The use of reflective and permeable pavements as a potential practice for heat island mitigation and stormwater management

2013 Environ. Res. Lett. 8 015023

(http://iopscience.iop.org/1748-9326/8/1/015023)

OPEN ACCESS
IOP PUBLISHING
ENVIRONMENTAL RESEARCH LETTERS
Environ. Res. Lett. **8** (2013) 049501 (2pp)
doi:10.1088/1748-9326/8/4/049501

Corrigendum: The use of reflective and permeable pavements as a potential practice for heat island mitigation and stormwater management

2013 *Environ. Res. Lett.* **8** 015023

H Li[1], J T Harvey[1], T J Holland[2] and M Kayhanian[3]

[1] University of California Pavement Research Center, Department of Civil and Environmental Engineering, University of California, Davis, CA 95616, USA
[2] California Department of Transportation, Sacramento, CA 95814, USA
[3] Department of Civil and Environmental Engineering, University of California, Davis, CA 95616, USA

E-mail: hili@ucdavis.edu, jtharvey@ucdavis.edu, t.joe.holland@dot.ca.gov and mdkayhanian@ucdavis.edu

Received 27 November 2013, revised 27 November 2013
Accepted for publication 27 November 2013
Published 16 December 2013
Online at stacks.iop.org/ERL/8/049501

Figure 9 and its caption are incorrect. The correct figure and caption are as follows.

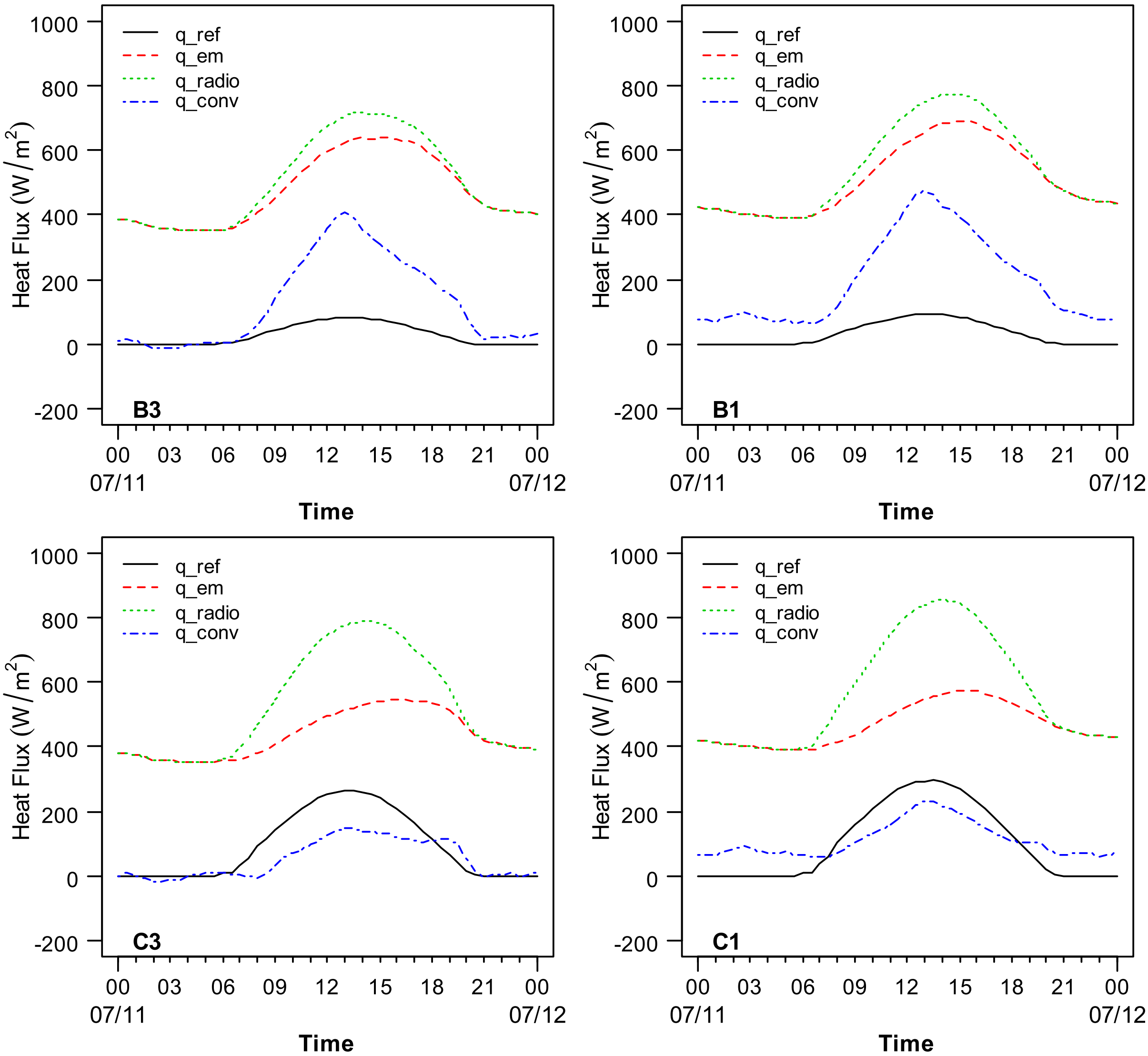


Figure 9. Heat flux from pavement surfaces for one full day during July 2012. (Reflected short-wave solar radiation q_ref = rI, r is albedo in figure 4, I is incident solar radiation in W m^{-2}; emitted long-wave radiation q_em= $\varepsilon\sigma(T_s + 273)^4$, ε is thermal emissivity and assumed 0.9, Stefan–Boltzmann constant $\sigma = 5.670 \times 10^{-8}$ W (m^2 K^4)$^{-1}$, T_s is pavement surface temperature in °C; radiosity q_radio = q_ref + q_em; convective heat q_conv = $h_c(T_s - T_a)$, in W (m^2 °C)$^{-1}$, convection coefficient $h_c = 6.1 + 3.7V_w$, V_w and T_a are wind velocity (m s^{-1}) and air temperature (°C) at 2 m above pavement, respectively. B3: permeable asphalt pavement; B1: impermeable asphalt pavement; C3: permeable concrete pavement; C1: impermeable concrete pavement.)

OPEN ACCESS
IOP Publishing	Environmental Research Letters
Environ. Res. Lett. **8** (2013) 015023 (14pp)	doi:10.1088/1748-9326/8/1/015023

The use of reflective and permeable pavements as a potential practice for heat island mitigation and stormwater management

H Li[1], J T Harvey[1], T J Holland[2] and M Kayhanian[3]

[1] University of California Pavement Research Center, Department of Civil and Environmental Engineering, University of California, Davis, CA 95616, USA
[2] California Department of Transportation, Sacramento, CA 95814, USA
[3] Department of Civil and Environmental Engineering, University of California, Davis, CA 95616, USA

E-mail: hili@ucdavis.edu, jtharvey@ucdavis.edu, t.joe.holland@dot.ca.gov and mdkayhanian@ucdavis.edu

Received 30 October 2012
Accepted for publication 6 February 2013
Published 25 February 2013
Online at stacks.iop.org/ERL/8/015023

Abstract
To help address the built environmental issues of both heat island and stormwater runoff, strategies that make pavements cooler and permeable have been investigated through measurements and modeling of a set of pavement test sections. The investigation included the hydraulic and thermal performance of the pavements. The permeability results showed that permeable interlocking concrete pavers have the highest permeability (or infiltration rate, ~0.5 cm s^{-1}). The two permeable asphalt pavements showed the lowest permeability, but still had an infiltration rate of ~0.1 cm s^{-1}, which is adequate to drain rainwater without generating surface runoff during most typical rain events in central California. An increase in albedo can significantly reduce the daytime high surface temperature in summer. Permeable pavements under wet conditions could give lower surface temperatures than impermeable pavements. The cooling effect highly depends on the availability of moisture near the surface layer and the evaporation rate. The peak cooling effect of watering for the test sections was approximately 15–35 °C on the pavement surface temperature in the early afternoon during summer in central California. The evaporative cooling effect on the pavement surface temperature at 4:00 pm on the third day (25 h after watering) was still 2–7 °C lower compared to that on the second day, without considering the higher air temperature on the third day. A separate and related simulation study performed by UCPRC showed that full depth permeable pavements, if designed properly, can carry both light-duty traffic and certain heavy-duty vehicles while retaining the runoff volume captured from an average California storm event. These preliminarily results indicated the technical feasibility of combined reflective and permeable pavements for addressing the built environment issues related to both heat island mitigation and stormwater runoff management.

Keywords: built environment, heat island, stormwater runoff, permeable pavement, cool pavement, reflective pavements, thermal comfort, energy use, hydraulic, structural and thermal performance

S Online supplementary data available from stacks.iop.org/ERL/8/015023/mmedia

1. Introduction

1.1. Background

The large fraction of urban areas related to transportation land use (roads, parking areas, sidewalks, commercial plazas and playgrounds) is usually covered with conventional paved areas [1]. Most of these conventional pavements are impervious (not permeable) which results in rainwater and excess urban irrigation water being directed to storm drains instead of the soil subgrade through infiltration. The increased impervious area increases the volumes and peak intensities of stormwater runoff and the associated water pollutant mass as well as reducing the groundwater recharge. In addition, for some developing regions with rapid urbanization, these substantially increased impervious areas (including pavements as well as building roofs) also potentially increase the risk of flooding in terms of both frequency and extent, especially during extreme storm events under potential climate change. The generated runoff and the related wash off pollutant under typical storm events must be treated before discharging them to the receiving waters. With the availability of land, conventional best management practices (BMPs) such as wet and dry detention basins are usually constructed to manage the stormwater runoff [2–5]. However, the construction of detention basins in most urban environment can be expensive and impractical.

Another built environmental issue related to pavements is the urban heat island (UHI) effect. In general, heat islands can be considered at two levels, referred to as surface and atmospheric heat islands [6–9]. Recently, a third type, near-surface heat islands, has been introduced dealing with the increased ambient air temperature just above the surface at heights where human outdoor activities occur. Surface and near-surface heat islands can potentially affect human thermal comfort, air quality and energy use of nearby vehicles and buildings, again primarily due to increased use of air conditioning. Most of the existing pavements (over 90% for many areas [10]) are black asphalt or dark seal coated pavements, which give high surface temperatures during hot periods when not shaded by trees, buildings or by other means. For example, surface temperatures on pavements with surface albedos of around 0.1 up to 70–80 °C (158–176 °F) have been measured on hot summer days around 3:00 pm in Phoenix, Arizona [11], and up to 70 °C (158 °F) in Davis, California as measured under study. Hot pavements can contribute to the heat island effect, especially the near-surface heat island.

Significant negative environmental and economic impacts can be associated with heat island effects, especially during summer in hot climates. These impacts include comprised human thermal comfort and health, increased cooling energy demand for buildings, impaired air quality (ground level ozone), as well as accelerated infrastructure deterioration [12]. Along with cool roofs [13–20], ‘cool pavements’ have been identified by the United States Environmental Protection Agency (US EPA) as one strategy for mitigating heat island [21], and the Leadership in Energy and Environmental Design (LEED), a green building certification program from the US Green Building Council (USGBC), awards points for installation of ‘cool pavement’ [22]. Permeable pavements (also referred to as pervious concrete, porous asphalt and interlocking concrete pavers), high-reflectance pavements, evaporative cooling pavements, and shade-cooled pavements are generally considered to be ‘cool’ because they can potentially reduce the temperatures of both pavements and near-surface air, and consequently mitigate heat island effect, reducing energy use for cooling buildings [23].

However, it should be noted that the impacts of higher pavement temperatures on urban heat islands are not always negative, and the significance of impacts is different for different locations and for different seasons. While producing negative impacts during hot seasons in hot climates, heat islands can also bring some benefits to building owners and occupants of the spaces near pavement surfaces by reducing building heating energy use and human thermal discomfort during cold weather and in cold regions [24, 25]. Moreover, these effects are different at the city-wide and local (site level) scales, which should be analyzed separately. A comprehensive evaluation of the extent of pavement heating on different sizes of urban areas, with differing pavement densities, tree canopies, building patterns, latitudes and climates has not been found in the literature. When considering the overall effect on atmospheric UHI for an urban area, large scales are appropriate, but when considering human thermal comfort and pavement life, the localized near-surface effects will be of more importance than the overall urban heat island effect.

To address the built environmental issues of both heat island and stormwater runoff in some urban areas with hot climates, it is desired to explore strategies that make the pavements more reflective and permeable. Among various possible pavement strategies, reflective pavements absorb less solar radiation and emit less heat at critical times of the day, while permeable pavements capture stormwater or excess irrigation water by allowing it to drain into the pavement and then later evaporate. The combined strategies of reflective and permeable pavements could be a potential practice for lowering high temperatures and thus mitigating heat island effects while reducing stormwater runoff and improving water quality.

1.1.1. Reflective pavement. The temperatures of pavement surfaces exposed to solar radiation are generally higher than the adjacent air temperatures due to heating by absorbed solar radiation, thus creating a surface heat island. The extent to which solar radiation influences surface temperatures depends on the solar reflectance of the exposed pavement surface.

As one major thermal characteristic, solar reflectivity or albedo is an indicator of the reflecting power of a surface. It is defined as the ratio of the reflected solar radiation to the incident solar radiation at the surface. Albedo is a dimensionless fraction and is measured on a scale from 0 to 1. Albedo of 0 means no reflecting power of a perfectly black surface (none reflected, all absorbed), Albedo of 1 means perfect reflection of a perfectly white surface (100% reflected) [26, 27].

Therefore, increasing the solar reflectivity of a pavement surface by using surfacing materials of light color (e.g. [28–30]) or applying light color coating on dark surfacing materials (e.g. [17, 31–38]), can lower the pavement surface temperature. However, the increased reflected radiation in an urban area might be directed and absorbed by the surrounding building surfaces, thus raising building temperatures and leading to increased cooling energy use.

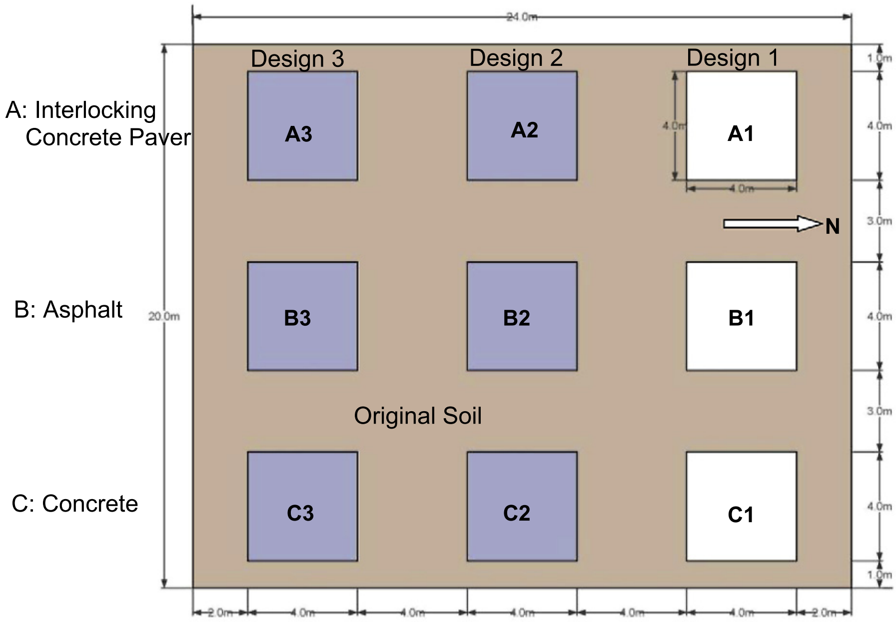


Figure 1. Schematic view of experimental test sections at the UCPRC facility (six permeable pavement sections shown in shaded area, i.e. left two columns) (adapted from [41]).

1.1.2. Permeable pavement. As another potential cool pavement type, permeable pavements, have many environmental benefits including reducing stormwater runoff, reducing the discharge of pollutant load to receiving waters, improving water quality and recharging underground water [2–5]. Besides these stormwater-related benefits, permeable pavements also could be an effective solution for improving outdoor thermal environment through evaporative cooling [24, 25]. Evaporative cooling could reduce pavement temperature and consequent air temperature during hot times of the day through latent heat absorbed during the phase change of water (from liquid to gas) when water is present in or on top of the pavement.

Permeable pavement contains more air voids than conventional impermeable pavement and is designed to allow water to drain through the surface into the sublayers and down into the groundwater. Conventional permeable pavements include porous asphalt pavements, pervious concrete pavements, pervious cast concrete pavement [39], and permeable interlocking concrete pavements [40]. These kinds of permeable pavements can be used in city streets, parking lots, highway shoulders, etc, but are generally not applicable for high-speed traffic.

Other non-conventional permeable pavements includes vegetated permeable pavements, such as grass pavers and concrete grid pavers, that use plastic, metal, or concrete lattices for support and allow grass or other vegetation to grow in the interstices [21]. Unlike the conventional permeable pavements, the typical use of vegetated permeable pavements is for lower traffic volumes such as alleys, parking lots, and trails and they are best suited to climate regions with adequate moisture to keep vegetation alive, or have available irrigation systems. Vegetated permeable pavements incorporate both evaporation and the transpiration of vegetation to provide additional cooling effect to help reduce the pavement temperature.

1.2. Objective of this study

The overall goal of this paper is to explore the feasibility of using permeable pavements as a potential practice to help manage stormwater runoff and mitigate heat island effects, particularly near-surface heat islands. Hence, a major portion of this paper is devoted to present a summary of some experimental results related to the thermal performance and cooling effect (both reflective cooling and evaporative cooling) of different permeable pavements under both dry and wet conditions compared to conventional impermeable pavements, as well as thermal impact and heat exchange on near-surface air. A summary of the hydraulic conductivities (infiltration rate) of the permeable pavements is also presented in this paper. In addition, a brief discussion is presented to show the potential application of full depth permeable pavements for stormwater runoff management and cool pavement effect in urban areas.

2. Materials and methods

2.1. Pavement materials and experiment plan

Cool pavement related results, including hydraulic conductivity, albedo and thermal performance data were obtained from six permeable and three non-permeable pavements test sections. The nine test sections were constructed with each having an area of 4 m × 4 m (13 ft × 13 ft) at the UCPRC test facilities in Davis, California (see figure 1). The characteristics of each test section used for cool pavement investigation is presented in table 1. As shown, besides

Table 1. Characteristics of nine test sections and experimental plan [41].

Section	Pavement layer		Base layer		Test locations[b]
	Type[a]	Thickness (cm)	Type	Thickness (cm)	
A1[c]	ICP-I	10[d]	AB-I	15	SE, NE, NW, SW, CT
A2	ICP-P	10[d]	AB-P	15	SE, NE, NW, SW, CT
A3	ICP-P	10[e]	AB-P	30	SE, NE, NW, SW, CT
B1[c]	AC-I	10	AB-I	15	SE, NE, NW, SW, CT
B2	AC-P	10	AB-P	30	SE, NE, NW, SW, CT
B3	AC-P	20	AB-P	30	SE, NE, NW, SW, CT
C1[c]	PCC-I	10	AB-I	15	SE, NE, NW, SW, CT
C2	PCC-P1[f]	10	AB-P	30	SE, NE, NW, SW, CT
C3	PCC-P2[f]	20	AB-P	30	SE, NE, NW, SW, CT

[a] ICP: interlocking concrete paver; AC: asphalt concrete; PCC: Portland cement concrete; AB: aggregate base. I: impermeable; P: permeable.
[b] SE: southeast; NE: northeast; NW: northwest; SW: southwest and CT: center.
[c] Only for albedo measurement, not for permeability measurement.
[d] Includes the thickness of paver (6 cm) and underline bedding layer (4 cm).
[e] Includes the thickness of paver (8 cm) and underline bedding layer (2 cm).
[f] The two pervious concrete materials have very different mix designs, cement and aggregate types.

the black asphalt materials (B), more reflective pavements (concrete [C] and interlocking concrete paver [A]) were also used in this study. It is important to note that there are more reflective experimental materials available [17, 32–38], which are planned to be part of future investigations. Three test sections (A1, B1 and C1) are impermeable pavement and the other six test sections (A2, A3, B2, B3, C2, C3) are permeable pavement. For additional information about the test sections, the reader may refer to [41].

2.2. Instrumentation and data collection for temperature

Eight type T thermocouple sensors (from Omega Engineering Inc.® and with measurement error of less than 0.5 °C) were embedded into the pavement layers and near-surface air for monitoring the temperatures of both pavements and near-surface air on each test section. Examples of the cross sections and the locations of thermocouple sensors for each section are shown in figure 2. Six out of eight thermocouple sensors were embedded into the pavements to monitor the pavement temperatures (two for pavement surface, and four for in-depth pavement layers at 1.3, 3.8, 6.4 and 25.4 cm [0.5, 1.5, 2.5 and 10 in] below the surface), and two for the near-surface air (namely at 5.1 and 12.7 cm [2 and 5 in] above the surface).

The temperature data were recorded and collected with a CR-10X Datalogger (from Campbell Scientific, Inc.®) with a time interval of 30 min. Besides the temperature data of pavements and near-surface air on the test sections, on-site weather data, including air temperature and humidity, solar radiation, wind speed and direction, rainfall and air pressure, were monitored with weather station instruments and recorded using the CR-10X Datalogger also with a time interval of 30 min.

2.3. Permeability and albedo measurement

Surface pavement permeability (also referred to saturated hydraulic conductivity or infiltration rate) was measured by the ASTM C1701 method (see [42] for details on the difference of permeability measurement methods and correlation of values measured with the different methods). The measurements were performed on the six permeable sections (A2–3, B2–3, and C2–3) and for each test section five measurements were made at the southeast corner (SE), northeast corner (NE), northwest corner (NW), southwest corner (SW) and center (CT). At least three measurements were performed at each location.

A dual-pyranometer (from NovaLynx Corporation® with measurement error of less than 1 W m^{-2}) with data acquisition systems (DAS) was used to measure the albedo of all experimental pavement test sections (paver, asphalt and concrete). The albedo measurement was also performed at five different locations (SE, NE, NW, SW and CT) for each test section. At each location, six or more measurements were performed. The albedo measurements on the nine experimental test sections (A1–3, B1–3 and C1–3) were performed at mid-day (mostly 12:00–14:00). The experimental plan for the permeability and albedo measurements for the nine test sections is also summarized in table 1.

2.4. Irrigation experiment

To examine the thermal behaviors of the different pavements and cooling effects of permeable pavements under both dry and wet conditions, an irrigation experiment was conducted in July 2012 (in California, summer is the dry season, typically with zero rainfall). From 3:00 pm 10 July 2012 to ∼1:00 am 11 July 2012, water was irrigated into the permeable test sections to saturate the pavements to their surface. Approximately 3.5 m^3 ($\sim 0.35\ m^3\ h^{-1} \times 10\ h = \sim 3.5\ m^3$; $3.5\ m^3/(4\ m \times 4\ m) = 0.22\ m^3$ of water per square meter of pavement or 48.3 gal/square yard) were irrigated into each of the six permeable sections (A2–3, B2–3 and C2–3). The temperatures of pavement and near-surface air were continuously monitored before, during and after the irrigation for comparison.

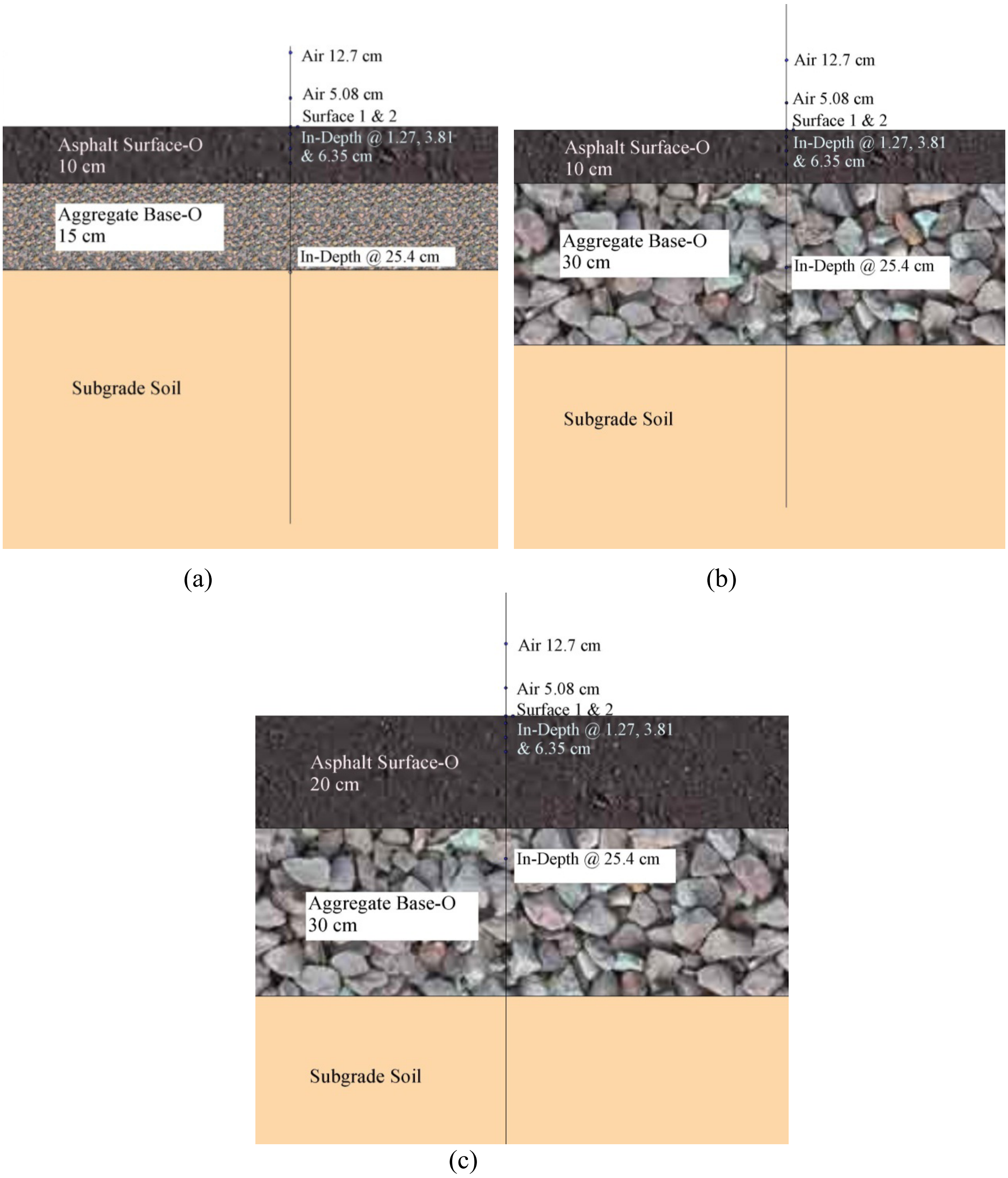


Figure 2. Example cross sections and sensor locations for test sections (B1–B3). (a) Section B1. (b) Section B2. (c) Section B3. Note: D = dense-graded, O = open-graded.

3. Results and discussion

3.1. Permeability and hydraulic performance of permeable pavements

The average permeability (a.k.a, saturated hydraulic conductivity or infiltration rate) for each of the six permeable test sections is shown in figure 3. The average permeability values presented in figure 3 were based on three measurements from each of the five different locations on each pavement test section. The method used and other details related to the reliability and precision of the permeability measurement can be obtained in [42].

The permeability results show that the interlocking concrete pavers having the highest permeability (or infiltration rate, $\sim$0.5 cm s^{-1}). The two permeable asphalt pavements show the lowest permeability, but still have an infiltration rate of $\sim$0.1 cm s^{-1} which is adequate to drain the rainwater without runoff for most average rain events in central California. One main goal of permeable pavements is to eliminate or reduce the stormwater runoff, which is primarily determined by the permeability of the pavement surface materials and the intensity of rainfall in that locale. Another goal is to eliminate or reduce the overflow from the pavement reservoir once the stormwater is stored in the pavement, which is dependent on the reservoir capacity and the rainfall load

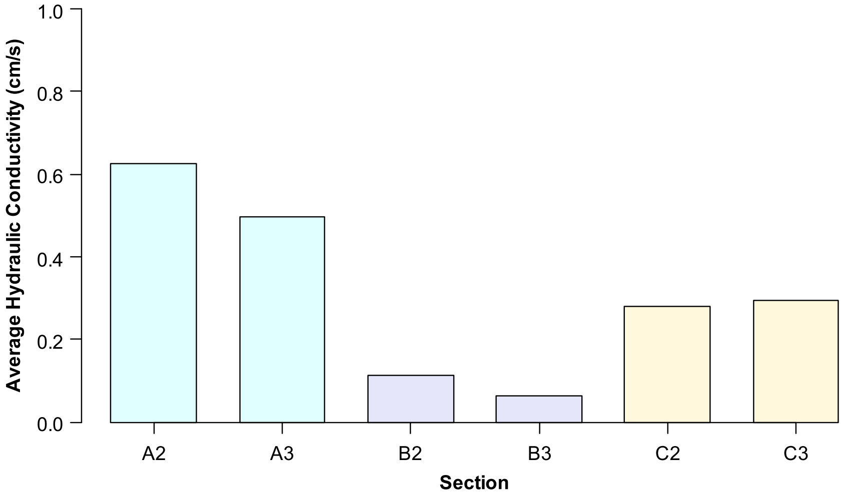


Figure 3. Average hydraulic conductivity (or infiltration rate) of six permeable test sections.

on the system. The reservoir capacity is determined by the thickness and void content of the granular reservoir base layer, the permeability of pavement subgrade materials (i.e. underlying soil) and the rainfall load on the system, which is determined by the intensity, duration and frequency of rainfall. Often the permeability of pavement subgrade soil materials (especially for clay soils) is relatively low (about 10^{-5} cm s^{-1}), and consequently it takes a relatively long time to completely drain the stormwater [43]. Therefore, a reservoir layer (usually made of granular materials with large air void content) with adequate thickness and capacity is required to store the stormwater giving it adequate time for it to drain into the ground. Simulation investigations conducted by UCPRC researchers indicated that full depth permeable pavements can provide adequate stormwater runoff volume storage for most climate regions and rain events in California, which typically involve slow steady rain over several days as opposed to thunder storms, without generating any overflow from pavements [43]. More details on the hydraulic performance and hydraulic design of permeable pavements can be found in [39, 43].

3.2. Structural performance of permeable pavement

Pavements are designed to carry various types of traffic, such as pedestrians, bicycles, cars and trucks, safely and efficiently. For light-duty and low-speed traffic such as pedestrians and vehicles on local streets and parking lots, there are not many critical issues related to the structural performance of conventional impermeable or permeable pavements. Permeable pavements have been used in many parking lots and alleys throughout the United States and other countries [44–46]. However, for pavements intended to carry heavy vehicles (including garbage trucks and buses on residential streets) there are challenges caused by the relatively weak mechanistic performance of permeable pavement materials and structures due to materials that are full of air avoids or holes and subgrades that are kept saturated, just the opposite of traditional good pavement engineering [39, 47, 48].

The researchers at UCPRC have recently completed a laboratory and modeling investigation to estimate the structural performance of permeable pavements for roads that might be subjected to heavy traffic loads. As part of the UCPRC investigation, a large number of structural simulations were performed for a wide range of design parameters, including surface permeable pavement material types; thickness and stiffness of granular base materials, with and without a pervious concrete subbase; different subgrade types, heavy truck numbers and speeds; climate region and season. A preliminary design method and preliminary catalog-type design tables considering both hydraulic and structural performance were developed for permeable pavement design. The preliminary study of both laboratory testing and numerical modeling and simulation indicated that the permeable pavements are technically feasible for heavy-duty roads such as highways and shoulders [39, 47, 48]. The allowable heavy truck traffic levels in terms of Equivalent Single Axle Loads (ESAL) for both concrete and asphalt permeable pavements can be calculated for various pavement thicknesses. A preliminary life cycle cost analysis (LCCA) suggested that the use of full depth permeable pavements is cost-effective compared to conventional impermeable pavements that use conventional best management practices for stormwater management [39]. These structural designs developed for heavy-duty roads have not yet been validated or calibrated with field test sections or accelerated pavement testing. Important issues remain to be resolved before they can be implemented on highways or other heavy-duty roads include constructability, maintenance method and schedule. More details on the structural performance and structural design of permeable pavements can be found in [39, 47, 48].

3.3. Thermal performance of permeable pavement

3.3.1. Albedo and effect on thermal performance. The overall average albedos of each of the nine test sections are

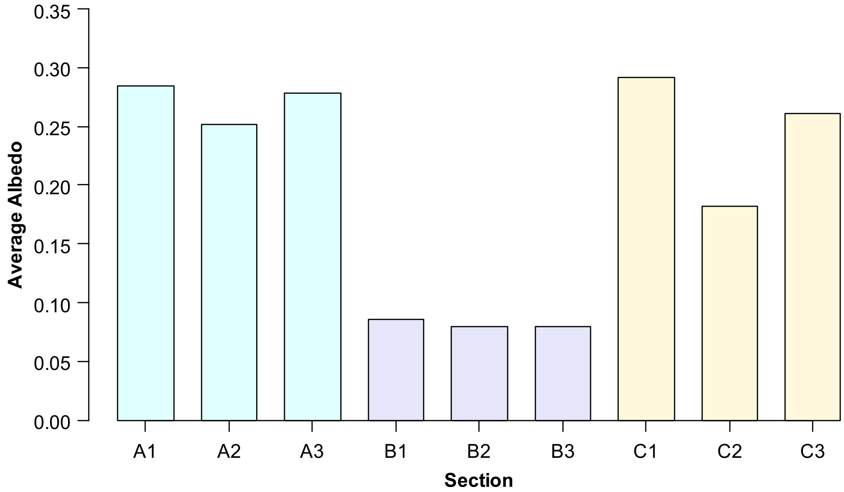


Figure 4. Overall average albedo of each of the nine test sections.

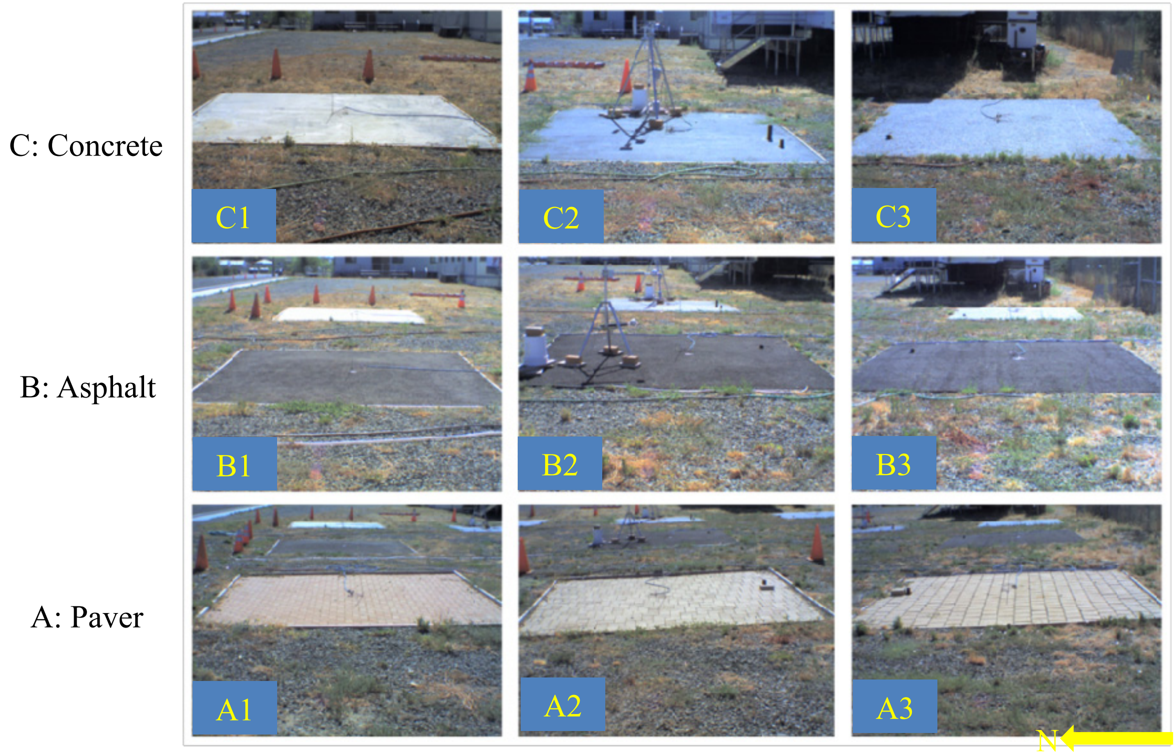
presented in figure 4. The albedos were measured at around noon at five different locations (four corners and one center).

Compared to concrete sections, the asphalt sections, which are black, have lower average albedos (0.09 for B1 and 0.08 for both B2 and B3). Sections B2 and B3 have the same permeable asphalt surface material (only thicknesses are different), and have the same albedo (0.08) as expected. If exposed to traffic, the albedo of the dark asphalt surface would go up once the asphalt coating is worn off, the extent depending on the albedo of the stone. The asphalt coating tends to become grayer with time as it oxidizes as well. The three concrete sections (C1–3) have a range of mean albedo of 0.18–0.29 ranging from the darker concrete section C2 with an albedo of 0.18, 0.26 for C3 and 0.29 for C1. Over time, the concrete would tend to get somewhat darker, depending on the mix and the extent of color change caused by traffic, although typically not as dark as aged asphalt. The interlocking concrete paver sections (A1–3) have albedos close to the more reflective concrete sections (C1 and C3) and are in the range of 0.25–0.28. The relatively low albedo of asphalt pavements will present a high surface temperature due to absorbing more incident solar radiation. In contrast, the concrete and interlocking concrete paver pavements generally have a higher albedo, and give a lower pavement temperature since more incident solar radiation is reflected from the surface [41, 49]. The average albedos of different pavement sections used in this current study range from 0.08 to 0.29. Additional details on variation of albedo on each of these nine sections and across them, as well as factors affecting albedo values, can be found in [11, 49]. Technologies of pavement with higher albedo (in particular, using reflective coatings based on infrared reflective pigments) are planned to be tested on some or all of the nine test sections in the next step of the study.

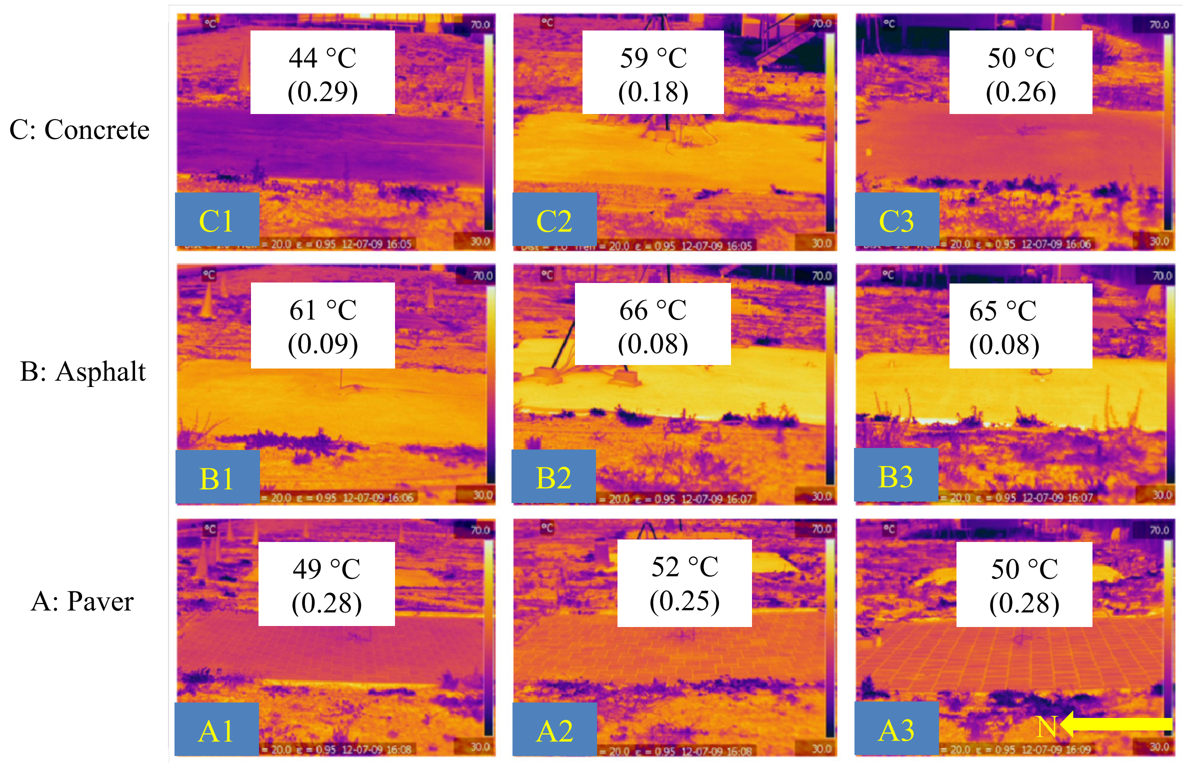
Thermal images taken with an infrared camera and showing pavement surface temperatures on 16:00 9 July 2012 (under dry condition) are presented in figure 5, along with the optical images. First, it shows that the highest temperatures occurred on the asphalt pavements (∼70 °C for B2 and B3 in figure 5), which were 10–25 °C higher than the concrete pavements (∼45 °C for C1 and ∼60 °C for C2 in figure 5). The paver pavements were also cooler than the asphalt pavements by ∼20 °C. It is also noted from figure 5 that the permeable pavements B2 and B3 under dry conditions produced higher surface temperatures than the impermeable pavement B1 by ∼10 °C. The effect of albedo on pavement surface temperature is presented in figure 6. It is clearly shown that the increased pavement albedo can significantly reduce the pavement surface temperature. This implies that using reflective pavement could potentially help mitigate heat island and improve human thermal comfort as well as reducing other negative impacts associated with urban heat island effect.

However, it is important to note that the increased reflected solar radiation caused by high albedo might hit and be absorbed by surrounding people or building/vehicle surfaces. Besides the potential issue of glare, the increases solar radiation reflected by high albedo pavement could increase the human thermal discomfort and building/vehicle cooling energy use during hot periods. Therefore, attention should be given to the complete assessment of both the benefit and penalty in one entire year to ensure a positive net benefit will be obtained. New generation colored reflective pavements based on the use of infrared reflective pigments might reduce the glare [15–20, 31, 36, 50]. Use of surface materials that increase the albedo during summer and reduce or do not change it in winter (e.g. using thermochromic coatings [35]) might be an optimal strategy for changing albedo in a hot climate. The benefit in summer could be maximized and the penalty in winter minimized with this approach.

Besides the albedo, the thermal emissivity, thermal conductivity and heat capacity of the materials, as well as convective heat transfer coefficient and wind speed on the pavement will also have some influence on the thermal performance of the pavement. Compared to albedo, however, thermal emissivity, thermal conductivity and heat capacity of the materials are second order factors affecting the thermal performance of pavement. In addition, only small differences in these parameters are expected for the materials used in



(a)



(b)

Figure 5. Optical and thermal images of experimental test sections on 9 July 2012. (a) Optical images. (b) Infrared thermal images under dry condition (16:00) (lighter is hotter, average surface temperatures are listed with albedo in parentheses).

these test sections [11]. Convective heat transfer coefficient and wind speed on these pavements, which influences the heat convection, are expected to be similar for each of the test sections in this study. Therefore, the effects of thermal emissivity, thermal conductivity and heat capacity as well as wind speed were assumed identical for each

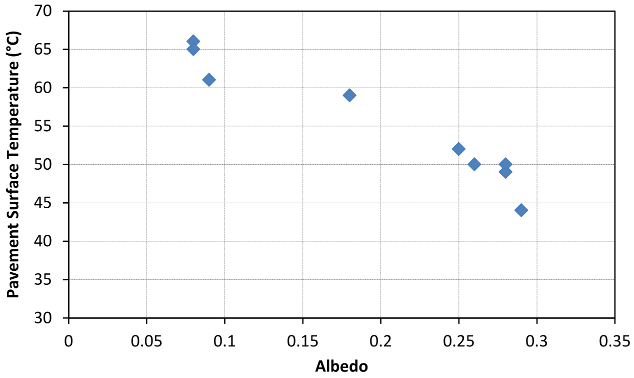


Figure 6. Effect of albedo on pavement surface temperature (16:00 9 July 2012).

case in this current study and not explicitly included in the analysis of cooling effect. The effect of wind speed should be included as well as other thermal proprieties of pavement materials (i.e. thermal conductivity and heat capacity, see [51] for the measurement method) when performing a more comprehensive analysis and/or developing a more comprehensive model.

3.3.2. Comparison of thermal performances of permeable pavements under dry and wet conditions. To examine the thermal performance and cooling effect of the permeable pavement under wet conditions during summer, water at a temperature of approximately 25 °C was irrigated into the permeable pavement section (take B3 as an example) from 15:00 (with highest surface temperature) to 23:00 h on 10 July 2012. The water flow rate was about 0.35 m^3 h^{-1} during irrigation. The pavement section was irrigated until it was filled up with water. The surface temperatures of the permeable asphalt pavement (B3) are presented in figure 7 for the period of 9 July–12 July 2012, which include one day before the irrigation and two days after. The surface temperatures of the impermeable pavement (B1) are also plotted for reference as well as the ambient air temperature during the period (see the supplementary material available at stacks.iop.org/ERL/8/015023/mmedia for more comparisons of thermal performance under dry and wet conditions).

Under the dry condition before irrigation (9 July 2012), the permeable pavement (B3) produced a higher daytime surface temperature than the impermeable pavement (B1), by about 5 °C. However, under the wet condition after irrigation (11 July 2012), the permeable pavement (B3) showed a lower daytime surface temperature than the impermeable pavement (B1), by about 5 °C as well, although the peak ambient air temperature under the wet condition (9 Jul 2012) was about 3 °C higher than that under the dry condition (9 Jul 2012). During the irrigation, especially immediately after the irrigation started (16:00 on 10 July 2012), the surface temperature of the permeable pavement (B3) was lowered down by over 30 °C. It is also noted that the cooling effect of irrigation into the permeable pavement diminishes over time as the moisture surface level moves down inside the pavement due to evaporation and infiltration into the subgrade.

These observations imply that irrigation can help to reduce the daytime pavement surface temperature of

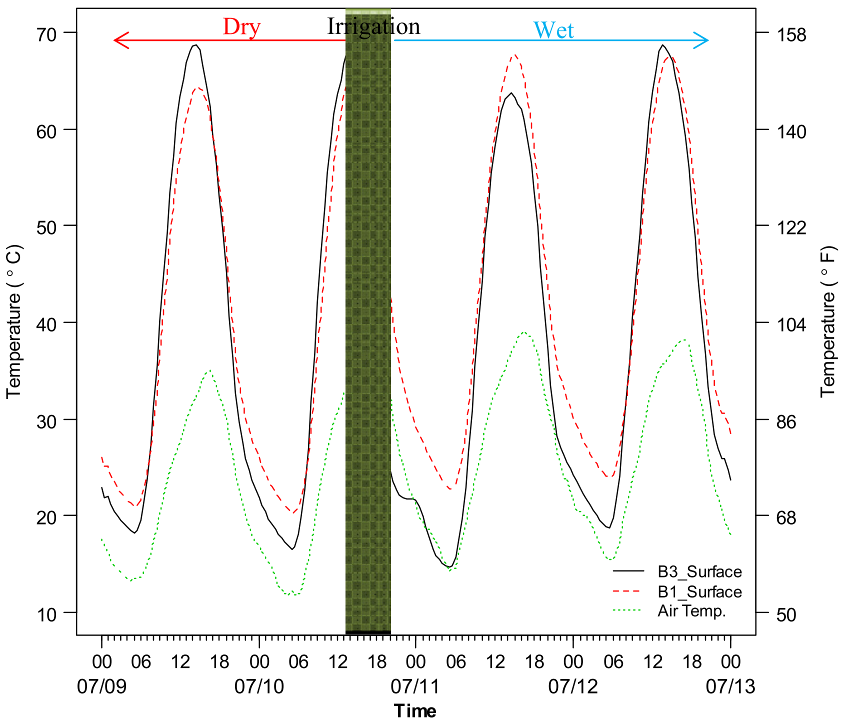


Figure 7. Thermal performance of permeable pavement (B3) with and without irrigation compared to impermeable pavement (B1) for four days on July 2012 (the time unit above mm/dd is hh with 00 representing midnight).

permeable pavements and consequently mitigate the heat island effect and improve thermal comfort. The cooling effect depends on the availability of moisture around the pavement surface and will vanish over time as the water level drops. One approach is that water can be irrigated from urban landscape runoff, such as the water used for vegetation in boulevard medians and in parks, into the permeable pavement during the late afternoons or evenings in summer. This is especially beneficial when the weather report forecasts a very hot day coming, this strategy can be conducted during the night before to mitigate the heat wave coming the next day and improve thermal comfort. In addition, using and/or adding water-retentive materials such as pea gravel, slag, fly ash and water-retentive fiber can potentially improve the water-retention capacity of pavement materials and create water-retentive pavements (e.g. [52–54]) to improve the cooling effect of watering and prolong the effective time of cooling.

Spraying of water onto impermeable pavement during mid-day will increase the cooling effect for a short period of time and the cooling of pavement will diminish as soon as the water evaporates. In contrast, the addition of water on permeable pavement will prolong the cooling effect with more water available for evaporation during daytime. In addition, as noted in figure 7, the surface temperature of permeable pavement is lower than that of impermeable pavement during nighttime under both wet and dry conditions. Hence, permeable pavement will have the added advantage of mitigating the night time heat island effect in urban area during hot summer.

To confirm the thermal behavior of the different pavements and the cooling effects of permeable pavements under both dry and wet conditions, infrared thermal images were taken at different times for all the test sections during the irrigation experiment. Comparison of the thermal images of six permeable pavements under dry and wet conditions as well as more details related to thermal performances for different pavements are presented in the supplementary material (available at stacks.iop.org/ERL/8/015023/mmedia). It is noted that when watered the pavements had much lower temperatures than under the dry condition. Even in the third day without watering but with higher air temperature, the pavements still showed lower temperatures due to evaporative cooling of some moisture existing in pavements. This implies that watering/irrigation can effectively reduce the pavement surface temperatures; evaporation of some moisture from pavements also can help produce a low pavement temperature, provided that there is sufficient waste water from irrigation of urban landscape. In most urban areas with impermeable pavement, the excess landscape irrigation water runs into the stormwater system.

The findings imply that keeping water near the surface of the pavement through enhancing the capillary effect or sprinkling water on the surface or injecting water into the pavement to keep the water level near the surface will increase the evaporation rate and consequently produces a better evaporative cooling effect. The capillary effect depends on the air void content and structure in the surface materials and the sizes, distribution and connectivity of the air voids. More experimental and theoretical studies are recommended to evaluate and optimally design the evaporative cooling effect of pavement materials.

3.3.3. Near-surface air temperatures on different pavements. The near-surface air temperatures of different pavements (5.1 cm [2 in] above pavement surface) are presented in figure 8 for one day in each season. The near-surface air temperatures are generally higher than the ambient air temperature measured at 2 m high, especially during the daytime. The high near-surface air temperatures heated up by pavement surfaces will potentially have an influence on air quality (especially ground level ozone formation) and human thermal comfort (especially close to the ground). The concrete pavement (C3) with high albedo (0.26, see figure 4) has generally lower daytime near-surface air temperatures compared to the asphalt pavement (B3 and B1) with low albedo (0.09 and 0.09, respectively, see figure 4). Compared to the impermeable asphalt pavement (B1), the permeable asphalt pavement (B3) has lower near-surface air temperatures. This implies that using high albedo and permeable pavement can potentially help mitigate near-surface heat island and improve the air quality as well as possibly improve human thermal comfort.

3.3.4. Heat exchange between pavement and near-surface air. Thermal interaction (or heat exchange) between pavement and near-surface air and other surroundings such as buildings is another important aspect to examine besides temperatures. The heat exchange processes include reflected short-wave solar radiation, emitted long-wave radiation, and convective heat. The sum of the reflected short-wave solar radiation and emitted long-wave radiation from the pavement surface is called radiosity. It is the total radiation (sensible heat) from the pavement surface which might hit and consequently be absorbed by the surroundings such as building/vehicle surfaces or human bodies. The convective heat is the energy exchanged through convection between pavement and near-surface air.

The heat flux of these heat exchanges of different pavements are calculated and presented in figure 9 for a typical sunny day in summer. The convective heat of the asphalt pavements (B1 and B3) is higher than concrete pavements (C1 and C3) due to their high surface temperatures. This means more convective heat will be released into the near-surface air by the asphalt pavement (B1 and B3) than the concrete pavement (C1 and C3). In addition, more long-wave radiation is emitted by the asphalt pavement with higher surface temperature. However, the concrete pavement with high albedo reflects more short-wave solar radiation than the asphalt pavement. The sum of the reflected short-wave solar radiation and the emitted long-wave radiation, i.e. radiosity, is higher for the concrete pavement (C1 and C3) than the asphalt pavement (B1 and B3). This implies that, although the concrete pavement produces a lower surface temperature, lower emitted long-wave radiation and convective heat due to the low surface temperature led by high albedo, it will increase

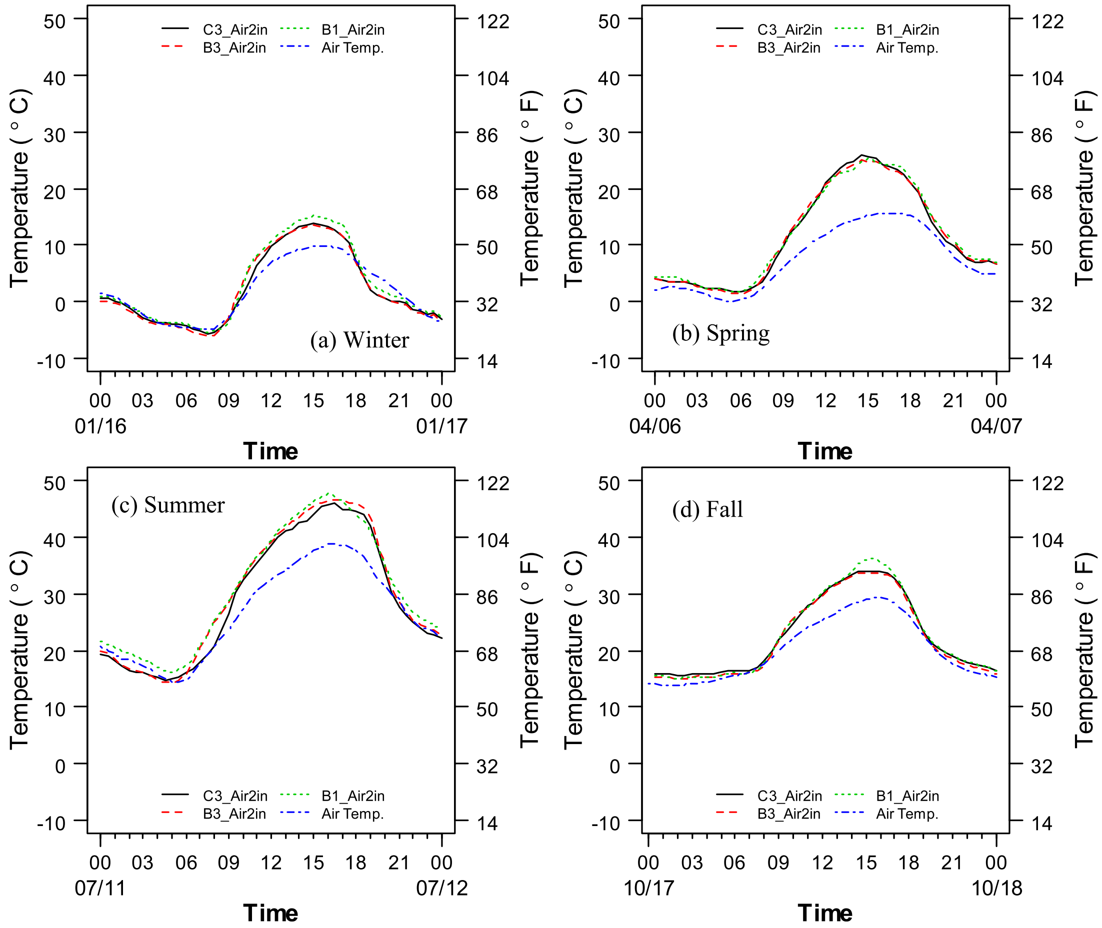


Figure 8. Near-surface air temperatures of different pavements (5.1 cm [2 in] above pavement surface) along with the ambient air temperature measured at 2 m high at one full day during four seasons of the year.

the reflected short-wave solar radiation and might increase the radiosity (i.e. the total sensible energy released by the surface). The increased radiosity of concrete pavement might hit and be absorbed by its surroundings, such as building surfaces and human bodies, leading to increased building energy use for cooling and reduced human thermal comfort. Therefore, optimal context-sensitive design of the pavement albedo is of great significance to ensure a net benefit in terms of energy use or human thermal comfort or both. The permeable pavement (B3 or C3) has low radiosity than the corresponding impermeable pavement (B1 or C1). This implies that permeable pavement has low thermal impact (i.e., heat exchange) on near-surface air compared to the impermeable pavement.

4. Conclusions

The conclusions drawn from this study are:

(1) The interlocking concrete pavers had the highest permeability (or infiltration rate, ∼0.5 cm s^{-1}) and the two permeable asphalt pavements had the lowest permeability (∼0.1 cm s^{-1}), which was still sufficient to drain the rainwater without generating surface runoff during typical rain events in central California (slow steady rain over several days).

(2) Albedo has a great influence on the pavement surface temperature. Increases in albedo can significantly reduce the daytime high surface temperature in summer for the latitude of Davis, California (i.e. ∼38.55°N).

(3) Permeable pavements under wet conditions could give lower surface temperatures than impermeable pavements. The cooling effect highly depends on the availability of moisture near the surface layer and the evaporation rate. The peak cooling effect of watering for the test sections was approximately 15–35 °C on the pavement surface temperature in the early afternoon during summer. The evaporative cooling effect on the pavement surface temperature at 4:00 pm on the third day (25 h after watering) was 2–7 °C lower compared to those in the second day, without considering the higher air temperature on the third day. Wet conditions in permeable pavements could be maintained in urban areas using landscape irrigation water runoff that would otherwise be wasted into the stormwater conveyance system.

(4) Results showed that using high albedo and permeable pavement can potentially help mitigate near-surface heat

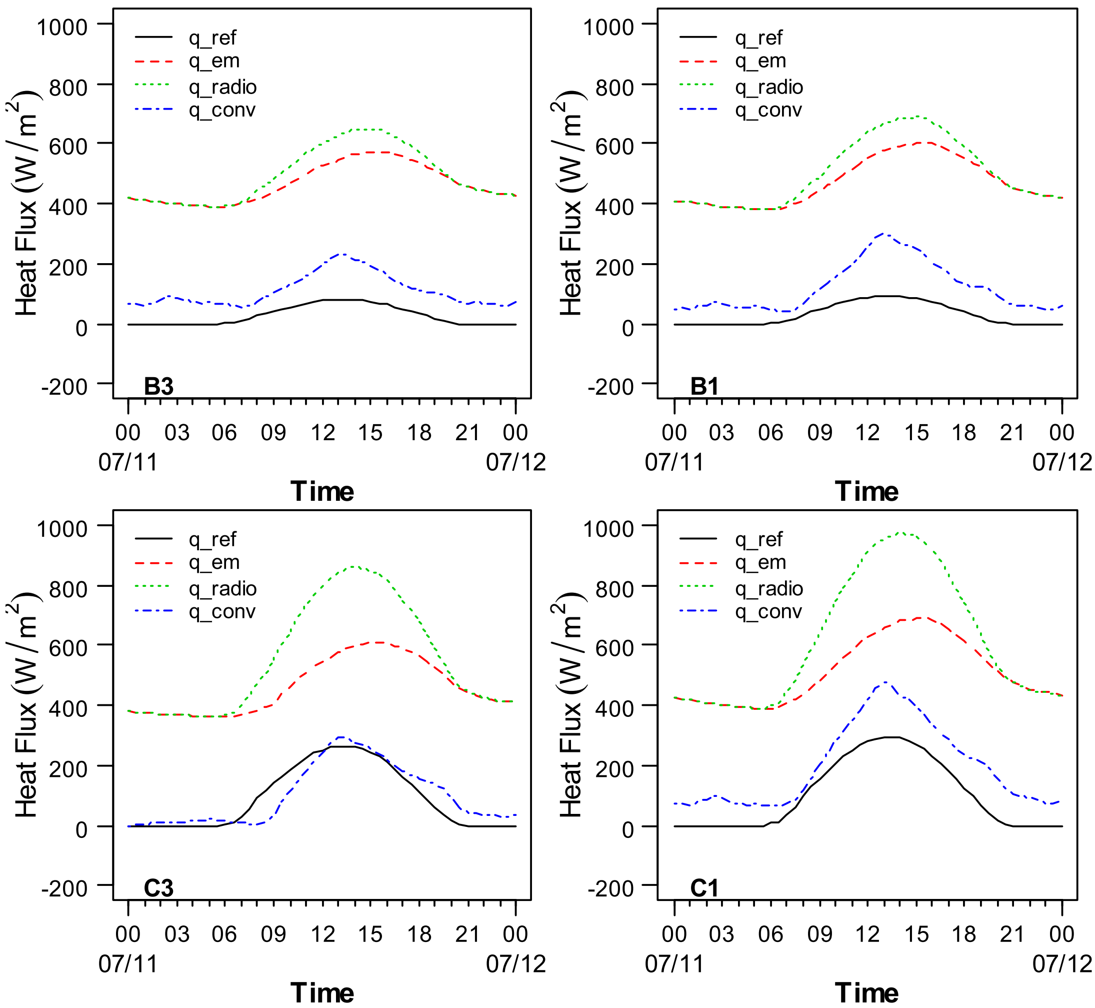


Figure 9. Heat flux from pavement surfaces for one full day during July 2012. (q_ref is reflected short-wave solar radiation; q_em is emitted long-wave radiation; q_radio is radiosity and equal to q_ref +q_em; q_conv is convective heat. C1: light concrete pavement; C2: dark concrete pavement; A1: paver pavement; B1: asphalt pavement.)

island and improve the air quality as well as possibly improving human thermal comfort. Compared to the impermeable pavement, permeable pavement has a low thermal impact (i.e. heat exchange) on near-surface air.

(5) The preliminary results presented in this paper and previously related studies conducted by researchers at UCPRC showed that the reflective and permeable pavements, if well designed, can potentially capture all the pavement stormwater runoff without creating surface ponding and/or overflow, and can carry heavy truck traffic as well as improving the thermal performance of pavement and near-surface air.

(6) Some research topics that are unresolved and require additional investigation include, but are not limited to: field studies to verify the hydraulic performance analysis and structural design performance under loading, field studies to investigate more cooling technologies (i.e. reflective pavement coating, high-evaporation materials) and to evaluate their thermal performance and the impacts on building energy use and human thermal comfort, and life cycle assessment (LCA) to evaluate the lifecycle environmental impacts.

Acknowledgments

The research was supported by a grant from the Sustainable Transportation Center at the University of California, Davis, which receives funding from the US Department of Transportation and Caltrans, the California Department of Transportation, through the University Transportation Centers program. The research activities described in this paper were also partly sponsored by the California Department of Transportation (Caltrans), Division of Research and Innovation. Both sponsorships are gratefully acknowledged. The contents of this paper reflect the views of the authors and do not reflect the official views or policies of the Sustainable Transportation Research Center, the US Department of Transportation, the State of California or the Federal Highway Administration. Construction of pavement test sections by the California Nevada Cement Association, the Southwest

Concrete Pavement Association and the Interlocking Concrete Pavement Institute is also gratefully acknowledged.

References

[1] Akbari H, Rose L and Taha H 1999 *Characterizing the Fabric of the Urban Environment: A Case Study of Sacramento, California* (Berkeley, CA: Lawrence Berkeley National Laboratory) p 65

[2] Brattebo B O and Booth D B 2003 Long-term stormwater quantity and quality performance of permeable pavement systems *Water Res.* **37** 4369–76

[3] *Urban Heat Island* [cited 10 May 2010]; available from: http://en.wikipedia.org/wiki/Urban_heat_island#cite_note-1

[4] Kayhanian M *et al* 2010 Water quality evaluation of leachate produced from pavement specimens under controlled laboratory conditions *Road Mater. Pavement Des.* **11** 9–28

[5] Kayhanian M *et al* 2009 Leachability of dissolved chromium in asphalt and concrete surfacing materials *J. Environ. Manag.* **90** 3574–80

[6] Navigant Consulting Inc. B T P 2011 *Building Technologies Program, Assessment of International Urban Heat Island Research—Literature Review of International Studies on Urban Heat Island Countermeasures. Draft Report* (Washington, DC: Office of Energy Efficiency and Renewable Energy, USDOE)

[7] Akbari H and Matthews H D 2012 Global cooling updates: reflective roofs and pavements *Energy Build.* **55** 2–6

[8] Akbari H, Matthews H D and Donny S 2012 The long-term effect of increasing the albedo of urban areas *Environ. Res. Lett.* **7** 024004

[9] Menon S *et al* 2010 Radiative forcing and temperature response to changes in urban albedos and associated CO_2 offsets *Environ. Res. Lett.* **5** 014005

[10] National Asphalt Pavement Association 2012 *Asphalt Pavement Overview* [cited 10 October 2012]; available from: www.asphaltpavement.org/index.php?option=com_content&view=article&id=14&Itemid=33

[11] Li H 2012 *Evaluation of Cool Pavement Strategies for Heat Island Mitigation in Civil and Environmental Engineering* (Davis, CA: University of California) p 387

[12] Gartland L 2008 *Heat Islands: Understanding and Mitigating Heat in Urban Areas* (London: Earthscan Press)

[13] Levinson R *et al* 2005 Inclusion of cool roofs in nonresidential title 24 prescriptive requirements *Energy Policy* **33** 151–70

[14] Akbari H, Levinson R and Rainer L 2005 Monitoring the energy-use effects of cool roofs on california commercial buildings *Energy Build.* **37** 1007–16

[15] Levinson R, Akbari H and Reilly J C 2007 Cooler tile-roofed buildings with near-infrared-reflective non-white coatings *Build. Environ.* **42** 2591–605

[16] Kültür S and Türkeri N 2012 Assessment of long term solar reflectance performance of roof coverings measured in laboratory and in field *Build. Environ.* **48** 164–72

[17] Karlessi T *et al* 2011 Development and testing of pcm doped cool colored coatings to mitigate urban heat island and cool buildings *Build. Environ.* **46** 570–6

[18] Carnielo E and Zinzi M 2013 Optical and thermal characterisation of cool asphalts to mitigate urban temperatures and building cooling demand *Build. Environ.* **60** 56–65

[19] Levinson R *et al* 2010 A novel technique for the production of cool colored concrete tile and asphalt shingle roofing products *Sol. Energy Mater. Sol. Cells* **94** 946–54

[20] Bretz S E and Akbari H 1997 Long-term performance of high-albedo roof coatings *Energy Build.* **25** 159–67

[21] EPA 2008 *Reducing Urban Heat Islands: Compendium of Strategies–Cool Pavements* (Washington, DC: US EPA)

[22] US Green Building Council 2009 *LEED 2009 for New Construction and Major Renovations Rating System*

[23] Akbari H, Pomerantz M and Taha H 2001 Cool surfaces and shade trees to reduce energy use and improve air quality in urban areas *Sol. Energy* **70** 295–310

[24] Kevern J T, Schaefer V R and Wang K J 2009 Temperature behavior of pervious concrete systems *Transp. Res. Rec.* **2098** 94–101

[25] Hisada Y, Matsunaga N and Ando S 2006 Summer and winter structures of heat island in Fukuoka metropolitan area *Int. J.* B **49** 65–71

[26] *Albedo* [cited 15 May 2012]; available from: http://en.wikipedia.org/wiki/Albedo

[27] Markvart T and Castañer L 2003 *Practical Handbook of Photovoltaics: Fundamentals and Applications* (New York: Elsevier)

[28] Pomerantz M *et al* 2003 *Examples of Cooler Reflective Streets for Urban Heat-Island Mitigation: Portland Cement Concrete and Chip Seals* (Berkeley, CA: Lawrence Berkeley National Laboratory) p 24

[29] Pomerantz M, Akbari H and Harvey J 2000 *Cooler Reflective Pavements Give Benefits Beyond Energy Savings: Durability and Illumination* (Berkeley, CA: Lawrence Berkeley National Laboratory)

[30] Levinson R and Akbari H 2001 *Effects of Composition and Exposure on the Solar Reflectance of Portland Cement Concrete* (Berkeley, CA: Lawrence Berkeley National Laboratory) p 61

[31] Synnefa A *et al* 2011 Experimental testing of cool colored thin layer asphalt and estimation of its potential to improve the urban microclimate *Build. Environ.* **46** 38–44

[32] Synnefa A, Santamouris M and Apostolakis K 2007 On the development, optical properties and thermal performance of cool colored coatings for the urban environment *Sol. Energy* **81** 488–97

[33] Santamouris M, Synnefa A and Karlessi T 2011 Using advanced cool materials in the urban built environment to mitigate heat islands and improve thermal comfort conditions *Sol. Energy* **85** 3085–102

[34] Kolokotsa D *et al* 2012 Development and analysis of mineral based coatings for buildings and urban structures *Sol. Energy* **86** 1648–59

[35] Karlessi T *et al* 2009 Development and testing of thermochromic coatings for buildings and urban structures *Sol. Energy* **83** 538–51

[36] Santamouris M *et al* 2012 Using cool paving materials to improve microclimate of urban areas–design realization and results of the flisvos project *Build. Environ.* **53** 128–36

[37] Synnefa A *et al* 2009 Measurement of optical properties and thermal performance of coloured thin layer asphalt samples and evaluation of their impact on the urban environment *2nd Int. Conf. on Countermeasures to Urban Heat Islands (Berkeley, CA)*

[38] Wong C W *et al* 2009 A study on the effectiveness of heat mitigating pavement coatings in Singapore *2nd Int. Conf. on Countermeasures to Urban Heat Islands (Berkeley, CA)*

[39] Jones D *et al* 2010 *Laboratory Testing and Modeling for Structural Performance of Fully Permeable Pavements Under Heavy Traffic: Final Report* (Davis, CA: University of California Pavement Research Center)

[40] Hunt W F and Collins K A 2008 *Permeable Pavement: Research Update and Design Implications* (Rayleigh, NC: North Carolina Cooperative Extension Service) p 12

[41] Li H, Harvey J and Kendall A 2013 Field measurement of albedo for different land cover materials and effects on thermal performance *Build. Environ.* **59** 536–46

[42] Li H, Kayhanian M and Harvey J T 2013 Comparative field permeability measurement of permeable pavements using ASTM C1701 and NCAT permeameter methods *J. Environ. Manag.* **118** 144–52

[43] Chai L *et al* 2012 Hydraulic performance of fully permeable highway shoulder for storm water runoff management *J. Environ. Eng.* **138** 711–22
[44] Hansen K 2008 *Porous Asphalt Aavements for Stormwater Management* (Lanham, MD: National Asphalt Pavement Association)
[45] ACPA 2009 *Stormwater Management with Pervious Concrete Pavement* (Skokie, IL: American Concrete Pavement Association)
[46] Smith D R 2006 *Permeable Interlocking Concrete Pavements. Selection, Design, Construction, and Maintenance* (Herndon, VA: Interlocking Concrete Pavement Institute)
[47] Li H, Harvey J and Jones D 2012 Developing a mechanistic-empirical design procedure for fully permeable pavement under heavy traffic *Transp. Res. Rec.: J. Transp. Res. Board* **2305** 83–94
[48] Li H, Harvey J and Jones D 2012 Material characterization for mechanistic design of fully permeable pavements: low-compaction subgrade and open-graded base materials *Transportation Research Board 91th Annual Mtg (Washington, DC)*
[49] Li H, Harvey J and Kendall A 2013 Measurement of pavement solar reflectivity and effect on thermal performance *Transportation Research Board 92th Annual Mtg (Washington, DC)*
[50] Ichinose M, Inoue T and Sakamoto Y 2009 Long-term performance of high-reflectivity exterior panels *Build. Environ.* **44** 1601–8
[51] Li H, Harvey J and Jones D 2013 Multi-dimensional transient temperature simulation and back-calculation for thermal properties of building materials *Build. Environ.* **59** 501–16
[52] Tomotsugu E *et al* 2012 Moisture and heat transfer characteristics of the pavement with water retention base course *Advances in Discontinuous Numerical Methods and Applications in Geomechanics and Geoengineering* (Boca Raton, FL: CRC Press) pp 407–12
[53] Pyun H B *et al* 2010 Study on thermal environmental characteristics of water-retentive asphalt pavement *Mater. Sci. Forum* **658** 264–7
[54] Karamanis D and Vardoulakis E 2012 Application of zeolitic materials prepared from fly ash to water vapor adsorption for solar cooling *Appl. Energy* **97** 334–9