Webinar: Center for Environmentally Sustainable Transportation in Cold Climates

Environmental Responsive Pavement Materials

Xiong (Bill) Yu, Ph.D., P.E.

Professor, Department of Civil Engineering, Courtesy with EECS, MAE, MSE
Director, Laboratory on Multiscale Multiphysics Geoengineering Processes
Director, Intelligent Infrastructure and Smart Systems Laboratory

Email: xxy21@case.edu, Phone: 216-368-6247
Case Western Reserve University
May 25, 2016
Self Introduction

Education and Training

- Ph.D. in Civil/Geotechnical Engineering, Purdue University, 2003
- M.S. Electrical Engineering and Computer Science, 2002
- M.S. in Civil/Geotechnical Engineering, Tsinghua University, 2000
- B.S. in Civil/Hydraulic Engineering, B.S. in Computer Science, Tsinghua University, 1997

Academic Appointments

- Associate Professor, Department of Civil Engineering, CWRU, since 2011
- Courtesy appointments with a few other departments, CWRU
- Assistant Professor, Department of Civil Engineering, CWRU, 2005
- Postdoctoral Associate, Purdue University, August 2003-January 2005
- Graduate and undergraduate research assistantships, 1993-2003
Research Program

• Geoengineering
  • Multiscale multiphysics processes in geomaterials
  • Energy geotechnology
  • Sustainable geosystem design, retrofit, and renewal

• Materials: fundamentals and innovation
  • Porous infrastructure materials (soil, rocks, asphalt, concrete, energy materials)
  • Functional materials (coating, film, fiber)
  • Smart materials

• Infrastructure
  • Sensor & structural health monitoring
  • Intelligent infrastructure system
Case Western Reserve University

- Cleveland, Ohio
My research group: past members

- Yan Liu
  Assistant Professor, Mount Union University

- Xinbao Yu
  Assistant Professor, University of Texas, Arlington

- Bin (Ben) Zhang
  Michael Baker Jr. Inc.

- Junliang (Julian) Tao
  Assistant Professor, University of Akron

- Zhen (Leo) Liu
  Assistant Professor, Michigan Technological University (Dept. of Civil & Environmental Engineering)

- Ye (Sarah) Sun
  Assistant Professor, Michigan Technological University (Dept. of Mechanical Engineering)

Welcome highly academically motivated students
Impacts of Environment on Pavement Design/Performance

- Environmental loads (temperature, humidity, temperature gradient, freeze-thaw, wet-dry cycles, solar radiation, ...): a major factor for pavement design and deterioration.
- Climate change leads to extreme environmental loads.
Perception of Pavement from Passive Environment Perspective?

- Pavement generally respond **passively** to environment
  - i.e., Asphalt under A Hot Day:
    - smell (volatile gas emission)
    - hot (urban heat island)
    - sticky (lower viscosity)
    - ...
  ➜ **Undesirable environmental footprint**
Perception of Pavement from An Active Environment Perspective?

- How about pavement that responds **actively** to the Environment?
  - i.e., Asphalt under A Hot Day:
    - smell (volatile gas emission): reduction of smell?
    - hot (urban heat island): reduction of heat?
    - sticky (lower viscosity): increase of viscosity?
    - ...

  ➔ Undesirable environmental footprint mitigation or even towards beneficial use
Turning Environmental Nuisance into Asset

- New pavement and pavement material design philosophy

![Diagram of pavement with labels](image1)

Nanomodified self-cleaning concrete (Zhang and Yu 2009)

![Diagram of self-cleaning concrete](image2)

Thermal energy harvesting (Wu and Yu 2013)

Piezoelectric Charging

- Charging pods set under the crosswalk collect energy from the vibrations of pedestrians and traffic moving across.
- Microscopic crystals embedded in the charging pods give off an electric charge when agitated. Magnets amplify this and then channel it to batteries.

Lithium Batteries

- Piezoelectric charging panels channel energy to lithium-ion batteries which then pipe energy to traffic signals, lights and cameras in the intersection.

Piezoelectric energy from vehicle loads (Nathan’s Product Design)
New Material Design Methodology

- Performance-driven material design
  - Defining the performance matrix, not limited to mechanical durability alone

- Multifunctional material design
  - Paradigm change due to new multifunctional requirements
    - Environmental friendliness
    - Life cycle cost benefits
    - etc.

- New tools and design methods required to accelerate material discovery
  - i.e., material genome
    - How to account for the inherent variability of non man-made materials
A Case Study of Thermochromic asphalt

Dr. Jianying (Jane) Hu, EIT
Motivation

• **Fact:** Asphalt has strong absorption of solar radiation
Motivation (cont.)

- **Problems**: Sustainability of asphalt pavement; Environmental issues; Energy consumption

**Rutting**

(https://www.google.com/search?q=hot+surface+of+asphalt+pavement+in+summer&espv=2&biw=1920&bih=935&tbm=isch&tbo=u&source=univ&sa=X&ved=0ahUKE)

**Heat Island Effect**

(https://www.weatherquestions.com/What_is_the_urban_heat_island.htm)

**Thermal Cracking**

(https://www.dot.state.mn.us/mnroad/projects/Low_Temperature_Cracking/ )
Motivation (cont.)

- **Cool Pavement**: to reduce temperature of asphalt pavement

[Links to further information]

- [Colored asphalt](http://wiki.coe.neu.edu)
- [Porous pavement](http://www.asphaltroads.org/water-quality/)
- [Solar Panel](http://asphaltmagazine.com/the-future-is-bright-for-solar-energy-and-asphalt-pavements/)

Low temperature cracking?
Innovation (cont.)

- **Innovative Strategy**: can we dynamically modulate surface temperature of the pavement?

Schematic principle of thermochromic asphalt pavement
Thermochromic Materials

- Change of Thermochromic Materials with Temperature
Thermochromic Materials (cont.)

• Molecules of Thermochromic Materials
Experimental Characterization

- Preparation of Thermochromic Asphalt Binder and Concrete

Black, blue and red thermochromic asphalt binder

Black, blue and red thermochromic asphalt concrete
Experimental Characterization

Thermal Properties
- Optical Properties
- Mechanical Properties
- Thermal Performance
- Stability during Production
**Thermal Properties of Asphalt Binder:** Heat Capacity and Thermal Conductivity by Modulated DSC

Specific heat capacity and thermal conductivity of various asphalt binders.
Thermochromic asphalt

Thermal Properties
Optical Properties
Mechanical Properties
Thermal Performance
Stability during Production
Optical Properties of Thermochromic Powders: Reflectance Spectra by UV-Vis-IR Spectrophotometer

Spectral reflectance of thermochromic powders under different temperatures
• Optical Properties of Asphalt Binders

Spectral reflectance of various asphalt binders under different temperatures.
• **Optical Properties of Asphalt Concrete**

Spectral reflectance of various asphalt samples under room temperature

- Black asphalt concrete
- Blue asphalt concrete
- Red asphalt concrete
- Pure asphalt concrete
- Pure asphalt binder
Thermochromic Asphalt Pavement (cont.)

- Study of Thermochromic Asphalt Pavement

Thermal Properties

Optical Properties

**Mechanical Properties**
*(Superpave Tests)*

Thermal Performance

Stability during Production
**Superpave Performance Tests on Asphalt Binder**

- **PG 64-22**
  - Asphalt binder

- **Original asphalt binder**
- **3%, 6% and 10% black asphalt binder**
- **3% and 6% blue asphalt binder**
- **3% and 6% red asphalt binder**

**Conventional tests**
- RV at 135 °C
  - ≤ 3 Pa·s

**Superpave Performance Tests on Asphalt Binder**

- **DSR**
  - Unaged, \( G*/\sin(\delta) \geq 1.00 \text{ kPa} \)
  - RTFO aged, \( G*/\sin(\delta) \geq 2.20 \text{ kPa} \)
  - RTFO+PAV aged, \( G*\sin(\delta) \leq 5000 \text{ kPa} \)

- **BBR**
  - Same as original binder
  - RTFO+PAV aged, \( S \leq 300 \text{ MPa}, m \geq 0.300 \)

Experimental design to characterize mechanical properties of binders using Superpave binder performance tests.
• RV Results

Viscosity (mPa·s) vs. Content of powder (%)

- Black asphalt binder
- Blue asphalt binder
- Red asphalt binder

Rotational viscometer

RV test results for various asphalt binders
• **Dynamic Shear Rheometer (DSR) Results:** Rutting Resistance

**High Temperature PG:**
- original asphalt binder: 64 °C
- 3% blue asphalt binder: 64 °C
- 3% red asphalt binder: 64 °C
- 3% black asphalt binder: 70 °C
- 6% black asphalt binder: 76 °C
- 10% black asphalt binder: 76 °C
- 6% blue asphalt binder: 70 °C
- 6% red asphalt binder: 70 °C
• **DSR Results:** Fatigue Cracking Resistance

![Graph showing DSR test results for RTFO and PAV aged asphalt binders.](image)

DSR test results for RTFO and PAV aged asphalt binders

- Fatigue Cracking Resistance
  - $G*\sin\delta$ (kPa)

<table>
<thead>
<tr>
<th>Black Binder Concentration</th>
<th>25 °C</th>
<th>28 °C</th>
</tr>
</thead>
<tbody>
<tr>
<td>0% original binder</td>
<td>4540</td>
<td>3560</td>
</tr>
<tr>
<td>3% black binder</td>
<td>4880</td>
<td>3720</td>
</tr>
<tr>
<td>6% black binder</td>
<td>5140</td>
<td>3710</td>
</tr>
<tr>
<td>9% black binder</td>
<td>5630</td>
<td>3810</td>
</tr>
<tr>
<td>10% black binder</td>
<td>5320</td>
<td>5500</td>
</tr>
<tr>
<td>3% blue binder</td>
<td>5340</td>
<td>5340</td>
</tr>
<tr>
<td>6% blue binder</td>
<td>5430</td>
<td>5430</td>
</tr>
<tr>
<td>3% red binder</td>
<td>5500</td>
<td>5500</td>
</tr>
<tr>
<td>6% red binder</td>
<td>5510</td>
<td>5510</td>
</tr>
</tbody>
</table>

(RTFO+PAV) aged asphalt binders
• **Bending Beam Rheometer (BBR) Results**

Low Temperature PG:
• Original asphalt binder: -22 °C
• 3% black asphalt binder: -22 °C
• 6% red asphalt binder: -22 °C

- 6% black asphalt binder: -16 °C
- 10% black asphalt binder: -16 °C
- 3% blue asphalt binder: -16 °C
- 6% blue asphalt binder: -16 °C
- 3% red asphalt binder: -16 °C
• **Rutting Resistance of Asphalt Concrete**

AASHTO TP63
(100 lb, 165-175 °F)

Rutting depth of the HMA over 8000 loading cycles
• Moisture Resistance of Asphalt Concrete

AASHTO T283 (100 lb, 59 °C)

$$TSR = 100 \frac{St_{\text{conditioned}}}{St_{\text{unconditioned}}}$$

Moisture Susceptibility of various HMA mixtures
**Thermal Performance: Experimental Setup**

- Red asphalt binder
- Blue asphalt binder
- Pure asphalt binder
- Black asphalt binder
- Conventional HMA
- Black HMA
- Blue HMA
- Red HMA

**Thermochromic asphalt binder**

- 7.5 cm × 4.2 cm × 0.2 cm

**Thermochromic asphalt concrete**

- 10 cm × 6 cm

Experimental Setup for surface temperature measurement of the samples
Thermal Performance of Thermochromic Asphalt Binder: Experimental Observation in Summer, 2012

Surface temperature and temperature difference between thermochromic asphalt binders and pure asphalt binder.
• **Thermal Performance of Thermochromic Asphalt Binder:**

**Experimental Observation in Winter, 2013**

Surface temperature and temperature difference between thermochromic asphalt binders and pure asphalt binder.
• **Long-term Thermal Performance of Thermochromic HMA** between May and June, 2014

**Daily cooling effects** using black, blue and red asphalt concrete.
• Long-term Thermal Performance of Thermochromic HMA between May and June, 2014

Nocturnal warm effects by using black, blue and red asphalt concrete
Thermal Performance of HMA: Temperature and Service Life

Service life of the Pavement versus maximum pavement temperature

(Mallick et al. 2013. Vol. 8, pp. 219-236: Springer Netherlands.)
Thermochromic asphalt

- Thermal Properties
- Optical Properties
- Mechanical Properties
- Thermal Performance
- Stability during Production
• **Stability during Production**

- Hot-mix asphalt (HMA) 140–170 °C
- Warm-mix asphalt (WMA) 105–140 °C

Thermal treatment of **asphalt binder** at 105, 140, 170 and 200 °C for 0.5 h, 1 h and 2 h

- TGA
- Change in solar reflectance
- FTIR analysis
• Weight Loss by TGA Analysis

TGA curves of thermochromic asphalt binders
• Change in Solar Reflectance

Change in solar reflectance of treated binders compared to untreated binders
• Fourier Transform Infrared Spectroscopy (FTIR) Analysis

- Black asphalt binder
- Blue asphalt binder
- Red asphalt binder

Wavenumber (cm⁻¹)

Absorption
Summary of Experimental Results

- **Thermal Properties:**
  - Heat capacity $\uparrow$
  - Thermal conductivity $\downarrow$

- **Optical Properties:**
  - Solar reflectance $\uparrow$
  - Refractive index $\uparrow$

- **Mechanical Properties:**
  - High temperature PG $\uparrow$
  - Low temperature PG $\uparrow$

- **Thermal Performance:**
  - Surface temperature of 6 °C $\downarrow$ (daytime or summer) and 2 °C $\uparrow$ (evening or winter)
  - Temperature gradient $\downarrow$

- **Production Conditions:**
  - Black asphalt using WMA
  - Blue and red asphalt using HMA and WMA
Summary of Environmental/Solar Responsive Asphalt Pavement

- Thermochromic solar responsive pavement positively modulate the surface temperature of asphalt road
  - Lower temperature during hot summer day, higher temperature during cold time
- Design and production conditions designed from a multifunctional material characterization matrix
  - Optical, thermal, mechanical, pyrolysis
- A new perspective to look at the design and application of infrastructure materials
  - Performance driven design of materials
The Next Step: Thermochromic Smart Coating

- Smart building envelope
• **Fabrication**: Hot Press

![Diagram showing the process of Hot Press](image)

Process of Hot Press

![Photographs of films](image)

- PVC film
- Blue/PVC film
- Blue-TiO$_2$/PVC film

Photograph of films
**Optical Properties:** Reflectance Spectra

Reflectance spectra of thermochromic Coatings

- PVC film
- 5% blue-PVC film
- 0.5% blue-3% TiO2-PVC film
Thermochromic Coating (cont.)

- FEM Simulation of Thermochromic Coatings

Comparison between surface temperatures of films

PVC based films:
- 5% blue: 3.7 °C
- 0.5% blue-3% TiO₂: 6.8 °C
Acknowledgement

- Funding Agencies
  - National Science Foundation
  - The Ohio Department of Transportation/FHWA
Thank you!