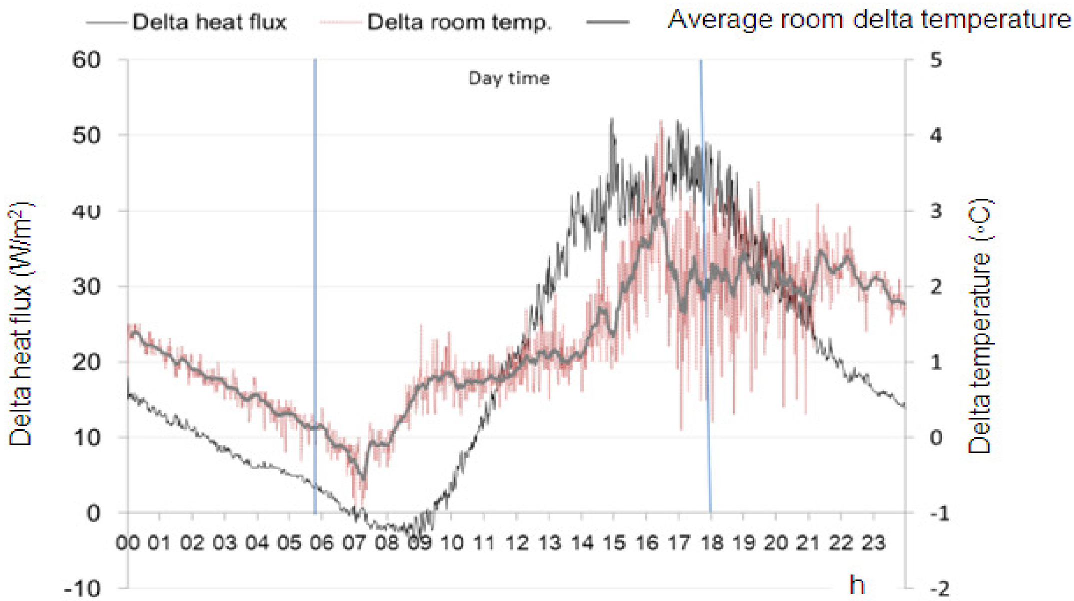

Figure 9. Diurnal heat flux and indoor temperature difference.

influence on reducing indoor cooling loads during work hours in daytime. Consecutive indoor heat gain occurred during the time other than heat loss period, which was mainly at night.

There was apparent time lags regarding heat gains under lawn planted area, as indicated in Figure 8. Solar heat gain received on top of the lawn surface during daytime was lagged for nearly 14 h when it began to transfer into the interior space. In comparison with the exposed slab condition, there was only approximate four hours' lag. It indicated that with lawn planted above the rooftop, the interior space underneath would not instantly respond to the solar radiation heat gain from the top of roof during daytime. Thus, the spaces that resulted underneath the lawn planted area were less responsive to outdoor climate, and were beneficial to the interior cooling energy reduction.

The diurnal variation range of heat flux under lawn condition was 11.4 W/m², which was only around one fifth amount comparing to the exposed slab condition, and moreover, the peak heat flux was not apparent. The total cumulative heat gain of a day was -0.25 W/m² with lawn planted condition and was 19.21 W/m² without lawn planted. The lawn had a significant influence on the amount of heat flux transferred. This was possibly due to grass leafs' sun blocking effect and the heat dissipation in substrate layer by both heat absorption and evaporation effect.

Figure 9 shows the differences of transferred heat flux and indoor room temperature between with and without lawn conditions. Maximum indoor temperature difference, 4.2℃, was detected at around 16:00 which corresponded to the maximum heat flux difference, which is around 50 W/m², occurring time. Comparison between Figures 8 and 9, shows that the lawn planted layer provides a good heat storage as well as heat dissipating means, reducing the fluctuation range of indoor temperature and transferred heat flux. The interior space underneath the lawn planted roof would have more stable indoor climate which significantly contributed to improve indoor thermal comfort and also reduced air-conditioning energy consumption.

Conclusions

In this research, comparisons of outdoor thermal comfort performance and indoor heat flux between lawn planted area and exposed slab area were made through investigating onsite field experiments in subtropical central Taiwan. Both with and without lawn planted experiment field on top of roof were established and were simultaneously measured for a yearlong for studying various parameter' reduction effect. Various parameters including physical measurements and calculated indices studied in the research are tabulated in the amount of reduction term as indicated in Table 1 for better understanding. Conclusions drawn from this research are as follows:

1. The planted lawn provides excellent solar radiation block to the rooftop slab, which greatly reduces transient heat flux through the rooftop slab and leads to lower surface temperature under the lawn panted slab.
2. Cooling effect from the lawn was confirmed by comparing the T_a drop. Lower ambient temperature of

Table 1. Reduction summary of varies parameters.

Parameters	Unit	Whole day			10:00-22:00 h		22:00-10:00 h	
		Reduction range	Avg.	Std.D.	Avg.	Std.D.	Avg.	Std.D.
Surface temperature above slab	℃	-3.6 to 30.1	9.12	11.28	16.44	10.24	1.81	6.53
Surface temperature beneath slab	℃	-0.3 to 9.5	4.24	3.11	6.64	2.27	1.83	1.60
Outdoor ambient temperature	℃	-1.09 to 2.00	0.24	0.42	0.25	0.28	0.23	0.52
Indoor ambient temperature	℃	-0.90 to 4.2	1.22	0.90	1.69	0.79	0.76	0.74
Heat flux	W/m^2	-3.9 to 52.3	19.49	15.73	31.85	12.06	7.13	6.63
MRT	℃	-0.87 to 3.19	1.16	0.73	1.44	0.69	0.88	0.67
WBGT	℃	-0.16 to 1.78	0.32	0.30	0.43	0.31	0.21	0.25
Relative humidity	%	-6.26 to 10.48	1.48	3.04	0.47	2.47	2.50	3.22
Globe temperature (T_g)	℃	-0.7 to 2.6	0.99	0.61	1.21	0.57	0.78	0.58

The calculated values in the above table are from onsite measured data recorded on 10th June 2009. The term of reduction is the values measured from the exposed slab condition deducted by those measured from the lawn planted area. Avg. denotes to average value; Std.D. denotes to standard deviation.

interior space under the lawn planted area was observed, which is capable of providing a more pleasant indoor thermal environment.

3. The time lag effect of lawn planted area was confirmed by investigating the diurnal heat flux variations. There were extra 10 h time lags with lawn planted above the rooftop, which implies that the lawn planted layer can be used as an efficient thermal barrier in passive building design.
4. Less long-wave radiation emitted from the lawn planted roof was confirmed through comparisons of T_g and MRTs measured/calculated on site. It indicated that thermal comfort is improved and is more feasible for rooftop outdoor activities above lawn planted area.
5. Heat flux transfer was greatly reduced under lawn planted area. This was also confirmed by comparing heat flux rate between both conditions. It reveals that great deal amount of summer cooling loads will be reduce under planted roof circumstance, and as a result, energy saving on air-conditioning systems will be achieved.

ACKNOWLEDGEMENT

The authors would like to express their greatest appreciation to Taiwan National Science Council for financial support to the research.

REFERENCES

ASHRAE (2005). ASHRAE Handbook - Fundamentals. Atlanta, USA, American Soceity of Heating, Refrigerating and Air-Conditioning Engineers, Inc.

Dukes-Dobos F, Henschel A (1973). Development of permissible heat exposure limits for occupational work. ASHRAE J., 9: 57.

Dvorak B, Volder A (2010). Green roof vegetation for North American ecoregions: A literature review. Landsc. Urban Plan., 96(4): 197-213.

Hwang RL, Lin TP (2007). Thermal comfort requirements for occupants of semi-outdoor and outdoor environments in hot-humid regions. Archit. Sci. Rev., 50(4): 60-67.

ISO 7243 (1989). Hot environments -- Estimation of the heat stress on working man, based on the WBGT-index (wet bulb globe temperature), International Organization for Standardization.

Jim CY, He H (2010). Coupling heat flux dynamics with meteorological conditions in the green roof ecosystem. Ecol. Eng., 36(8): 1052-1063.

Kumar R, Kaushik SC (2005). Performance evaluation of green roof and shading for thermal protection of buildings. Build. Environ., 40(11): 1505-1511.

Lazzarin RM, Castellotti F, Busato F (2005). Experimental measurements and numerical modelling of a green roof. Energy Build., 37(12): 1260-1267.

Niachou A, Papakonstantinou K, Santamouris M, Tsangrassoulis A, Mihalakakou G (2001). Analysis of the green roof thermal properties and investigation of its energy performance. Energy Build., 33(7): 719-729.

Teemusk A, Mander U (2010). Temperature regime of planted roofs compared with conventional roofing systems. Ecol. Eng., 36(1): 91-95.

Theodosiou TG (2003). Summer period analysis of the performance of a planted roof as a passive cooling technique. Energy Build., 35(9): 909-917.

Wong NH, Chen Yu, Ong CL, Sia A (2003). Investigation of thermal benefits of rooftop garden in the tropical environment. Build. Environ., 38(2): 261-270.

Wong NH, Li S (2007). A study of the effectiveness of passive climate control in naturally ventilated residential buildings in Singapore. Build. Environ., 42(3): 1395-1405.

Wong NH, Tan PY, Chen Y (2007). Study of thermal performance of extensive rooftop greenery systems in the tropical climate. Build. Environ., 42(1): 25-54.