Pavements Materials and the Urban Climate

INTERNATIONAL
CONCRETE SUSTAINABILITY CONFERENCE
DECEMBER 13-14, 2010 - DUBAI

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NRMCA

ASU Ira A. Fulton School of Engineering
ARIZONA STATE UNIVERSITY

Grey Matters
Consultancy

Pavements & Sustainability

- Performance / Durability
  - Material / Design
- Safety
- Ride Quality or Comfort
- Life Cycle Cost
- Quality of Life Issues
  - Highway Noise
  - Air Quality
  - Urban Heat Island
- Energy Consideration
- Recyclability

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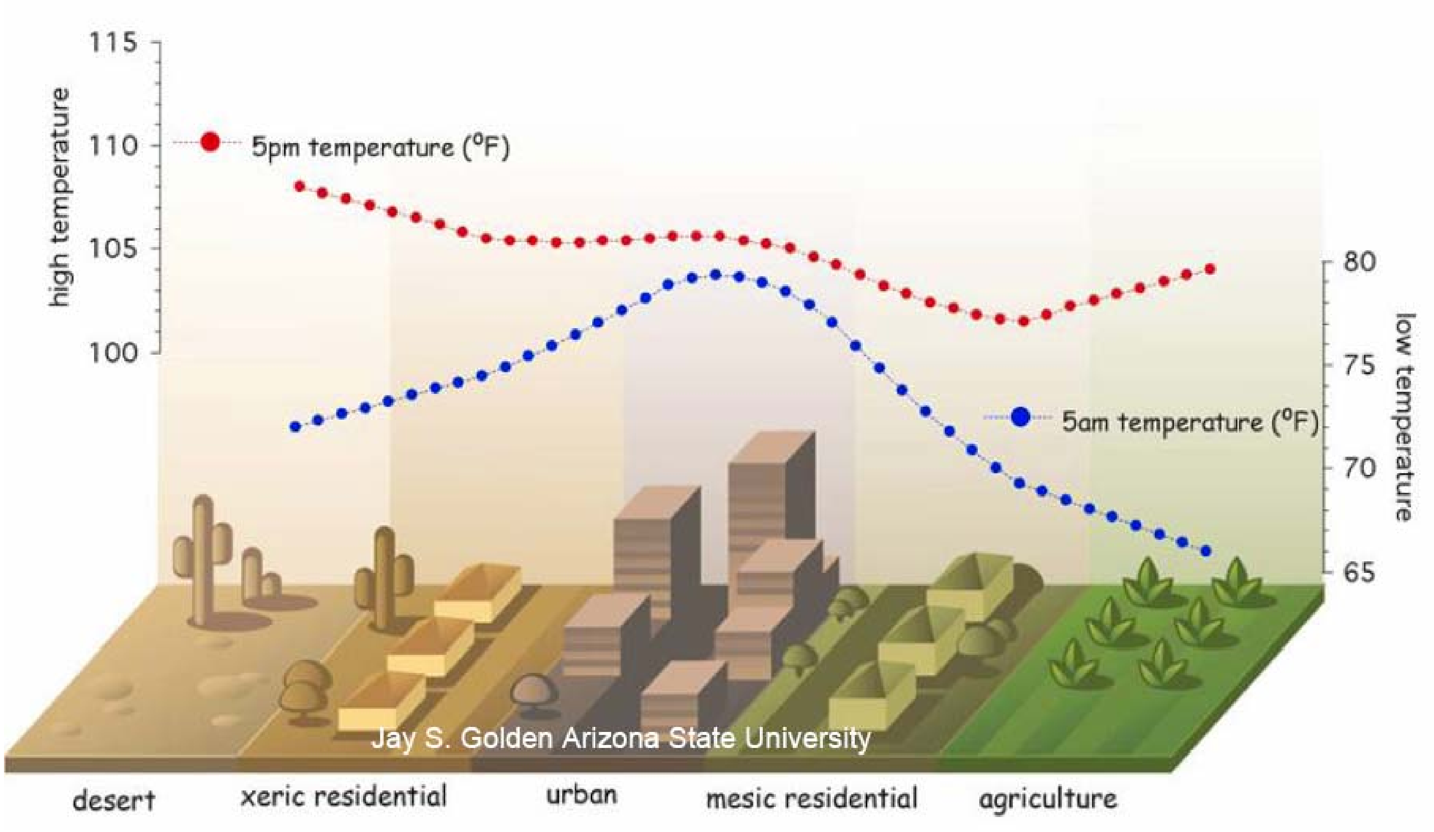
Urban Heat Island



Zehnder, Golden and Brazel

Pavements and the Urban Heat Island Effect

Do pavements contribute to UHI?

- How much?
- What are the:
  - evaluation techniques?
  - driving factors?
  - properties of materials?
  - design characteristics?
  - mitigation strategies and opportunities to pavements industries?
  - tools and models?

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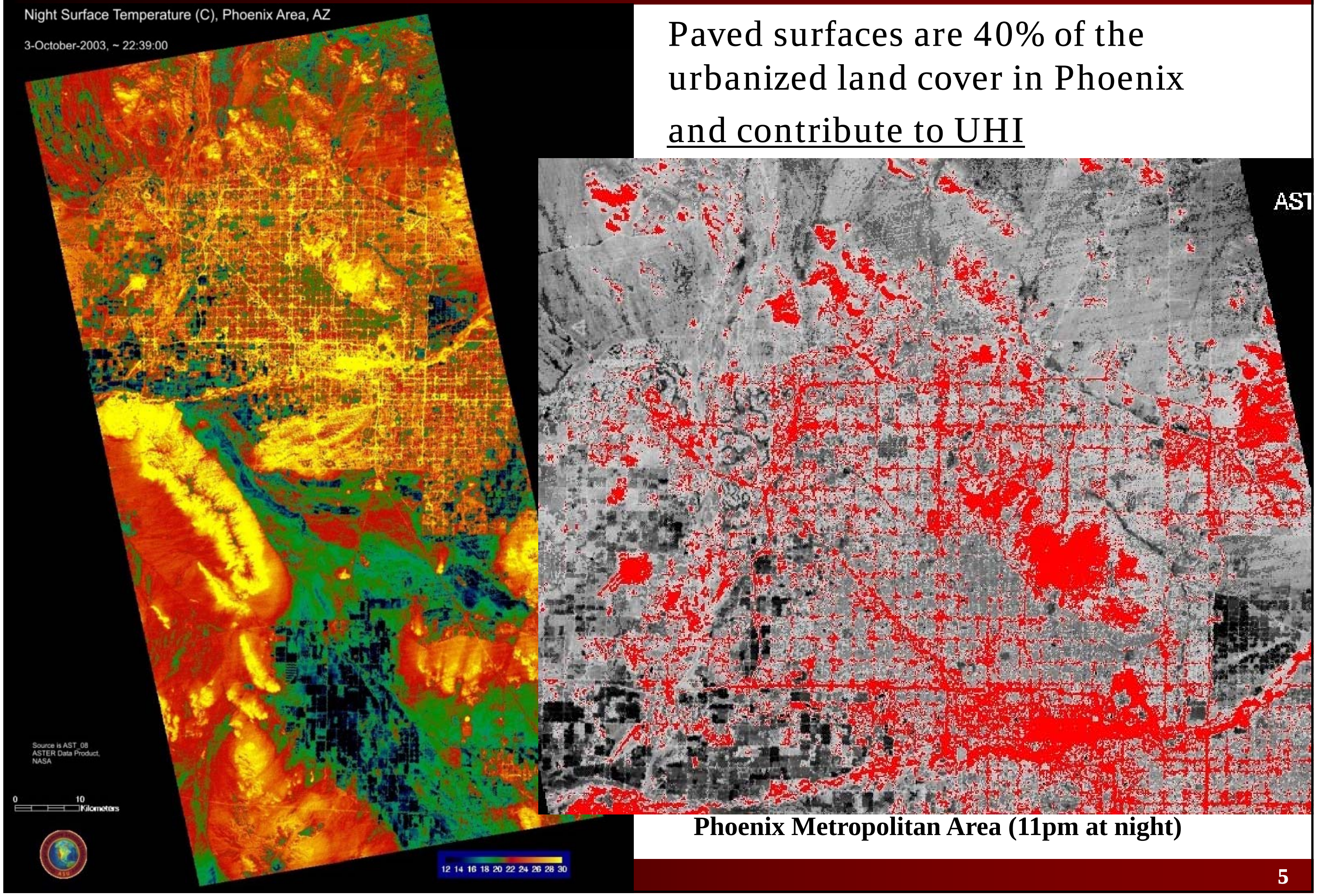
ASTER Satellite Imagery

Paved surfaces are 40% of the urbanized land cover in Phoenix <u>and contribute to UHI</u>

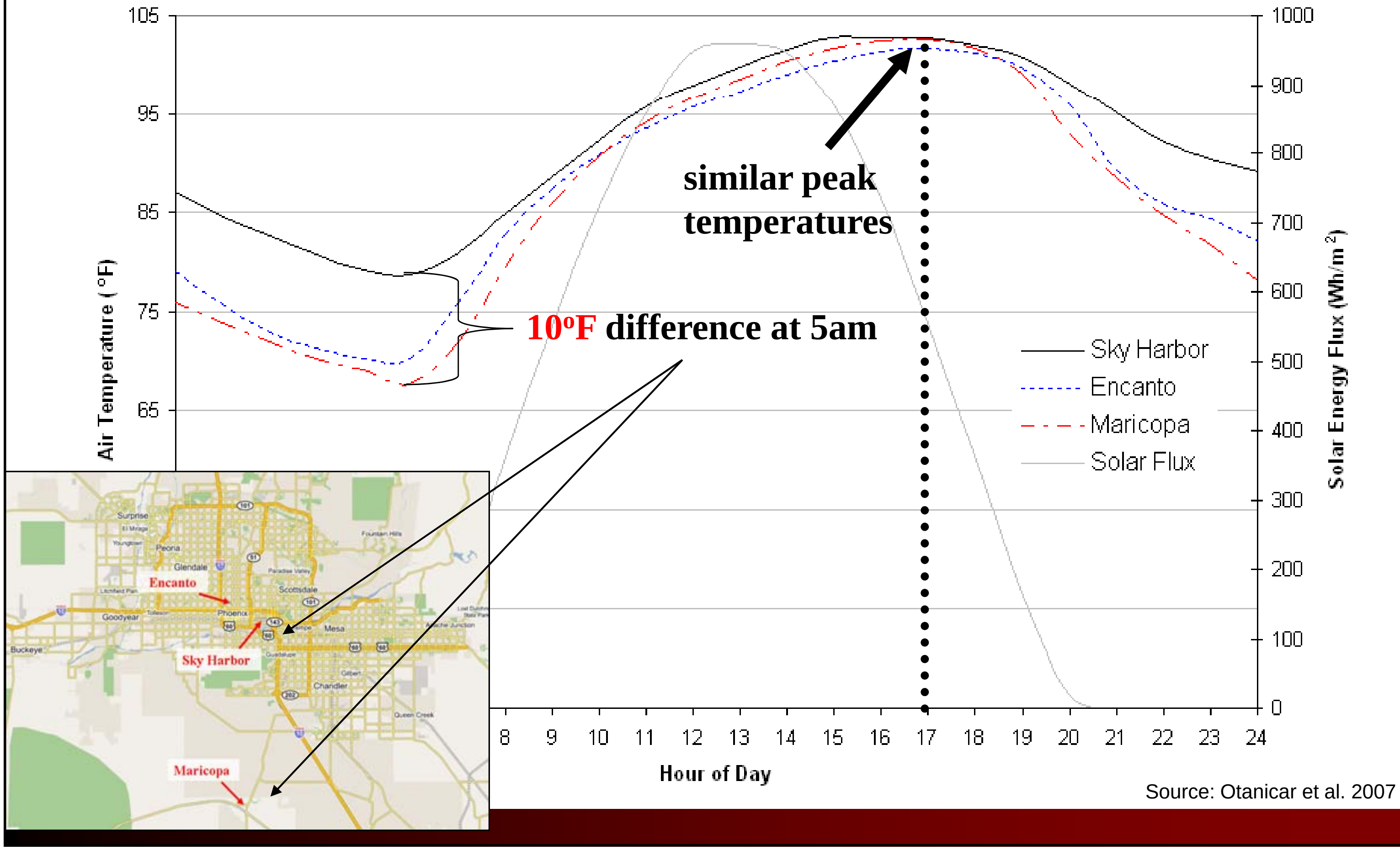


Phoenix Metropolitan Area (11pm at night)

How Much?

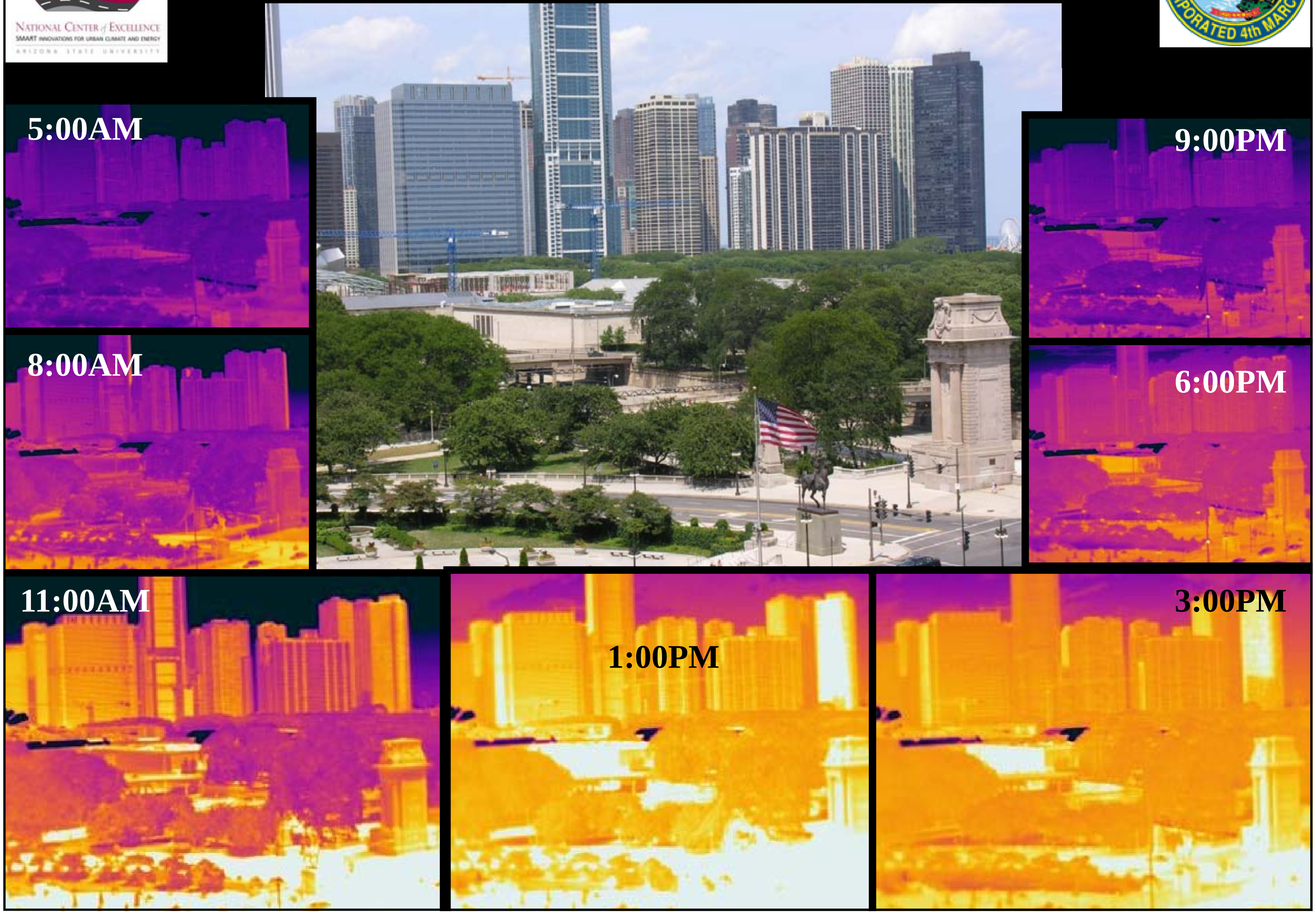
Average Hourly Air Temperatures (July 2005)

for Sky Harbor Airport (Urbanized), Encanto Park (Green Space), and the City of Maricopa (Rural)



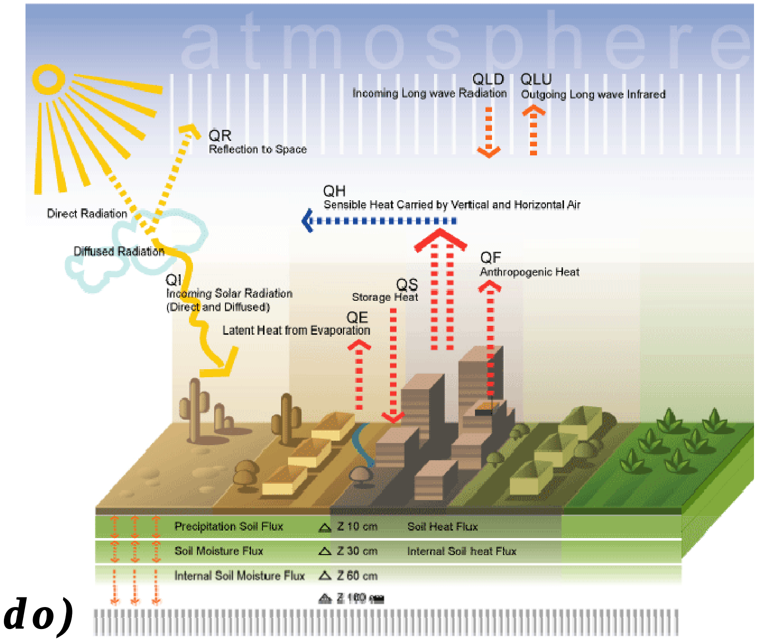
Source: Otanicar et al. 2007

Time lapse infrared view of Chicago near Millennium Park
July 14 – 15, 2007



What are the driving factors?

- ***Canyon Geometry***
- ***Thermal Properties***
- ***Anthropogenic Heat***
- ***The Urban Greenhouse Effect***
- ***The Effective Reflectivity (Albedo)***
- ***Reduction of Evaporating Surfaces***
- ***Reduced Turbulent Transfer of Heat***

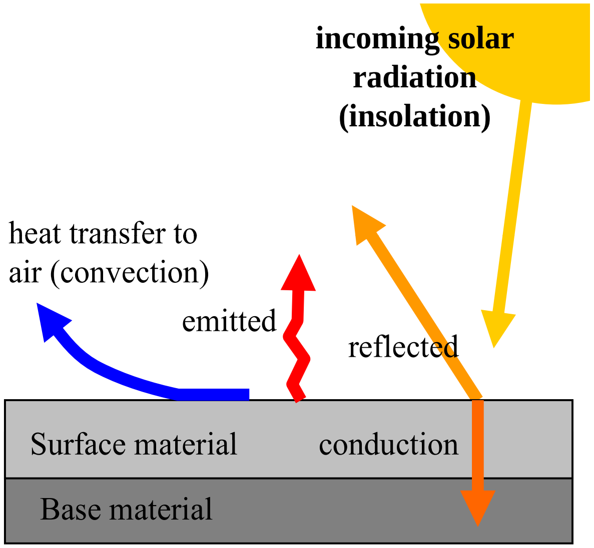


■ Golden, Zehnder, Brazel 2004

Oke et al. (1997)

Fundamental Properties

- Albedo, α
- Emissivity, ε
- Convection Coefficient, h
- Thermal Conductivity, *k*
- Specific Heat, C
- Density, *ρ*
- Thermal Diffusivity, α,κ


incoming solar radiation (insolation)

heat transfer to air (convection)

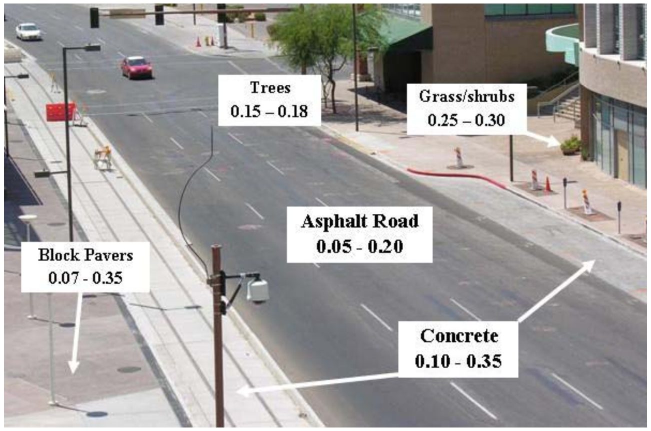
emitted

reflected

Surface material

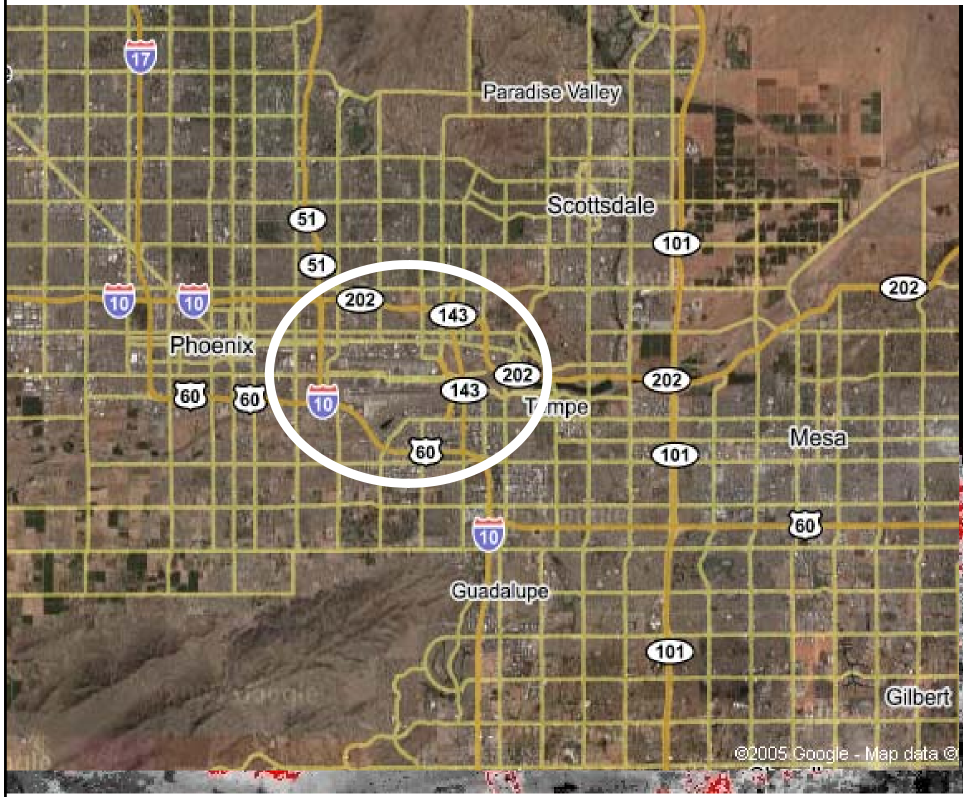
conduction

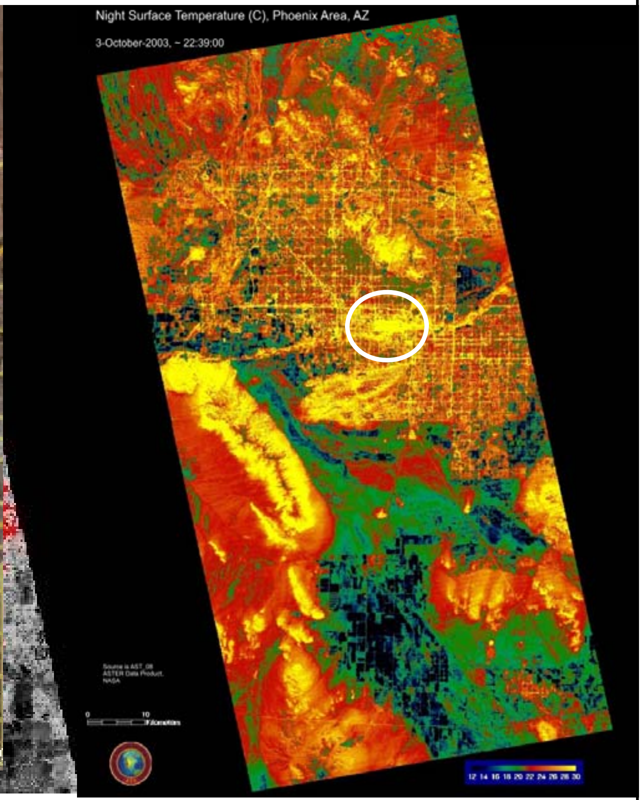
Base material



Evaluation Techniques

- ASTER Satellite Imagery Reveals Airport

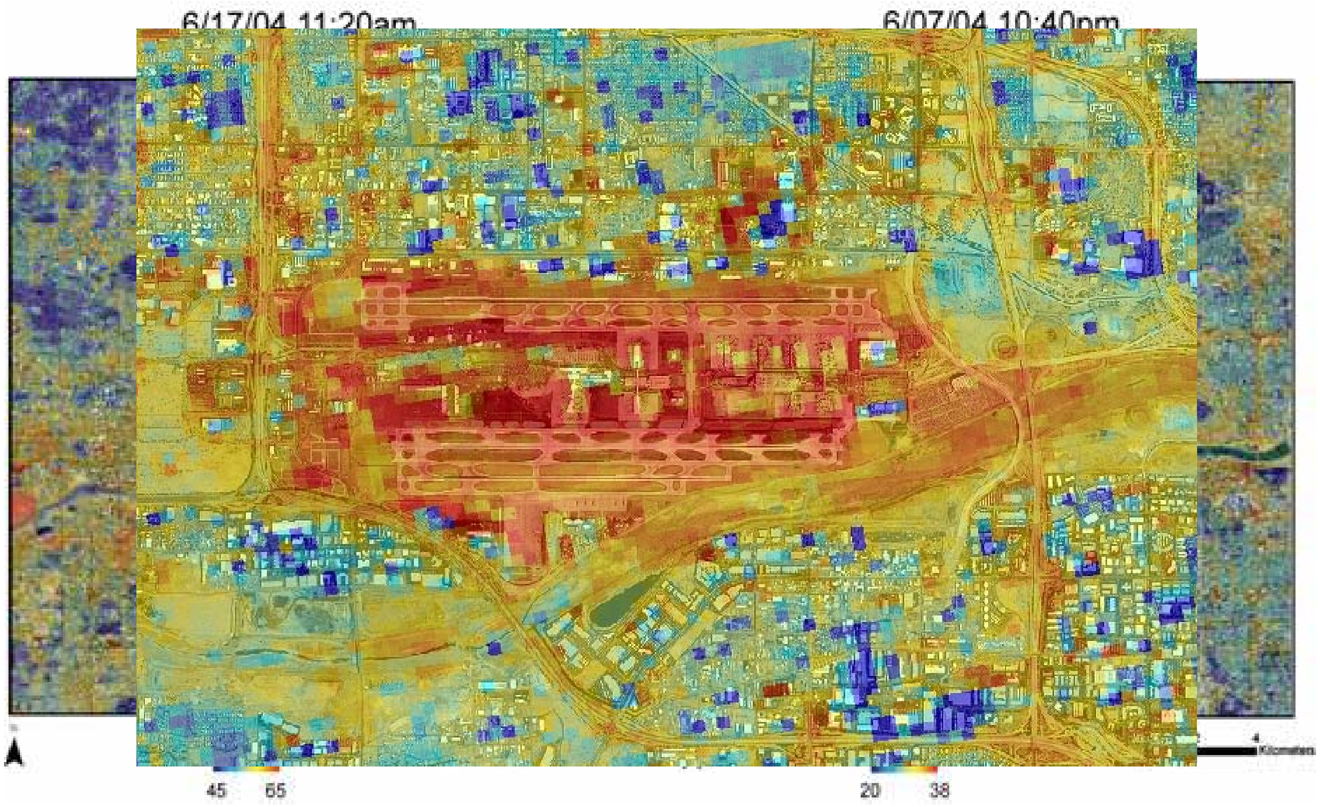




Satellite Imagery

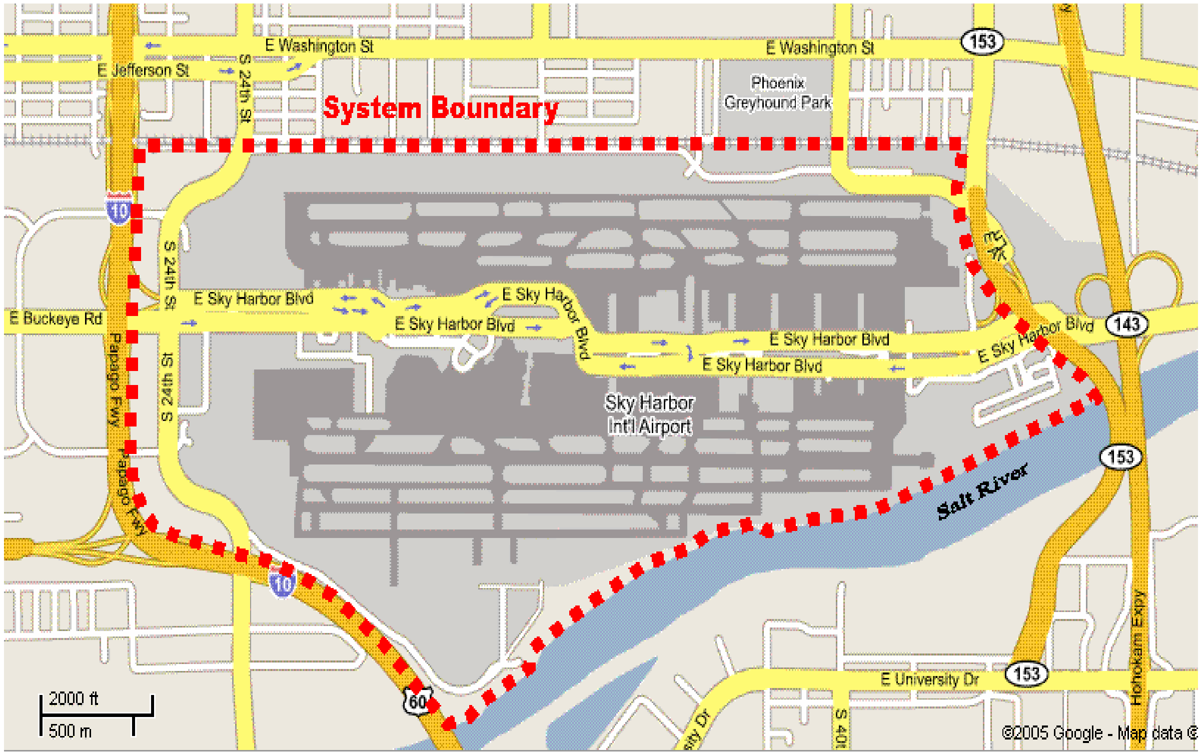
- **Satellite Imagery** – Too low of resolution (90m/pixel)

Unable to determine where to focus mitigation efforts



Surface Characterization

- Defining the System Boundary



Surface Characterization

Sky Harbor Airport

System Boundary

Buildings

Unpaved

Mesic Landscaping

Xeriscape

Bare Soil

Pavements

Stabilized Soil

RAP Infields

AC Public Roads

AC Service Roads

PCC Public Roads

PCC Bridges

PCC Aprons

PCC Taxiways

PCC Connectors

PCC Runways

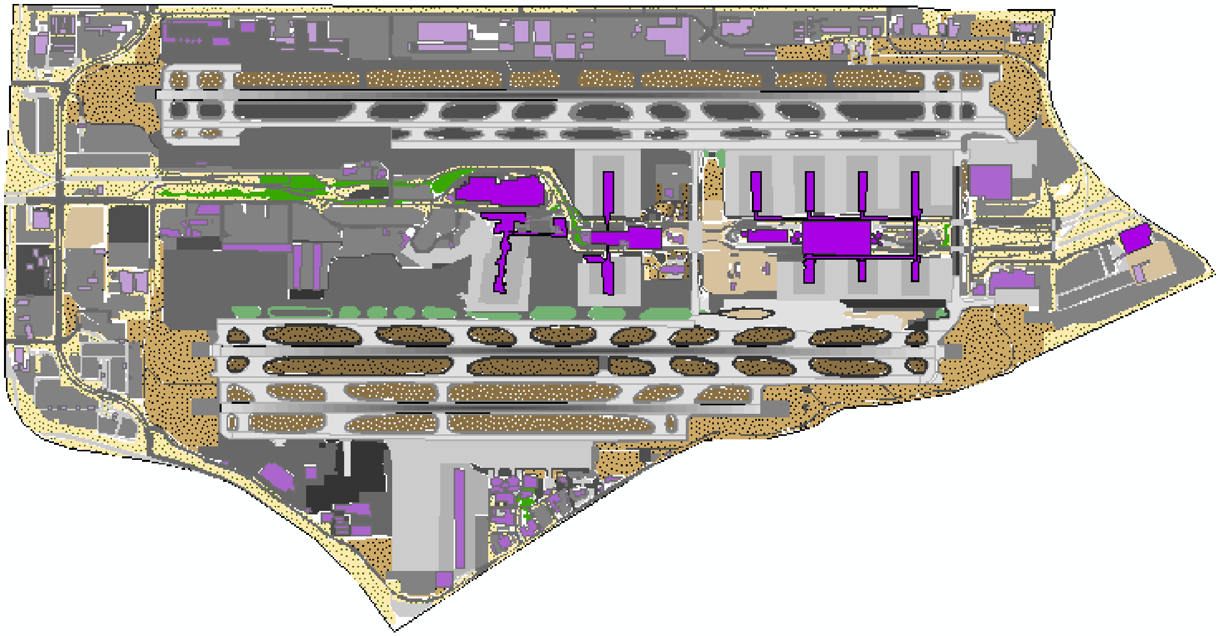
AC Infields

AC Infield Shoulders

AC Aircraft Access

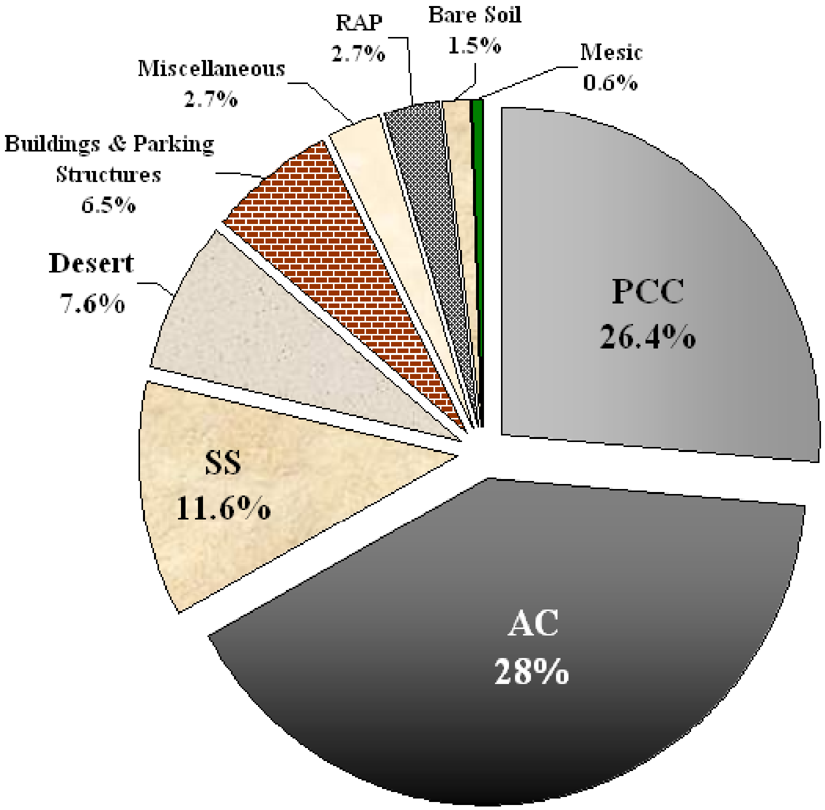
AC Public Parking

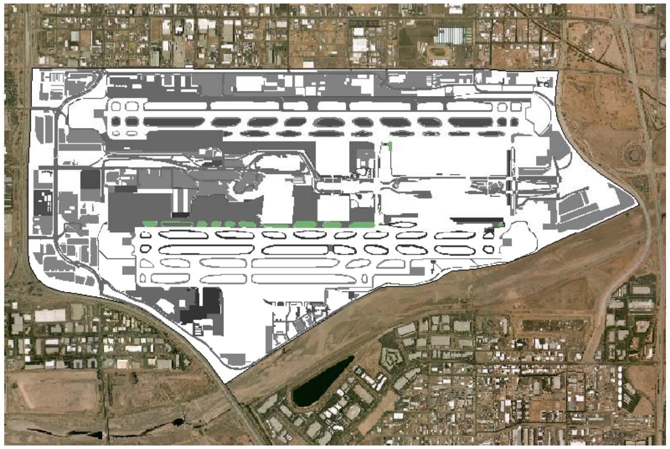
Analysis Area



Surface Characterization

Surface Area by Material Type

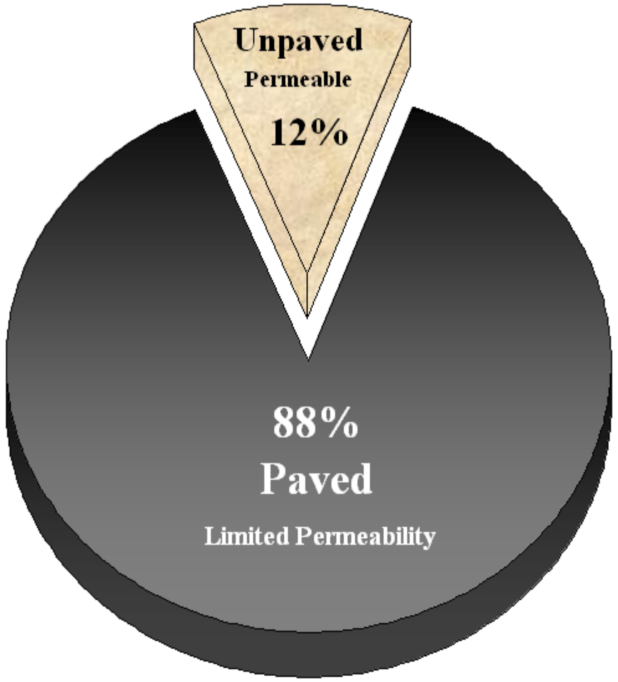


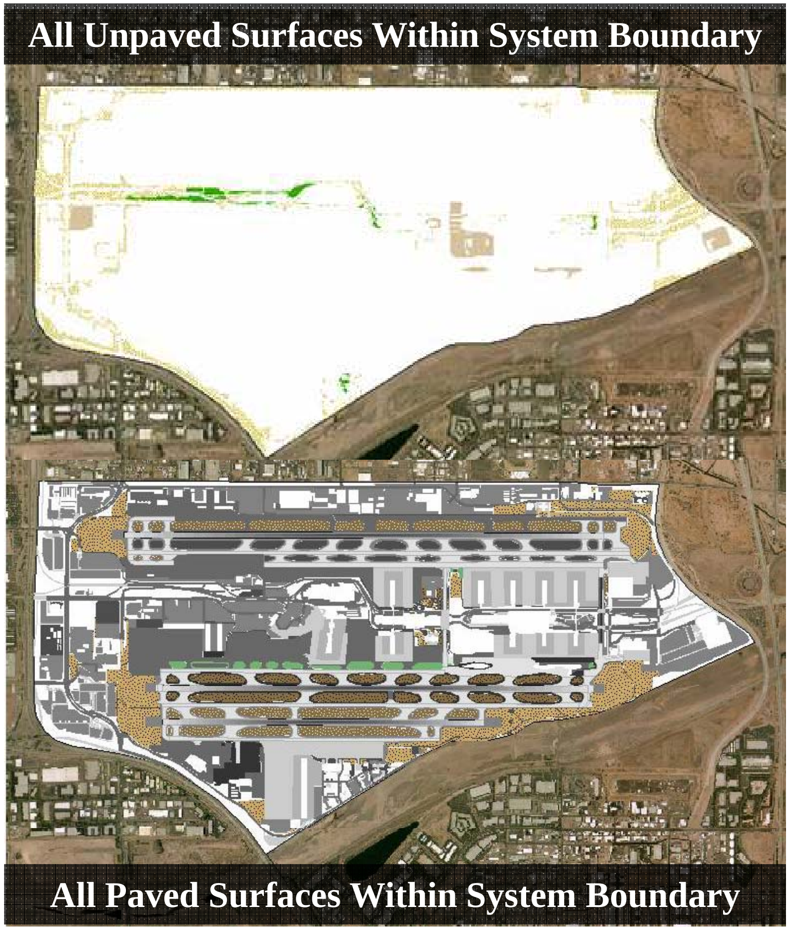


All Surfaces Within System Boundary

Surface Characterization

Paved vs. Unpaved Surfaces





Surface Temperature Study

Equipment Descriptions

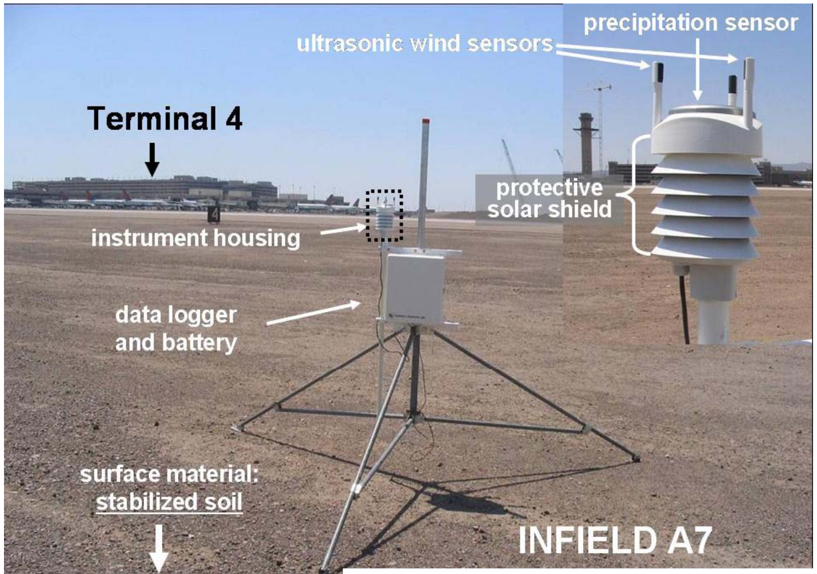
Mobile Transect Equipment

- Designed and operated by Brent Hedquist
  - Doctoral student in the School of Geographical Science at ASU
  - Part of PhD dissertation
- Equipment mounts to most vehicles
- Data Logger
  - IR Thermometer
  - GPS (coordinates)
  - Inside a solar shield
    - Relative humidity
    - Air temperature
- Required escort when airside

Surface Temperature Study

Weather Stations

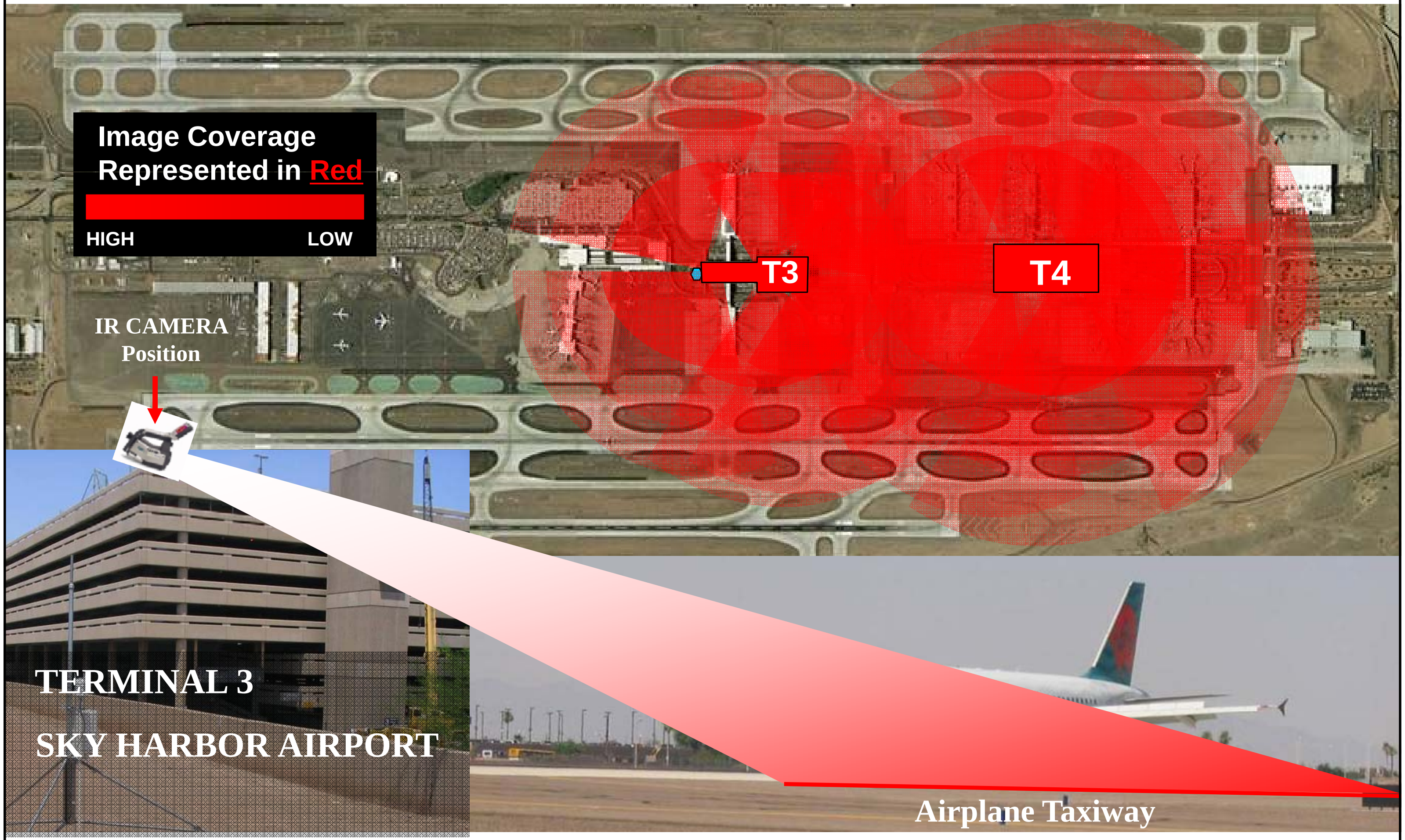
- **Vaisala Stations**
  - Temporary (SRP)
  - Height ~ 2 meters
  - Records
    - Air temperature
    - Relative humidity
    - Wind speed/direction
    - Every 1 minute



- **ASOS**
  - Automated Surface Observation System
    - Sponsored by the F.A.A., N.W.S., and D.O.D.
    - Permanently at almost all airport
  - Records meteorological data including solar radiation

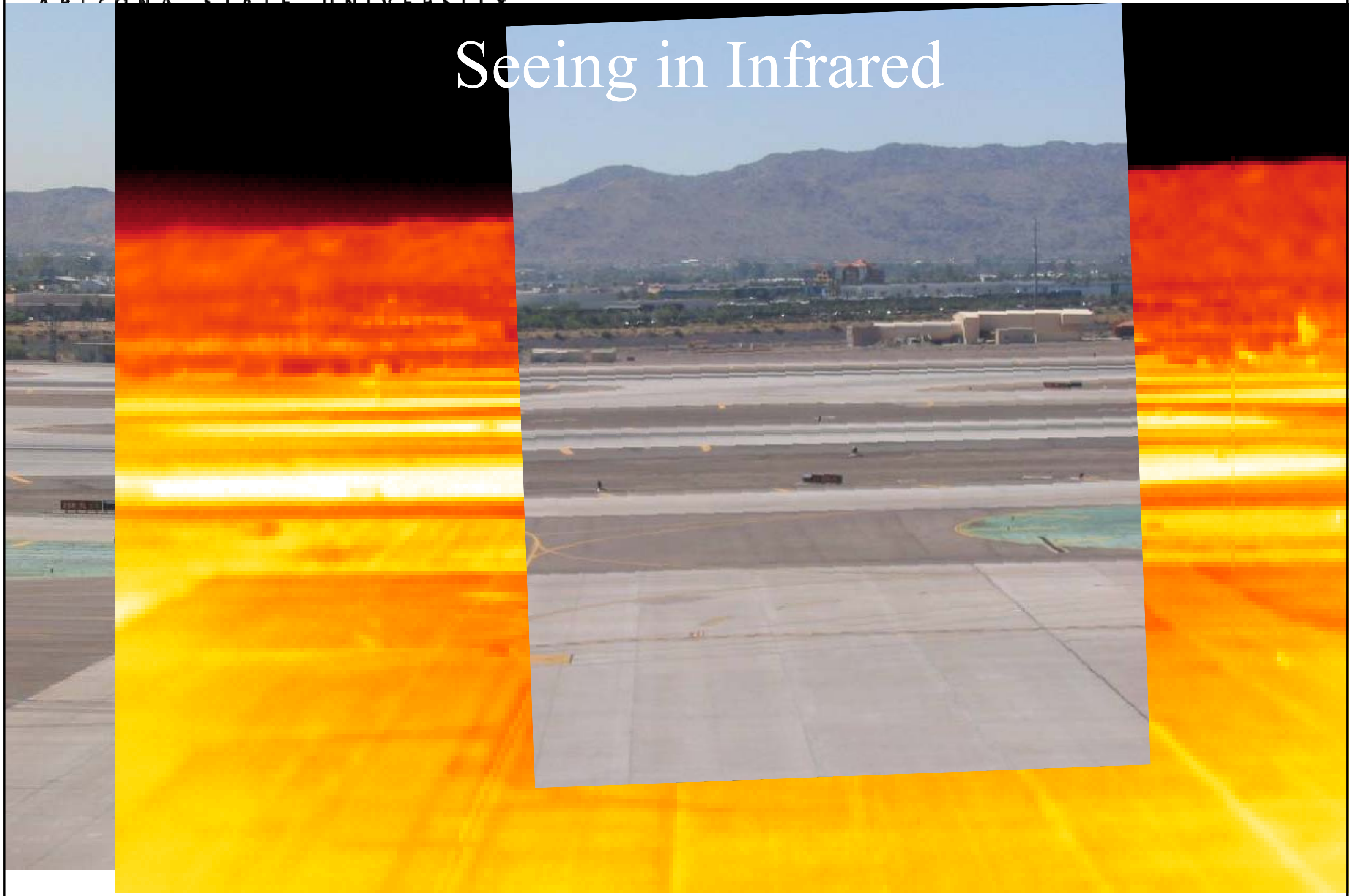
Surface Temperature Study

IR Camera Field of View

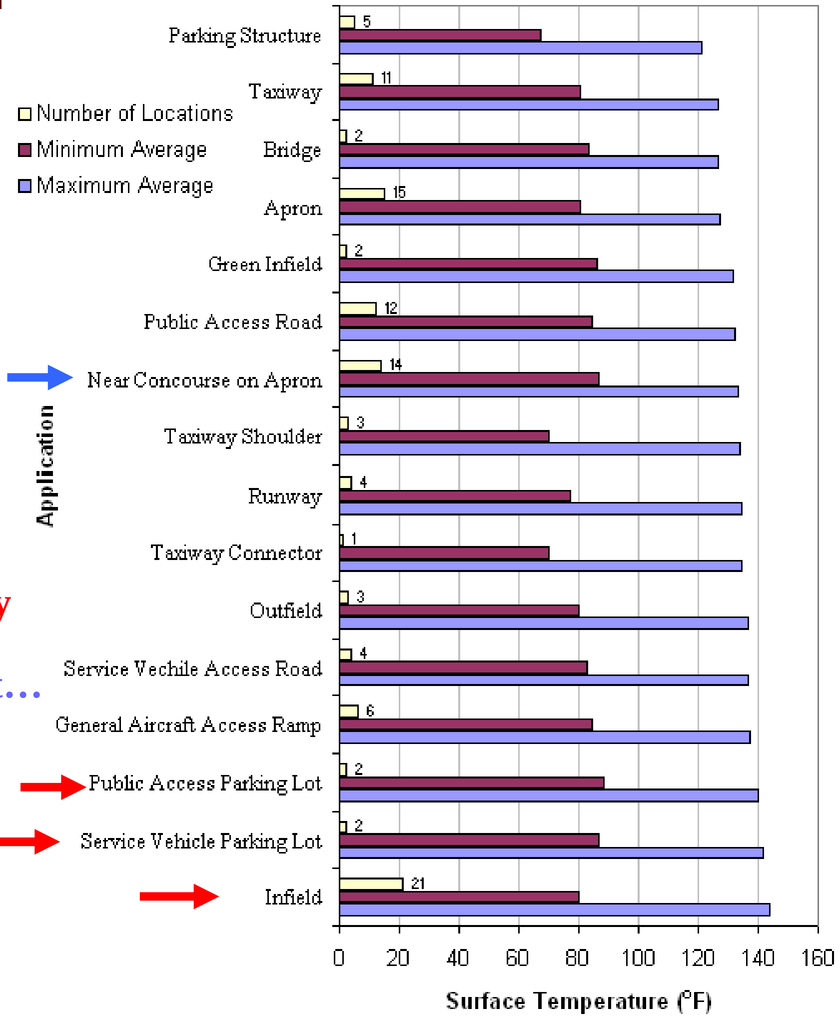


Surface Temperature Study

Seeing in Infrared



Surface Temperature Results



Infields - hottest surfaces during the day

Parking lots - warmest surfaces at night…

and during the day

Mitigation Matrix

- **Recommended UHI mitigation options for common airport applications.**

Airport Application	Area [acres]	%	Portland cement concrete	Reflective asphalt surface treatment	Reflective surface coating	Pervious concrete	Open grid pavements	Ground cover supprot structures	Stabilized graded aggregate	Energy Star™ Cool Roofing	Vegetated roofs	Shade canopies	Build underground	Photovoltaic shading arrays
Parking Lots	350	17%	X	X		X	X	X	X			X	X	X
General Aircraft Access Areas	302	15%	X	X	X									
Aprons	227	11%	X	X										
Infields	226	11%			X	X	X	X	X					
Outfields	172	8%			X	X	X	X	X					
Roads	167	8%	X	X			X	X	X					
Taxiway Shoulders	121	6%	X	X	X	X								
Taxiway Connectors	120	6%	X	X	X									
Taxiways	115	6%	X	X										
Runways	104	5%	X											
Commercial Buildings	96	5%								X	X	X		X
Parking Structures	32	2%	X		X							X		X
Terminal and Concourses	24	1%								X	X	X		X
Total	2056	100%												

Regional Guidebook

Climate, Energy and Urbanization

A Guide on Strategies, Materials and Technologies for Sustainable Development in the Desert

Audience

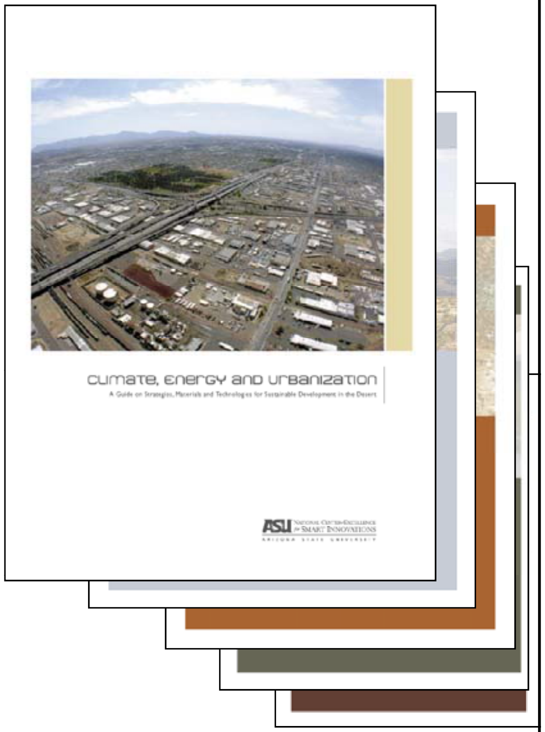
City Managers, Planners, Architects/Engineers, Academics, General Public

Guidebook: 4 Chapters, 360 pages

- Chapter 1: Urban Sustainability in a Desert Region
- Chapter 2: Urban Heat Island Mitigation
- Chapter 3: Design for Climate and Energy
- Chapter 4: Systems, Products and Materials

Brochure: Executive Overview, 20 pages

Joby Carlson, ASU



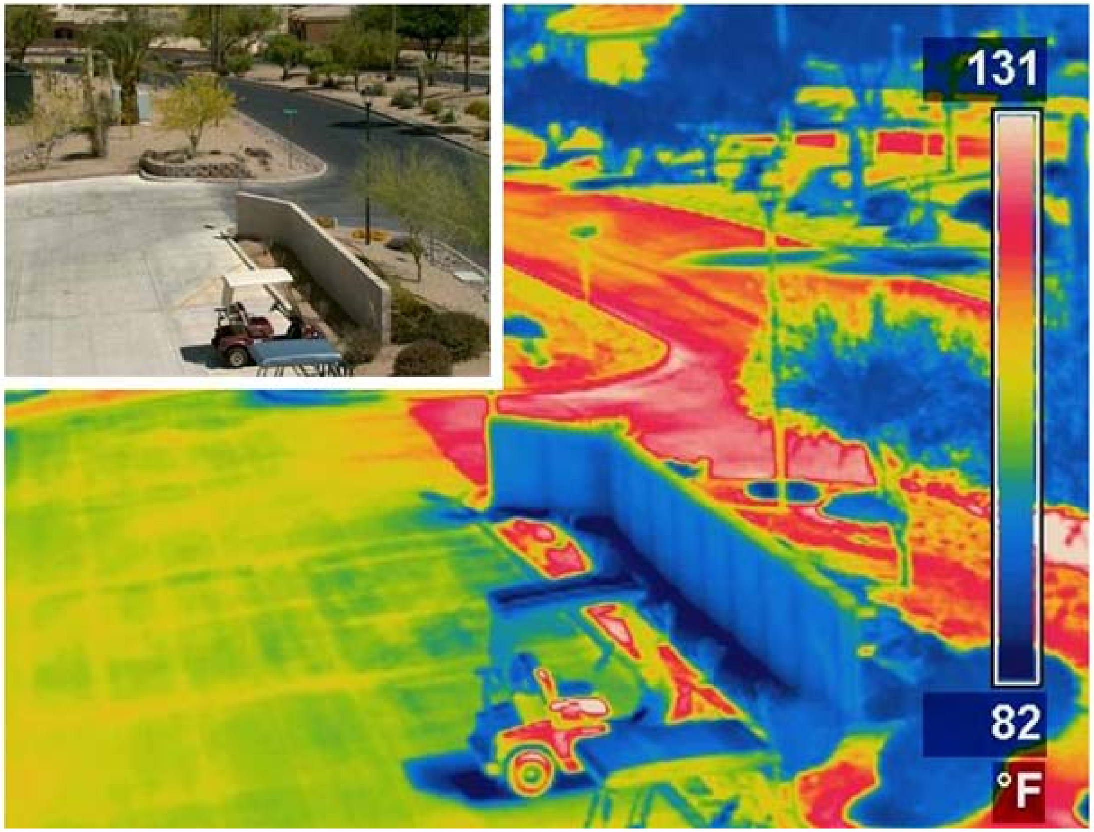
CLIMATE, ENERGY AND URBANIZATION
A Guide on Strategies, Materials and Technologies for Sustainable Development in the Desert

UHI Mitigation
Winning Strategies for PCC

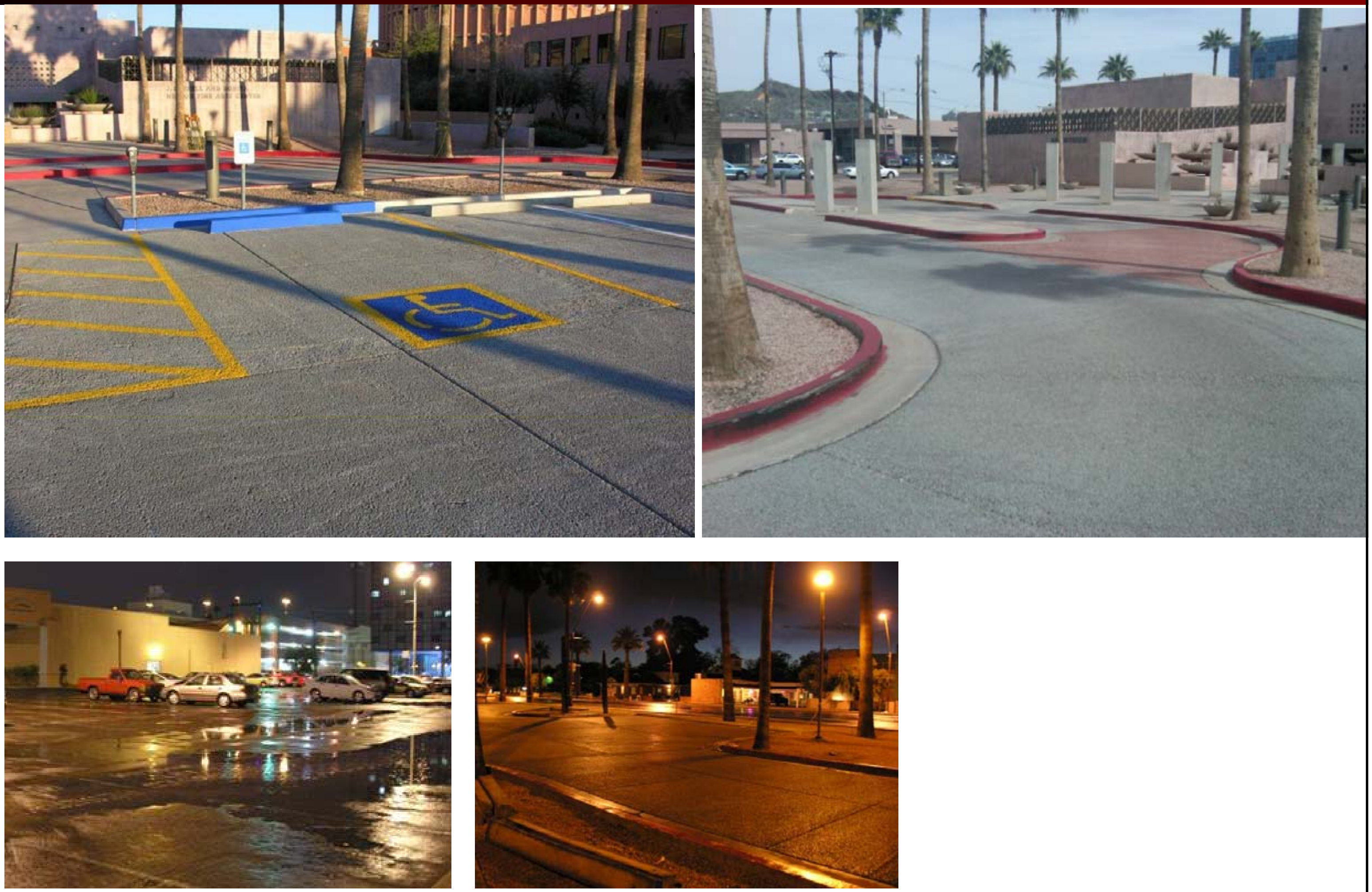
- Albedo
  - – Innovations to sustain initial higher values
- Pervious concrete
- Whitetopping strategies
  - – Thin and Ultra-Thin
- Thermal resistant materials
  - – Aggregates, admixtures, crumb rubber
- Provide cover: trees, solar panels (parking structures)

Pavement Design Characteristics

Thin and Ultra-Thin Whitetopping PCC



Pervious Concrete



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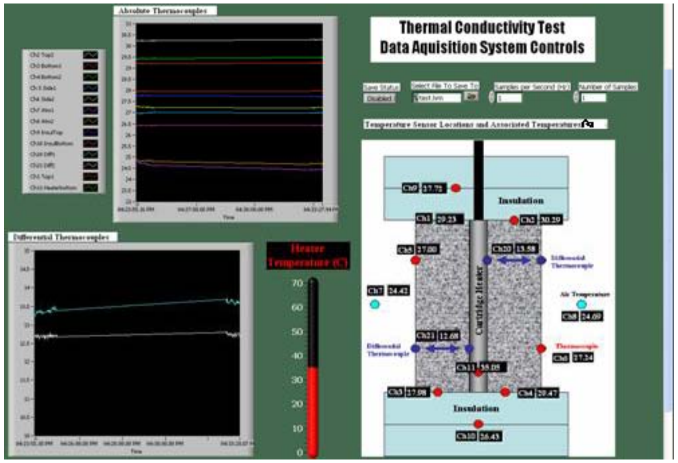
Laboratory Evaluation



Method Description

- **Theoretical Analysis**

1. Heat Transfer Through a Cylinder Wall

$$\dot{Q}_{cond,cyl} = \frac{T_1 - T_2}{R_{cyl}}$$

2. Thermal Resistance of the Cylinder Wall

$$R_{cyl} = \frac{\ln(r_2/r_1)}{2\pi Lk} = \frac{\ln(\text{Outer radius/Inner radius}}{2\pi\times(\text{Length})\times(\text{Thermal conduc}}$$

3. Substituting Variables

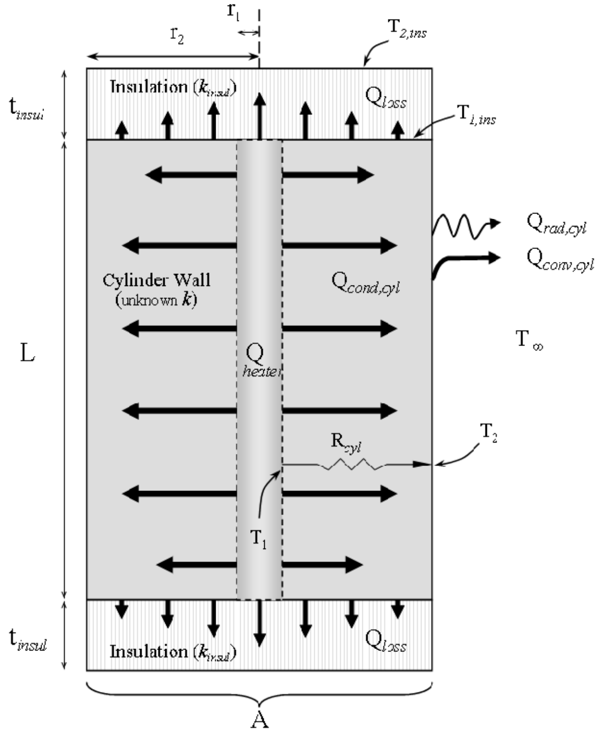
$$\dot{Q}_{cond,cyl} = 2\pi Lk\frac{T_1 - T_2}{\ln(r_2/r_1)}$$

4. Accounting of Heat Loss

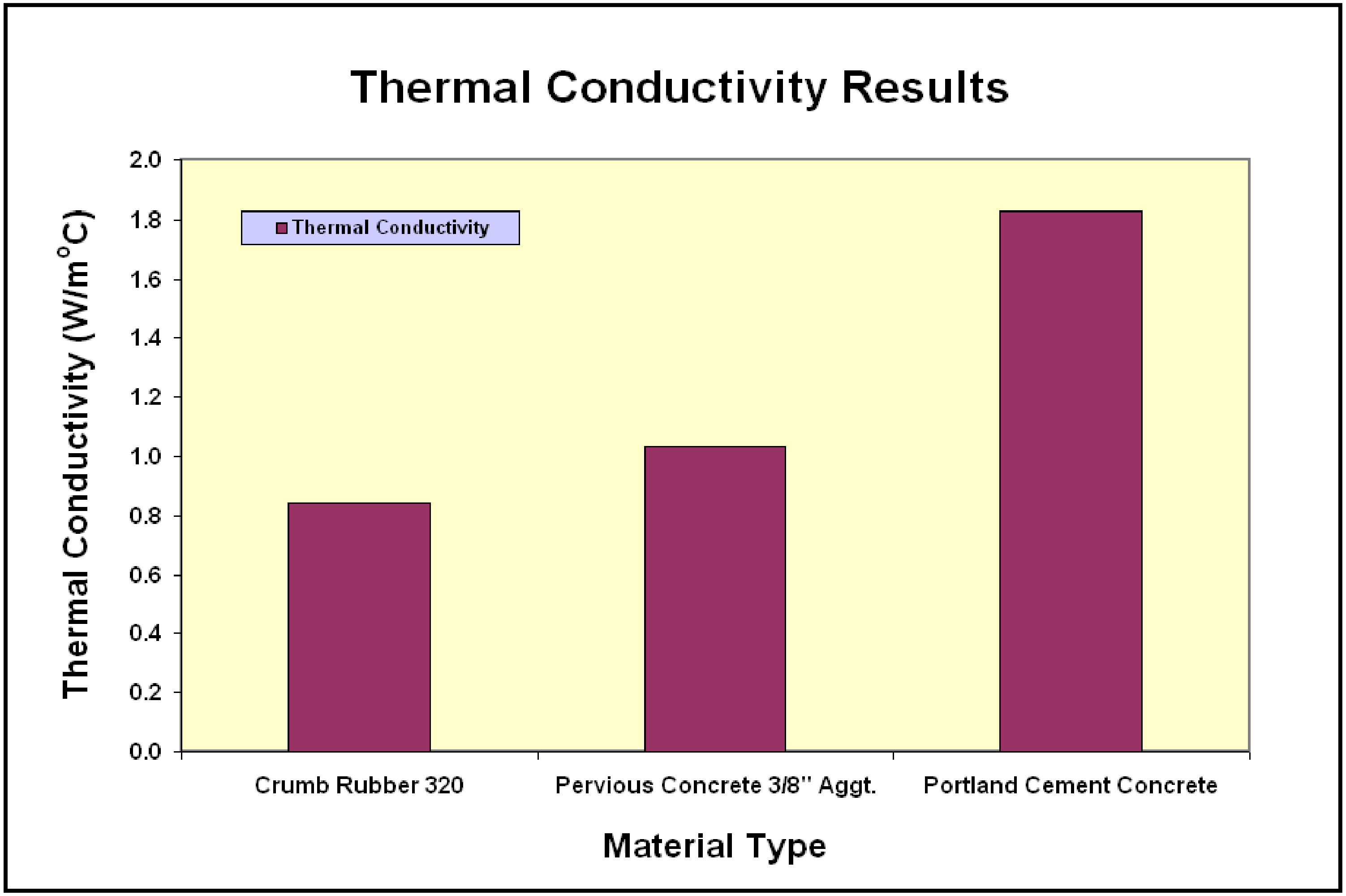
$$\dot{Q}_{cond,cyl} = \dot{Q}_{heater} - \dot{Q}_{loss} \qquad \dot{Q}_{heater} = \mathrm{V}\times\mathrm{I}$$

5. Calculating Thermal Conductivity, *k*

$$k = \frac{\dot{Q}_{cond,cyl}\ \ln(r_2/r_1)}{2\pi L(T_1 - T_2)}$$



$$\boxed{k = \frac{(\mathrm{VI} - \dot{Q}_{loss})\ln(r_2/r_1)}{2\pi L(T_1 - T_2)}}$$


Thermal Conductivity Results
Thermal Conductivity (W/m°C)
2.0
1.8
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
■ Thermal Conductivity
Crumb Rubber 320
Pervious Concrete 3/8" Aggt.
Portland Cement Concrete
Material Type

U.S. Green Building Council's Rating System

Leadership in Energy and Environmental Desig

LEED Rating System

- Sustainable Sites
- Water Efficiency
- Energy and Atmosphere
- Materials & Resources
- Indoor Environmental Quality
- Innovation & Design Process

LEED Platinum, Arizona Biodesign Institute at ASU

LEED™ and Concrete Pavements

Concrete Pavement may contribute in the following categories…

- Sustainable Sites
  - Credit 7: **<u>Landscape and Exterior Design to Reduce UHI</u>** (2 points)

    Intent – Reduce heat islands to minimize impact on microclimate

    <u>7.1 NON-ROOF SURFACES (1 point)</u>

    - Provide Shade – (<5years) on at least 30% of non-roof impervious surfaces

      OR use light colored (reflectance >0.30) for 30% of non-roof

      → – TECH/STRATEGY – PORTLAND CEMENT CONCRETE

      OR place a minimum of 50% of parking underground

      OR open-grid for minimum of 50% of parking lot area

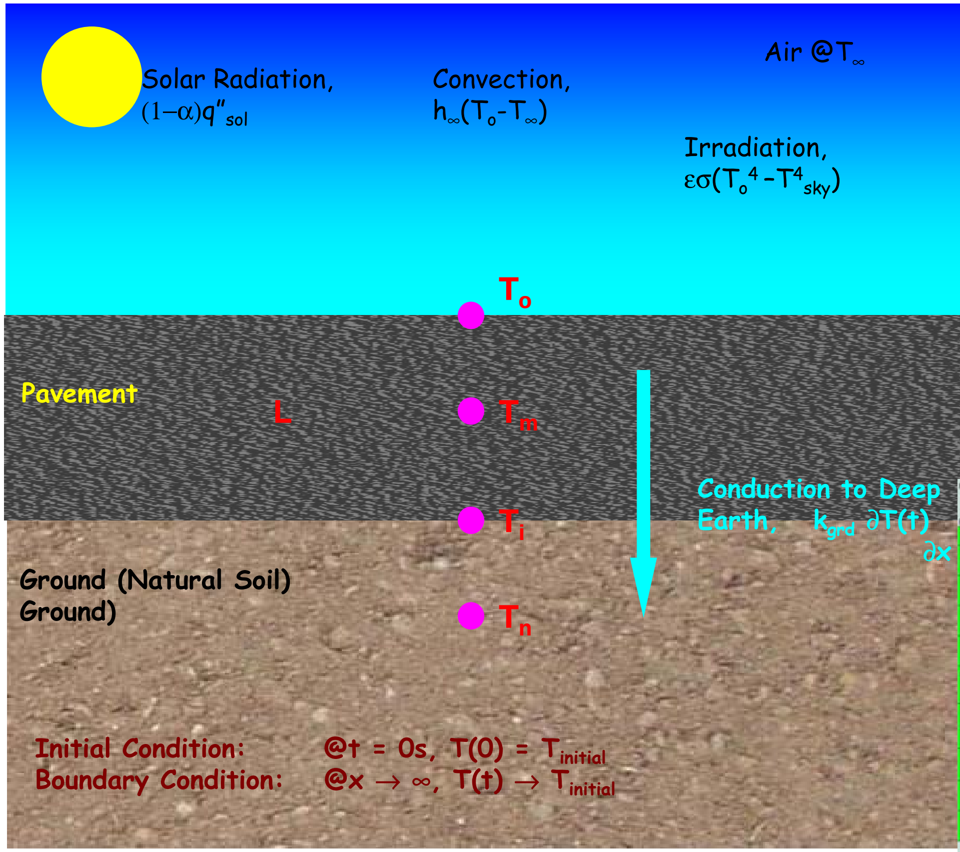
      → – TECH/STRATEGY – PORTLAND CEMENT <u>OPEN CELLED</u> CONCRETE PAVERS

Other non UHI related credits…

- Materials and Resources
  - Credit 2: Construction Waste Management (1-2 points)
  - Credit 3: Resource Reuse (1-2 points)
  - Credit 4: Recycled Content (1-2 points)
  - Credit 5: Local/Regional Materials (1-2 points)

Tools - Models

Heat Transfer between Pavement and its Surroundings



- No. of Pavement Layers
- Density
- Specific Heat Capacity
- Thermal Conductivity
- Pavement Layer Thickness
- Pavement Layer Interface Thermal Contact Resistance
- Albedo of Top Layer
- Emissivity of Top Layer
- Deep Ground Properties
  - Temperature
  - Depth
- Sky View Factor
- Solar View Factor

Number of Layers of Pavement (inclusive of Ground) 3

Fill in the Layers Properties in the following Table:

Layer S/N	1	2	3	4	5	REMARK
Material (Last layer - Ground)	Fill in below (type)	Fill in below (type)	Fill in below (type)	–	–	
	PCC	Old HMA	Ground			OK
Density (kg/m3)	Fill in below	Fill in below	Fill in below	–	–	
	2350	2238	1500			
SHC (J/kgK)	Fill in below	Fill in below	Fill in below	–	–	
	1000	921	1900			
Conductivity (W/mK)	Fill in below	Fill in below	Fill in below	–	–	
	1.5000	1.2100	1.0000			
Pavement Thickness (inch) (To the nearest 0.5")	Fill in below (in inches)	Fill in below (in inches)	–	–	–	
	7.5	3.0				
Conversion to m	0.1905	0.0762	0.0000	0.0000		
Interface	Yes	Yes	No	No		
Interface Contact Resistance	Fill in below (0 to 1.0)	Fill in below (0 to 1.0)	–	–	–	
	0.0	0.0				
Albedo	Fill in below	–	–	–	–	
	0.46					
Emissivity	Fill in below	–	–	–	–	
	0.88					

Deep Ground Properties: i. Temperature 33.5 °C
ii. Depth of Ground Layer 3.0480 m

Sky View Factor 1.00

Solar View Factor 1.00

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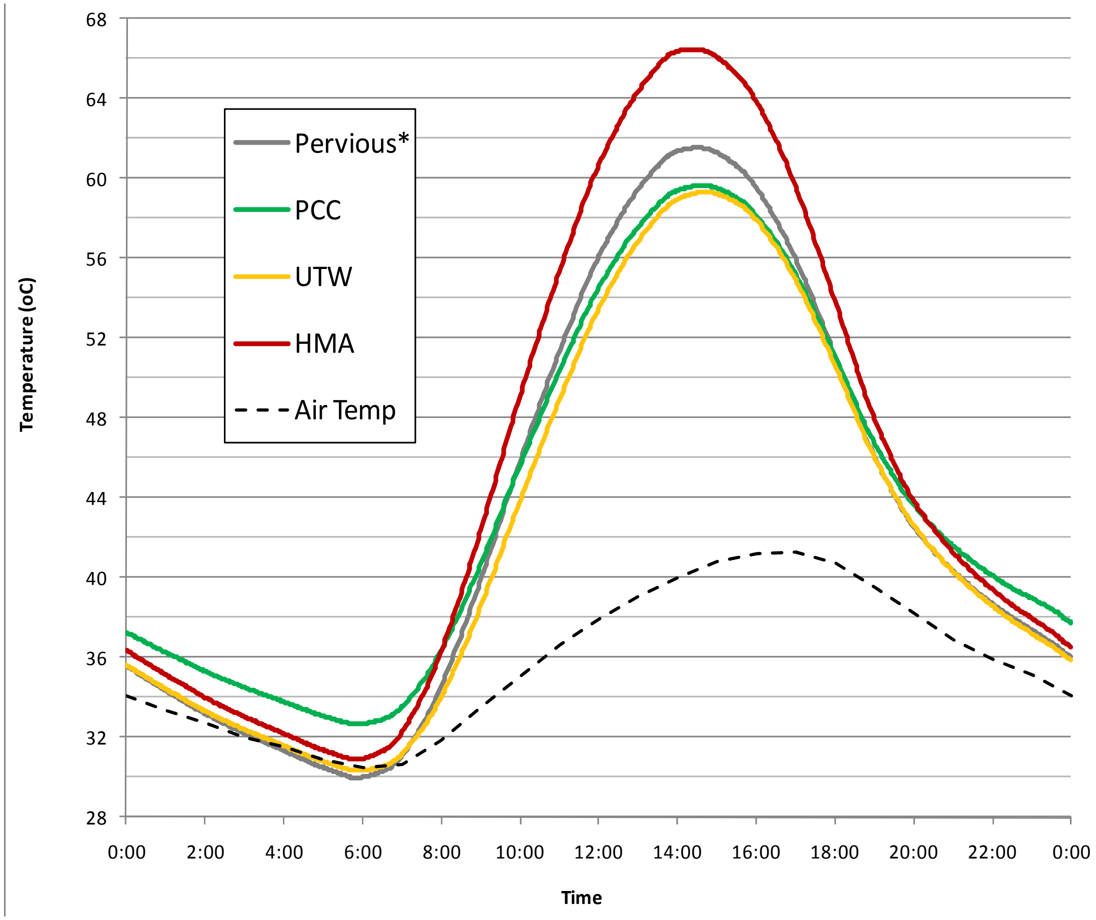
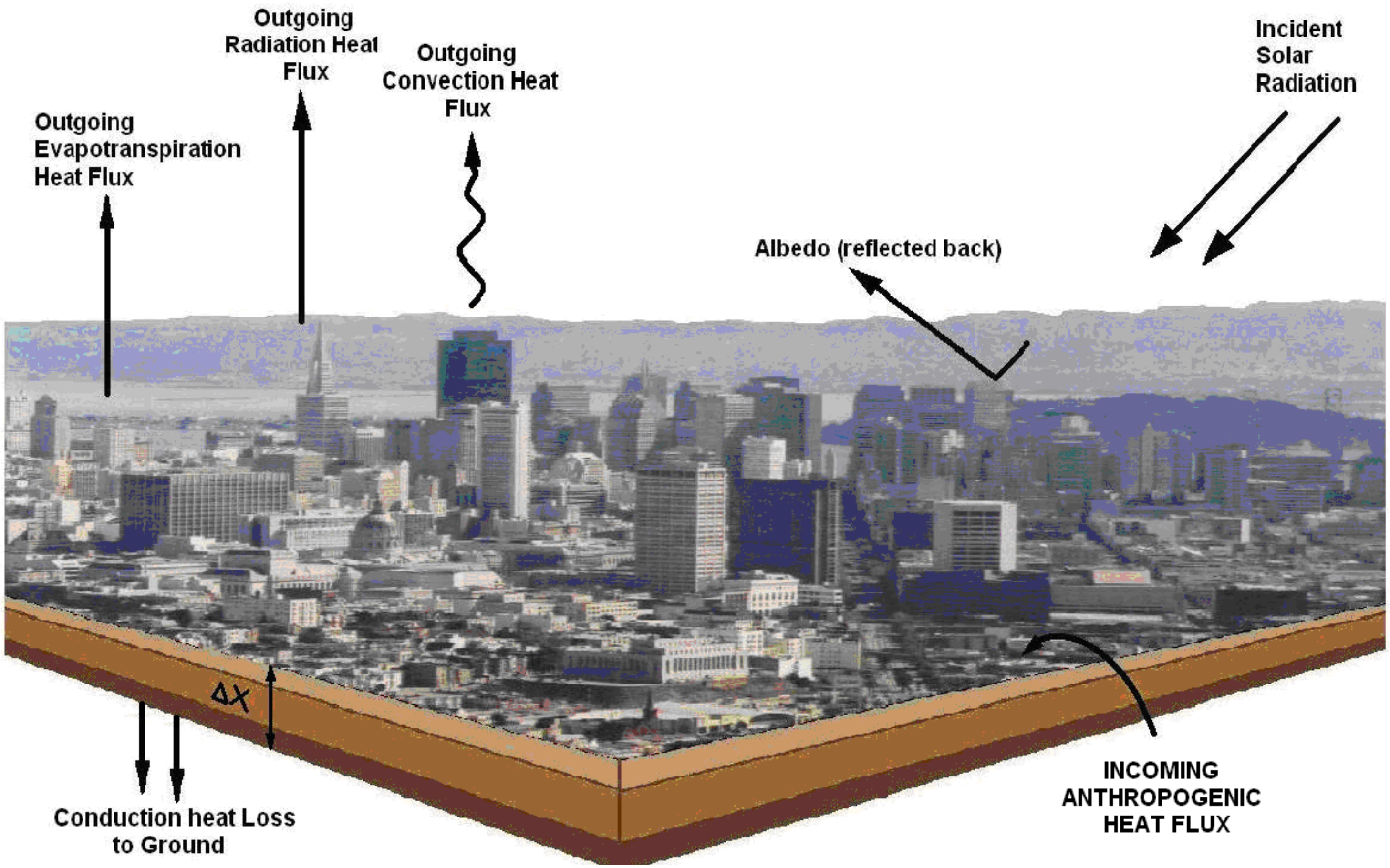
Alternative Pavement Designs

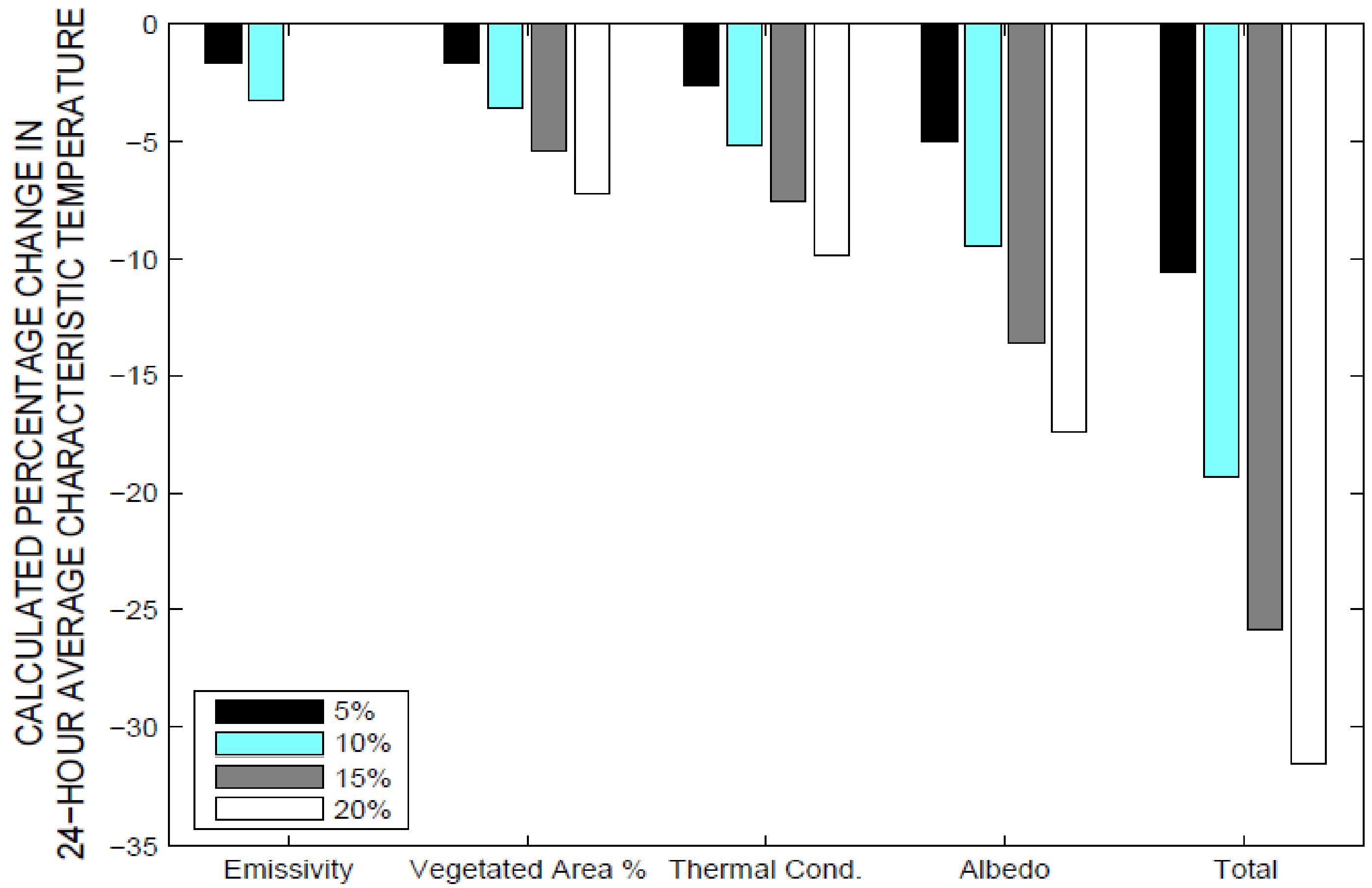


City – Wide Analysis



$$mc\frac{dT}{dt} = (1-\alpha)\, q''_{sol}A + q''_{anthro}A - q''_{rad}A - q''_{conv}A - q''_{Cond}A - q''_{evap}A$$

∆T from UHI Mitigation Strategies



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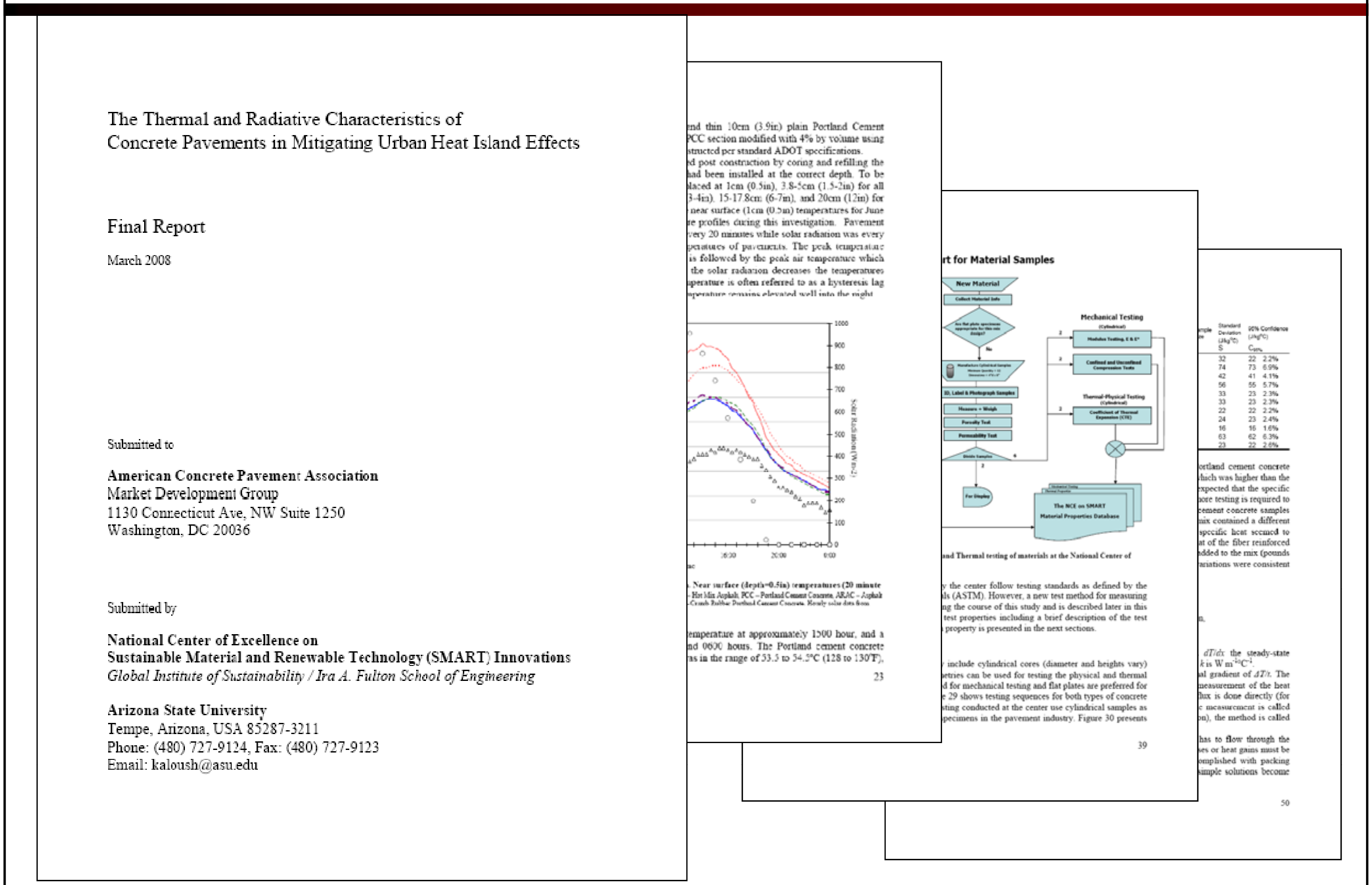
Portland Cement Association / American Concrete Pavement Association Study



The Thermal and Radiative Characteristics of
Concrete Pavements in Mitigating Urban Heat Island Effects

Final Report

March 2008

Submitted to

American Concrete Pavement Association
Market Development Group
1130 Connecticut Ave, NW Suite 1250
Washington, DC 20036

Submitted by

National Center of Excellence on
Sustainable Material and Renewable Technology (SMART) Innovations
Global Institute of Sustainability / Ira A. Fulton School of Engineering

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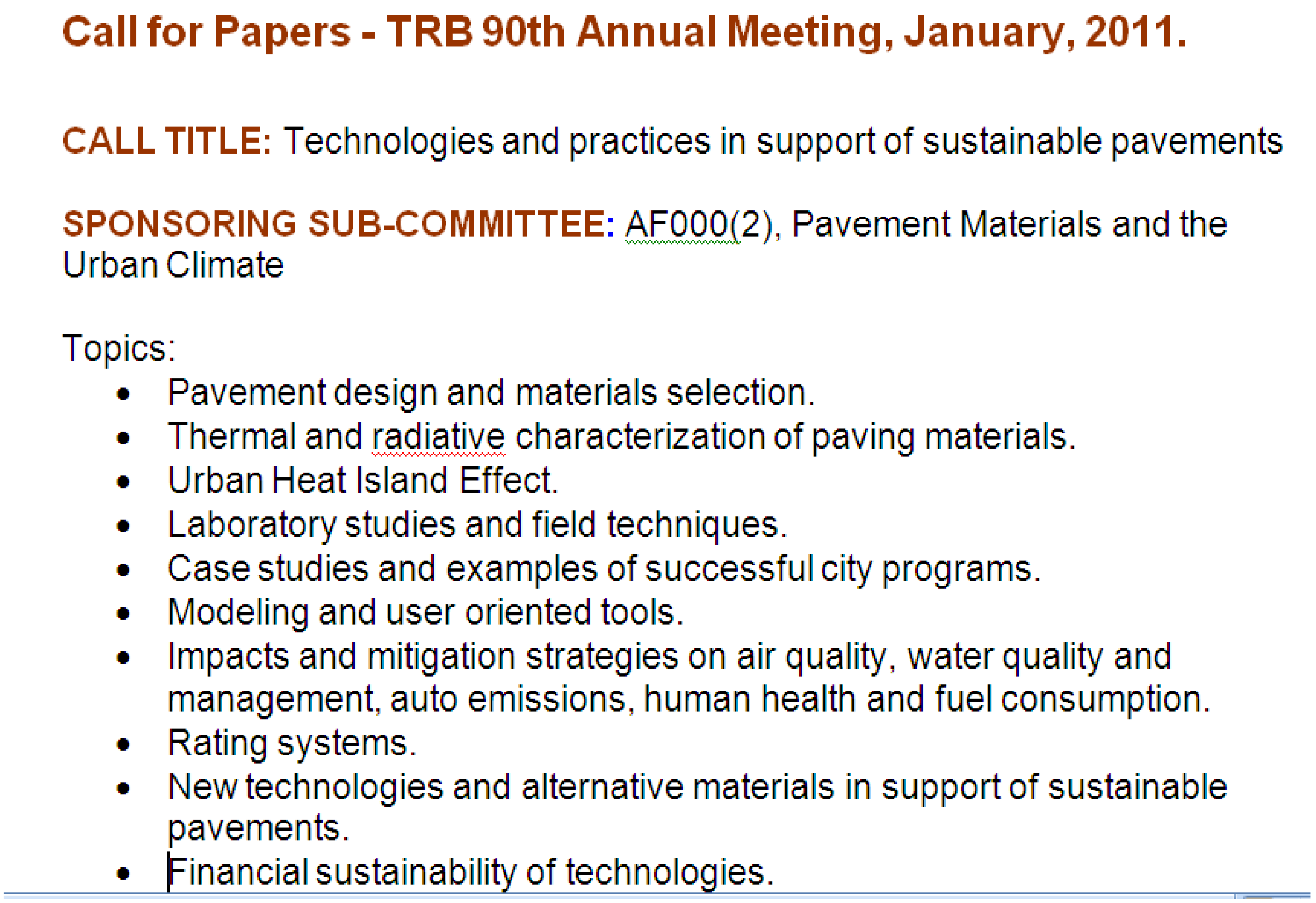
Transportation Research Board



Call for Papers - TRB 90th Annual Meeting, January, 2011.

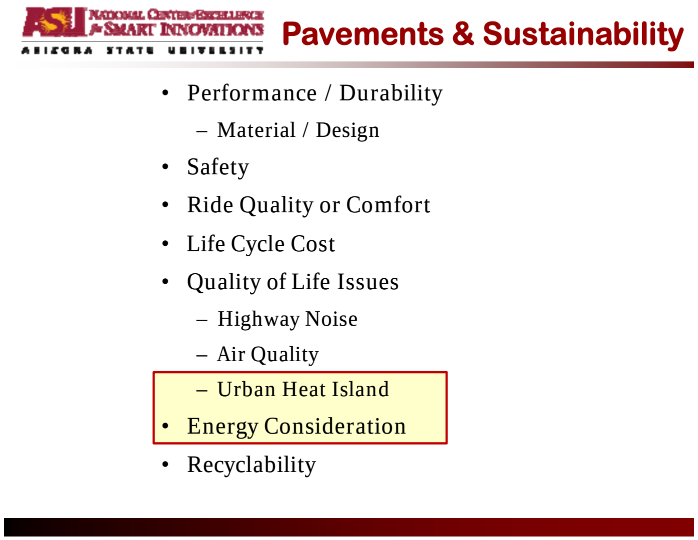
CALL TITLE: Technologies and practices in support of sustainable pavements

SPONSORING SUB-COMMITTEE: AF000(2), Pavement Materials and the Urban Climate

Topics:

- Pavement design and materials selection.
- Thermal and radiative characterization of paving materials.
- Urban Heat Island Effect.
- Laboratory studies and field techniques.
- Case studies and examples of successful city programs.
- Modeling and user oriented tools.
- Impacts and mitigation strategies on air quality, water quality and management, auto emissions, human health and fuel consumption.
- Rating systems.
- New technologies and alternative materials in support of sustainable pavements.
- Financial sustainability of technologies.

TRB on Climate Change



Pavements & Sustainability

- Performance / Durability
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- Safety
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- Life Cycle Cost
- Quality of Life Issues
  - Highway Noise
  - Air Quality
  - Urban Heat Island
- Energy Consideration
- Recyclability

> “Reducing transportation-related emissions of carbon dioxide ….. will be among the biggest public policy challenges facing the transportation profession over the coming decades. “

US GHG Estimates

- Fact: coal is the primary generator of electricity (~50%) in the US
- Electric power generation: ~80% of total GHG emissions , *EPA 2006*
- Transportation Sector: 15-30%
- Pavements???

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Components Used to Model Estimates of Kg CO2 Equivalent

Global Warming Gas	**kg CO_2 Eq./kg Portland cement Z 42.5**	**kg CO_2 Eq./kg Gravel, at mine**	**kg CO_2 Eq./kg Sand, at mine**	**kg CO_2 Eq./ kg Asphalt Cement, at refinery**	**kg CO_2 Eq/ kW-hr Electricity, US average**	**kg CO_2 Eq/ ton-km Transport, 20 - 28 ton truck**
Carbon dioxide, fossil	0.8048	0.0027	0.0023	0.3817	0.7155	0.2713
Methane, fossil	0.0151	0.0001	0.0001	0.0410	0.0308	0.0084
Carbon monoxide, fossil	0.0008	0	0	0.0010	0.0004	0.0011
Dinitrogen monoxide	0	0	0	0.0023	0.0055	0.0012
Total Kg CO2 Eq. /kg substance	**0.8207**	**0.0028**	**0.0025**	**0.4260**	**0.7468**	**0.2821**

Model

$$Total \cdot annual \cdot kgCO_2.Eq/km = \frac{\sum\left[T*W*1000*Dn*\left(\left(Pn+Mn\right)+\left(Di*Tp\right)\right)\right]}{Y}$$

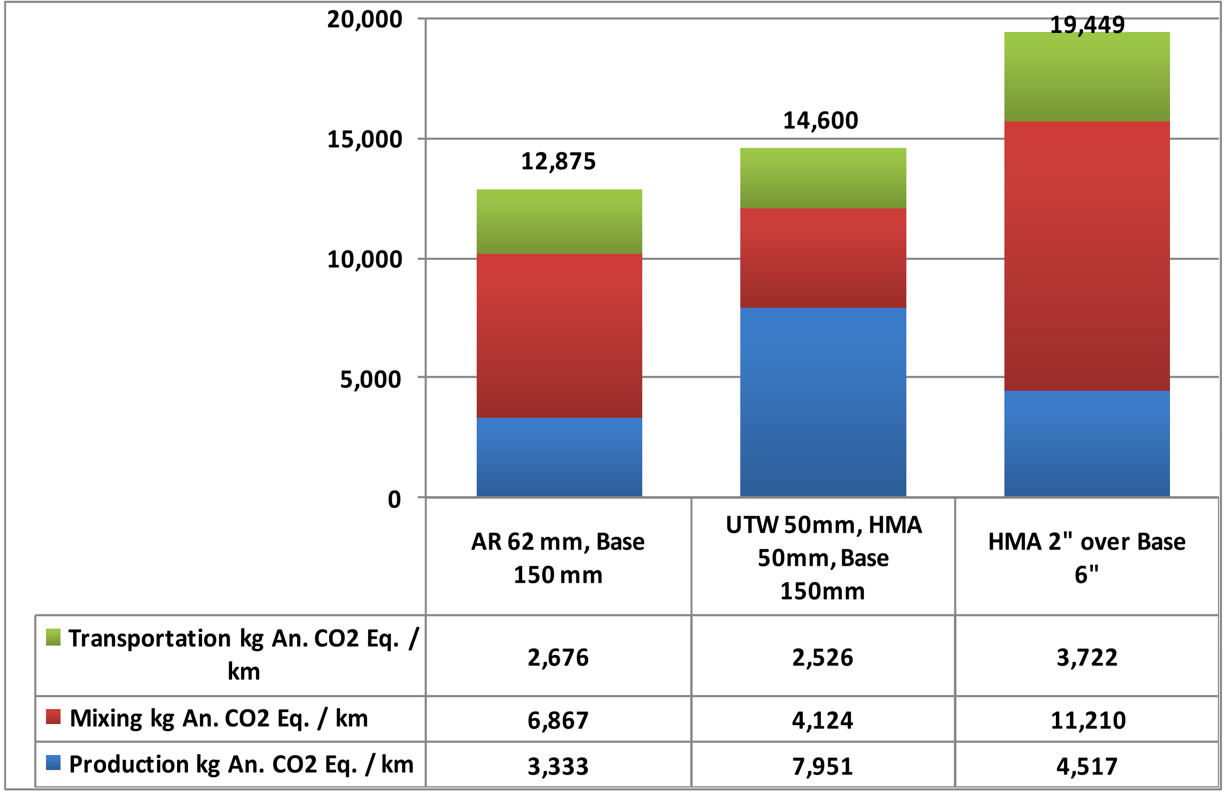
Where,
T **= thickness of pavement layer, meters**
W **= width of road, meters**
Dn **= density of pavement material, kg/m**^{3}
Pn **= material production value, kg CO2 Eq. /kg**
Mn **= material mixing value, kg CO2 Eq. /kg**
Di **= distance from material production site to application site, km**
Tp **= transport from production site to application site value, kg CO2 Eq. /kg material-km**
Y **= road life, years**

Input Values

Pavement CO_2 equivalency values	***Density*** Kg / m^3	***Production*** Kg CO_2 Eq./kg	***Transportation*** Kg CO_2 Eq./kg - km	***Mixing*** Kg CO_2 Eq./kg
Sand	1600	0.0028	0.0002821	0
Gravel	1800	0.0025	0.0002821	0
Aggregate	1700	0.0026	0.0002821	0
PCC	2403	0.1055	0.0002821	0.00650
HMA	2275	0.0238	0.0002821	0.06630
AR	2035	0.0299	0.0002821	0.07230

Example

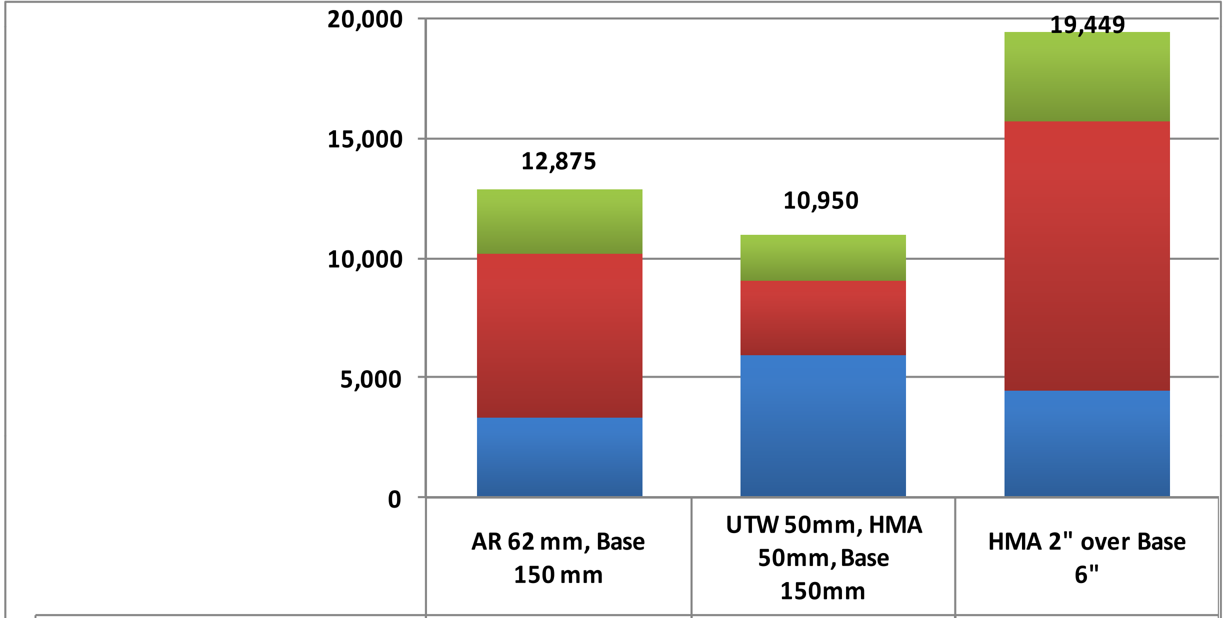
	Road Life (years)
AR 62 mm, Base 150 mm	10
UTW 50mm, HMA 50mm, Base 150mm	15
HMA 100mm, Base 150mm	10



	AR 62 mm, Base 150 mm	UTW 50mm, HMA 50mm, Base 150mm	HMA 2" over Base 6"
🟩 Transportation kg An. CO2 Eq. / km	2,676	2,526	3,722
🟥 Mixing kg An. CO2 Eq. / km	6,867	4,124	11,210
🟦 Production kg An. CO2 Eq. / km	3,333	7,951	4,517

Example

	Road Life (years)
AR 62 mm, Base 150 mm	10
UTW 50mm, HMA 50mm, Base 150mm	20
HMA 100mm, Base 150mm	10



	AR 62 mm, Base 150 mm	UTW 50mm, HMA 50mm, Base 150mm	HMA 2" over Base 6"
🟩 Transportation kg An. CO2 Eq. / km	2,676	1,894	3,722
🟥 Mixing kg An. CO2 Eq. / km	6,867	3,093	11,210
🟦 Production kg An. CO2 Eq. / km	3,333	5,963	4,517

Concluding Remarks

- Pavements play a role / have impact on the urban climate.
- Appreciate the complexity of various designs.
- There is no one pavement design and type that fits all!
- We need more robust input data and user’s tools

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Thank You!

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