Journal of Environmental Science International
24(6); 819~826; June 2015

pISSN: 1225-4517 eISSN: 2287-3503
http://dx.doi.org/10.5322/JESI.2015.24.6.819

ORIGINAL ARTICLE

Impacts of Different Urban Surfaces on Summer Thermal Performance[a]

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Abstract

This study measured temperatures and albedos of urban surfaces for different colors and materials during summer, and calculated the energy budget over different urban surfaces to find out the thermal performance affecting the heat built-up. The study selected six surface colors and 13 materials common in urban landscape. Their surface temperatures (Ts) and albedos were measured at a given time interval in the daytime from June to August. Average Ts over summer season for asphalt-colored brick was 4.0℃ higher than that for light red-colored one and 9.7℃ higher than that for white-colored one. The Ts for artificial surface materials of asphalt paving, brown brick wall, and green concrete wall was 6.0℃ higher than that for natural and semi-natural ones of grass, grassy block, and planted concrete wall. There was the greatest difference of 16.3℃ at midafternoon in the Ts between asphalt paving and planted concrete wall. Average albedo over summer season of surface materials ranged from 0.08 for asphalt paving to 0.67 for white concrete wall. This difference in the albedo was associated with a maximum of 15.7℃ difference at midafternoon in the Ts. Increasing the albedo by 0.1 (from 0.22 to 0.32) reduced the Ts by about 1.3℃. Average storage heat at midday by natural and semi-natural surfaces of grass and grassy block was about 10% lower than that by artificial ones of asphalt, light-red brick, and concrete. Reflected radiation, which ultimately contributes to heating the urban atmosphere, was 3.7 times greater for light-red brick and concrete surfaces than for asphalt surface. Thus, surfaces with in-between tone and color are more effective than dark- or white-colored ones, and natural or semi-natural surfaces are much greater than artificial ones in improving the urban thermal environment. This study provides new information on correlation between Ts and air temperature, relationship between albedo and Ts, and the energy budget.

Key words: Material, Color, Surface temperature, Albedo, Energy budget

1. Introduction

The urban thermal environment is significantly affected by urban hardscape and greenspace. There are not enough greenspace and cool sink in downtown area, and this hampers airflow in the canyons which will increase the air temperature (Andreou, 2014). The expansion of hard surfaces leads to the increase of urban air temperature which is called the urban heat island (Racine and Fabiana, 2005). Energy budget over urban surfaces is one of the important factors which can influence the urban microclimate (Jo and Ahn, 2010). The storage heat of hard surfaces is one of the reasons why the air temperature in downtown area is much higher than rural area (Racine and Fabiana, 2005). The materials and colors with lower surface temperatures (Ts) can decrease the storage heat of horizontal and vertical surfaces, and thereby contribute to reducing the ambient temperature and improve the urban thermal environment (Synnefa et al., 2011).

Received 6 April, 2015; **Revised** 5 May, 2015;
Accepted 6 May, 2015
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[a] This study was developed from Wu and Jo (2014)'s presentation at the Korean Environmental Sciences Society Conference.

Thus, the reduction of the urban heat island effect can be achieved through changing the materials and colors used in urban surfaces.

In the world, Synnefa et al. (2007) studied the thermal performance for different surface colors to affect the urban thermal environment by measuring Ts during summer. Their results showed that using cool color could improve the thermal environment and reduce the heat island effect. Arthur et al. (1995) investigated the albedo of different surface colors and its effect on the thermal environment during summer, emphasizing that light-colored surfaces could offset or reverse the heat island and conserve energy. Li et al. (2013) also conducted a similar work measuring Ts and albedo during one month period in July and showed an inversely proportional relationship between Ts and albedo. They mentioned that application of materials with lower Ts and appropriate albedo could improve the urban thermal environment. In Korea, a study performed in August on albedo and Ts of different materials showed that light-colored surfaces were better than dark-colored ones to lower the heat build-up (Jo and Ahn, 1999).

There is little information about Ts, albedo, and energy budget for a variety of surface colors and materials in Korea. Despite the useful information expressed in the above-mentioned studies, they were limited to measurement with few replicates and within a short period of time. They did not include various surface types and colors distributed in real urban settings either. This study aimed to: 1) measure Ts and albedo for diverse horizontal and vertical surfaces common in urban landscape, 2) calculate the energy budget over different surfaces to find out the thermal performance, 3) explore practical information to contribute to creation of comfortable thermal environment. This study pioneers in tackling the difficulty associated with repetitive measurements throughout summer season and computing the energy budget for major urban surfaces in Korea.

2. Materials and methods

2.1. Selection of surface colors

Six brick colors were prepared to measure Ts in the experiment performed on a building roof. Thirty concrete bricks were purchased and painted with six different colors common in urban landscape. The colors included asphalt, brown, green, concrete, light red, and white (concrete and light red were original brick colors). All the conditions were the same except the colors in this experiment. Coloring and arrangement of concrete bricks on a building roof are shown in Fig. 1.

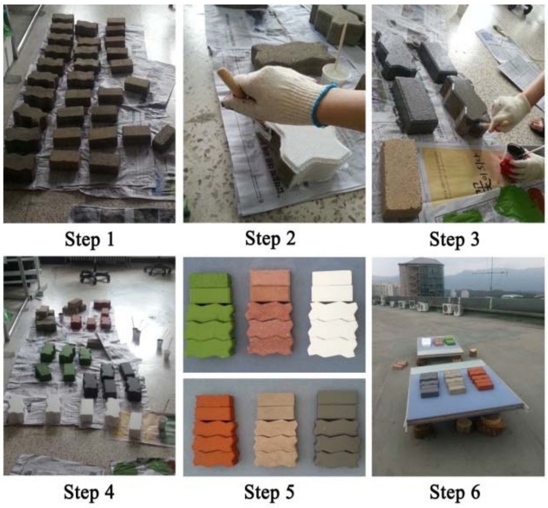

Fig. 1. Coloring and arrangement of concrete bricks to measure Ts.

2.2. Selection of surface materials

Thirteen types of vertical and horizontal surfaces, which are common in real urban settings, were selected in Chuncheon to measure Ts and albedo (Fig. 2). Vertical surfaces included brown brick wall, green concrete wall, planted concrete wall, stone wall, and white concrete wall. The five types of vertical surfaces were all on south side. Horizontal surfaces included asphalt paving, bare soil, concrete paving, flagstone paving, grass, grassy block, light-red brick, and wood deck.

Fig. 2. Thirteen types of vertical and horizontal surfaces selected for study.

2.3. Ts and albedo measurement

Ts and albedo of the surface colors and materials selected were measured at 3 hour intervals from 6 am to 6 pm on the 5, 15 and 25th of every month during summer from June to August, 2014. Simultaneously, microclimatic conditions such as solar radiation (SR), air temperature (Ta), and relative humidity (RH) were measured at 1.5 m above the ground. The Ts and albedo were measured using a digital thermometer (LINE SEIKI CO., TC-400) and a pyranometer (LI-COR, LI-200SA), respectively. The equipments used are shown in Fig. 3. The energy budget for typical surfaces was calculated with measured albedos for reflected radiation and applying measured Ts to the Stefan and Boltzmann recipe (Brown and Gillespie, 1995) for storage heat. Latent heat from grass was also estimated using measured Ts and evapotranspiration of about 0.43 kg/m^2/h (Kim and Park, 2013).

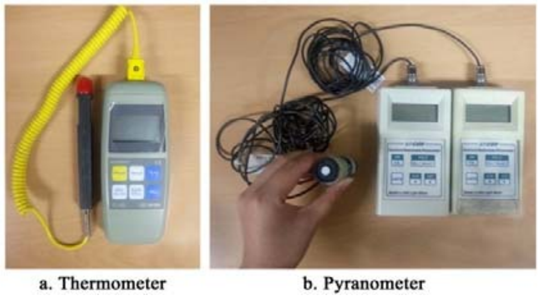

Fig. 3. Equipments to measure Ts and albedo.

3. Results and discussion

3.1. Microclimatic conditions

Average microclimatic conditions in summer at the measurement places of Ts and albedos were summarized in Table 1. SR from June to August averaged about 339 W/m^2. Ta in summer ranged from 25.7 to 29.1℃ with an average of 27.4℃. RH averaged 70% in summer with the highest 76% in July due to the rainy season. There were no significant differences ($p > 0.05$) in the SR, Ta, and RH between the measurement places and the Chuncheon weather station (Korea Meteorological Administration, 2014).

Table 1. Average microclimatic conditions in summer at measurement places of Ts and albedos

Month	SR (W/m^2)	Ta (°C)	RH (%)
Jun.	305.2±39.7	25.7±2.9	65.8±6.3
Jul.	323.0±37.4	27.3±1.3	75.5±8.5
Aug.	388.5±40.4	29.1±3.4	68.6±11.1
Mean	338.9±43.9	27.4±1.7	70.0±5.0

3.2. Ts of different surface types

Average Ts over summer season for different surface colors was 39.2℃ for asphalt color, 37.8℃ for brown, 37.5℃ for green, 35.2℃ for light red, 35.1℃ for concrete, and 29.5℃ for white. Thus, the Ts of asphalt color was 4.0℃ higher than that of light red and 9.7℃ higher than that of white. There was a slight difference in the Ts (0.1-0.3℃) between brown and green colors and also between concrete and light red colors. Hourly changes in the Ts for different surface colors were shown in Fig. 4. The Ts of all the colors showed the similarly changing trend at hourly base, and the highest Ts was recorded at midafternoon.

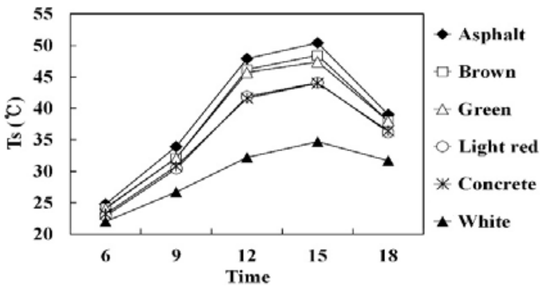

Fig. 4. Hourly changes in summer Ts for different surface colors.

Average Ts over summer season for different surface materials was 35.1℃ for asphalt paving, 30.4℃ for brown brick wall, 29.2-29.6℃ for bare soil, concrete paving, light-red brick, flagstone paving, and green concrete wall, 27.7-28.2℃ for wood deck and stone wall, 26.1-26.5℃ for grass and grassy block, and 24.6-24.8℃ for planted and white concrete walls (Table 2). The Ts of planted concrete wall was lowest, while that of asphalt paving was highest. Difference in the Ts between planted concrete wall and asphalt paving was 10.5℃, and the greatest difference in hourly Ts between them was 16.3℃ at midafternoon (Fig. 5). The Ts for natural and semi-natural surface materials of grass, grassy block, and planted concrete wall was 6.0℃ lower than that for artificial ones of asphalt paving, brown brick wall, and green concrete wall. These results reveal that natural or semi-natural surfaces are better than artificial ones with no evapo-transpiration and light-colored artificial surfaces are better than dark-colored ones to lower the heat build-up.

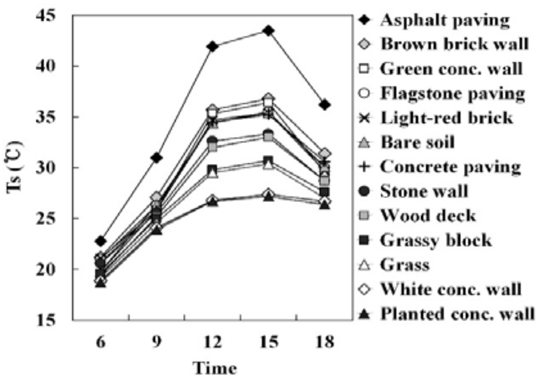

Fig. 5. Hourly changes in summer Ts for different surface materials.

Table 2. Summer Ts and albedos for different surface materials

Surface type	Ts (°C)				Albedo			
	Jun.	Jul.	Aug.	Mean	Jun.	Jul.	Aug.	Mean
Planted concrete wall	24.5	24.6	24.7	24.6±0.1	0.21	0.18	0.25	0.21±0.04
White concrete wall	24.5	24.9	24.9	24.8±0.2	0.67	0.67	0.68	0.67±0.01
Grass	25.8	26.3	26.3	26.1±0.3	0.23	0.25	0.28	0.25±0.03
Grassy block	26.3	26.6	26.7	26.5±0.2	0.20	0.28	0.20	0.23±0.05
Wood deck	27.1	27.9	28.0	27.7±0.5	0.42	0.43	0.44	0.43±0.01
Stone wall	27.8	28.3	28.6	28.2±0.4	0.33	0.37	0.35	0.35±0.02
Concrete paving	29.2	29.0	29.4	29.2±0.2	0.31	0.29	0.31	0.30±0.01
Bare soil	28.7	29.3	29.6	29.2±0.5	0.40	0.40	0.38	0.39±0.01
Light-red brick	29.1	29.4	29.5	29.3±0.2	0.28	0.28	0.30	0.29±0.01
Flagstone paving	29.4	29.3	29.6	29.4±0.2	0.19	0.24	0.28	0.24±0.05
Green concrete wall	29.4	29.7	29.8	29.6±0.2	0.26	0.23	0.24	0.24±0.02
Brown brick wall	30.2	30.4	30.7	30.4±0.3	0.19	0.23	0.22	0.21±0.02
Asphalt paving	34.5	35.2	35.6	35.1±0.6	0.08	0.07	0.10	0.08±0.02

Fig. 6 presents relationship between Ts and Ta in summer of typical urban surfaces such as asphalt, concrete, grassy block, and grass. The Ts had a positive proportional relationship with the Ta and regression models between them showed high fitness with r^2 values of 0.95-0.98. When the Ta was 27.4℃, a summer average, the Ts for asphalt, concrete, and grassy block was about 9℃, 3.5℃, and 0.7℃ higher, respectively, while the Ts for grass was 0.3℃ lower. The regression models can be useful for estimating the Ts of the urban surfaces using the Ta as an independent variable.

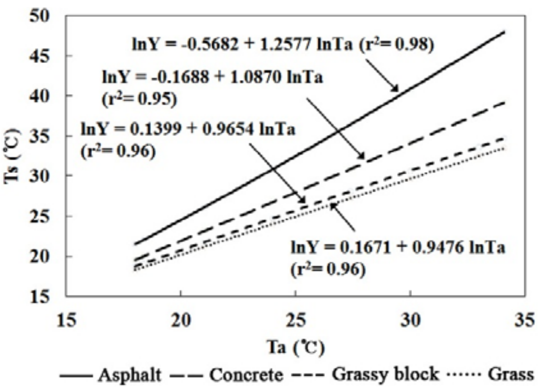

Fig. 6. Relationship between Ts and Ta in summer of typical urban surfaces.

3.3. Albedo of different surface types

Albedo of objects determines their Ts and affects thermal comfort for humans and the environment (Livada et al., 2002). Average albedo over summer season for different surface materials was 0.08 for asphalt paving, 0.21-0.25 for brown brick wall, planted concrete wall, grassy block, flagstone paving, green concrete wall, and grass, 0.29-0.39 for light-red brick, concrete paving, stone wall, and bare soil, and 0.67 for white concrete wall (Table 2). The highest difference in the albedo between asphalt paving and white concrete wall was associated with a maximum of 15.7℃ difference at midafternoon in the Ts (a diurnal average of 10.3℃ difference). Simpson and McPherson (1997) found that white roofs with an albedo of 0.75 were up to 30℃ cooler than brown roofs with an albedo of 0.10 in Arizona, showing much greater difference in the Ts compared to this study.

Due to the inversely proportional relationship between Ts and albedo, increasing albedo is one of the methods which can decrease Ts (Karlessi et al., 2011). Li et al. (2013) showed that increasing albedo by 0.1 equaled the cooling effect to reduce Ts by 0.6℃. Based on this study, converting brown and green walls with mean albedo of 0.22 to light-colored ones such as concrete and stone colors with mean albedo of 0.32 (about 45% increase) reduced the summer Ts by about 1.3℃, two times greater than Li et al.'s result. However, white -colored surfaces are not the best choice to improve thermal comfort, because high reflection of incoming solar radiation by high albedo is an ultimate source of waste heat increasing urban air temperatures.

3.4. Energy budget for surface materials

A stable thermal environment requires a balance of the energy budget between the radiant energy supplied and the energy removed by all consumers (Oke et al., 1981). The consumers are composed of reflected radiation from surfaces, conduction and convection of storage heat by surfaces, and latent heat from evapo -transpiration (Brown and Gillespie, 1995; Jo and Ahn, 2010). As shown in Table 3, average storage heat in summer by artificial surface materials was highest (511 W/m^2) for asphalt paving, followed by brown brick wall (481 W/m^2), concrete paving (473 W/m^2), and white concrete wall (447 W/m^2). Average reflected radiation in summer from the artificial surfaces, which is directly associated with albedo, varied in the reverse order of the storage heat. The storage heat by natural and semi-natural surface materials with evapotranspiration from plants was much lower than that by artificial ones. The storage heat by planted concrete wall was about 7% (31 W/m^2) lower than that by green concrete wall without climbing plants, and 13% (66 W/m^2)

lower than that by asphalt paving.

Table 3. Average storage heat in summer for different surface materials

Surface type	Storage heat (W/m^2)
Planted concrete wall	445.6±9.3
White concrete wall	446.7±9.3
Grass	455.7±12.2
Grassy block	457.7±11.6
Wood deck	463.3±15.6
Stone wall	467.7±14.4
Concrete paving	473.1±18.0
Bare soil	473.9±17.4
Light-red brick	474.8±16.0
Flagstone paving	475.7±17.6
Green concrete wall	476.7±18.3
Brown brick wall	480.7±18.0
Asphalt paving	511.2±25.0

Fig. 7 illustrates the energy budget over six typical urban surfaces at summer midday. Note that the relative magnitude of the energy flows through the different channels was depicted as the width of the arrows. Storage heat at midday averaged 466-477 W/m^2 for grass and grassy block, 503-510 W/m^2 for concrete, flagstone, and light-red brick, and 558 W/m^2 for asphalt. The storage heat averaged across natural and semi-natural surfaces of grass and grassy block was about 10% lower than that averaged across artificial ones of asphalt, light-red brick, and concrete. On the other hand, mean reflected radiation at midday was about 63 W/m^2 for asphalt, 182-197 W/m^2 for grassy block, flagstone, and grass, and 229-237 W/m^2 for light-red brick and concrete. The reflected radiation was 3.7 times greater for light-red brick and concrete surfaces than for asphalt surface. Latent heat at midday averaged about 201 W/m^2 for flagstone, 246 W/m^2 for grassy block, and 290 W/m^2 for grass. Thus, the natural and semi-natural surfaces played an important role converting sensible heat to latent heat through evapotranspiration.

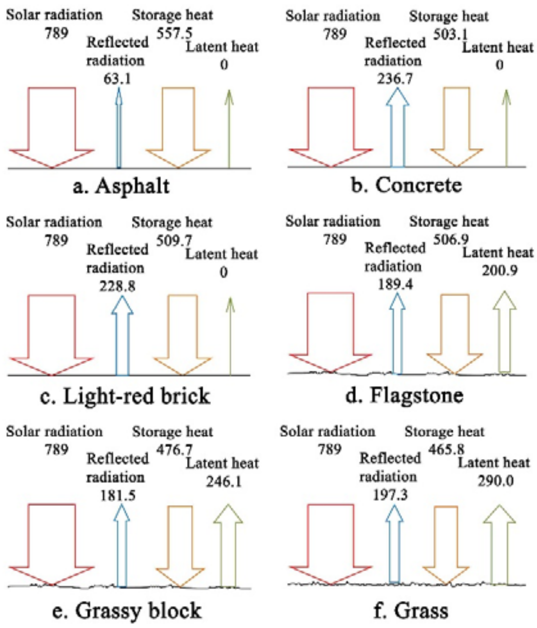

Fig. 7. Average energy budget (W/m^2) over typical urban surface materials at summer midday.

3.5. Implication and strategies

The urban thermal environment can be manipulated by changing surface albedos, surface materials, and the ratios of artificial and natural surfaces, as implied above. Dark-colored surfaces, which had lower albedo and higher Ts, showed lower reflected radiation but higher storage heat. Contrary, white-colored surfaces, which had higher albedo and lower Ts, showed higher reflected radiation but lower storage heat. Natural surface materials, which had lower Ts and evapotrans -piration, were characterized by lower storage heat and great latent heat, compared to artificial ones.

Both reflection and absorption of solar radiation cause accumulation of waste heat in the urban air due to the principles of energy conservation and degradation (Miller, 1990), as long as the waste heat is not moved out of the urban atmosphere. Therefore, it is desirable to avoid both dark- and white-colored surfaces and to use surfaces with inbetween or medium tone and color to minimize the heat build-up. The use of natural surface materials is also required to reduce sensible heat and to create comfortable thermal environment. If their use is limited or impossible, combination of natural and artificial surface materials such as grassy block is another effective way.

4. Conclusion

The heat island effect is one of great concerns to create comfortable quality of life in urban environment. This study measured Ts and albedo for various horizontal and vertical surfaces common in urban landscape, and calculated the energy budget over typical urban surfaces to understand the thermal performance. Dark-colored surfaces showed lower albedo and higher Ts, while white-colored ones showed higher albedo and lower Ts. Thus, there is a negative relationship between albedo and Ts. Average albedo over summer season of surface materials ranged from 0.08 for asphalt paving to 0.67 for white concrete wall. This difference in the albedo was associated with a maximum of 15.7℃ difference at midafternoon in average Ts. Natural surface materials with evapotranspirational cooling, had much lower Ts than artificial ones. The Ts of planted concrete wall was 16.3℃ lower at midafternoon than that of asphalt paving.

Higher albedo causes greater reflected radiation from surfaces and higher Ts is associated with greater storage heat by surfaces. Average reflected radiation at midday from light-red brick and concrete surfaces was 3.7 times greater than that from asphalt surface. Average storage heat at midday by natural and semi-natural surfaces of grass and grassy block was about 10% lower than that by artificial ones of asphalt, light-red brick, and concrete. The natural and semi-natural surfaces also played an important role converting sensible heat to latent heat through evapotranspiration. Reflected radiation and storage heat all ultimately contribute to heating the urban air. Appropriate colors and materials for horizontal and vertical surfaces should be selected to create comfortable thermal environment: 1) avoid to use both dark- and white-colored surfaces, 2) choose surfaces with a variety of inbetween tones and colors instead, 3) use natural materials widely rather than artificial ones, 4) apply semi-natural materials when using natural ones is impossible.

There is rising concern about color design of and plantings on horizontal and vertical surfaces in urban landscape to improve aesthetic and ecological functions. Results from this study can be useful for not merely mitigating the heat build-up, but exploring desirable urban greening and color design. The study also provides new information including correlation between Ts and Ta, relationship between albedo and Ts, and the energy budget, based on repetitive measurements for common urban surfaces in real settings throughout summer season. There are other factors such as shading and wind affecting urban air temperatures, as not considered in this study. Future research is required to explore relationships among those different parameters in the urban energy budget.

Acknowledgement

This study was supported by 2014 Research Grant from Kangwon National University (No. 120140242).

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