Life-Cycle Assessment and Co-benefits of Cool Pavements

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ARB Research Seminar
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Pavements are an important part of the urban environment

Sacramento

Fractions of land area were measured above tree canopy

Akbari et al. 2003 <doi:10.1016/S01692046(02)00165-2>
Pavements can contribute to urban heat islands but can be designed to stay cooler.
Project seeks to advise communities on energy and environmental consequences of "cool" pavements.

- ENERGY
- AIR POLLUTION
- GLOBAL WARMING
- LOCAL AIR TEMP & AIR QUALITY

PAVEMENT LIFE-CYCLE ASSESSMENT (pLCA) TOOL
(50 year analysis period)
The pLCA tool can be useful in many contexts, but it was designed for local governments

- Study findings are relevant for a variety of pavements
  - E.g., those constructed and maintained by Caltrans

- However, local governments are the primary audience for the pLCA tool
  - Key project goals to facilitate decision-making at the local level, inform climate action planning, etc.
The tool presents life-cycle assessment (LCA) results to aid decision making.

Enable scenario planning to evaluate consequences of switching to cool pavement.

TOOL → CITY PLANNING → PAVEMENT DECISIONS

- Climate action/adaptation plans
- Building codes
- Zoning ordinances
- Pavement maintenance
- Materials specification
Pavement Life-Cycle Assessment Tool
Scope
Pavement manufacturing, construction, and transportation requires energy & produces emissions.
We assessed energy and environmental effects across the 50-year pavement life-cycle stages

1. Materials and construction stage [MAC] (materials, transportation, construction, end-of-life)
2. Use stage (cooling, heating, and lighting of buildings)
Many environmental impacts of the pavement life-cycle were beyond the scope of this project.

**Construction**
- Work zone traffic

**Use**
- Carbonation
- Vehicle/road interaction
- Stormwater runoff
- Dynamic construction equipment emissions
- Global cooling
We analyzed use-stage effects that result from change in pavement albedo

- Indirect effect
- Direct effect
Pavement Life-Cycle Assessment Tool
Operating the Tool
To operate the tool, the user only needs to select a few inputs:

**USER INPUTS**
- City
- Fraction of pavement area to modify
- Typical pavement design
- Less-typical (cool) pavement design

**LIFE CYCLE ASSESSMENT TOOL**

**CITYWIDE ENVIRONMENTAL IMPACTS**
- Global warming potential
- Energy use
- Criteria air pollutants
- Local air temperature
- Local air quality
The tool interface updates the results as the inputs change.
The tool user selects inputs with drop-down menus and sliders.

City & fraction of modified pavement area

Fraction of total pavement area to modify [0 - 100 %]

Modified pavement area in Los Angeles is 66.4 km²

Pavement Scenario A

Typical pavement design

Typical albedo of Conventional Asphalt Concrete, Hveem (mill and fill): 0.05 - 0.15

Pavement albedo [0 - 1]

Upper surface treatment (UST)

Typical service life of Conventional Asphalt Concrete, Hveem (mill and fill): 2 - 12 years (2.5 - 5 cm); Varies with traffic and design

UST service life [1 - 50 years]

Default thickness of Conventional Asphalt Concrete, Hveem (mill and fill): 6 cm

Allowable thickness range for Conventional Asphalt Concrete, Hveem (mill and fill): 2.5 - 37.5 cm

UST thickness [2.5 - 37.5 cm]

Lower surface treatment (LST)
Inputs and outputs can be viewed onscreen, or saved to CSV (tables) & PDF (graphs)

**Pavement Scenario B**

Less-typical “cool” pavement design

Typical albedo of Bonded Concrete Overlay on Asphalt (BCOA) OP267SCM71 (low SCM): 0.2 - 0.35

Pavement albedo [0 - 1] 0.25

Upper surface treatment (UST) Bonded Concrete Overlay on Asphalt (BCOA) OP267SCM71 (low SCM)

Typical service life of Bonded Concrete Overlay on Asphalt (BCOA) OP267SCM71 (low SCM): 10 - 20 years (7.6 - 12.7 cm)

UST service life [1 - 50 years] 30

Default thickness of Bonded Concrete Overlay on Asphalt (BCOA) OP267SCM71 (low SCM): 12.5 cm

Allowable thickness range for Bonded Concrete Overlay on Asphalt (BCOA) OP267SCM71 (low SCM): 6.25 - 17.5 cm

UST thickness [6.25 - 17.5 cm] 12.5

Lower surface treatment (LST) NONE
Outputs can be viewed as graphs or tables
**The tool reports LCA metrics, annual metrics, and instantaneous metrics**

<table>
<thead>
<tr>
<th>LCA metrics</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Global Warming Potential (GWP)</td>
<td>kg CO$_2$e*</td>
</tr>
<tr>
<td>Photochemical Ozone Creation Potential (POCP)**</td>
<td>kg O$_3$e</td>
</tr>
<tr>
<td>Particulate Matter, less than 2.5 micrometers in diameter (PM2.5)</td>
<td>kg</td>
</tr>
<tr>
<td>Primary Energy Demand (PED) excluding feedstock energy</td>
<td>MJ</td>
</tr>
<tr>
<td>Feedstock Energy (FE)</td>
<td>MJ</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Use-stage metrics</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Annual Site Electricity Use</td>
<td>kWh/y</td>
</tr>
<tr>
<td>Annual Site Gas Use</td>
<td>therm/y</td>
</tr>
<tr>
<td>Outdoor Air Temperature (city mean, near the top of the urban canopy)</td>
<td>°C</td>
</tr>
<tr>
<td>Ozone Concentration (city mean at 15:00 local standard time)</td>
<td>parts per billion (ppb)</td>
</tr>
</tbody>
</table>

*CO$_2$e, or carbon dioxide equivalent, is a standard unit for measuring carbon footprints or “global warming potential.” The idea is to express the impact of each different greenhouse gas in terms of the amount of CO$_2$ that would create the same amount of warming.

**POCP (O$_3$e) is used to classify compounds according to their ability to form tropospheric ozone. Similar to the CO$_2$e unit for GWP, O$_3$e is used to express different emission compounds in terms of the amount of O$_3$ that would have the same impact on formation of smog.
Pavement Life-Cycle Assessment Tool Methodology (for developing the tool)
Tool applies datasets and algorithms developed through complementary research efforts

Local pavement practices
CA life-cycle inventories
Urban climate modeling

Urban air quality

Building energy modeling
We investigated pavement management and maintenance practices used by local governments in California

• Conducted interviews with 8 cities to survey their pavement practices
• Cities interviewed treated 1.3 to 20% of their pavement networks annually

- Slurry seal
  Used for 28 to 82% of treated area (average 41%)

- Asphalt overlay
  Used for 13 to 100% of treated area (average 37%)
We developed California-specific pavement material and electrical energy production life-cycle inventories.

Based on CA utilities’ projected electric grid mix in 2020 using Renewable Portfolio Standard.

Manufacture

Construction

Transportation

GaBi Life Cycle Assessment Software v. 6.3 & UCPRC models and data
We modeled urban climate to estimate city-wide air temperature reductions from cool pavement adoption.

Simulated increases in pavement albedo in CA urban areas

Mohegh et al. 2017
We estimated reduction in urban ozone concentration when cool pavements lower air temperature

1. Reviewed literature for modeled and observed ozone-temperature sensitivities in CA air basins

2. Applied sensitivities to our modeled air temperature results at 14:00 local standard time to calculate urban ozone changes
We modeled buildings to calculate changes in energy use from modifying albedo of city and local streets.

### Residential
- single-family home
- apartment building

### Commercial
- 2 offices
- 2 retail
- 2 restaurants
- primary school
- large hotel

10 prototypes were modeled with EnergyPlus v. 8.5.
We matched each city’s building stock to the 10 prototypes to calculate city-wide changes.

Los Angeles:
- Single-family home prototype: 47%
- Apartment building prototype: 40%
- Other prototypes: Large office, Large hotel, School, Stand-alone retail, Restaurants

96 km² (~37 m²) of building stock floor area

- Medical buildings
- Medium offices
- Strip malls
- Multi-family buildings
- Single-family homes

Matched to our 10 prototypes
Pavement Life-Cycle Assessment Tool
Case Studies


http://doi.org/10.1016/j.enbuild.2017.03.051
We evaluated 3 pavement scenarios: routine maintenance, rehabilitation, and long-life rehabilitation (i)

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Case study</th>
</tr>
</thead>
<tbody>
<tr>
<td>Slurry seal</td>
<td>Typical pavement for Case 1A</td>
</tr>
<tr>
<td>Styrene acrylate reflective coating</td>
<td>Less-typical pavement for Case 1A</td>
</tr>
</tbody>
</table>
We evaluated 3 pavement scenarios: routine maintenance, rehabilitation, and long-life rehabilitation (ii)

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Case study</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mill-and-fill AC</td>
<td>Typical pavement for Cases 2A, 2B, and 2C</td>
</tr>
<tr>
<td>BCOA (no SCM)</td>
<td>Less-typical pavement for Case 2A</td>
</tr>
<tr>
<td>BCOA (low SCM)</td>
<td>Less-typical pavement for Case 2B</td>
</tr>
<tr>
<td>BCOA (high SCM)</td>
<td>Less-typical pavement for Case 2C</td>
</tr>
</tbody>
</table>

SCM = supplementary cementitious materials
<table>
<thead>
<tr>
<th>Case study</th>
<th>Typical treatment</th>
<th>Less-typical treatment</th>
<th>Albedo</th>
<th>Albedo increase</th>
<th>Service life (y)</th>
<th>Thickness per installation (cm)</th>
<th>Thickness installed over 50 y (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Routine maintenance</td>
<td>Slurry seal</td>
<td></td>
<td>0.10</td>
<td></td>
<td>7</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>1A: Styrene acrylate reflective coating</td>
<td>0.30</td>
<td>0.20</td>
<td>5</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>2. Rehabilitation</td>
<td>Mill-and-fill AC</td>
<td></td>
<td>0.10</td>
<td></td>
<td>10</td>
<td>6</td>
<td>30</td>
</tr>
<tr>
<td></td>
<td>2A: BCOA (no SCM)</td>
<td></td>
<td>0.25</td>
<td>0.15</td>
<td>20</td>
<td>10</td>
<td>25</td>
</tr>
<tr>
<td></td>
<td>2B: BCOA (low SCM)</td>
<td></td>
<td>0.25</td>
<td>0.15</td>
<td>20</td>
<td>10</td>
<td>25</td>
</tr>
<tr>
<td></td>
<td>2C: BCOA (high SCM)</td>
<td></td>
<td>0.25</td>
<td>0.15</td>
<td>20</td>
<td>10</td>
<td>25</td>
</tr>
</tbody>
</table>

*Case study 3 is similar but with longer lives and thicker pavements*

**METRICS**

<table>
<thead>
<tr>
<th>Global Warming Potential (GWP), kg of CO₂e</th>
<th>Primary Energy Demand (PED) w/o FE, MJ</th>
<th>Outdoor Air Temperature, °C</th>
</tr>
</thead>
</table>
All cases evaluated for Fresno and Los Angeles with 30% of city pavement modified
The modeled changes to air temperature are consistent with other urban heat island mitigation strategy studies.

Simulated cooling rate (0.9°C per 0.1 increase in urban albedo) matches Santamouris (2014).

Los Angeles

Fresno

The materials & construction (MAC) stage primary energy demand (PED) changes exceed use-stage changes in LA.

1A = slurry seal → reflective coating; 2A, 2B, 2C = mill-and-fill AC → no-, low-, or high-SCM BCOA.
The MAC-stage global warming potential changes exceed use-stage changes in LA.

1A = slurry seal → reflective coating; 2A, 2B, 2C = mill-and-fill AC → no-, low-, or high-SCM BCOA.
The MAC-stage primary energy demand changes exceed use-stage changes in Fresno.

1A = slurry seal → reflective coating; 2A, 2B, 2C = mill-and-fill AC → no-, low-, or high-SCM BCOA
The MAC-stage GWP changes exceed use-stage changes in Fresno

1A = slurry seal → reflective coating; 2A, 2B, 2C = mill-and-fill AC → no-, low-, or high-SCM BCOA
The manufacture of cool pavements is frequently more energy intensive than typical treatments.

* Feedstock energy reported separately
It also tends to be more carbon intensive
The results can be evaluated in the context of city GHG emission goals.

### Los Angeles

<table>
<thead>
<tr>
<th>Case Study</th>
<th>Reflective coating [1A]</th>
<th>BCOA (no SCM) [2A]</th>
<th>BCOA (low SCM) [2B]</th>
<th>BCOA (high SCM) [2C]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Routine maintenance</td>
<td></td>
<td>0.018</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2. Rehabilitation</td>
<td></td>
<td>0.097</td>
<td>0.034</td>
<td>-0.006</td>
</tr>
</tbody>
</table>

Los Angeles has a 2025 GHG emission target: 20 Mt/y CO$_2$e

Relative to this target, the city-wide GWP change ranges from savings 0.03% to penalty 0.49%
The one-time GWP offset from global cooling exceeds the changes in 50-y life-cycle GWP. The chart shows the GWP offset or increase (kg CO$_2$e/m$^2$) for different scenarios:

- **One-time offset**: Green bars
- **Los Angeles 50-y increase**: Orange bars
- **Fresno 50-y increase**: Blue bars

The chart indicates that the one-time GWP offset from global cooling exceeds the changes in 50-y life-cycle GWP. Specific values and comparisons are indicated in the chart. Additional details are provided in the reference [IPCC AR5; Akbari et al. 2012](https://doi.org/10.1088/1748-9326/7/2/024004).

1A = slurry seal → reflective coating; 2A, 2B, 2C = mill-and-fill AC → no-, low-, or high-SCM BCOA
Annual building energy cost savings for cool pavements are less than those for cool roofs

Substituting a reflective coating for a slurry seal (albedo increase 0.20):
   Building conditioning energy cost savings per square meter of pavement modified in LA
   $0.03/y

Substituting a cool roof for a dark roof (albedo increase 0.35):
   Building conditioning energy cost savings per square meter of roof modified in LA
   $0.47/y

→ 15 times the annual cool pavement conditioning energy cost savings
Pavement Life-Cycle Assessment Tool
Conclusions
Key takeaways about cool pavements: 
50-year life-cycle changes in PED, GWP

For case studies:

• In use stage,
  — PED decreases in LA and Fresno
  — GWP decreases in LA, increases in Fresno

• In MAC stage, PED and GWP usually rise

• MAC-stage changes typically >> use-stage changes

• Total PED, GWP tend to rise
Key takeaways about cool pavements: mitigating life-cycle penalties

- 50-y GWP change $< \text{ or } \ll$ than one-time global cooling GWP offset
- Introduction of new approaches for cool pavement materials (e.g., reducing cement content) can mitigate these impacts
- If cool pavements reduce global warming, and they are found to be cost effective relative to other strategies, then further work is warranted in the development of these technologies
Resources (i)

- CARB project website & link to final report
  
  https://www.arb.ca.gov/research/single-project.php?row_id=65149
  
  – Information for accessing and operating the pLCA tool can be found in final report (Section 2.8, beginning on page 57)

  
  http://doi.org/10.1016/j.enbuild.2017.03.051
Resources (ii)

• Related publications

  – Pomerantz M et al. 2015. A simple tool for estimating city-wide annual electrical energy savings from cooler surfaces. *Urban Climate* 14(2), 315-325. [https://doi.org/10.1016/j.uclim.2015.05.007](https://doi.org/10.1016/j.uclim.2015.05.007)


Thank you!
Reference Slides
Pavements with high albedo can cool the city air, but may increase reflected sunlight that strikes buildings.
We evaluated 3 pavement scenarios: routine maintenance, rehabilitation, and long-life rehabilitation (i)

### Routine maintenance case study

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Composition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Slurry seal</td>
<td>6.5 kg crushed fine aggregate and 0.68 kg residual asphalt per m² pavement</td>
</tr>
<tr>
<td>Styrene acrylate reflective coating</td>
<td>7.7% styrene, 6% titanium dioxide, 13% butyl acrylate, 5.4% methyl acrylate, 3% methacrylic acid, 6% zinc oxide, 0.18% ammonium persulfate, 0.1% N-dodecyl mercaptan, 0.02% ammonium sulfite, 1.6% hydroxypropane-1-sulphonate, 1% azirdine, 1% ammonium hydroxide, and 55% water by mass, applied at 1 kg per m² pavement</td>
</tr>
</tbody>
</table>
We evaluated 3 pavement scenarios: routine maintenance, rehabilitation, and long-life rehabilitation (ii).

### Mill-and-fill asphalt concrete (AC)

- **Composition:** 38% coarse aggregate, 57% fine aggregate, 5% dust, 4% asphalt binder, and 15% reclaimed asphalt pavement by mass.

### Bonded cement concrete overlay over asphalt (BCOA)

#### With no, low or high supplementary cementitious materials (SCM)

- **BCOA (no SCM):** 1071 kg coarse aggregate, 598 kg fine aggregate, 448 kg cement, 1.8 kg polypropylene fibers, 1.9 kg water reducer (Daracern 65 at 390 mL per 100 kg of cement), 1.6 kg retarder (Daratard 17 at 325 mL per 100 kg of cement), 0.6 kg air entraining admixture (Daravair 1400 at 120 mL per 100 kg of cement), and 161 kg water per m³ wet concrete.

- **BCOA (low SCM):** 1085 kg coarse aggregate, 764 kg fine aggregate, 267 kg cement, 71 kg fly ash, 1.8 kg polypropylene fibers, and 145 kg water per m³ wet concrete.

- **BCOA (high SCM):** 1038 kg coarse aggregate, 817 kg fine aggregate, 139 kg cement, 56 kg slag, 84 kg of fly ash, and 173 kg water per m³ wet concrete.
<table>
<thead>
<tr>
<th>Case study</th>
<th>Typical treatment</th>
<th>Less-typical treatment</th>
<th>Aged albedo</th>
<th>Albedo increase</th>
<th>Service life (y)</th>
<th>Thickness per installation (cm)</th>
<th>Thickness installed over 50 y (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3. Long-life rehabilitation</td>
<td>Mill-and-fill AC</td>
<td></td>
<td>0.10</td>
<td>-</td>
<td>20</td>
<td>15</td>
<td>37.5</td>
</tr>
<tr>
<td></td>
<td>3A: BCOA (no SCM)</td>
<td></td>
<td>0.25</td>
<td>0.15</td>
<td>30</td>
<td>15</td>
<td>25</td>
</tr>
<tr>
<td></td>
<td>3B: BCOA (low SCM)</td>
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<td>0.25</td>
<td>0.15</td>
<td>30</td>
<td>15</td>
<td>25</td>
</tr>
<tr>
<td></td>
<td>3C: BCOA (high SCM)</td>
<td></td>
<td>0.25</td>
<td>0.15</td>
<td>30</td>
<td>15</td>
<td>25</td>
</tr>
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