Experimental Study the Albedo of Urban Canyon Prototype with Reflective Pavements (Atreets)

Yinghong Qin[1], Jia Liang[1], Kanghao Tan[1], Fanghua Li[2]

[1] College of Civil Engineering and Architecture, Guangxi University; Key Laboratory of Disaster Prevention and Structural Safety of China Ministry of Education

[2] The Science & Technology Division, Guangxi University

Abstract: Urban structures consist of buildings, roofs, walls and streets. Buildings at both sides of the street create a canyon-like environment that is called urban canyon (UC). In a UC, conventional impervious pavements absorb and store solar radiation but negate the evaporative cooling, contributing to the development of urban heat island (UHI). One popular option to mitigate UHI is to make the pavements more reflective than conventional pavements and to absorb less solar radiation in the urban area. However, it remains unknown if a reflective pavement in an urban canyon can effectively reduce the solar absorption of the urban surfaces. This study prepares ten UC prototypes with differential pavement reflectivity and with south-north orientation, west-east orientation, and cross-street orientation, respectively. The albedo of these UC prototypes is measured by a new method that is proposed to estimate the reflectivity of urban canyon prototypes. It is found that raising the albedo of the pavement is inefficient to increase the albedo of the UC, especially for UC with great aspect ratio. In low aspect-ratio UC or parking lot, reflective pavements reflect a sizable additional diffuse radiation to pedestrians. Therefore, it should be caution to develop reflective pavements as urban cooling strategy.

Keywords: Multiple reflections; Urban heat island; Albedo; Reflectivity; Diffuse radiation

1. Introduction

Urban structures consist of buildings, roofs, walls, and streets. Buildings at both sides of a street create a canyon-like environment that is called street canyon or urban canyon (UC). Solar irradiance incident on any surfaces in the canyon is absorbed or reflected. But unlike the reflections from a flat and open surface, the reflections from one surface in an UC tend to be intercepted by other surfaces and then be subjected to multiple reflections[1-10]. Urban areas thus absorb more solar radiation than suburban and rural areas. The solar absorption is stored and mainly partitioned into sensible heat because construction materials have high thermal inertia[2,11], resulting in the development of the urban heat island (UHI).

Mitigating the UHI effect by using engineered solutions has gained extensive studies. As pavement comprises 20-40% of a typical urban fabric[12-14], one popular option is to make the street pavements more reflective than conventional pavements and to reflect more solar radiation back to the sky. Conventional asphalt pavements can be more reflective by using chip seal techniques (sealing the surface with light-colored aggregates)[15,16], by coating the surface with high near-infrared radiation reflectance[17—19], and/or by doping the surface with reflective pigments[20,21]. Conven-

tional concrete pavements can be more reflective by filling concrete with white filler[22], by using light-colored cementitious mixture[23,24], and by whitetopping techniques[25]. Reflective pavements can have albedo of 0.20 to 0.80[22], depending on the surface materials and the aging of the materials. Experiments have confirmed that reflective pavements effectively decrease the pavement surface temperature[19,26]. However, these experiments observed either the temperatures of the flat brick samples or those of pavements in open areas[27-30]. It remains unknown whether increasing the albedo of the UC can efficiently raise the reflectivity of the street canyon can be used as an urban cooling strategy.

This study prepares ten UC prototypes with different pavement reflectivity and with south-north orientation, west-east orientation, and cross-street orientation. The albedo of these UC prototypes is measured by a new method that is proposed to measure the albedo of the UC prototype. The albedo of the pavement and of UC is regressed to estimate if painting pavement with high reflectivity efficiently raises the albedo of the UC. We discuss the feasibility of adopting reflective pavements as an urban cooling strategy for low and great aspect-ratio UCs.

2. Theory

2.1 The albedo of a flat, homogeneous surface

Albedo, or reflectivity, is the percentage of solar radiation reflected by a surface. It is quantified as the proportion of solar radiation of all wavelengths reflected by a body or surface to the amount incident upon it. Let $i(\lambda)$ represent incident power per unit surface area per unit wavelength λ. Considering a surface that has a spectral reflectance $r(\lambda)$, the albedo (ρ) (or reflectivity) of a flat, homogeneous surface is

$$\rho = \frac{\int_{\lambda_0}^{\lambda_1} i(\lambda) r(\lambda) d\lambda}{\int_{\lambda_0}^{\lambda_1} i(\lambda) d\lambda} \tag{1}$$

where $\lambda_0=250\text{nm}$ and $\lambda_1=2.5\mu\text{m}$ are usually considered.

2.2 The albedo of an UC prototype

An UC consists of building roofs, buildings walls, and streets. The reflection from the roofs can fully escape to the sky if the neighboring buildings are no higher than the roofs. The reflection from the wall and the street cannot completely escape to the sky because the blocking of the buildings. The reflection from the wall is partially intercepted by the street and the opposing wall, and a portion of the reflection from the street is absorbed by the building walls. The albedo of these heterogeneous, rough surfaces cannot be estimated by Eq.(1).

According to the Akbari *et al*.[31], the albedo of a heterogeneous surface can be measured by centering one pyranometer down-facing over a target area to measure the diffuse reflection and another pyranometer up-facing over the area to measure the global horizontal irradiance. The reflection is the weighted reflections from the target area and from the surrounding area. To estimate the reflection from the target area, one must get the albedo of the surrounding area. This can be achieved by sequentially covering the target area with a white solar-opaque mask and a black solar-opaque mask. The reflections from the masks and from the surrounding area obey

$$I_w = [\rho_w F + \rho_s(1 - F)]I_{hw} \tag{2}$$

$$I_b = [\rho_b F + \rho_s(1 - F)]I_{hb} \tag{3}$$

where I_w (W/m^2) and I_b (W/m^2) are the diffuse radiation received by the down-facing pyranometer when the white mask and the black mask are covered on the target area; and I_{hw} (W/m^2) and I_{hb} (W/m^2) are the horizontal global irradiance incident on the up-facing pyranometer, respectively. F is the view factor from the target area to the down-facing pyranometer. ρ_w, ρ_b, and ρ_s are the albedo of the white mask, of the black mask, of the surrounding media, respectively.

When the ρ_w and ρ_b are known, one can solve for the surrounding albedo, ρ_s, and for the view factor, F. If the target area is covered by an UC prototype, the edge of the prototype is protruding to a certain height so that the view factor, F, from the prototype to the pyranometer varies. Setting this varying view factor as F', one has

$$I_c = [\rho_c F' + \rho_s(1 - F')]I_{hc} \tag{4}$$

where ρ_c is the albedo of the UC prototype; I_c (W/m^2) and I_{hc} (W/m^2) is the irradiance reading from the down- and up-facing pyranometer when the target area is covered by the UC prototype. There are two unknown variables (F' and ρ_c)

in Eq.(4) so ρ_c cannot be solved. To find ρ_c, we can introduce another equation by covering the target area with a black UC prototype that has the same configuration as the UC prototype whose albedo is measured. Assuming the albedo of the black UC prototype is ρ_{cb}, one has

$$I_{cb} = [\rho_{cb}F' + \rho_s(1 - F')]I_{hcb} \qquad (5)$$

where I_{cb} (W/m^2) and I_{hcb} (W/m^2) are the radiation received by the down-facing pyranometer and the up-facing pyranometer when the target area is covered by the black UC model.

Solving for ρ_c, one gets

$$\rho_c = \frac{\left(\dfrac{I_c}{I_{hc}} - \dfrac{\rho_{cb} - \dfrac{I_{cb}}{I_{hcb}}}{\rho_{cb} - \rho_s}\rho_s\right) \times (\rho_s - \rho_{cb})}{\dfrac{I_{cb}}{I_{hcb}} - \rho_s} \qquad (6)$$

where

$$\rho_s = \frac{\rho_w I_b/I_{hb} - \rho_b I_w/I_{hw}}{(\rho_w - \rho_b) - (I_w/I_{hw} - I_b/I_{hb})} \qquad (7)$$

The albedo of this black UC prototype, ρ_{cb}, is unknown because multiple reflections occur in the canyon. However, multiple reflections are minimized because the black surface is absorptive. Assuming that the half of the diffuse reflection left the black UC surface finally escapes to the sky, the albedo of the black UC prototype can be set as

$$\rho_{cb} = \rho_{bm}/2 \qquad (8)$$

where ρ_{bm} is the material properties of the black UC prototype. As long as the albedo of the black block surface albedo is sufficiently low (for instance $\rho_{bm}=0.05$), the error is negligibly small (error<0.025).

3. Experiments

Totally, ten UC prototypes with wood blocks mounted on a flat 1m×1m plate were prepared. Of which, five of them were arranged to parallel-street model; and other, to cross-stress model (**Figure 1**). For all UC prototypes (except the black one), the wall and the roof were painted with unicolor pigment, whose spectral reflectance was measured by a spectrophotometer Lambda 750 and shown in **Figure 2.** The albedo of painted wood, estimated by using the standard spectral solar irradiance (the red line in Figure 2), was 0.417. For either the parallel-street model or the cross-street mode, the street of one UC prototype was painted with the same color as the wall, and the streets (or the pavements) of other four prototypes were painted with different color (Figure 1). The spectral reflectance of these four paints was measured by the spectrophotometer Lambda 750; their albedo, estimated by using the standard solar irradiance spectrum, is 0.148, 0.271, 0.535, and 0.654, respectively (Figure 3).

The black UC model was painted black and then was submitted to the spectrophotometer Lamda750 to test its reflectance spectrum, which was shown in **Figure 4.** Other than the black UC prototype, a white mask and a black mask with 1m×1m were needed. The spectral reflectance of these two masks was shown in Figure 4. The spectral reflectance curves of both masks looks like flat lines, meaning that the spectral reflectance i(λ) is close to constant. Therefore, according to Eq.(1), both ρ_w and ρ_b can be deemed as a constant regardless of the variations of the arriving solar irradiance.

The albedo of the UC prototypes was measured on an on-campus road in Guangxi University (22.82N, 108.32E), China on August 14, 2015 from 7:00 to about 17:00 at local standard time (After that, the experimental site rained). The traffic was closed when measuring. The albedo was measured in approximately one-hour interval. A specific albedo of an UC prototype was gotten according to the following procedures.

(1) Label a $1 \times 1\text{m}^2$ domain on the ground as the target area.

(2) Center an albedometer (with two pyranomters, in which one faces down and the other faces up) over the target area such that the down-facing pyranometer is 0.5m above the target area;

(3) Place the white mask on the target area and read the reflective and arriving radiation I_w and I_{hw}, respectively (**Figure 5a**);

(4) Replace the white mask with the black mask and read I_b and I_{hb}, respectively (**Figure 5b**);

(5) Replace the black mask with the black UC prototype and record I_{cb} and I_{hcb}, respectively (**Figure 5c**);

(6) Replace the black UC prototype with the UC prototype in north-south orientation and record I_c and I_{hc}, respec-

tively (**Figure 5d**); compute the albedo ρ_c;

(7) Repeat the steps (3)-(6) to measure the albedo of UC prototype with west-east orientation and with cross-street orientation.
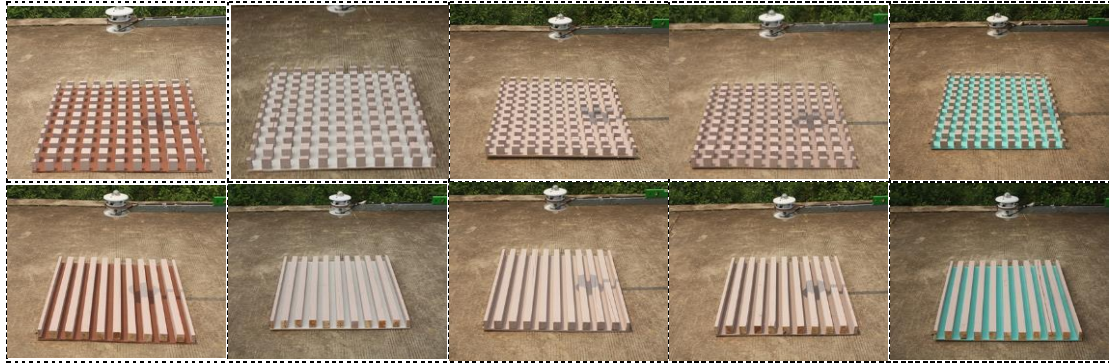

Figure 1. The UC prototypes. The first row are the UC prototype with cross-street orientation and the second row, parallel-street orientation. The east-west orientation UC is the 90°-rotation of the UC with north-south orientation.
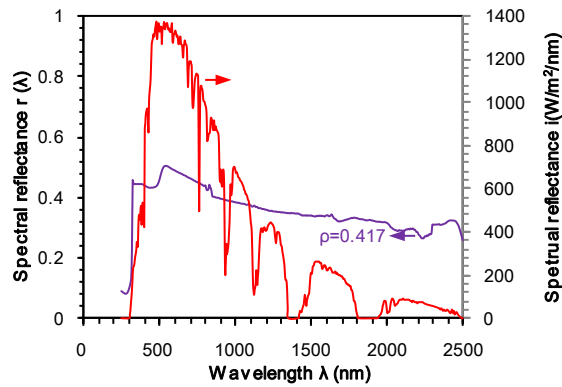

Figure 2. The solar reflectance of the roof and wall of the UC prototypes
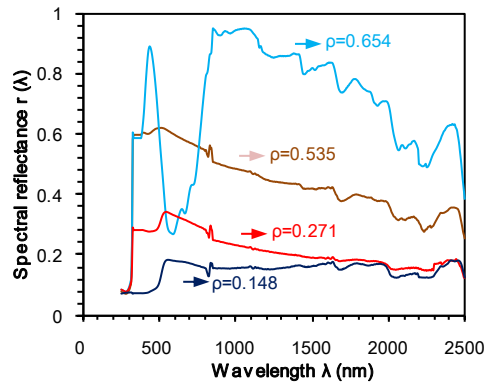

Figure 3. The solar reflectance of the pavements in the UC, where the pavements are assumed be painted with different reflective pigments.
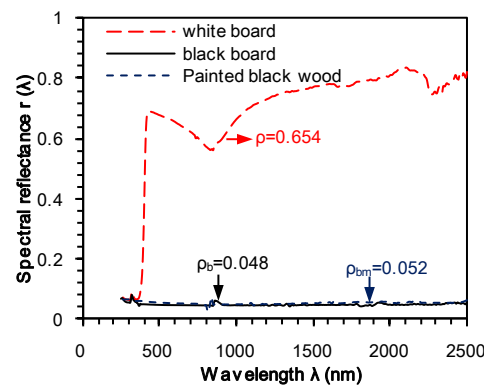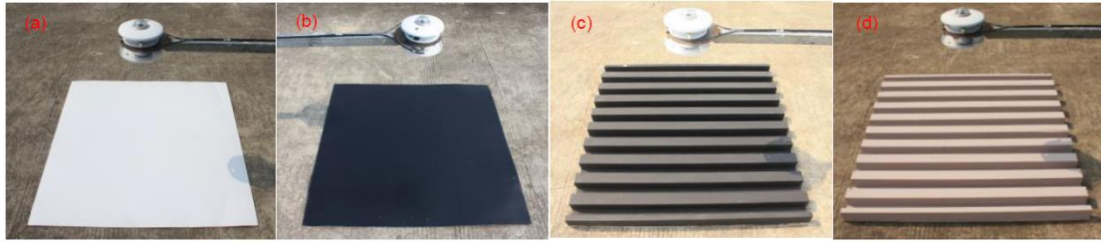
Figure 5. Procedure of measuring the albedo of an UC model (a) white solar-opaque mask; (b) black solar-opaque mask; (c) black UC model; (d) UC model painted unicolor.

4. Results

4.1 The albedo of the UC prototype

The albedo of the canyon prototype varies diurnally, possibly because of the variations of the incoming solar irradiance during the measurement. According to Eq.(1), this variation changes the albedo of a material and consequently changes the albedo of the UC prototype. This can be seen from the great drop of the albedo of the UC prototype when the weather changes from partly cloudy to cloudy (**Figure 6**). At cloudy weather, the arriving solar irradiance is only diffuse radiation but not beam radiation. The diffuse radiation strikes every corns of the canyon and enhances multiple reflections in the canyon while the beam radiation may be partially blocked by the building. The enhancement of the multiple reflections of diffuse radiation causes a drop of the albedo, as indicated in **Figure 6**.

The albedo of the UC prototype increases with the reflectivity of the pavement. The albedo of the UC prototype with east-west and north-south orientations increases in a lower rate than that with a cross-street orientation. This is because the cross-street prototype has a greater pavement (street) surface to be painted. However, the UC albedo increases in a lower ratio than the rise of the pavement reflectivity. For all UC prototypes, the albedo of the roof and wall are 0.417 but the albedo of all UC prototypes is lower than 0.40 even if the albedo of the street has rose to 0.652. This is because multiple reflections reduce the diffuse radiation escaping to the sky.

Figure 7 shows the correlation between the pavement reflectivity and the UC albedo, which is the average of the diurnal albedo in **Figure 6**. The albedo of the cross-street UC prototype exhibits higher albedo than both north-south and east-west orientations when the pavement is of high reflectivity (**Figure 7**). It is hard to distinguish the difference between the albedo of north-south orientation UC prototype and of east-west orientation UC prototype. But a close look at the curves found that compared to the north-south UC prototype, the east-west UC prototype has greater albedo for high-reflective street but lower albedo for low-reflective street (**Figure 7**). This reason may be that at the measuring date, the sun stays south related to the measuring location. In the case, an east-west UC has more sunlight striking on the pavement than a north-south UC, resulting in a drop (rise) of the ease-west UC's albedo in low (high)-reflective pavement case.
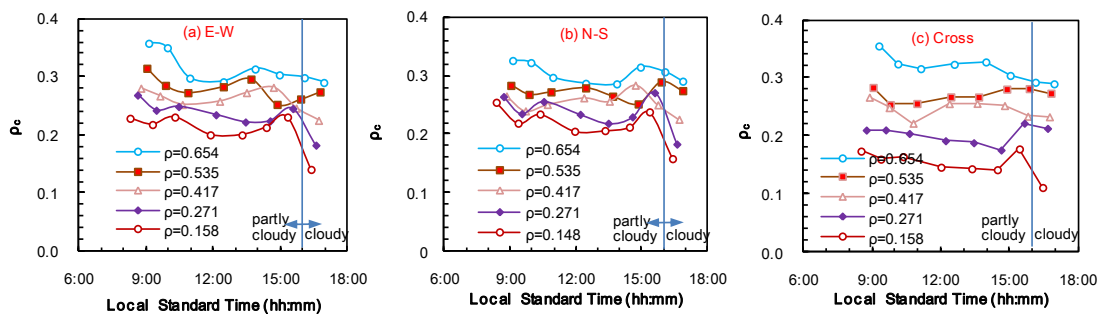

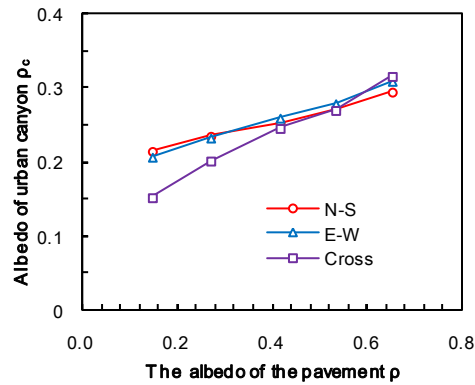**Figure 6.** The albedo of UC prototype varies over time.

Figure 7. The correlation between pavement albedo and the UC albedo.

The average of the diurnal albedo of the urban canyon further indicates that painting the pavement in urban streets with high reflectivity is insufficient to raise the UC albedo. When the pavement is of low reflectivity, the albedo of UC is about 0.15 to 0.20; increasing the albedo of the pavement to 0.652 could raise the UC albedo to about 0.30 only, even though the roof and the wall have an albedo of 0.417 (**Figure 7**).

5. Discussion

It is not a practical solution to develop reflective pavements in UCs with a high-aspect ratio as canyon cooling strategy. As the findings of the study shows, raising the pavement albedo does not help the diffuse radiation escaping to the sky. The reflections from the pavement are recaptured by the other surfaces in the urban canyon, such as the adjacent building wall. According to Qin[8], the building wall of an UC with an aspect ratio of 1.0 would be struck by about 50-80 W/m^2 additional diffuse radiation when the pavement albedo rose from 0.15 to 0.50. For a greater aspect-ratio UC, the sunlight insolating on the pavement will last shorter, so painting the street with high reflectivity does not reduce the heat intake of the UC. For a lower aspect-ratio UC, the sunlight insolating hours will be longer so the reflective streets may be an urban street cooling strategy.

However, this does not necessarily mean that it is feasible to paint a low aspect ratio UC with reflectivity. Reflective pavements may increase the radiative flux absorbed by the pedestrians. For simplification, we consider a pedestrian standing on an infinitely wide parking lot, as shown in **Figure 8** and we take the radiation flux at the noontime into account. Varying the pavement albedo changes the surface temperature. Here the pavement-surface maximum temperature and the albedo is regressed according to Pomerantz[26]; the correlation is:

$$T_g = 43.2(1 - \rho_g) + 11 \tag{9}$$

where T_g (^{o}C) is the ground temperature at noontime. When the pavement is painted with higher-reflectivity, the pedestrian receives more reflective diffuse radiation but less ground-emitted long-wave radiation, as shown in **Figure 8.**

The net radiative flux absorbed by the pedestrian is A:

$$A = (1 - \rho_p)\rho_g I F_{g \to p} + \varepsilon_p \varepsilon_g \sigma (T_g + 273.15)^4 F_{g \to p} \tag{10}$$

where σ is Stefan-Boltzmann constant, $\sigma = 5.67 \times 10^{-8}$ kg·s^{-3}·K^{-4}, $F_{g \to p}$ is the view factor of the ground to the pedestrian, and $F_{g \to p}$=0.5 for an infinite flat ground.

For nonmetal materials, the emissivity is about 0.85-0.95. Taking ε_p= ε_g=0.90 and I=1000W/m^2 (for a typical sunny day), one gets the diffuse radiative flux absorbed by the pedestrian, as shown in **Figure 9.** It can be seen that for a pedestrian with an albedo of 0.20, increasing the pavement albedo from 0.20 to 0.60 would increase the absorption of the pedestrian about 100W/m^2 (140-40W/m^2, **Figure 9**); the magnitude is agreed with the findings of Lynn[32]. If the pedestrian albedo is greater than 0.70, increasing the ground albedo will not increase the heat loadings of the pedestrians. Therefore, seflective pavements will cool the object only if the object's albedo exceeds a critical value. Similar findings are reported by Levinson[33], who found that increasing the ground albedo could heat or cool a near-ground object, depending on the object's albedo. When the object has an albedo of 0.3, increasing ground albedo by 0.25 perturbs the environmental temperature by 1.1 to 0.3 ℃ for a human, 0.4 to 0.9 ℃ for a car, and 1.0 to 2.3 ℃ for a bungalow near ground. An experimental study by Li[34] showed that temperature of building walls would be heated up by reflected en-

ergy from pavement surfaces, which could be 2–5 ℃ around noon.

Although this additional absorption depends on the pedestrian coating (ρ_p), it may cause thermal discomfort. In case that the pavement is not infinite length, pedestrians standing alongside the pavement still receive a sizable radiative flux because the pavement close to pedestrians contributes most of diffuse radiation to the walker. Therefore, it should be also cautious to develop reflective pavements in low aspect-ratio UC or parking lot.
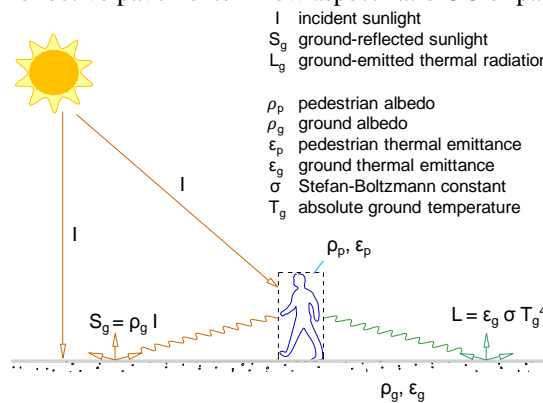

Figure 8. Radiative flux balance of a pedestrian on an open area with reflective surface.
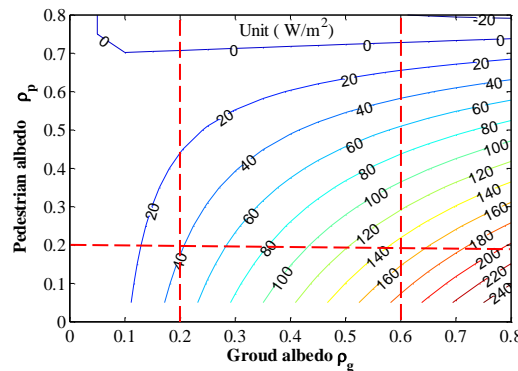

Figure 9. Radiative flux absorbed by a pedestrian on an open area with different pavement (ground) albedo.

6. Conclusions

The albedo of ten urban canyon (UC) prototypes with different pavement's (or street's) reflectivity was measured, respectively. For an UC with an aspect ratio of 1.0, raising the pavement albedo from 0.15 to 0.65 increases the albedo of the UC from only 0.15 to 0.35 when the albedo of the roof and wall is about 0.40 (represent the reflectivity of common roof and wall). Raising the albedo of the pavement in an urban canyon is thus inefficient to increase the albedo of the UC, especially for UC with a great aspect ratio. Raising the albedo of the pavement in low aspect-ratio UC or in parking lot introduces a sizable additional diffuse radiative flux to the pedestrians. Therefore, it should be cautious to develop reflective pavements as an urban cooling strategy.

Acknowledgements

References

1. Panão MNO, Gonçalves HP, Ferrão PC. A matrix approach coupled with monte carlo techniques for solving the net radiative balance of the urban block. Boundary-Layer Meteorology 2007; 122(1): 217-241.
2. Qin Y, Hiller JE. Understanding pavement-surface energy balance and its implications on cool pavement development. Energy and Buildings 2014; 85(0): 389-399.

3. Mills GM. Simulation of the energy budget of an urban canyon—I. Model structure and sensitivity test, Atmospheric Environment. Part B. Urban Atmosphere 1993; 27(2): 157-170.

4. Kastendeuch PP, Najjar G. Simulation and validation of radiative transfers in urbanised areas. Solar Energy 2009; 83(3): 333-341.

5. Aida M, Gotoh K. Urban albedo as a function of the urban structure — A two-dimensional numerical simulation. Boundary-Layer Meteorology 1982; 23(4): 415-424.

6. Aida M. Urban albedo as a function of the urban structure — A model experiment. Boundary-Layer Meteorology 1982; 23(4): 405-413.

7. Fortuniak K. Numerical estimation of the effective albedo of an urban canyon. Theoretical and Applied Climatology 2008; 91(1-4): 245-258.

8. Qin Y. Urban canyon albedo and its implication on the use of reflective cool pavements. Energy and Buildings 2015; 96(0): 86-94.

9. Dimoudi A, Zoras S, Kantzioura A, Stogiannou X, Kosmopoulos P, Pallas C. Use of cool materials and other bioclimatic interventions in outdoor places in order to mitigate the urban heat island in a medium size city in Greece. Sustainable Cities and Society 2014; 13: 89-96.

10. Li H, Harvey JT, Holland TJ, Kayhanian M. The use of reflective and permeable pavements as a potential practice for heat island mitigation and stormwater management. Environmental Research Letters 2013; 8(1): 015023.

11. Anandakumar K, A study on the partition of net radiation into heat fluxes on a dry asphalt surface. Atmospheric Environment 1999; 33(24–25): 3911-3918.

12. Akbari H, Rose L. Characterizing the fabric of urban environment: a case study of metropolitan Chicago, Ilinois, in: Paper LBNL-49275, Lawrence Berkeley National Laboratory, Berkeley, CA, 2001.

13. Akbari H, Konopacki S, Pomerantz M. Cooling energy savings potential of reflective roofs for residential and commercial buildings in the United States. Energy 1999; 24(5): 391-407.

14. Wang H, Wu S, Chen M, Zhang Y. Numerical simulation on the thermal response of heat-conducting asphalt pavements, Physica Scripta 2010 (T139) (2010) 014041.

15. Pomerantz M, Akbari H. Cooler paving materials for heat-island mitigation, in: Proceedings of the 1998 ACEEE summers study on energy efficiency in building, 1998, p.135.

16. Pomerantz M, Akbari H, Chen A, Taha H, Rosenfeld AH. Paving materials for heat island mitigation, in: Lawrence Berkeley National Laboratory Report LBL-38074, Berkeley, CA, 1997.

17. Karlessi T, Santamouris M. Improving the performance of thermochromic coatings with the use of UV and optical filters tested under accelerated aging conditions. International Journal of Low-Carbon Technologies 2013; 10(1): 45-61.

18. Synnefa A, Dandou A, Santamouris M, Tombrou M, Soulakellis N, On the use of cool materials as a heat island mitigation strategy. Journal of Applied Meteorology & Climatology 2008; 47(11): 2846-2856.

19. Synnefa A, Santamouris M, Apostolakis K. On the development, optical properties and thermal performance of cool colored coatings for the urban environment. Solar Energy 2007; 81(4): 488-497.

20. Ma Y, Zhu B. Research on the preparation of reversibly thermochromic cement based materials at normal temperature. Cement and Concrete Research 2009; 39(2): 90-94.

21. Karlessi T, Santamouris M, Apostolakis K, Synnefa A, Livada I. Development and testing of thermochromic coatings for buildings and urban structures. Solar Energy 2009; 83(4): 538-551.

22. Levinson R, Akbari H. Effects of composition and exposure on the solar reflectance of portland cement concrete. Cement and Concrete Research 2002; 32(11): 1679-1698.

23. Boriboonsomsin K, Reza F. Mix design and benefit evaluation of high solar reflectance concrete for pavements. Transportation Research Record: Journal of the Transportation Research Board 2011 (-1) (2007) 11-20.

24. Marceau NL, Vangeem MG. Solar reflectance values for concrete: intrinsic material properties can minimize the heat island effect. Concrete International. 2008; 52-58.

25. Sultana S. Extending asphalt pavement life with thin whitetopping. Kansas State University 2010.

26. Pomerantz M, Pon B, Akbari H, Chang SC. The effect of pavements' temperatures on air temperatures in large cities, in: LBNL 43442, LBNL, Berkeley, CA, 2000; p.1-16.

27. Santamouris M, Gaitani N, Spanou A, Saliari M, Giannopoulou K, Vasilakopoulou K, Kardomateas T. Using cool paving materials to improve microclimate of urban areas – Design realization and results of the flisvos project. Building and Environment 2012; 53(0): 128-136.

28. Kinouchi T, Yoshinaka T, Fukae N, Kanda M. Development of cool pavement with dark colared high albedo coating, in: 5th conference for the urban evironment, Vancouver, Canada, 2004, pp. 1-4.

29. Anak Guntor N, Md Din M, Ponraj M, Iwao K. Thermal performance of developed coating material as cool pavement material for tropical regions. Journal of Materials in Civil Engineering 2014; 26(4): 755-760.

30. Synnefa A, Dandou A, Santamouris M, Tombrou M, On the use of cool materials as heat island mitigation strategy, Journal of Applied Meteorology and Climatology 2008; 47: 2846-2857.

31. Akbari H, Levinson R, Stern S. Procedure for measuring the solar reflectance of flat or curved roofing assemblies. Solar Energy 2008; 82(7): 648-655.

32. Lynn BH, Carlson TN, Rosenzweig C, Goldberg R, Druyan L, Cox J, Gaffin S, Parshall L, Civerolo K. A modifi-

cation to the NOAH LSM to simulate heat mitigation strategies in the New York City metropolitan area. Journal of Applied Meteorology and Climatology 2009; 48(2): 199-216.

33. Levinson R. Near-ground cooling efficacies of trees and high-albedo surfaces. University of California 1997.
34. Li H. Evaluation of cool pavement strategies for heat island mitigation. Department of civil and environmental engineering, University of California, Davis, 2012.