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ScienceDirect

Procedia Engineering 00 (2017) 000–000

Procedia Engineering

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International High- Performance Built Environment Conference – A Sustainable Built Environment Conference 2016 Series (SBE16), iHBE 2016

The Study on the Evaluation of Thermal Insulation Efficiency with Typical Plant Species of Roof Greenery in Kaohsiung

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Abstract

This research focuses on the buildings with relevant landscape engineering, and taking the public building as the targets including the sustainable campus project in Kaohsiung. Relevant studies and cases regarding roof greening are also collected and compiled as references for this research. Temperatures of the surface layers, soil layers and ceiling surfaces of different greening types are simultaneously measured in different locations on a 24-hour basis to explore the price-performance ratio of an effective heat-insulation green roof that meets users' demands.
Through filed experiment from real projects, the study compares the highest temperature of the top floors and ceilings with different roof greening types, with the data analyzed through the time-lag effect. The results show that factors influencing the heat capacity of greening types in their performance of temperature reduction and heat dissipation are surface temperature, solar radiation, height of the greening installations, shade and ventilation. Ranking of the most effective types from the best to the worst is: solar panel>planting at a certain height>soil with a certain thickness>planting>stony building materials>wood plastic composite path>soil>original surface. The one with the best price-performance ratio is planting at a certain height and a large shade, which can create a temperature difference by 10 Celsius degrees and achieve a constant indoor temperature. The test result is expected to serve as a reference to create an effective roof greening type in energy saving, temperature reduction and heat insulation. It can be applied to cities with overheating problems, and thus improve the comfort of the urban space in the future by creating a sustainable green space for living.

Keywords: Roof Greenery; Urban heat island; Thermal Insulation Efficiency; Typical Plant Species

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Peer-review under responsibility of the organizing committee iHBE 2016.

1. Introduction

The Urban Heat Island effect has become a growing problem in recent years, as the large population has caused living space to become much more crowded and the industrial development has led people to build increasingly taller high-rises and expand their living quarters into locations that possess microclimate regulating functions, such as green spaces and parks [1]. The temperature in cities has gradually risen, which renders it difficult for the heat to dissipate, thereby causing worsening Urban Heat Island effects. To accustom our cities to these climate changes [2], countries around the world have come together to enact related laws and regulations for the sustainable development of the planet. There are several studies focusing on roof greenery and vertical plantings, and some successful cases, such as Chicago City hall etc., introduce a trend of roof greenery in cities. In this study, buildings that are currently undergoing the process of being greened are designated as demonstration research bases, where the effect that different roof greenery [3] types and solar PV panels have on lowering the temperature on the rooftops [4] of buildings and the interior roof plates is measured. The aims of this research is to provide a better life quality for all in the future by determining ways to effectively lower the temperature inside buildings despite the Urban Heat Island effect brought by industrialization.

2. Methodology

The Kaohsiung City Government started a 3D greenery policy from 2012, and some pilot projects were planed and finished with our research group. With the green roofs of Kaohsiung City as research subjects, this study integrates relevant literature on green roofs and existing cases, both international and domestic, as major research references. Thermocouple temperature measurement lines were used to measure the temperature of various sampling points on the surface layer, the soil layer and the interior roof plates of the selected green roof subjects over the full span of the summer, and the hourly temperature data gathered at each sampling point was analyzed through physical computing. The temperatures of each point were recorded every 10 minutes from 8:00 am to the same time on the following day.

2.1 Measurement instruments

The data on the hourly accumulated amount of radiation and temperature were used to calculate the temperature of each sampling point, which was then used for analysis of the temperature changes and the effectiveness of temperature lowering on different points in the material layer, the soil layer, and the interior roof plates. Figure 1 shows the test point distribution as concept, and the instruments include on-site stationary weather station, a comprehensive thermal modular for rooftop air condition for black-ball, dry bulb and wet bulb thermometers. The thermocouple T-type probes were located average for surface temperature measurement. At the same time, the soil thermometers also were measured at the same positions.

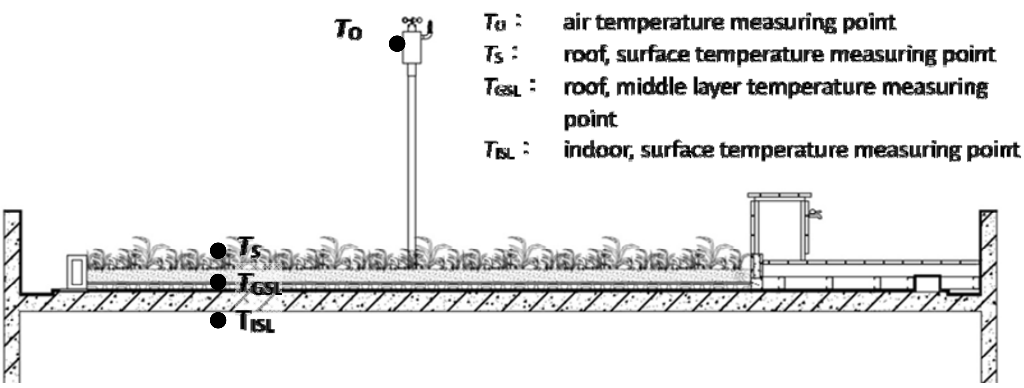


Fig. 1. Position diagram of measuring point

2.2 Sampling points

The areas where the temperatures were measured included the interior space of the floor right under the roof, above surface layer and soil layer on the roof greenery. To obtain comprehensive data for each area, the bases were split into several grids of the same size according to the scale of the area, and sampling points were then determined through a chess grid coordinate system. Thermometers were placed at multiple points determined by the total area of greenery on the roof and the interior roof plates as well as the relative positions of the greenery. The locations of the sampling points were slightly adjusted according to the actual conditions of the targeted buildings, so as to better collect a more comprehensive set of data at the bases as well as inside the buildings. All openings of the sampling points were sealed for the purpose of obtaining more accurate and complete data of the interior temperature of the building.

3. Measured results

In comparison of experimental results analyzed the difference of temperature in between. There were three factors conducted to verify the efficiency: first was the difference of different layer, second was the time lag effect, and the third was the slope of cooling effect after sunset. Through the literature summarized cooling with heat dissipation factors for grass, material, height, the shadow of the four items, analysis will be the indoor roof surface temperature and atmospheric temperature subtraction, to obtain the temperature difference analysis.

3.1 Plant species

There were several types of plants used for greening in the observed areas: Brazilian carpet grass, Shortleaf lilyturf and Blue daze, Calico plaut can be found, Bojer’s spurge, Common jasmine orange, Manila grass, and Golden dewdrop. These were the types of grass used for comparative analysis in this study.

The temperature difference between different plant species is not significantly large, though it is found that the temperature at points with Blue daze planted appears to increase slower and decrease faster, while the Golden dewdrop has shown a better capability of thermal insulation, as sampling points with it planted did not show an obvious increase in temperature even at mid-day when the sun shone directly on the spot. This is likely because the Golden dewdrop plant covered a larger area, causing the soil to be in less contact with heat, and therefore the heat could not have been conducted into the soil easily and therefore could be effectively kept out. Calico plaut, on the other hand, appears to be less effective when it comes to insulation. The temperature at sampling points with Calico plaut planted spiked at mid-day, and the temperature on the surface of the interior roof plates was just as high as the outdoor temperature. This is likely because the surface of Calico plaut was located quite close to the soil layer and was therefore unable to effectively block out the heat source. The heat became trapped easily in the soil layer and was then conducted to the interior RC roof plates, causing them to remain at a high temperature, as Table 1 shows.

Table 1. District Grass patterns table

Grass species	*T*s(℃)	*T*gsl(℃)	*T*isl(℃)	ΔT(*T*s- *T*isl)
Brazilian carpet grass	39	35	30.4	8.6
Shortleaf Lilyturf	38.9	34	30.1	8.8
Blue daze	40.2	34.2	30.2	10
Calico plaut	36.9	31.4	31.7	5.2
Bojer's Spurge	38.6	33	32.1	6.5
Common Jasmin Orange	32	31.6	31.6	0.4
Manila grass	40.1	33.1	31.5	8.6
Golden Dewdrop	33.7	31.1	31.1	2.6

Regarding sampling points with Brazilian carpet grass planted, the temperature on the plant surface was recorded to be 7.4℃ higher than the outdoor temperature, while the temperature on the soil layer is 3.4℃ higher than the outdoor temperature. The indoor temperature, reaching the peak 6 hours later due to the time-lag effect, was 1.2℃ lower than the outdoor temperature. Refer to figure 2(a) for details. Figure 2 shows the different temperature patterns of different plant species, which conducts three types of cooling effects.

(1). Provide average cooling effect as thickness effect

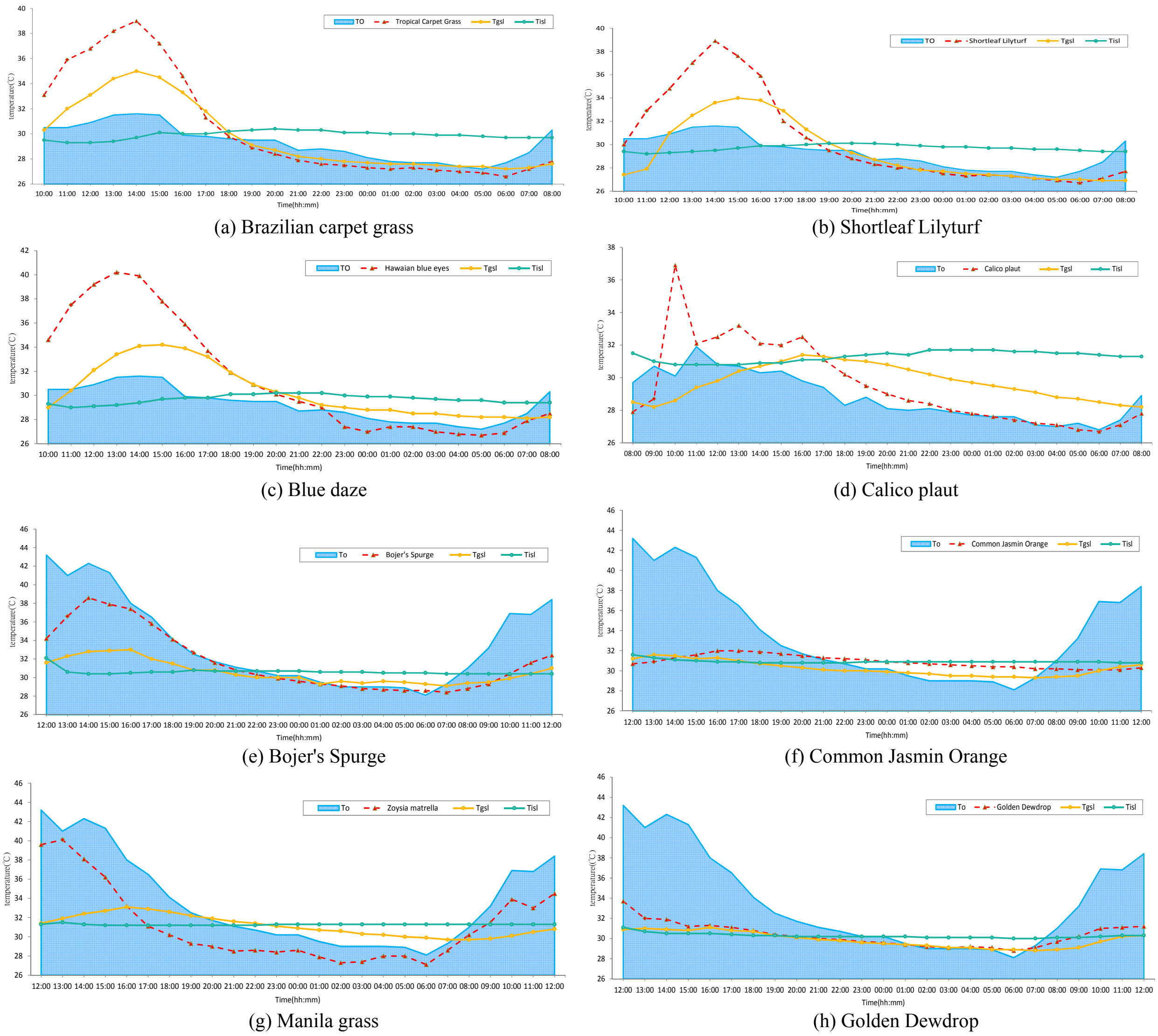
Regarding sampling points with Brazilian carpet grass, Shortleaf lilyturf, and Blue daze planted area: the temperature on the plant surface was recorded to be 7.3℃-8.6℃ higher than the outdoor dry bulb temperature, while the temperature on the soil layer peaked an hour later and was 2.4℃-2.6℃ higher than the outdoor temperature. The indoor temperature, reaching the peak 5-6 hours later due to the time-lag effect, and the effects were 1.4-1.5℃ lower than the outdoor temperature. Refer to figure 2 (a) (b) (c) for details. These data show the same variation and effect as the former studies as the cooling effect of various kinds of greenery cover, and the Temperature profiles, including air temperature in the air space under the roof were measured along with other environmental parameters to calculate the cooling effect. The results matched reasonably well with the measured ones, and the cooling effect increased with increase in leaf area per unit roof area (LAI). [5]

(2). Provide higher cooling effect as integrated effect

Regarding sampling points with Bojer's spurge and Manila grass planted area, the temperature on the plant surface was recorded to reach its peak as 2 hours later than the outdoor temperature with 3.1℃-4.6℃ lower than the outdoor temperature. It took 17 hours decreasing to the lowest temperature-point, which was 0.3℃-1.0℃ higher than the outdoor temperature. The temperature difference between the peak and the lowest point was 10.2 ℃. The temperature on the soil layer were average 4 hours later to reach the peak than the outdoor temperature, and the effects were 10.2℃-13℃ lower than the outdoor temperature. The period took 15 hours to reach its lowest point, which was 1.0℃-1.6℃ higher than the outdoor temperature. The results show the quiet average decreasing period for the night time as building envelope effects. The temperature difference between the peak and the lowest point was 3.4℃-3.9℃. The indoor temperature were 11.1℃-11.7℃ lower than the outdoor temperature. The lowest temperature of the day was reached 2 hours later, followed by 16 hours of gradual temperature increase and then reaching the lowest point once more. The difference between the peak and the lowest point stood small at 1.7℃. Refer to figure 2(e)(g) for details.

(3). Provide great cooling effect as shadowing and thickness effect

Regarding sampling points with Common jasmine orange and Golden dewdrop planted area, the temperature on the plant surface was recorded to reach its peak 3-4 hours later than the outdoor temperature and was 9.5℃-11.2℃ lower than the outdoor temperature. It took 16-18 hours to decrease to the lowest point with 0.7-2℃ higher than the outdoor temperature. The temperature difference between the peak and the lowest point was 1.9℃-4.9℃. The temperature on the soil layer were average 1 hours later to reach the peak than the outdoor temperature, and the effects were 2.9-12.1℃ lower than the outdoor temperature, which depends on the shadowing area. It took 18 hours to reach its lowest point, being at 1.2℃ higher than the outdoor temperature. The temperature difference between the peak and the lowest point was 2.3℃-4.9℃. The indoor temperature reached its peak at the same time as the outdoor variation, which were 11.6℃-12.1℃ lower than the outdoor temperature. The lowest temperature of the day was reached 23 hours later, being 1.9℃-2.7℃ higher than the lowest point of the outdoor temperature. The difference between the peak and the lowest point was 0.8℃-1.1℃. Refer to figure 2(f)(h) for details. The results show an interesting effect with the plant which achieve the height over 45 cm and can provide the shadowing effect combined the leaf covering ratio and the material thermos effect. More efficiency was conducted by this comprehensive effect that the great cooling concept for the roof greenery, which may encourage the small bushed or Flower stand species selection.



(a) Brazilian carpet grass (b) Shortleaf Lilyturf

(c) Blue daze (d) Calico plaut

(e) Bojer's Spurge (f) Common Jasmin Orange

(g) Manila grass (h) Golden Dewdrop

Fig. 2. Influence of temperature variation of different grass species plants

3.2 Materials

In comparison of the difference with non-plant roof, all non-plant materials used at observed areas were also taken into consideration with underwent comparative analysis in this study. The so called “non-planted reference type” with materials included: wood plastic composite planks, solar PV panels, grain tiles, Culture soil, the building’s original RC structure, pebble pavements, and granite boards. Table 2 shows the summary result of different material.

The solar PV panels showed a better capability of thermal insulation, likely because they are able to block out most of the sunlight and achieve heat convection easily when the highest temperature is reached. With solar PV panels installed, the heat is less likely to accumulate on the roof layer and cause the interior roof plates to increase in temperature, and the heat is thus effectively kept out. Culture soil, on the other hand, did not perform so well at thermal insulation, rising in temperature 1 hour earlier before mid-day and taking nearly as much time to decrease in temperature as a completely unblocked surface. This is likely because of the lack of plants or other shadings to shield the surface from the source of heat, leading to the soil directly accumulating heat, which was then conducted to the interior roof plates, making it hard for the inside of the building to cool down. Refer to Table 2 for more details.

Table 2. The comparison of planted and non-planted material surface

Material	Height	Ts(℃)	Tgsl(℃)	Tisl(℃)	ΔT(*T*s- *T*isl)
the building's original RC	0cm	52.2	-	33.5	18.7
Wood plastic composite planks,	20cm	39.7	35.6	29.5	10.2
Solar PV panels,	300cm	34.6	33.1	31.5	10.2
Culture soil,	12cm	39.2	33.6	31.8	7.4
Culture soil,	20cm	44.0	32.2	31.1	12.9
Pebble pavements,	5cm	49.5	37.9	31.5	18.0
Floor tile,	6cm	44.5	43.8	31.6	12.9
Granite boards.	6cm	45.0	39.5	31.8	13.2
Shortleaf Lilyturf	4cm	38.9	34.0	30.1	8.8
Manila grass	2cm	40.1	33.1	31.5	8.6
Golden Dewdrop	45cm	33.7	31.1	31.1	2.6

*: the "Height" means the distance above from rooftop RC plate.

The surface temperature of sampling points with nothing but the building's original RC surface installed showed 1 hour earlier to reach the peaked than the outdoor temperature. The surface temperature was 20.3℃ higher than the outdoor temperature; and it took 19 hours to decrease to its lowest point with a 13.1℃ difference. The indoor temperature reached its highest point as 5 hours later than outdoor temperature, which was 1.6℃ lower than the outdoor temperature, and it took 15 hours to decrease to its lowest point with only 2.5℃ difference.

(1). Wood plastic composite planks

The surface temperature of wood plastic composite planks (PP) with 20cm elevated was 8.1℃ higher than the outdoor temperature, while the temperature of soil layer peaked 2 hours later. The surface temperature was 4℃ higher than the outdoor temperature. The indoor temperature reached its highest point as 6 hours later which was 2.1℃ lower than the outdoor temperature and remained so for 2 hours.

The surface temperature of wood plastic composite planks (PVC) peaked 1 hour earlier than the outdoor temperature, being 19.6℃ higher than the outdoor temperature; it took 19 hours to decrease to its lowest point. The temperature of the soil layer peaked 3 hours later than the outdoor temperature, with a 2.9℃ difference from the outdoor temperature, and took 16 hours to decrease to its lowest point. The interior temperature, due to the time-lag effect, reached its highest point 8 hours later than did the outdoor temperature, being 0.3℃ lower than the outdoor temperature.

(2). Rooftop with 3m height PV panels

The results of the study show that the highest temperature for roof plates underneath solar PV panels was 2℃ lower than outdoor temperature and 32.2℃ lower than the surface of the solar PV panel. The highest temperature of the surface of the roof, as well, was 3.8℃ lower than the outdoor temperature. The interior temperature, meanwhile, reached its highest point was 6 hours earlier with 2℃ lower than the outdoor temperature.

(3). Rooftop with frequent material

1. Typical Floor Tile: the result showed 1 hour earlier than the outdoor temperature to the peak with 17.3℃ higher than outdoor temperature. It took 19 hours to decrease to its lowest temperature with a 23.1℃ difference between the highest and lowest points.
2. Pebble pavements: the result showed 1 hour later than the outdoor temperature to the peak with 6.3℃ higher than the outdoor temperature. It took 17 hours to decrease to its lowest temperature with 2.1℃lower than the outdoor temperature, and 23.5℃ difference between the highest and lowest points.

3. Grain plastic boards: the immediate heat transfer effect conducted the upper surface peaked at the same time as the outdoor temperature with 1.3℃ higher. It took 18 hours to decrease to its lowest point with 19℃ difference between the highest and lowest points.
4. Granite boards: the result showed 1 hour later than the outdoor temperature to the peak with 1.8℃ higher than the outdoor temperature. It took 17 hours to decrease to its lowest point with a 0.2℃ difference from the outdoor temperature. There was a 17.1℃ difference between the highest and lowest points.

(4). Rooftop with Culture soil covered

The surface temperature of sampling points with Culture soil used peaked 1 hour earlier than did the outdoor temperature, being 12.1℃ higher than the outdoor temperature, and it took 20 hours to decrease to its lowest point, with a 18.1℃ difference between the highest and lowest points. The temperature of the soil layer peaked 6 hours later than did the outdoor temperature, being 0.3℃ higher than the outdoor temperature, and it took 15 hours to decrease to its lowest point, being 2.2℃ higher than the outdoor temperature, with a 3.2℃ difference between the highest and lowest points. The indoor temperature reached its highest point 3 hours earlier than did the outdoor temperature, being 0.8℃ lower than the outdoor temperature. The temperature then took 1 hour to decrease to its lowest point and gradually climbed again after that. The difference between the highest and lowest points stood small at 0.9℃.

3.3 Air layer Thickness

Materials and plants that can create observable heights, including solar PV panels, wood plastic composite planks, Culture soil, Bojer's spurge, Common jasmine orange, and Golden dewdrop were selected for comparative analysis.

The solar PV panels showed the greatest effectiveness at thermal insulation, followed by the 60cm-tall Golden dewdrop, as sampling points where it was planted did not show a significant increase in temperature even at mid-day in direct contact with the sun. This is likely because the plant's height ensured that a smaller area of the soil received sun rays and less heat entered the soil layer, thus leading to effective thermal insulation. The 45-cm high wood plastic composite planks showed the least effectiveness in keeping out the heat, with the temperature starting to rise an hour earlier than mid-day. This is likely because that, despite the planks being quite tall, their surfaces are prone to trap heat inside with no means of air circulation, and this in turn caused the original surface to stay hot, thus leading to ineffective heat insulation in the interior roof plates. Also, a significant difference was observed between the rates at which the temperature lowered for 12cm-thick culture soil and 20-cm thick culture soil. The deeper soil layer was found in this study to be less affected by the surface temperature and the radiation from the sun, with a much smaller difference in temperature throughout the day. Meanwhile, the highest soil temperature occurs later when the soil layer was deeper. Refer to Table 3 for more details.

Table 3. Height difference comparison table

Measuring points	Height	Ts(℃)	Tgsl(℃)	Tisl(℃)	ΔT(*Ts*- *Ti*sl)
Solar PV panels	300cm	34.6	33.1	31.5	10.2
Wood plastic composite planks	20cm	39.7	35.6	29.5	10.2
Wood plastic composite planks	45cm	51.5	34.8	32.2	19.3
Culture soil	12cm	39.2	33.6	31.8	7.4
Culture soil	20cm	44.0	32.2	31.1	12.9
Bojer's spurge	30cm	38.6	33	32.1	6.5
Common Jasmin Orange	45cm	32	31.6	31.6	0.4
Golden Dewdrop	60cm	33.7	31.1	31.1	2.6

4. Conclusions

Through analyzing the difference between the highest and lowest temperature points at the surface level and interior roof planks for greened roofs and taking the time-lag effect into consideration, it is found that the heat capacity, the temperature lowering rates and heat dissipating effectiveness can be ranked as follows: solar PV panels > plants with observable heights > thick soil > plants > stone materials > wood plastic composite planks > soil > the building's original surface.

The effectiveness for thermal insulation, temperature lowering and heat dissipating of the roof layer and interior roof planks, after taking the time-lagging effect into consideration, can be ranked as follows: Golden dewdrop > Common jasmine orange > solar PV panels > Bojer's spurge > Calico plaut > Culture soil (20cm) > Manila grass > Floor tile > granite boards > pebble pavements > Culture soil (12cm) > wood plastic composite > Shortleaf lilyturf > Blue daze > Brazilian carpet grass.

The recorded data as well as the analysis results of the interior and exterior surface factors proved that the greening method, the building's top layer surface temperature, radiation, the height of the plant or material, shade and the air circulation rate are significantly correlated to each other.

As the plants that are more effective at thermal insulation, usually of observable height and capable of creating shade in a large area, can be obtained at a much cheaper price than solar PV panels (excellent heat blockers), and wood plastic composite planks (which do not perform well at blocking heat), clearly there would be a significant difference in the price-performance ratio. The price-performance ratio, from high to low, can be determined as follows: plants of observable height > thick soil > pebble pavements > floor tile > plants that do not stand much higher than the surface layer > wood plastic composite planks > solar PV panels.

Acknowledgement

This study is granted by the "Sustainable Campus Program" from Ministry of Education, and the Project of Green Roof Promotion from Kaohsiung City Government.

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