MEASUREMENT OF REFLECTED SOLAR RADIATION OF URBAN PAVEMENT MATERIALS

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ABSTRACT

This paper discusses the outdoor pavement materials used in cities in Taiwan and the amount of reflected solar radiation they release. The study sample was comprised of a selection of high-pressure concrete slabs, divided into white and gray types. The white samples included white flat tiles, iridescent crystal sandblasted tiles, sandblasted tiles and terrazzo tiles; and the gray samples include gray flat tiles, rustic tiles and permeable tiles, for a total of seven different types. A tool was developed in this study to aid in the screening of the sample from the external environment during the measurement process, according to the design proposed by Sailor. It was found that for the white samples, the addition of waste glass resulted in no obvious increase in the reflectance of the samples. For the iridescent crystal sandblasted tile, the reflectance of the white flat tile of the control group without any admixture was 71-82 W/m². However, after iridescent crystal (waste glass) was added, the reflectance of the sample was reduced by 5-6 W/m². It is obvious that the compressed concrete paving units without treatment had the most efficient reflectance, and that it is unnecessary for them to be mixed with any components.

I. INTRODUCTION

This study measured the reflected solar radiation of outdoor compressed concrete paving units. Related works have shown the cooling effect of pavement reflectance in the urban areas of Taiwan to be about 273.39 K [1]. This phenomenon is called the urban heat island (UHI), and it has been extensively studied [2-3]. The phenomenon of heat islands is becoming increasingly intense in urban areas, modifying the microclimate of these areas, aggravating the climatic phenomena, and causing all kinds of damage.

The thermal or long-wave radiation coming from surfaces contributes to the development of specific local climatic characteristics, such as air temperature, relative humidity, and wind speed [4]. The thermal characteristics of paved surfaces (albedo, heat capacity, thermal conductivity) interacting with solar radiation are among a number of causal factors affecting the UHI, which also includes the population and population density of the urban area, building materials, spacing and height of buildings, waste heat generated by vehicles and building equipment, vegetative cover, and geographic location [4-11].

The spectrum of solar radiation is divided in three distinct regions: the ultraviolet region, the visible region, and the short-wave infrared region. The ultraviolet region (UV) represents approximately 6% of the solar spectrum, with a wavelength range between 290 and 380 nm. It can have negative physical-chemical effects on materials, as well
as on living beings, such as damage to cell structures resulting in skin cancer, fading or discoloration, erythema and burning, and it contributes to vitamin D synthesis. The visible region, with a wavelength varying between 380 and 780 nm, comprises approximately 46% of the entire solar spectrum and can be seen the human eye. Its alterations of frequency manifest as colors. It directly influences the degree of illumination of environments and, therefore, it is associated with the intensity of transmitted white light. The visible wavelength range varies from person to person, depending on the sensitivity of the retina of each person. The wavelength of infrared radiation (IV) ranges between 780 nm and around 2500 nm, and makes up approximately 43% of the solar spectrum [12].

The materials used in urban structures play an important role in the urban thermal balance. They absorb solar and infrared radiation and dissipate part of the accumulated heat through convective and radiative processes to the atmosphere, thus increasing the ambient temperature [13]. Many studies have been carried out in an effort to better understand the optical and thermal characteristics of various types of materials, as well as the impact of their use on a city’s climate and systematic ambient temperature differences [14-23]. The use of cool materials, which have a high reflectivity to solar radiation and high spectral emissivity, has been shown to increase urban albedo, and the use of such materials is considered to be one of the more promising and powerful techniques for mitigating the heat island phenomenon [24]. As the nature of this type of radiation is mainly thermal, the desired reduction of the heat island effect can be achieved through changing the materials used in urban areas, which, in turn, can lead to direct and indirect benefits for people and for the environment. With urban development, people’s activities have been extended from indoor spaces to outdoor spaces for such purposes as recreation, exercise, entertainment, cooking, and other leisure-time pursuits.

However, the outdoor environment deteriorates gradually over time, and the considerations and problems faced in order to maintain healthy outdoor environments have become of critical importance in current environmental design and planning. Thus, the objectives of this study were to provide:

1. A description and analysis of the materials best utilized in the planning and design of different outdoor environments, by measuring the reflectance of the different compressed concrete paving units.
2. Data on paving material reflectivity, as regards to how the temperature of the material affects the thermal environment, based on environmental micro-climate, material reflectivity, outdoor thermal environment, the environment and other hot thermal comfort environment-related literature, to show the relationships between the slab temperature, the thermal environmental factors and the reflectivity of the material.

II. THEORY AND FORMULA

Reflectance can be measured in the laboratory or in the field. The measurements in the laboratory are to determine the characteristics of the material itself, while the measurements in the field are to determine the characteristics of the final product. The laboratory results are precise values of reflectance for particular wavelengths or defined ranges, while the field results are the values for the entire spectrum of the solar radiation [25].

Thermal radiation has an electromagnetic wave, so its heat transmission is free from media. According to modern physics, an ideal radiator is the radioactive energy of a black body, as represented by the Stefan-Boltzmann law:

\[ q^* = \sigma T_s^4 \]  

where \( q^* \) represents the radioactive energy of a black body; \( T_s \) represents the absolute temperature of the object; and \( \sigma \) represents the Stefan-Boltzmann constant (\( = 5.67 \times 10^{-8} \text{ W/m}^2\text{K}^4 \)). However, most objects are not ideal radiators, in which case the object is multiplied by its emissivity:

\[ q^* = \varepsilon T_s^4 \]  

where \( \varepsilon \) is the radiation quality of the black body’s surface material, called its emissivity. In extraordinary circumstances, the radiant heat transfer capacity between the heat transfer surfaces of two objects can be expressed as:

\[ q_r = A\varepsilon\sigma(T_s^4 - T_{aw}^4) \]  

where \( q_r \) is the radiant heat transfer capacity; \( A \) is the surface area; and \( T_{aw}^4 \) represents the outside absolute temperature, expressed as:

\[ q_r = h_A(T_s - T_{aw}) \]  

where \( h_A \) can be expressed as:

\[ q_r = \varepsilon\sigma(T_s - T_{aw})(T_s^2 - T_{aw}^2) \]
where $h_r$ is the radiation heat transfer coefficient.

Two pyranometers were mounted above the test samples, one pointing towards the sky, $I_{th}$, and the other aligned downwards towards the white standard sample, $I_w$, black standard sample, $I_b$, and the test sample, $I_t$. The data of the two pyranometers were read at the same time, and one reading was divided by the other to obtain the relevant albedo, $A'w$, $A'b$ and $A't$. The albedometer used in this study was a two-way type, which simultaneously measured the amount of solar radiation and the sample reflectance, thus increasing accuracy. In Equations (6) to (16), $A'w$ was the reflectance of the experimental group; $A'b$ was the reflectance of the control group; $A't$ was the reflectance of the test group; $I_{th}$ was the horizontal solar radiation intensity; $F$ was the view factor; and $A_e$ was the environmental reflectance [26]. This study used the double-pyranometer measurement method, by which the amount of solar radiation and the amount of reflection can be measured simultaneously, thus improving the accuracy of the measurements. The double-pyranometer measurement method is described below:

$$A'_w = \frac{I_w}{I_{th}}$$  

(6)

$$A'_b = \frac{I_b}{I_{th}}$$  

(7)

$$A'_t = \frac{I_t}{I_{th}}$$  

(8)

After equation transposition:

$$\frac{I}{I_t} = A \times F + A_e \times (1 - F)$$  

(9)

Consequently:

$$\frac{I_w}{I_{th}} = A'_w \times F + A_e \times (1 - F)$$  

(10)

$$\frac{I_b}{I_{th}} = A'_b \times F + A_e \times (1 - F)$$  

(11)

$$\frac{I_t}{I_{th}} = A'_t \times F + A_e \times (1 - F)$$  

(12)

From (7) minus (8):

$$\frac{I_w}{I_{th}} - \frac{I_b}{I_{th}} = (A'_w - A'_b) \times F$$  

(13)

From (9) minus (8):

$$\frac{I_w}{I_{th}} - \frac{I_b}{I_{th}} = (A'_w - A'_b) \times F$$  

(14)

From (7), (8) into (13) to obtain:

$$A'_w - A'_b = (A'_w - A'_b) \times F$$  

(15)

Similarly, from (6), (7) into (14) to obtain:

$$A'_b - A'_w = (A'_w - A'_b) \times F$$  

(16)

By Equations (16)/(15) finishing:

$$A_e = A_b + \frac{A'_b - A'_w}{A'_w - A'_b} (A'_w - A'_b)$$  

(17)

The double-pyranometer measurement method requires measurements from three groups of data only: the first group was $I_{thw}$, $I_{w}$; the second group was $I_{thb}$, $I_{b}$; and the third group was $I_{tht}$, $I_{t}$. The measurement process was then completed.

III. EXPERIMENTAL SETUP

1. Measurement Site and Environment

The measurement site was located on the top floor of the Science and Technology Building, Kuang-Fu Campus, National Cheng Kung University, Tainan City in the south of Taiwan; the site coordinates are 23.0000°N, 120.2167°E. In order to avoid measurement errors, the highest building in Kuang-Fu Campus was selected, so as to avoid facilities or plants casting shadows on the samples during the measurement period (Fig. 1).

The insolation distribution in Taiwan, over the whole region at an altitude of 500 meters or less, roughly from northeast to southwest, has been increasing. The reference meteorological station in this study was the Tainan Meteorological Station. The mean annual solar radiation quantity was 3.9 kWh/m² (Table 1).

The measurement process was carried out on days with sufficient sunshine, taking into account the influence of the sun’s illumination angle on the sample in different seasons.
Table 1. Data from Tainan Meteorological Station

<table>
<thead>
<tr>
<th>Location</th>
<th>Altitude (m)</th>
<th>Station Number</th>
<th>Solar radiation (kWh/m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tainan City</td>
<td>13.8</td>
<td>467410</td>
<td>3.9</td>
</tr>
</tbody>
</table>

Fig. 1. Measurement site: National Cheng Kung University, Tainan City

Fig. 2. Albedo test stand showing dual pyranometers (albedometers) for the sample tests

Fig. 3. Overall onsite measurement experiment

2. Measurement Model Design

Previous studies [12] have reported that the measurement of the reflectance of small-area materials can be influenced by the ambient environment. A tool was made in this study to aid the screening of the external environment during the measurement process, according to the design proposed by Sailor [27] (Fig. 2).

First, a wooden case, 40 cm in length, width and height was designed (Fig. 3). The test sample was placed in the wooden case to avoid any environmental disturbance. The second step was to paint the interior of the case with black oil-based paint to avoid any secondary reflection inside the case. The third step was to unify the mounting heights of the measuring instrument. The mounting devices were hard wooden bars, which would minimize any bending or errors as a result of long-term operation and solarization. The mounting position was marked to ensure the same measurement position was used each time, and thus reduced human error.
Table 2  Study sample (Size: 20 × 20 × 6)

<table>
<thead>
<tr>
<th>Surface</th>
<th>Color</th>
<th>Photo</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>White flat tile</td>
<td>White</td>
<td>![Image]</td>
<td>Basic rectangular compressed concrete paving units, with a compressive strength of 7200 PSI and minimum water absorption of 5%. Customized sizes are available if there are special planning or design demands.</td>
</tr>
<tr>
<td>Iridescent crystal sandblasted tile</td>
<td>White</td>
<td>![Image]</td>
<td>Iridescent crystal sandblasted tile was made by adding waste cullet during the compressed concrete manufacturing process; the addition follows the recovered container glass aggregate ((1~3.5) mm) as set by the Environmental Protection Administration.</td>
</tr>
<tr>
<td>Sandblasted tile</td>
<td>White</td>
<td>![Image]</td>
<td>The difference between sandblasted tile and flat tile was that the sandblasted ground tile is not mixed with any material in the second surfacing. The finished surface presents as natural rock or a rough surface.</td>
</tr>
<tr>
<td>Terrazzo</td>
<td>White</td>
<td>![Image]</td>
<td>Terrazzo was the cement product extensively applied to walls and floors. The cement was mixed with sand and water, as well as a mixing agent and different crushed stones, crushed powder and paints, and is painted on walls or poured into molds for forming.</td>
</tr>
<tr>
<td>Gray flat tile</td>
<td>Gray</td>
<td>![Image]</td>
<td>Basic rectangular compressed concrete paving units have a compressive strength of 7200 PSI and minimum water absorption of 5%. Customized sizes are available if there are special planning and design demands.</td>
</tr>
<tr>
<td>Rustic tile</td>
<td>Gray</td>
<td>![Image]</td>
<td>The rustic tile was made using a processing machine to process the overall concrete tile directly. The finished concrete ground tile has an irregular surface and shape.</td>
</tr>
<tr>
<td>Permeable tile</td>
<td>Gray</td>
<td>![Image]</td>
<td>The production mode for the permeable tile was the same as that for the compressed concrete paving units. The major differences were the composition and higher water penetration. The increased permeability coefficient of the surface can be (1 \times 10^{-2}) cm/sec, which enhanced the water retention ability of the strata and contributes to drainage and temperature control.</td>
</tr>
</tbody>
</table>

3. Study Samples

Common compressed concrete paving units were used as the measurement samples. The ultimate composition of the compressed concrete was cement, aggregate, and water. The constituent ratio was approximately: water (15-20%), cement (7-14%) and aggregate (66-78%). The cement was white Portland cement and general Portland cement. This study assumed the measurement sample material to be rich concrete: water, cement, and aggregate = 20%, 14%, and 66%, respectively. The common ground tile types are described in Table 2.

4. Research Equipments (Fig. 4)

i. Universal recorder – GRAPHTEC midi LOGGER GL200A

A universal recorder was used to record the reflectance data of the samples. The total measurement period was 3-4 h, and the instrument recorded at 5 s intervals. The experimental data were integrated into a diachronic chart and form for description.
ii. Albedometer – LP PYRA 06

An albedometer was used to measure the amount of reflected radiant of each sample’s surface. The measurement unit was W/m². The measurement followed ASTM E1918A [28]. The albedometer was placed above the sample in order to measure the white canvas, black canvas and test samples, respectively. The measurement was repeated five times. The reflectance of each sample was calculated from the obtained data using ASTM E1918A theory.

5. Sample Measurement and Record Description

For the reflectance measurement, the sample was placed inside the wooden case, designed with reference to the design proposed by Sailor [27]. The polystyrene hollow brick and ASTM E1918A material reflectance measurement method were adopted to obtain the sample reflectance, and the measured data were substituted into the ASTM E1918A computing formula to obtain the reflec-
IV. RESULTS AND DISCUSSION

As small-sized samples were used, the instruments cast too much of a shadow on the samples at noon; thus, the measured data were obtained mainly from 10:00 to 11:00 or from 13:00 to 14:00. The selection time in the form represents the current reflectance of the sample, and the selection criteria are the points in time when the solar radiation quantity was sufficient (over 800 W/m²) and the weather was cloudless. The discussion of the measurement results was based on the samples, as the measurement frequency was too low in winter because of the reduced hours of sunshine. The measurement results from the winter showed only a small variation and difference, so these data were for reference only.

As to the instruments and manpower limitations in the reflectance measurement experiment, the albedometer measured one group of samples (control group) and the sunshine recorder measured the other group of samples (experimental group), with the two instruments working at the same time. The measurement result was determined by the measured value difference between the control group and the experimental group (test samples), the purpose being to avoid measurement errors as a result of different weather conditions. The difference value was calculated by subtracting the measured data of the experimental group from the measured data of the control group: a positive value meant the experimental group data were lower, and a negative value meant the experimental group data were higher.

1. White Sample Reflectance Measurement in Summer

In this study, the samples were classified into white flat tiles, iridescent crystal sandblasted tiles, sandblasted tiles, and terrazzo tiles. The control group was the white flat tile.

Fig. 6 shows the reflectance of the sample ground tiles, sequenced according to the difference value, with a larger difference representing the lower reflectance of the samples of the experimental group (lower than the control group). The average reflectance of the control group (white flat tiles) comprising various samples of ground tiles was 70 to 83 W/m².

Of the sample ground tiles in this study, the terrazzo tile had the maximum difference in reflectance in summer (36 to 47 W/m²), followed by the sandblasted tile (28 to 39 W/m²), while the iridescent crystal sandblasted tile had the minimum difference value (5 to 6 W/m²). The average solar radiation quantity of the white terrazzo tile measured during the day was 1314 W/m²; the sunshine was unstable all day, but still remained above 800 W/m². The solar radiation quantity was lower than 800 W/m² from 12:26 to 12:36. The duration of influence was about 10 min, and the influence of solar radiation was lower in the other hours.

The reflectance difference between the white terrazzo tile (experimental group) and the white flat tile (control group) was 36 to 47 W/m². The reflectance of the white terrazzo tile was 40 to 54 W/m² under sufficient sunshine. When internal foreign matters (dark foreign matter that is unable
to increase reflectance) were adhered to the surface, the reflectance was reduced by over 30 W/m², as compared with the white flat tile (control group) (Fig. 7).

In winter, the average reflectance of the control group of white samples (white flat tile) was 81 to 84 W/m². The terrazzo tile had the maximum difference in reflectance of 27 to 28 W/m², followed by the sandblasted tile at 20 to 16 W/m². The iridescent crystal sandblasted tile had the minimum difference value of 7 to 8 W/m² (Fig. 8).

2. Gray Sample Reflectance Measurement in Summer

The gray ground tile samples were classified into flat tile (control group: white flat tile), rustic tile (control group: gray flat tile), and permeable tile (control group: gray flat tile).

The reflectance difference values of the gray samples were in explicit sequence; the control group of the gray flat tile was the white flat tile, so the difference value was the highest, with the average reflectance of the control group of gray ground tile samples (gray flat tile) at 28 to 38 W/m² (Fig. 9).

Of the gray ground tiles, the permeable tile difference value was 13 to 16 W/m², while the rustic tile difference value was -4 to -7 W/m². The average solar radiation quantity of the gray rustic tile measured on the day was 1463 W/m². The influence of the cloud cover lasted about 5 minutes, from 11:30 to 11:35, and the solar radiation quantity was lower than 800 W/m². The control group was the unbleached (gray) flat tile.

Fig. 9  Changes in difference value of gray sample reflectance in summer

Fig. 10  Changes in reflectance of gray rustic tile in summer

Fig. 11  Changes in reflectance difference of gray samples in winter
The reflectance difference between the gray rustic tile (experimental group) and the gray flat tile (control group) was -4 to -7 W/m². The reflectance of the gray rustic tile was 33 to 41 W/m² when the sunshine was sufficient. When internal foreign matter (increasing reflecting power) adhered to the surface, the reflectance increased by 4 to 7 W/m², as compared with the gray flat tile (control group) (Fig. 10).

In winter, the average reflectance of the control group of gray ground tile samples (gray flat tile) was 24 to 35 W/m². The reflectance difference value of the permeable tile was 11 to 12 W/m², and the rustic tile reflectance difference value was -15 to -16 W/m² (Fig. 11).

V. CONCLUSIONS

1. It was found in this study that for the white samples, the addition of waste glass had no obvious effect in terms of increasing their reflectance.
2. As for the iridescent crystal sandblasted tile, the reflectance of the white flat tile of the control group without any admixture was 71 to 82 W/m². However, after the iridescent crystal (waste glass) was added, the reflectance of the sample was reduced by 5 to 6 W/m². It was obvious that the compressed concrete paving units without treatment had the most efficient reflectance, making any added component unnecessary.
3. The findings showed that when the flat tile became a rustic tile after surface treatment, the sample’s reflectance increased. The rustic tile had a small iridescent crystal component, which adhered to the surface after the surface was processed, thus increasing the reflectance.
4. Another permeable tile sample measurement result showed that the permeable tile had large surface pores after the surface of the flat tile sample was processed, so that the surface reflectivity decreased, as did the reflectance.
5. To sum up, the surface roughness of the compressed concrete paving units was proportional to the reflectance. When the material surface was smooth, the reflectance of the material was high; while for a rough surface (e.g., sandblasted, waterproofed), the material reflectance was low.
6. Therefore, the use of smooth-surfaced materials in the planning and design of urban paving projects would increase the material reflectance and reduce the urban environment temperature.

REFERENCES


