TRB 95th Annual Meeting. Jan 10th – 14th, 2016
Lectern Session 756: Research Progress on Cool Pavement Strategies

Cool Pavement Strategies for Enhancing Urban Sustainability

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UCPRC
UNIVERSITY of CALIFORNIA | PAVEMENT RESEARCH
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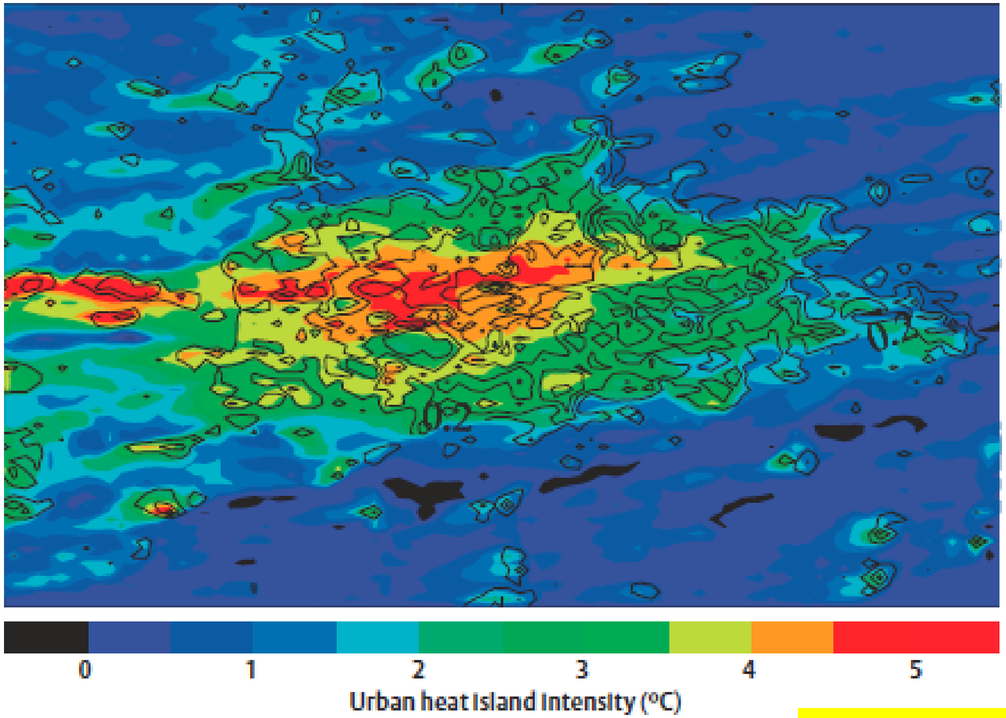
Outline

- 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

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

Types of heat island effect

- Urban
- Near-surface air
- Surface (hot spot)

Research Highlights 2010, http://www.walker-institute.ac.uk

Flooding & Water Pollution

from impervious surface

USGS
science for a changing world

Effects of Urban Development on Floods

Over the past century, the United States has become an increasingly urban society. The changes in land use associated with urban development affect flooding in many ways. Removing vegetation and soil, grading the land surface, and constructing drainage networks increase runoff to streams from rainfall and snowmelt. As a result, the peak discharge, volume, and frequency of floods increase in nearby streams. Changes to stream channels during urban development can limit their capacity to

Flooding in Hickory Hills, Illinois, prompted the construction of a reservoir to control runoff from upstream areas. Source: Loren

Even in suburban are
and other permeable
be common, rainfall
saturate thin soils and
flow, which runs off
networks of ditches a
reduce the distance th
overland or through s
to reach streams and
enters a drainage netw
than either overland o
With less storag
in urban basins and m

EPA United States Environmental Protection Agency

LEARN THE ISSUES | SCIENCE & TECHNOLOGY | LAWS & REGULATIONS | ABOUT EPA

Tampa Bay Ecosystem
Research on the large-scale phy

- TBES Home
- Biodiversity Support
- A Stable Climate
- Flood Protection
- Usable Air
- Usable Water
- Culture
- Food and Fiber Production
- Water Supply
- Stressor Links
- Land Use / Land
- Production Matrix

Result in

Altered Drainage

European Environment Agency

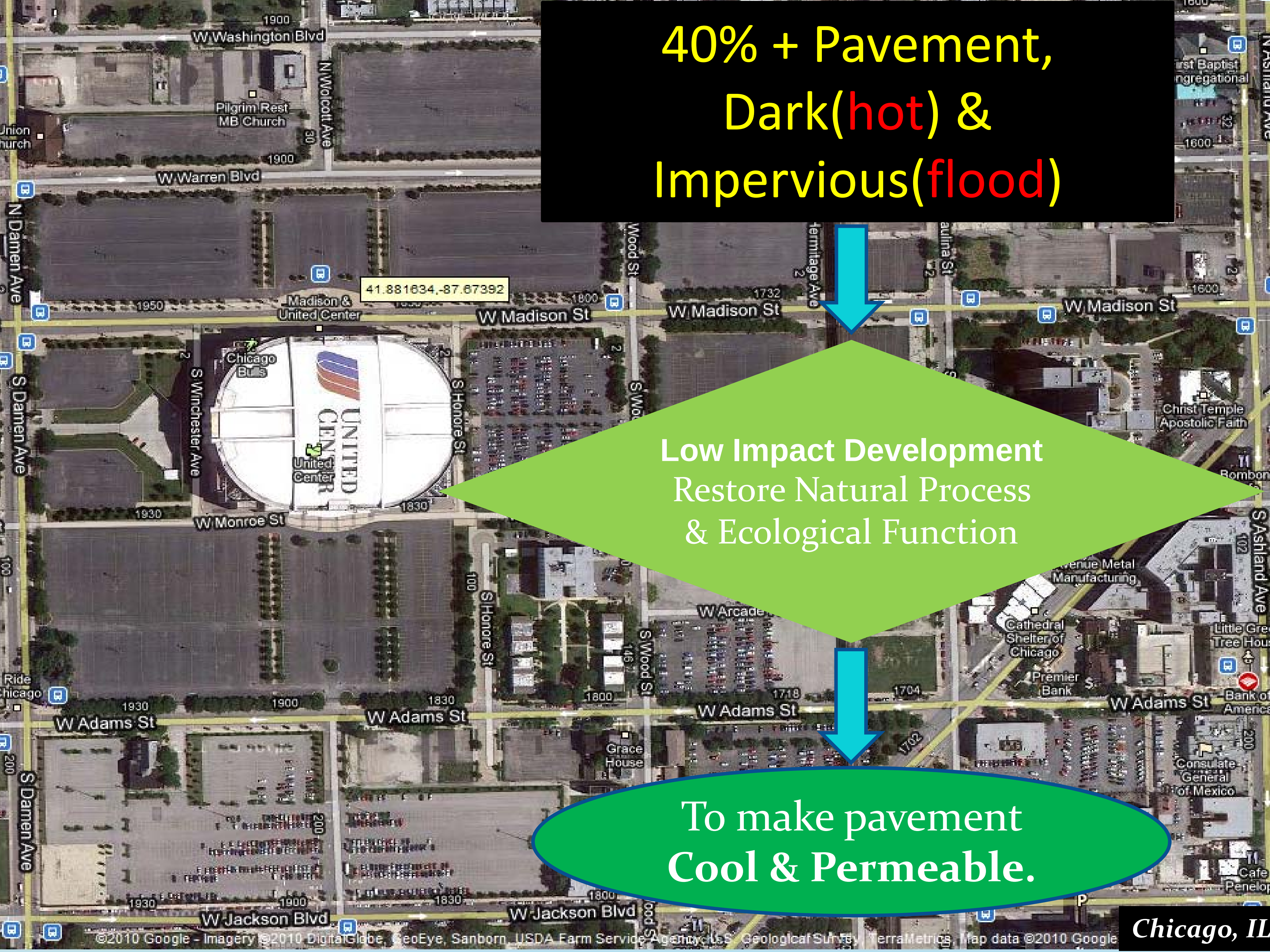
Topics | Data and maps | Indicators | Publications | Mu

You are here: Home > Data and maps > Maps and graphs >
Urban flooding — impervious surfaces reduce the drainage of rain water and increase the risk for urban floo
flooding — impervious surfaces reduce the drainage of rain water and increase the risk for urban flooding

Urban flooding — impervious surfaces reduce the drainage of rain water and increase the risk for urban flooding

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.
Chicago, IL
W Madison St
W Adams St
W Jackson Blvd
W Monroe St
W Warren Blvd
W Washington Blvd
United Center
41.881634,-87.67392
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Potential Cool Pavement Strategies

Strategy	Mechanism	Co-Benefits
1. Modify material thermal properties		
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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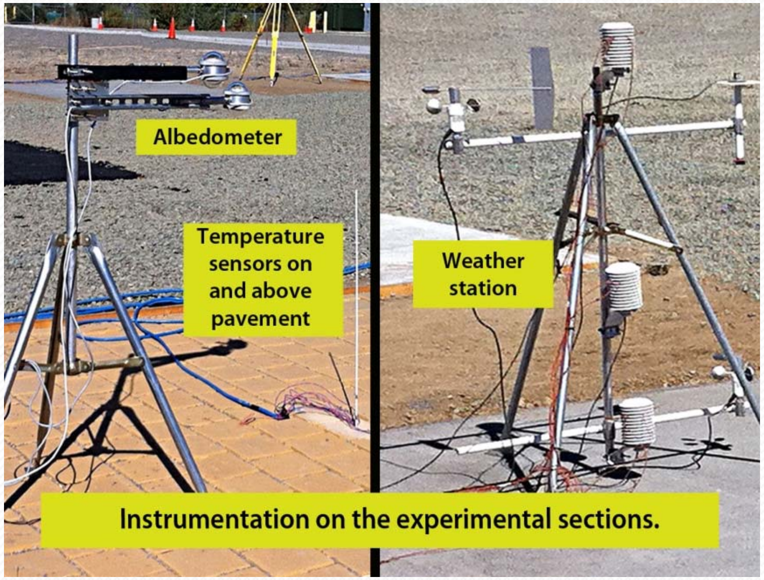
Goal & Scope of Pilot Study

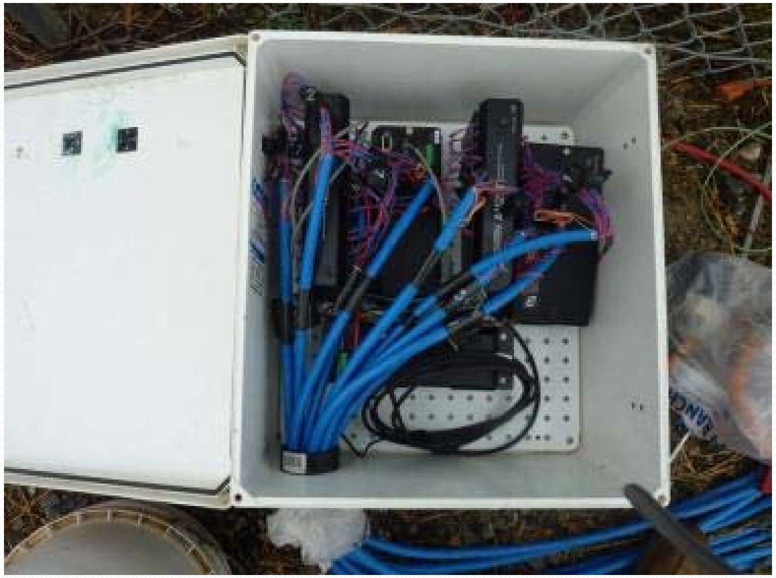
- Explore thermal behavior of several potential cool pavement strategies (particularly permeable pavement)
  - Asphalt, concrete vs. paver (different albedos)
  - Permeable vs. impermeable
  - Dry vs. wet (irrigation)
- Evaluate effectiveness and applicability when applied in different contexts
  - Surface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

Experiment + Modeling

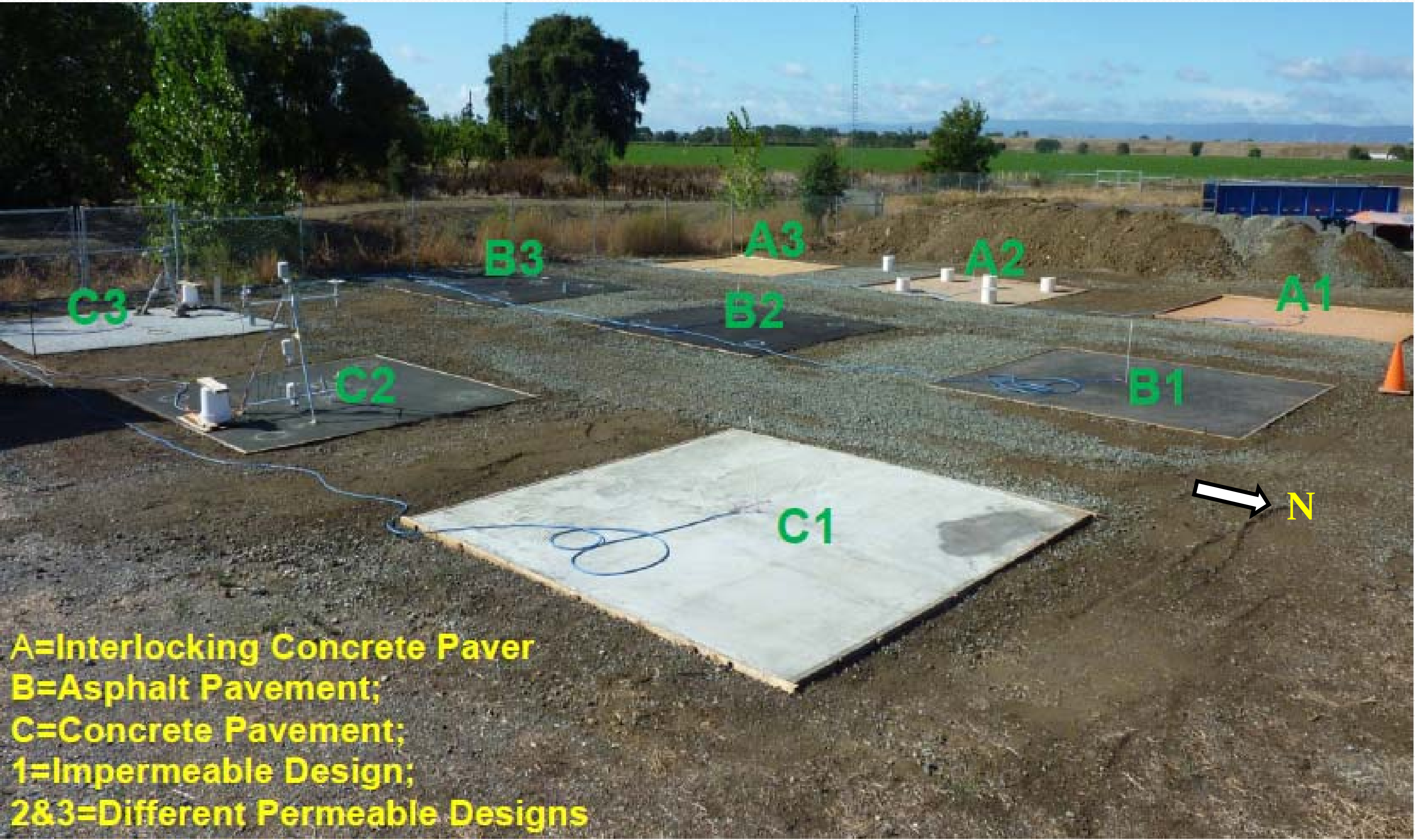
Construction of Test Sections

Instrumentation





View of Test Sections



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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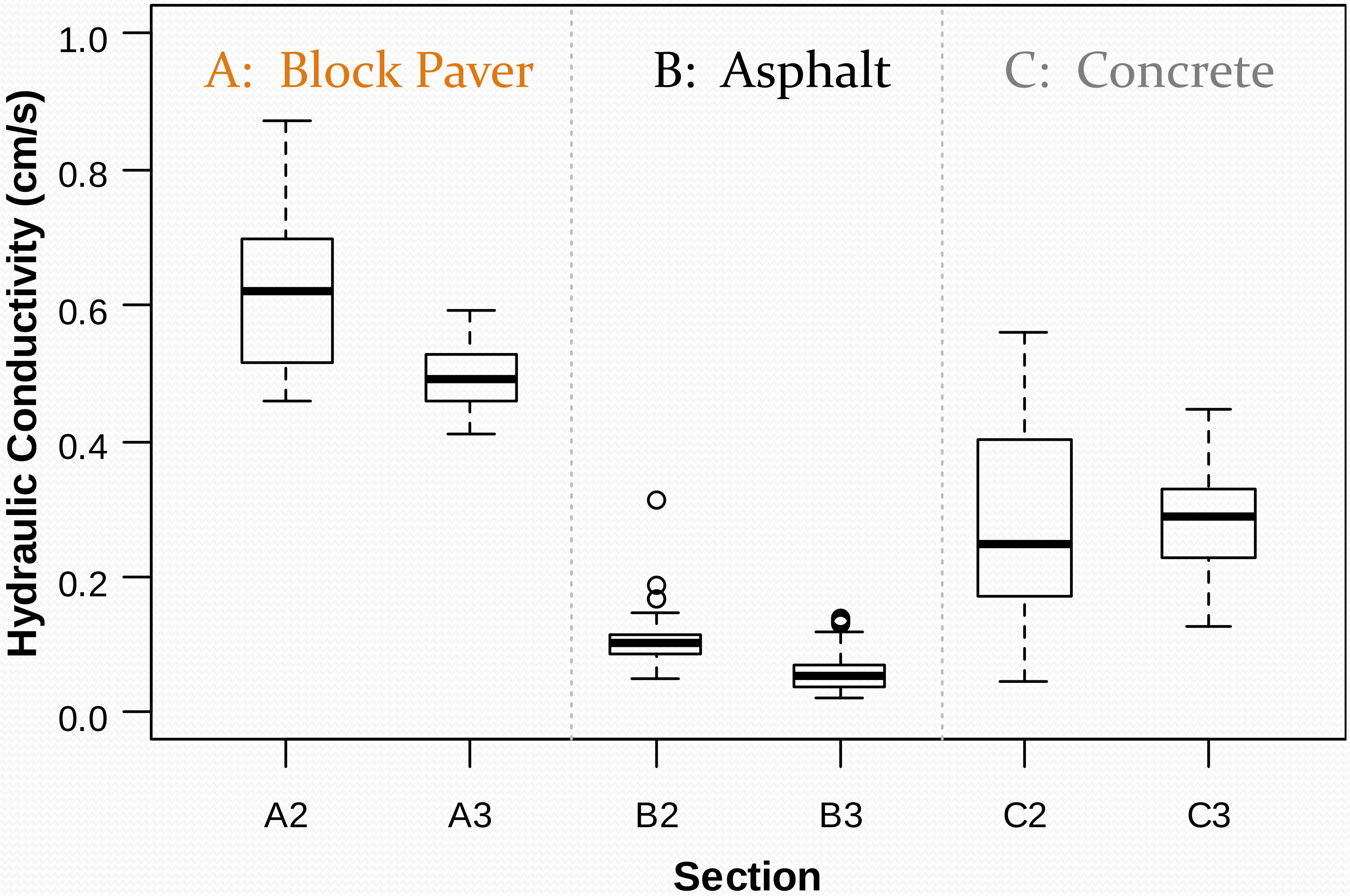
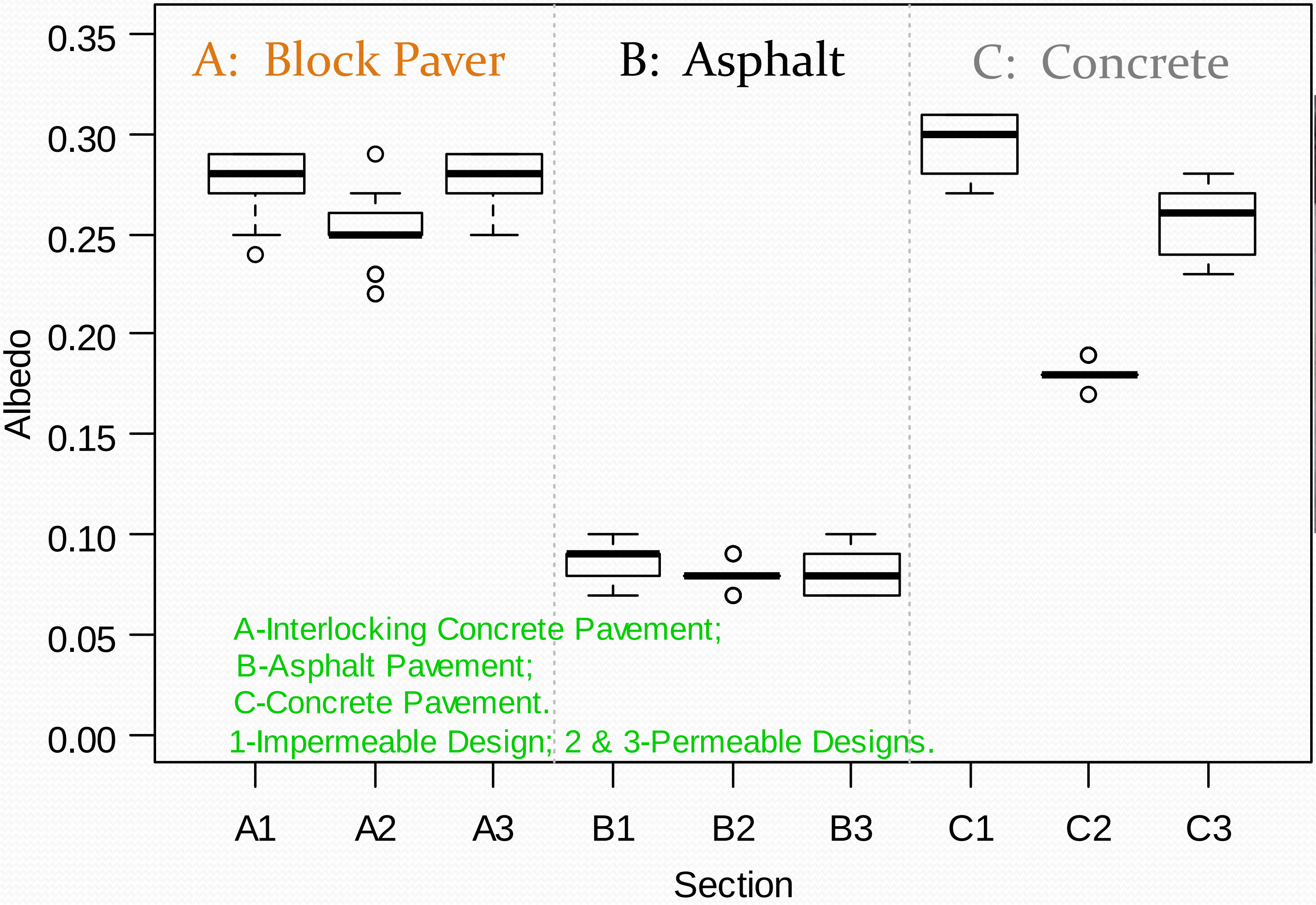
Permeability



Permeameter
(ASTM)

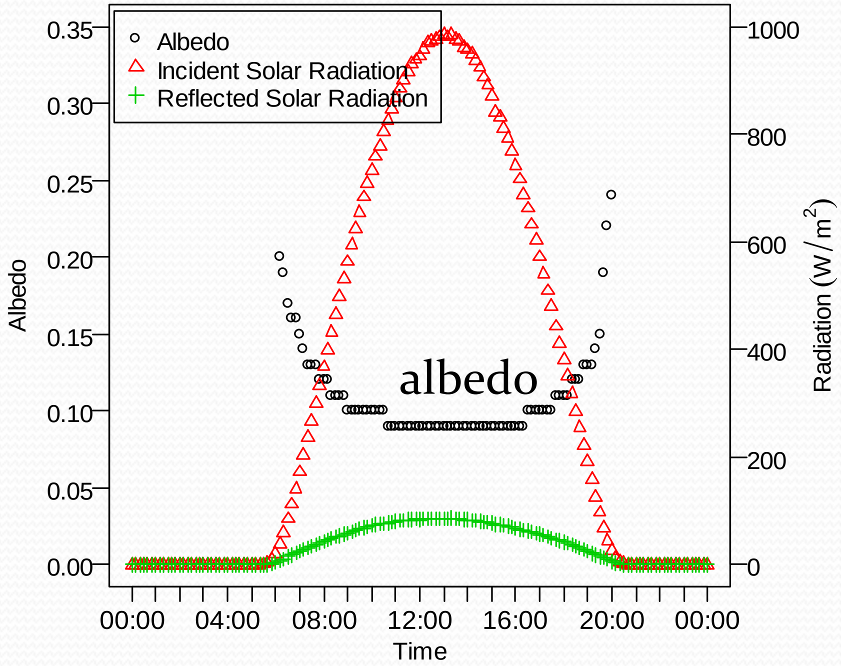
Permeability (a.k.a. hydraulic conductivity or infiltration rate)

Albedo (Solar Reflectivity)

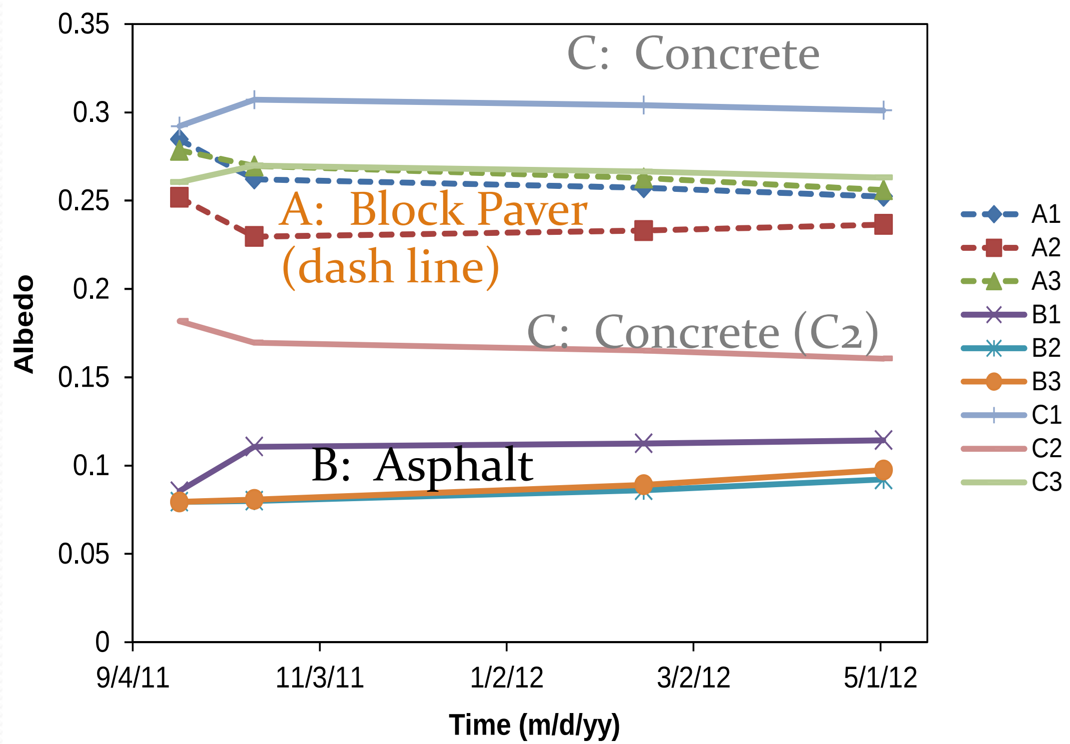


Albedometer

Albedo Change over Time

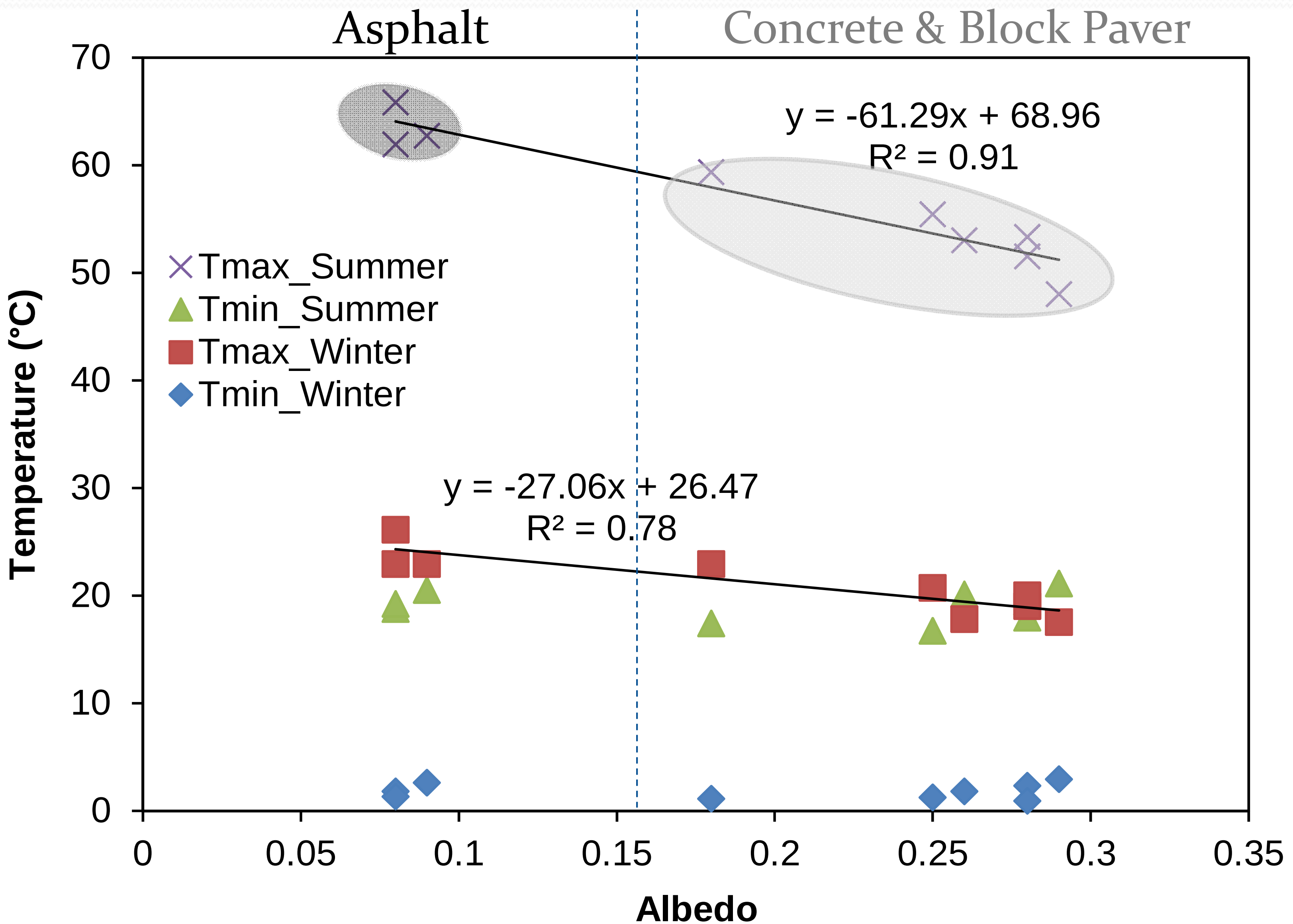


Diurnal variation of albedo (B2)

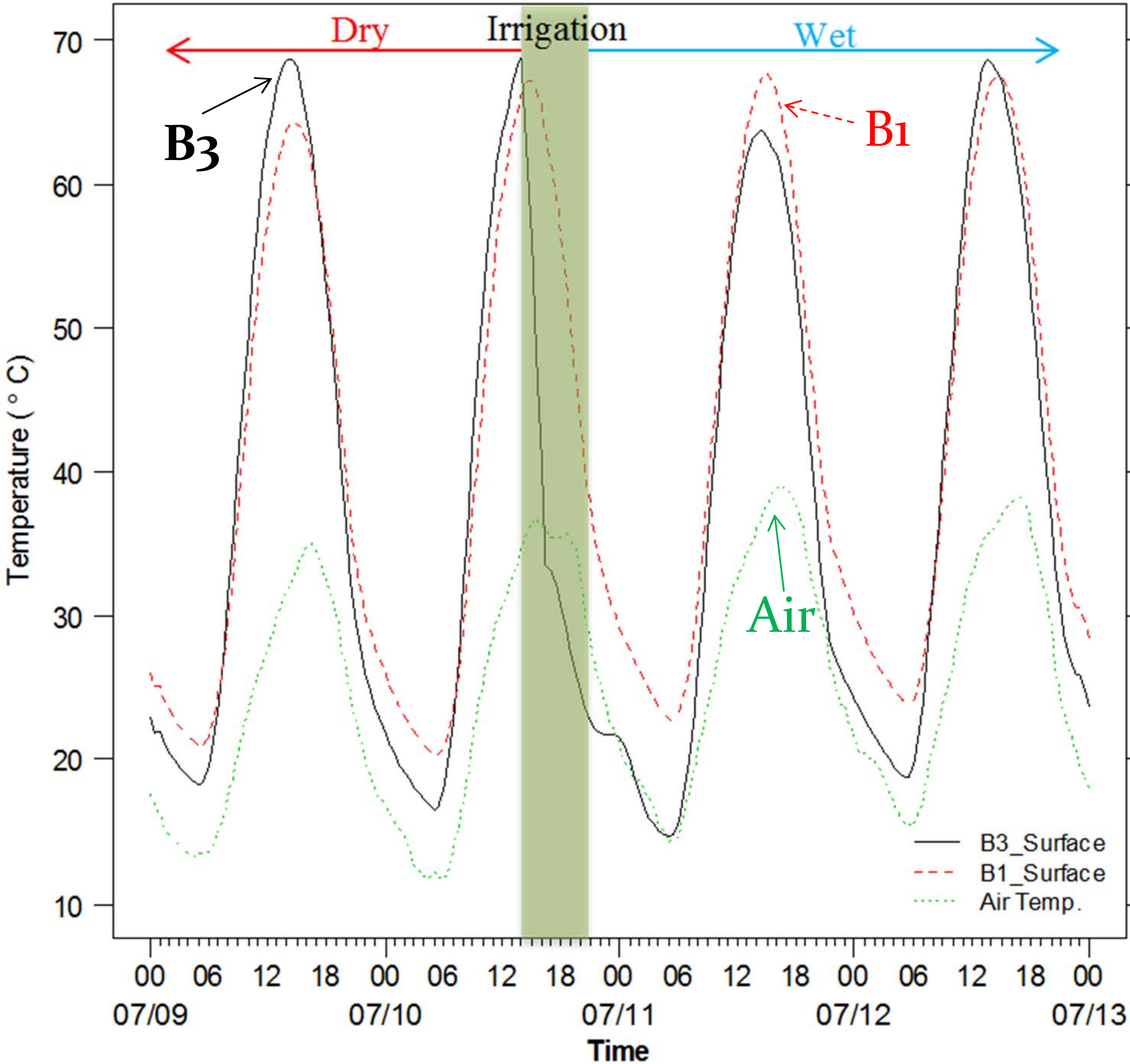


Change of albedo over time (nine test sections, only weathered)

Surface Temperature vs. Albedo



Thermal Behavior of Permeable Pavement under Dry & Wet Conditions (e.g. B3).



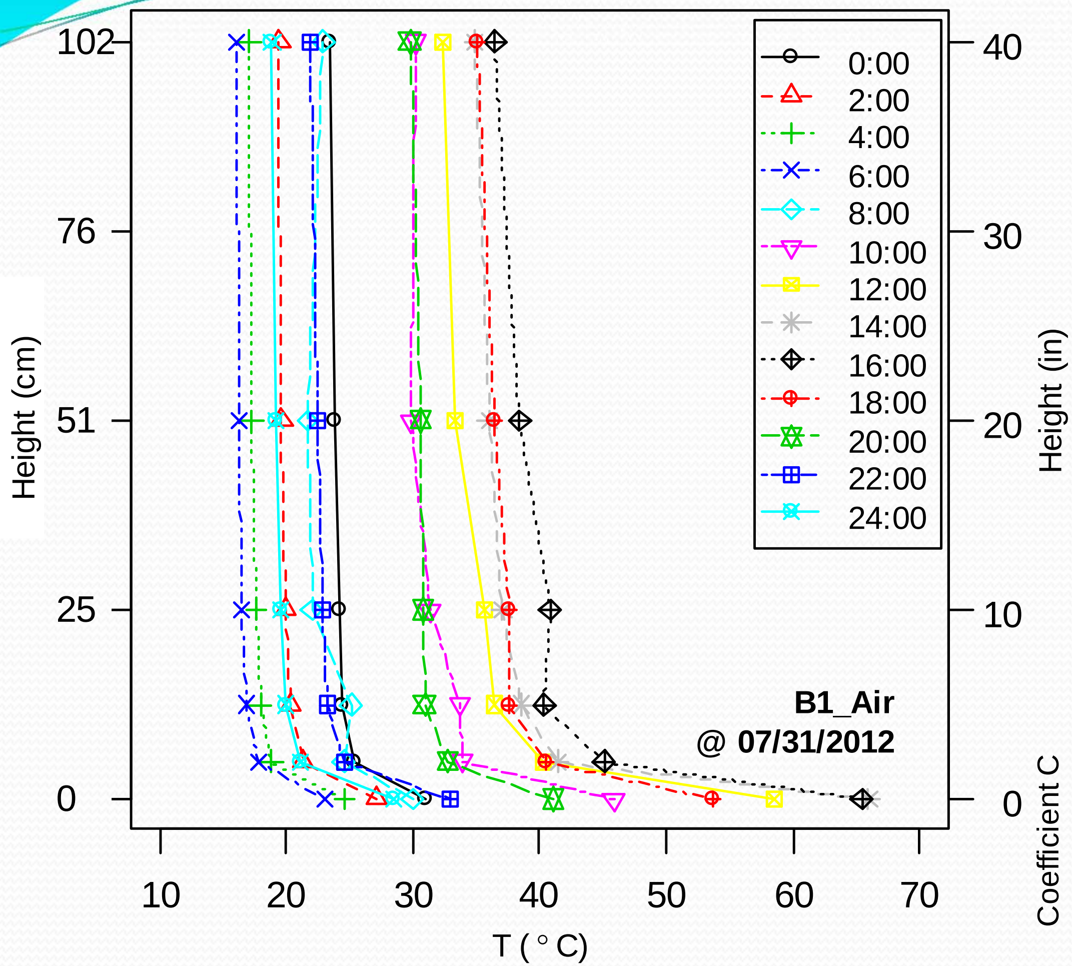
(mm/dd)

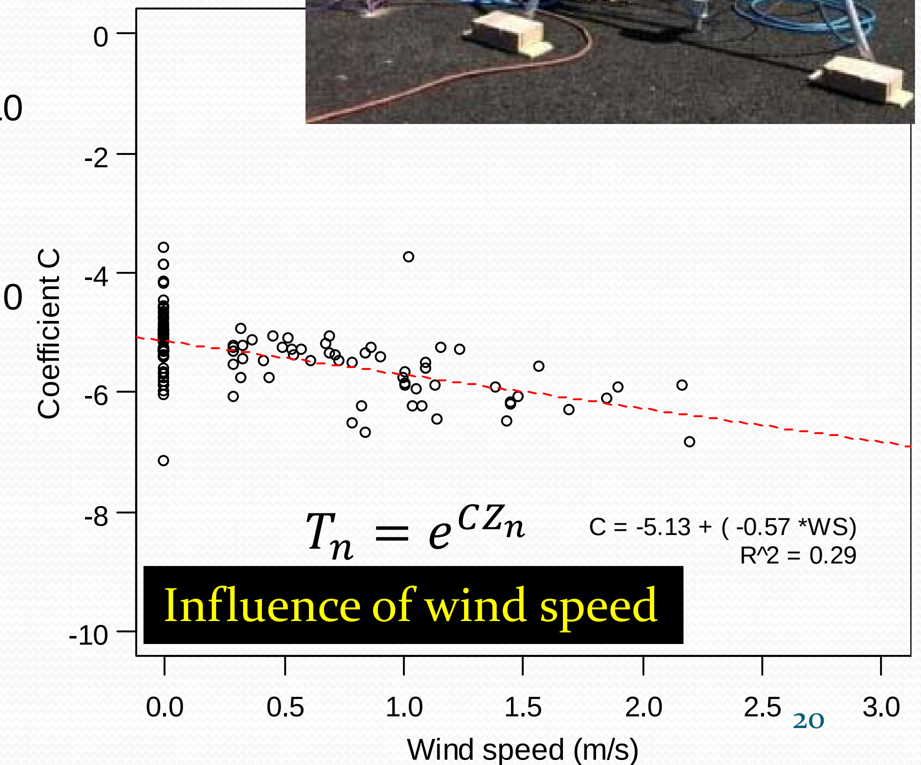
Irrigation

B3: permeable

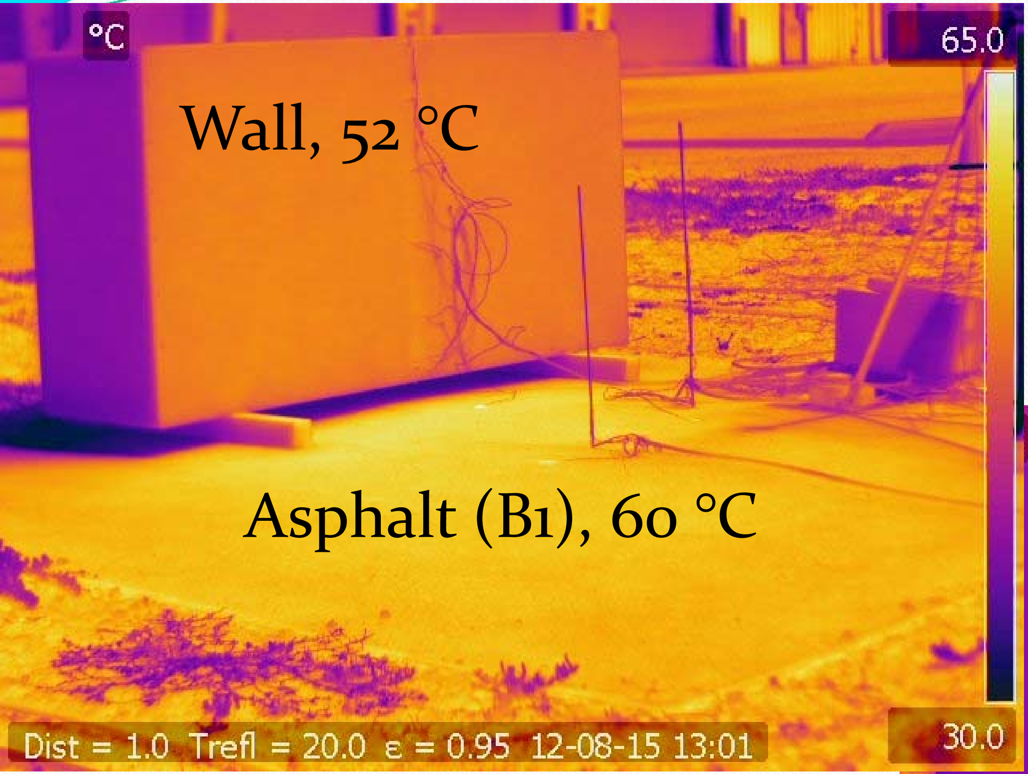
B1: impermeable

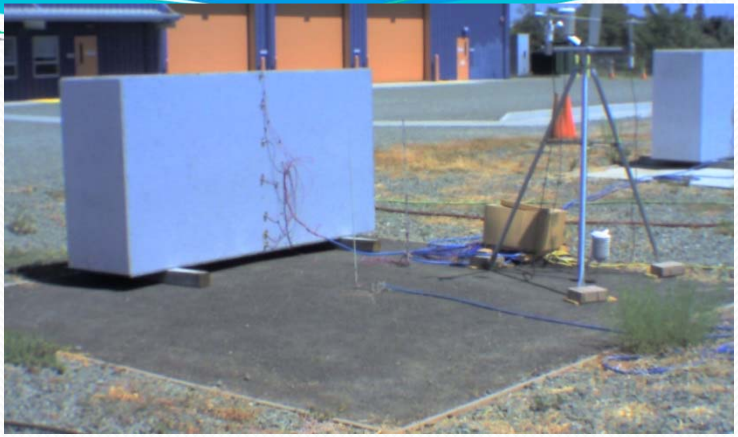
Thermal Impact on Near-surface Air





Thermal Impact on Wall





13:00 8/15/2012

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

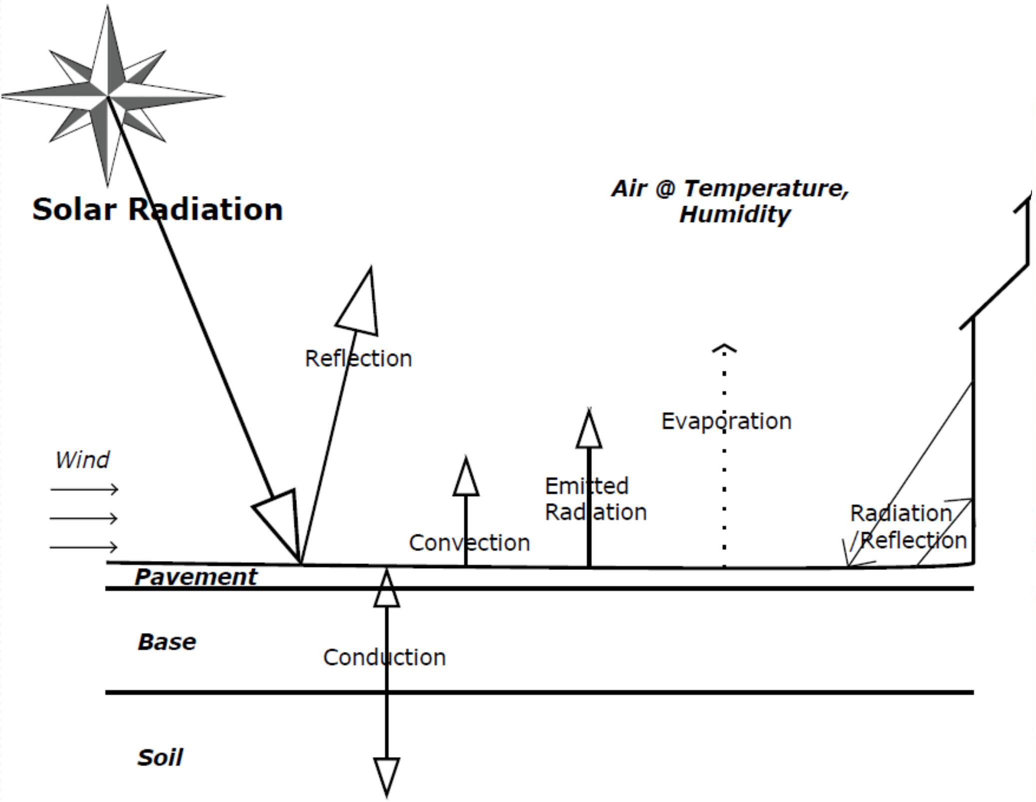
Human Thermal Comfort Index

- 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.

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

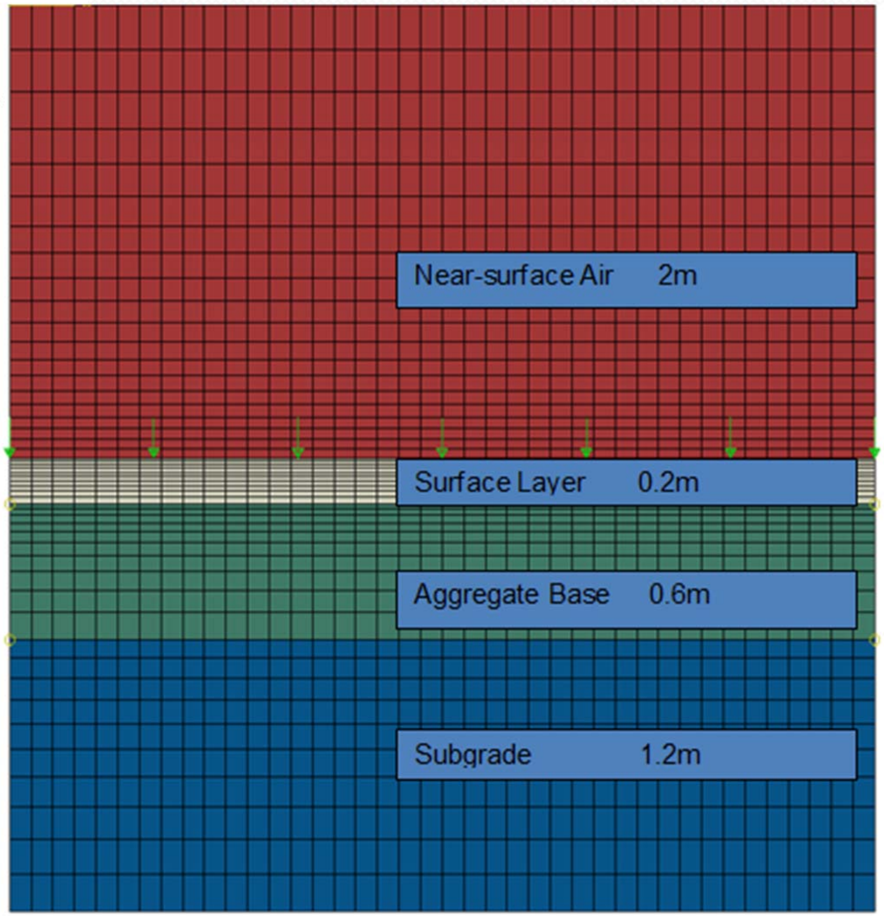
- Physiological Equivalent Temperature (PET)
  - Defined as the equivalent air temperature at which, in a typical indoor setting (T_{mrt}=T_a; VP=12 hPa; v=0.1 m/s,), the heat balance of the human body is maintained with core and skin temperatures equal to those under the actual complex conditions being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

Modeling & Simulation for Temperature



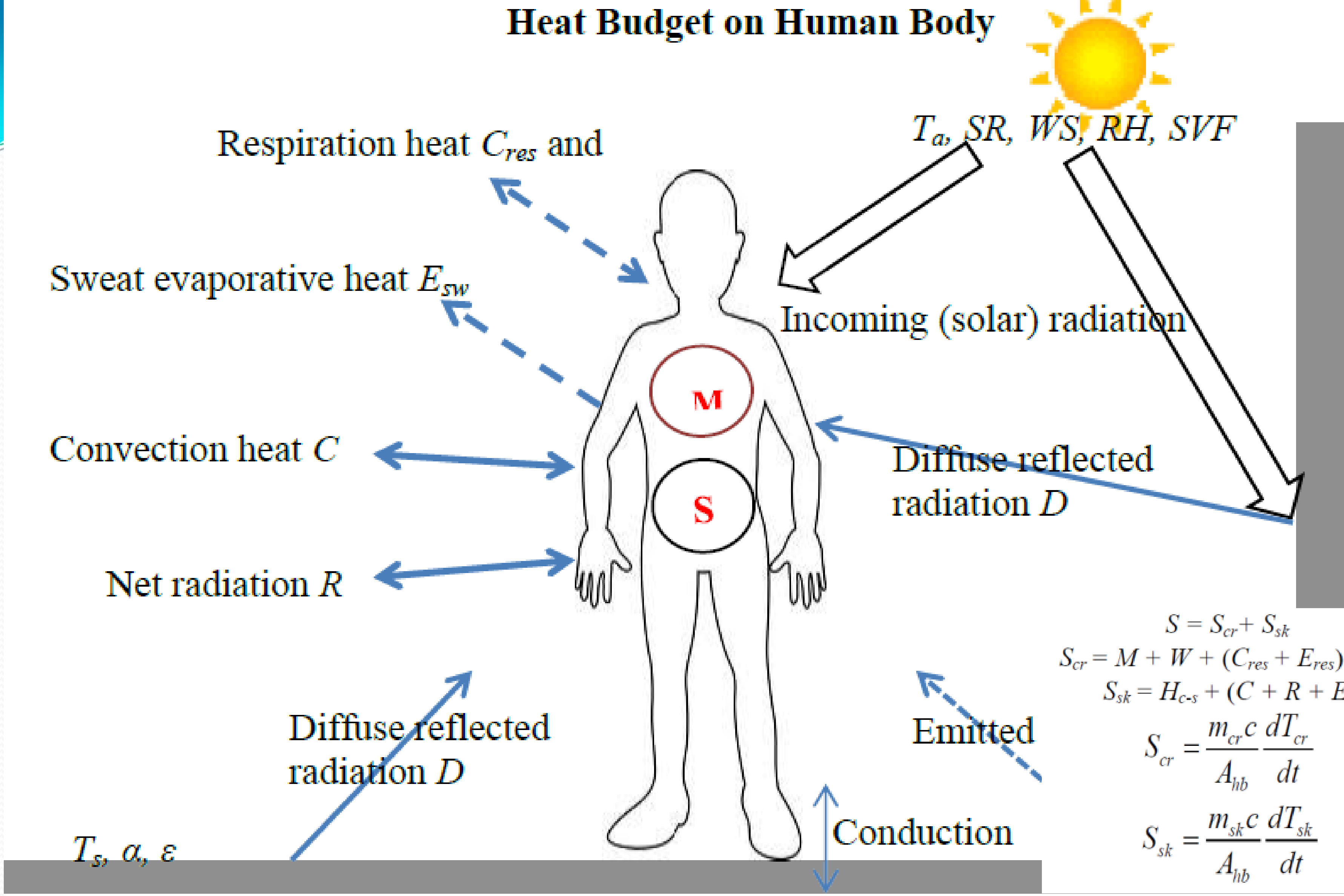
The model considers :

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



Finite Element Method implemented in ABAQUS.

Heat Budget on Human Body



$$S = S_{cr} + S_{sk}$$

$$S_{cr} = M + W + (C_{res} + E_{res}) - H_{c\text{-}s}$$

$$S_{sk} = H_{c\text{-}s} + (C + R + E_{sk})$$

$$S_{cr} = \frac{m_{cr} c}{A_{hb}} \frac{dT_{cr}}{dt}$$

$$S_{sk} = \frac{m_{sk} c}{A_{hb}} \frac{dT_{sk}}{dt}$$

$$M + W + C + R + E_{sw} + C_{res} + E_{res} = S$$

M is the metabolic rate (W/m²). *W* is the rate of mechanical work (W/m²). *S* (W/m²) is the total storage heat flow in the body.

Energy Balance on Human Body

Heat Balance on Human Body

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

Metabolic rate M: 110 W/m^2

Rate of mechanical work W: 0 W/m^2

Convection heat C: -2 W/m^2

Net emitted radiation R: 76.1 W/m^2

Sweat evaporative heat E_{sw}: -227.4 W/m^2

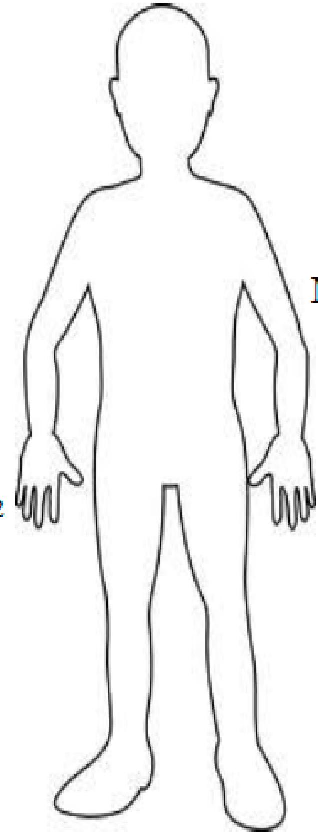
Respiration convective heat C_{res}: -0.62 W/m^2

Respiration evaporative heat E_{res}: -4.84 W/m^2

Skin heat storage heat S_{sk}: -173.6 W/m^2

Core heat storage heat S_{cr}: 103.0 W/m^2

Total heat storage heat S: -70.6 W/m^2



PET: 42.0 °C

Clothing temperature T_{cl}: 41.85 °C

Mean skin temperature T_{sk}: 37.94 °C

Core temperature T_{cr}: 38.44 °C

Sweating rate R_{sw}: 0.14 g/m^{2}s:

Skin wittedness w: 1

Skin blood flow v_{bl}: 90 L/m^{2}hr

Body parameters: 1.80 m, 75 kg, 0.5 clo

Inputs Parameters

Table 1. Typical summer and winter climate data in three regions

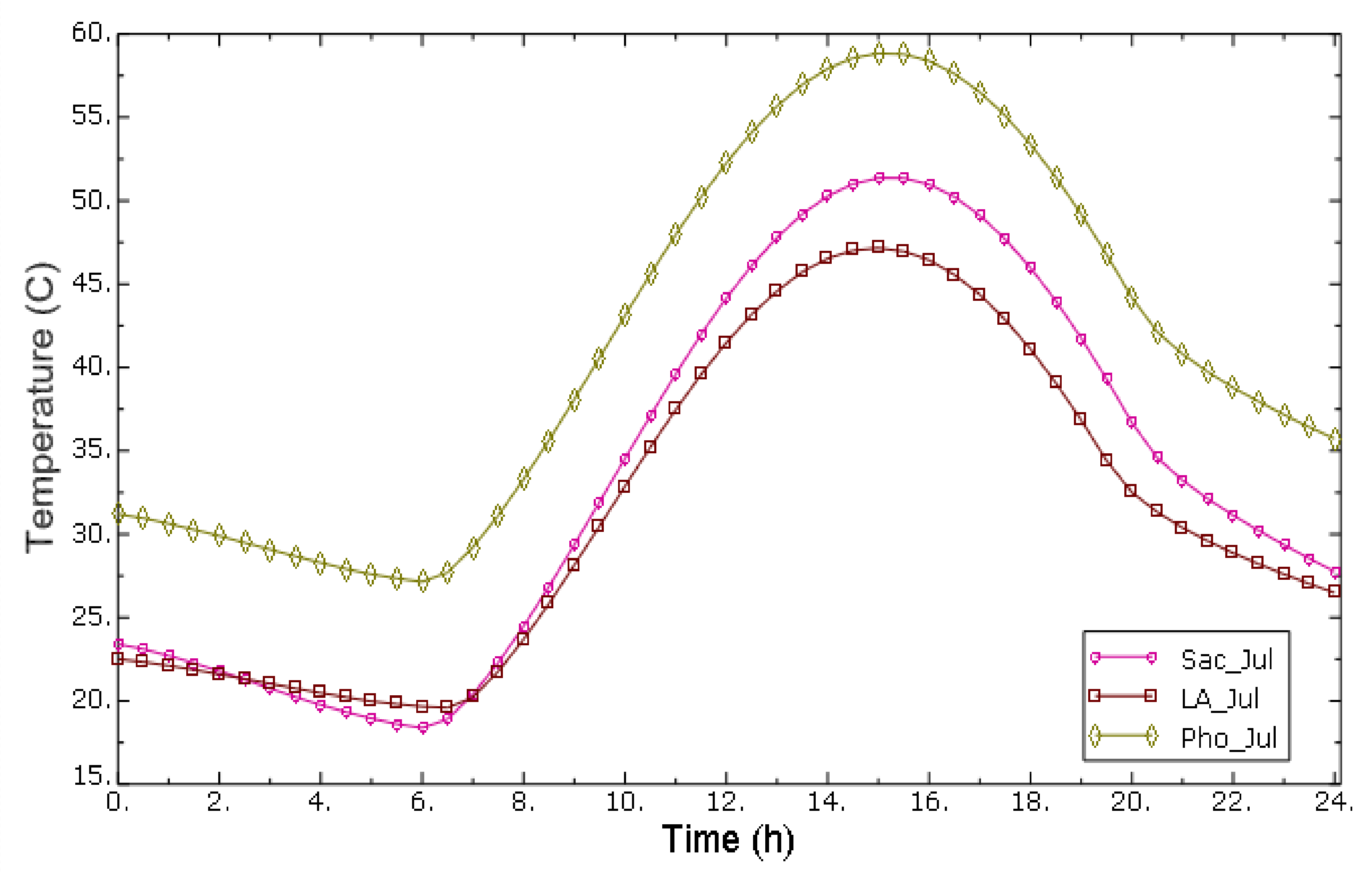
Season	Daily peak air temperature T_a^{max} [℃][a]	Daily lowest air temperature T_a^{min} [℃][a]	Daily total solar radiation volume Q [MJ/m^2][b]	Daily effective sunlight hour c [h][b]	Daily average wind velocity v_w [m/s][c]
Sacramento (Sac), California					
Summer (Jul, average)	34	16	28.3	11	4.0
Winter (Jan, average)	13	5	6.3	8	3.2
Los Angeles (LA), California					
Summer (Jul, average)	29	18	22.6	10	2.8
Winter (Jan, average)	20	9	9.7	8	2.2
Phoenix (Pho), Arizona					
Summer (Jul, average)	40	25	27.4	11	3.2
Winter (Jan, average)	19	4	11.4	9	2.4

Table 2. Pavement scenarios used for analysis

Parameter	Pavement Scenario				
	Baseline	High-Reflectance	Evaporation	High Reflectance + Evaporation	Shading
Albedo *r*	0.1	<u>0.5</u>	0.1	<u>0.5</u>	0.1
Evaporation Rate *ER* (*mm/h*)	0	0	<u>1.5</u>	<u>1.5</u>	0
Sky View Factor *SVF*	1	1	1	1	<u>0</u>

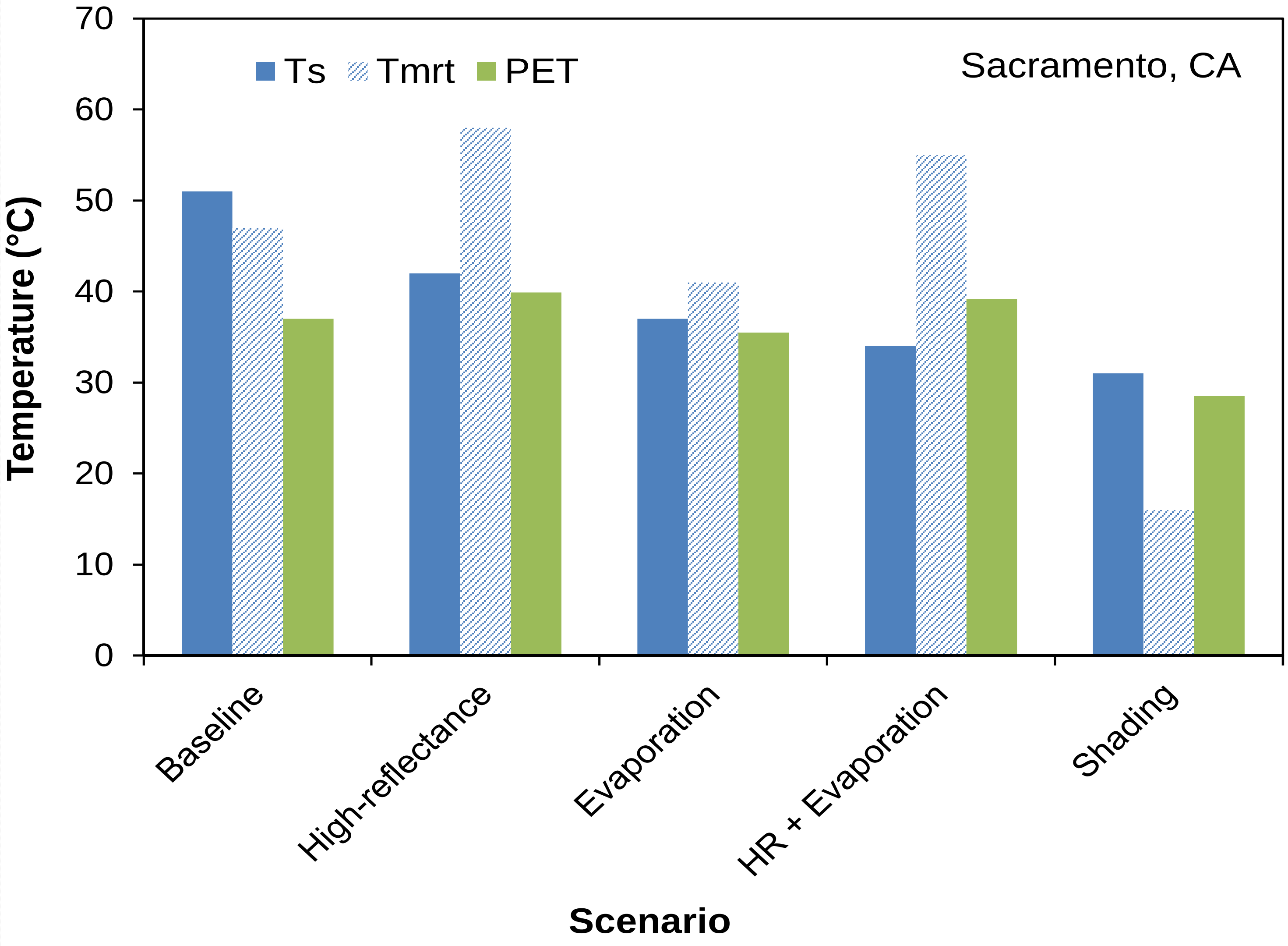
Note: Changed parameter is underlined for each scenario.

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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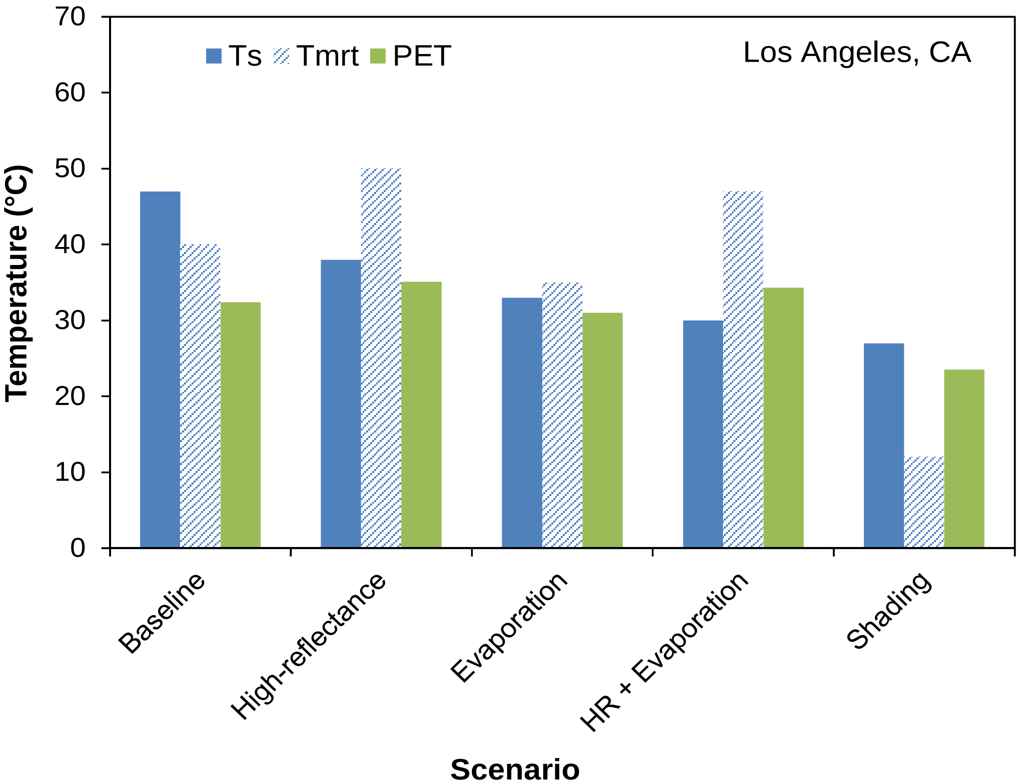

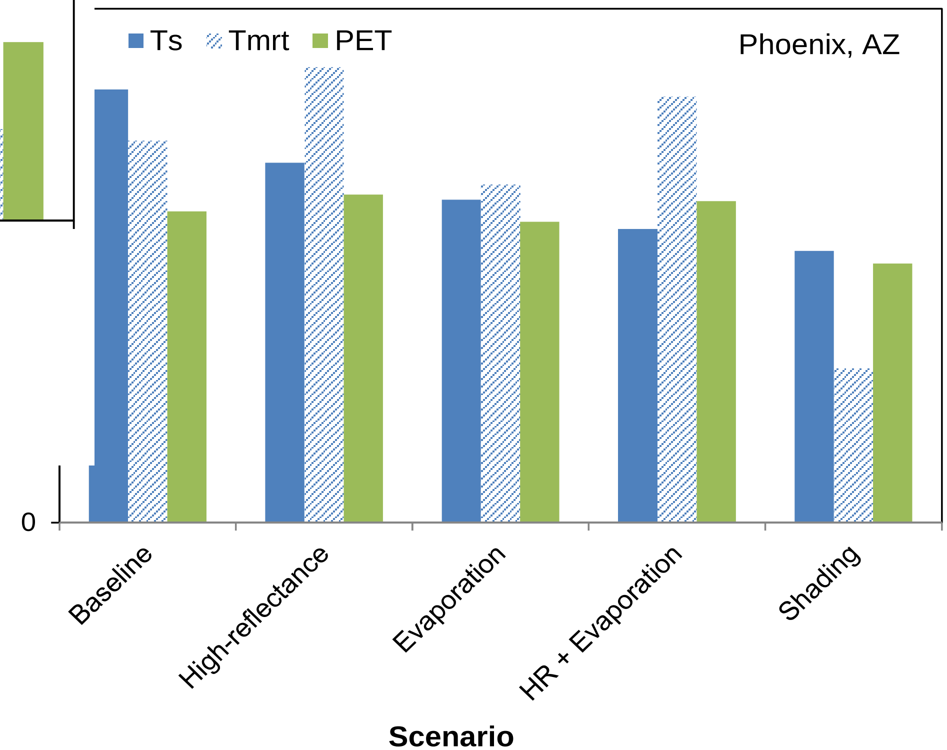

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Main Conclusions from Pilot Study

- 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

Cool Pavements Research and Implementation Act

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

Caltrans

UC PRC
UNIVERSITY of CALIFORNIA Davis • Berkeley
PAVEMENT RESEARCH CENTER

ACPA
AMERICAN CONCRETE PAVEMENT ASSOCIATION

ICPI
INTERLOCKING CONCRETE PAVEMENT INSTITUTE®

National Center for Sustainable Transportation

California Environmental Protection Agency
AIR RESOURCES BOARD

Collaborators:

BERKELEY LAB
LAWRENCE BERKELEY NATIONAL LABORATORY

Cal/EPA
California Environmental Protection Agency

NAPA
NATIONAL ASPHALT PAVEMENT ASSOCIATION

Thanks!
Q&A

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