Cool Pavement Strategies for Enhancing Urban Sustainability

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Outline

- Urbanization & Environmental Impacts
- Cool Pavement & Potential Strategies
- Cool Pavement Pilot Study at UCPRC
- Main Results & Conclusions
- Policy Effort & Research Needs
Heat Island Effect was first identified in the early 1800s in London.

‘London’s growth over the next decade needs to ensure that new development is located, designed and constructed to minimise, and if possible reduce its contribution to London’s urban heat island.’

From London’s Urban Heat Island: A Summary for Decision Makers, Greater London Authority 2006

Types of heat island effect
- Urban
- Near-surface air
- Surface (hot spot)

Heat Island Effect:
- Increase heat stress
- Compromise human thermal comfort and health
- Impair air quality (ground-level ozone, i.e. smog)
- Increase cooling energy consumption
  - Total energy use
  - Peak demand for energy

Impervious Surface:
- Create stormwater runoff
- Pollute the waterbody
- Reduce groundwater recharge
- Increase risk of flooding
- Contribute to heat island effect
40% + Pavement, Dark(hot) & Impervious(flood)

Low Impact Development
Restore Natural Process & Ecological Function

To make pavement Cool & Permeable.
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# Potential Cool Pavement Strategies

<table>
<thead>
<tr>
<th>Strategy</th>
<th>Mechanism</th>
<th>Co-Benefits</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>1. Modify material thermal properties</strong></td>
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</tbody>
</table>
| 1.1 *Increase albedo/emissivity* (?) | • Increase reflected/emitted radiation | • Enhance illumination  
• Offset radiative forcing (?) |
| 1.2 Increase heat capacity/density | • Increase heat capacity | -- |
| 1.3 Reduce thermal conductivity | • Reduce transfer readiness | -- |
| **2. Evaporation/evapotranspiration** | | |
| 2.1 *Permeable pavements* (+ vegetation) | • Increase latent heat  
• Increase thermal insulation  
• Increase convection | • Reduce stormwater runoff  
• Reduce water pollution  
• Reduce flooding risk  
• Recharge groundwater  
• Increase greening |
| 2.2 Water-retentive pavements (+ sprinkling) | • Increase latent heat | • Reuse wastewater |
| **3. Shading** | | |
| 3.1 Canopy cover (+ trees) | • Reduce absorbed heat | • Increase greening (+ tree) |
| 3.2 PV panels | • Reduce absorbed heat | • Reduce land use for solar farms |
| **4. Enhance convection** | | |
| 4.1 Ventilation paths | • Increase convection | -- |
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Goal & Scope of Pilot Study

- Explore thermal behavior of several potential cool pavement strategies (*particularly permeable pavement*)
  - Asphalt, concrete vs. paver (different albedos)
  - Permeable vs. impermeable
  - Dry vs. wet (irrigation)
- Evaluate effectiveness and applicability when applied in different contexts
  - Surface and near-surface heat effect
  - Human thermal comfort
  - Building thermal load

*Experiment + Modeling*
Construction of Test Sections
Instrumentation

Instrumentation on the experimental sections.
View of Test Sections

A=Interlocking Concrete Paver
B=Asphalt Pavement;
C=Concrete Pavement;
1=Impermeable Design;
2&3=Different Permeable Designs
Field Measurements

- Permeability
- Albedo (i.e. solar reflectivity) & effect on pavement thermal performance
- Thermal behavior of permeable pavements under dry and wet conditions
- Thermal impact of pavement on near-surface air
- Thermal interaction between pavement and wall
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Permeability

Permeameter (ASTM)

Hydraulic Conductivity (cm/s)

Section

A: Block Paver  B: Asphalt  C: Concrete

Permeability (a.k.a. hydraulic conductivity or infiltration rate)
Albedo (Solar Reflectivity)

A: Block Paver
B: Asphalt
C: Concrete

A-Interlocking Concrete Pavement; B-Asphalt Pavement; C-Concrete Pavement.
1-Impermeable Design; 2 & 3-Permeable Designs.
Albedo Change over Time

Diurnal variation of albedo (B2)

Change of albedo over time (nine test sections, only weathered)
Surface Temperature vs. Albedo

Asphalt

Concrete & Block Paver

$y = -61.29x + 68.96$

$R^2 = 0.91$

$y = -27.06x + 26.47$

$R^2 = 0.78$
Thermal Behavior of Permeable Pavement under Dry & Wet Conditions (e.g. B3).

B3: permeable
B1: impermeable

Irrigation
Thermal Impact on Near-surface Air

\[ T_n = e^{CZ_n} \]

\[ C = -5.13 + (-0.57 \times WS) \]

\[ R^2 = 0.29 \]
Thermal Impact on Wall

Wall, 52 °C

Asphalt (B1), 60 °C

Wall, 55 °C

Concrete (C1), 45 °C

Lighter is hotter: legend range of 30 to 65 °C

13:00 8/15/2012
Human Thermal Comfort Index

- **Mean Radiant Temperature (MRT)**
  - Defined as the *uniform temperature* of an imaginary environment in which radiant heat transfer from/to the human body is equal to the radiant heat transfer in the actual non-uniform environment.

\[
T_{mrt} = \left[ \frac{1}{\sigma} \sum_{i=1}^{n} (E_i + \alpha_{hb} \frac{D_i}{\varepsilon_{hb}})VF_i + F_{hb}\alpha_{hb} \frac{SVF_{hb}I}{\sigma\varepsilon_{hb}} \right]^{0.25} - 273
\]

- **Physiological Equivalent Temperature (PET)**
  - Defined as the *equivalent air temperature* at which, in a typical indoor setting (\(T_{mrt}=T_a; VP=12\) hPa; \(v=0.1\) m/s,), the heat balance of the human body is maintained with core and skin temperatures equal to those under the actual complex conditions being assessed.
The model considers:

- Energy balance on the pavement surface;
- Coupled processes of radiation, conduction, convection, shading and evaporation.

Finite Element Method implemented in ABAQUS.
$M$ is the metabolic rate ($W/m^2$). $W$ is the rate of mechanical work ($W/m^2$). $S$ ($W/m^2$) is the total storage heat flow in the body.
Heat Balance on Human Body

Activity: walking at 2 km/h (1.9 met = 110 W/m²), exposure time: 60 min
Weather: \( T_{mrt} = 55^\circ C, \ T_a = 38^\circ C, \ RH = 50\%, \ v_w = 0.5 \text{ m/s} \)

Metabolic rate \( M \): 110 W/m²
Rate of mechanical work \( W \): 0 W/m²
Convection heat \( C \): -2 W/m²
Net emitted radiation \( R \): 76.1 W/m²
Sweat evaporative heat \( E_{sw} \): -227.4 W/m²
Respiration convective heat \( C_{res} \): -0.62 W/m²
Respiration evaporative heat \( E_{res} \): -4.84 W/m²
Skin heat storage heat \( S_{sk} \): -173.6 W/m²
Core heat storage heat \( S_{cr} \): 103.0 W/m²
Total heat storage heat \( S \): -70.6 W/m²

Body parameters: 1.80 m, 75 kg, 0.5 clo
### Table 1. Typical summer and winter climate data in three regions

<table>
<thead>
<tr>
<th>Season</th>
<th>Sacramento (Sac), California</th>
<th>Los Angeles (LA), California</th>
<th>Phoenix (Pho), Arizona</th>
</tr>
</thead>
<tbody>
<tr>
<td>Daily peak air temperature $T_{\text{max}}^a$ [°C]$^a$</td>
<td>34</td>
<td>29</td>
<td>40</td>
</tr>
<tr>
<td>Daily lowest air temperature $T_{\text{min}}^a$ [°C]$^a$</td>
<td>16</td>
<td>18</td>
<td>25</td>
</tr>
<tr>
<td>Daily total solar radiation volume $Q$ [MJ/m$^2$]$^b$</td>
<td>28.3</td>
<td>22.6</td>
<td>27.4</td>
</tr>
<tr>
<td>Daily effective sunlight hour $c$ [h]$^b$</td>
<td>11</td>
<td>10</td>
<td>11</td>
</tr>
<tr>
<td>Daily average wind velocity $v_w$ [m/s]$^c$</td>
<td>4.0</td>
<td>2.8</td>
<td>3.2</td>
</tr>
</tbody>
</table>

### Table 2. Pavement scenarios used for analysis

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Pavement Scenario</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Baseline</td>
</tr>
<tr>
<td>Albedo $r$</td>
<td>0.1</td>
</tr>
<tr>
<td>Evaporation Rate $ER$ (mm/h)</td>
<td>0</td>
</tr>
<tr>
<td>Sky View Factor $SVF$</td>
<td>1</td>
</tr>
</tbody>
</table>

*Note: Changed parameter is underlined for each scenario.*
Example pavement surface temperatures for three climates (baseline, summer)
**Human Thermal Comfort Index, PET**

**Ts:** Surface Temperature  
**Tmrt:** Mean Radiant Temperature  
**PET:** Physiological Equivalent Temperature

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Sacramento, CA

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<table>
<thead>
<tr>
<th>Scenario</th>
<th>Ts (°C)</th>
<th>Tmrt (°C)</th>
<th>PET (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Baseline</td>
<td>55</td>
<td>40</td>
<td>45.5</td>
</tr>
<tr>
<td>High-reflectance</td>
<td>50</td>
<td>35</td>
<td>42.5</td>
</tr>
<tr>
<td>Evaporation</td>
<td>45</td>
<td>30</td>
<td>37.5</td>
</tr>
<tr>
<td>HR + Evaporation</td>
<td>40</td>
<td>25</td>
<td>33.5</td>
</tr>
<tr>
<td>Shading</td>
<td>35</td>
<td>20</td>
<td>28.5</td>
</tr>
</tbody>
</table>

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Temperature (°C)
Human Thermal Comfort Index, PET

**Ts:** Surface Temperature
**Tmrt:** Mean Radiant Temperature
**PET:** Physiological Equivalent Temperature

![Graphs showing temperature comparison between Phoenix, AZ and Los Angeles, CA for different scenarios: Baseline, High-reflectance, Evaporation, HR + Evaporation, Shading. The graphs illustrate the temperature variations under different conditions with respect to Surface Temperature (Ts), Mean Radiant Temperature (Tmrt), and Physiological Equivalent Temperature (PET).](image-url)
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Main Conclusions from Pilot Study

- **Reflective Pavement**
  - Albedo has significant effects on the pavement temperature.
  - Greatly increasing albedo might cause negative impacts on human thermal comfort and building/vehicle energy use.

- **Permeable Pavement**
  - Permeable pavement is a cool pavement strategy with many environmental benefits.
  - Evaporation from permeable pavement plays an important role in reducing daytime UHI.
  - High thermal resistance of porous materials helps reduce UHI, especially during nighttime.

- **Permeable pavements with a designed albedo** are a promising cool pavement strategy for mitigating UHI.
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Potential Benefits
of Cool & Permeable Pavement

- Mitigate heat island
  - Create a livable & walkable communities during hot summer (*mitigated local heat stress*)
  - Reduce energy use for building and vehicle cooling
  - Improve air quality (*ground-level ozone*)
- Reduce stormwater runoff
  - Improve water quality
  - Recharge groundwater
  - Reduce flooding risk
  - Reduce need for drainage/retention systems
- Reduce pavement distress
  - Rutting
  - Cracking
Assembly Bill No. 296

CHAPTER 667
[Approved by Governor September 27, 2012. Filed with Secretary of State September 27, 2012.]

LEGISLATIVE COUNSEL’S DIGEST

AB 296, Skinner. Department of Transportation: paving materials.
(1) Existing law provides that the Department of Transportation is responsible for the maintenance and improvement of the state highway system.

This bill would make legislative findings and declarations regarding the meaning of urban heat island effect (UHIE). The bill would require the California Environmental Protection Agency to develop a definition for the term UHIE and, upon completion of an UHIE index, develop a standard specification for sustainable or cool pavements.

(2) The California Building Standards Law requires any building standard adopted or proposed by a state agency to be submitted to, and approved or adopted by, the California Building Standards Commission prior to codification.

This bill would require the commission, in the next triennial adoption process of the California Green Building Standards Code to consider incorporating a standard specification for sustainable or cool pavements.

http://www.leginfo.ca.gov/cgi-bin/postquery?bill_number=ab_296&sess=CUR
Research Needs on Cool Pavement

- Challenges & uncertainties in the technologies
  - Albedo & durability of reflective cement/binder & coating/treatment
  - Durability of porous materials
  - Permeability vs. wicking/evaporation of porous materials
  - Tradeoff between different seasons & different goals

- Comprehensive impact evaluation (what-if analysis)
  - Human comfort; energy use (building & vehicle)
  - Air quality; groundwater quality
  - Climate (e.g. rainfall)
  - Life cycle cost analysis
  - Environmental life cycle assessment (on-going)

- Evaluating impacts at different scales (multi-scale modeling)
  - Local/street level
  - Small/block scale
  - Large/city/regional scale
Sponsors for Cool Pavement Study

Collaborators:
Thanks!

Q&A

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