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Evaluating the Potential of Using Foamed Concrete as the Insulation Layer for Pavements in Cold Regions

Cheng Zhu, Ph.D., P.E.

Center for Research & Education in Advanced Transportation Engineering Systems (CREATES)
Department of Civil and Environmental Engineering
Rowan University

NJDOT Lunchtime Tech Talk
April 21

US Army Corps of Engineers®

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Acknowledgement

- Cold Regions Research and Engineering Laboratory
  - Dr. Wade Lein
  - Dr. Mohamed Elshaer
  - Ms. Danielle Kennedy
  - Mr. Christopher DeCarlo
- Rowan University
  - Dr. Zhuang Zhuo
  - Dr. Ayman Ali
  - Dr. Yusuf Mehta
- Companies
  - Aero Aggregates
  - Troxler Electronic Laboratories
  - Lehigh Technologies
  - Aerix Industries

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Outline

- Background & Objectives
- Foamed Concrete Laboratory Tests and Results
- Large-scale Pavement Tests and Results
- Numerical Modeling Configuration and Results
- Conclusions

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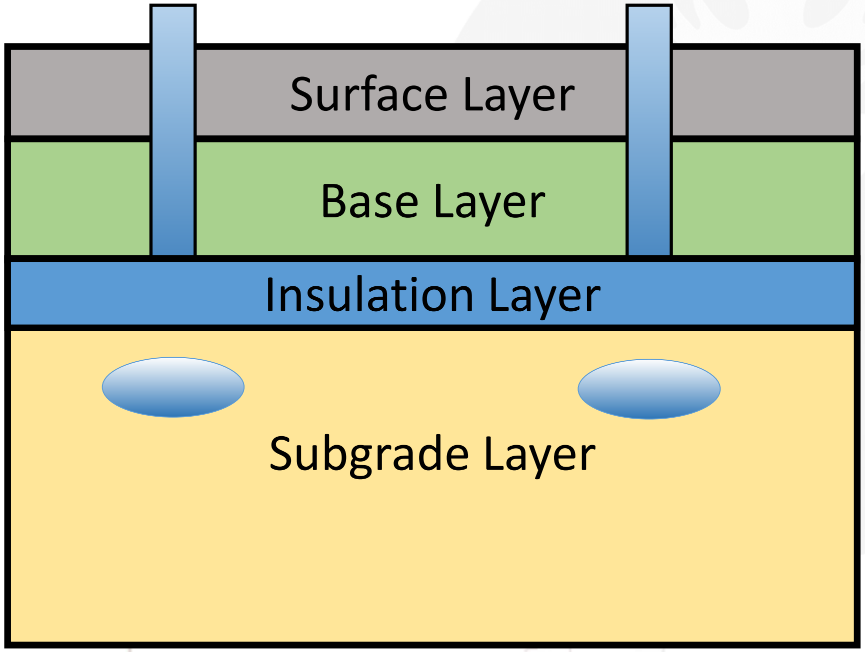
Background

- Pavement in Cold Regions



https://www.semanticscholar.org/paper/Frost-heave-and-thaw-weakening-of-pavement-Zhang/3490d2b88862f9c3b5ccfa9ec692a5282521ac32

Background

UFC 3-250-01
14 November, 2016

APPENDIX D USE OF INSULATION MATERIALS IN PAVEMENTS

D-1 INSULATING MATERIALS AND INSULATED PAVEMENT SYSTEMS.

The only acceptable insulating material for use in roads is extruded polystyrene board stock. Results from laboratory and field tests have shown that extruded polystyrene does not absorb a significant volume of moisture and that it retains its thermal and mechanical properties for several years. The material is manufactured in board stock ranging from 1 in (25 mm) to 4 in (100 mm) thick. Approval from the Government Civil Engineer is required for use of insulating materials other than extruded polystyrene.

DoD, U. S. (2016). Unified facilities criteria: pavement design for roads and parking areas. UFC 3-250-01. United States Department of Defense

- Extruded Polystyrene (XPS) boards is the most commonly used material for insulated pavement

Background

- However, XPS boards suffer from several major drawbacks:
  1. Degradation of the long-term field insulation ability with moisture accumulation
  2. The requirement for a time-consuming, labor intensive, and detailed approach for installation and sealing

Background

- Investigation of alternative materials for the insulation layer
  1. Tire Chips (Lee[1], Kardos[2], Shao[3], Dore[4])
  2. Bottom Ash (Haghi[5]-[7])
  3. Foamed Glass Aggregates (Huang[8], Emersleben[9], Arulrajah[10])

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Background

Foamed Concrete

- Features:
  1. Self-compacting
  2. Lightweight
  3. Thermal insulation
  4. Low strength
  5. Fireproof
- Current application:
  - Cavity filling
  - Fire insulation
  - Trench reinstatement
  - Soil stabilization

https://www.foamedconcrete.co.uk/uncategorized/new-applications-for-foamed-concrete-no-2/

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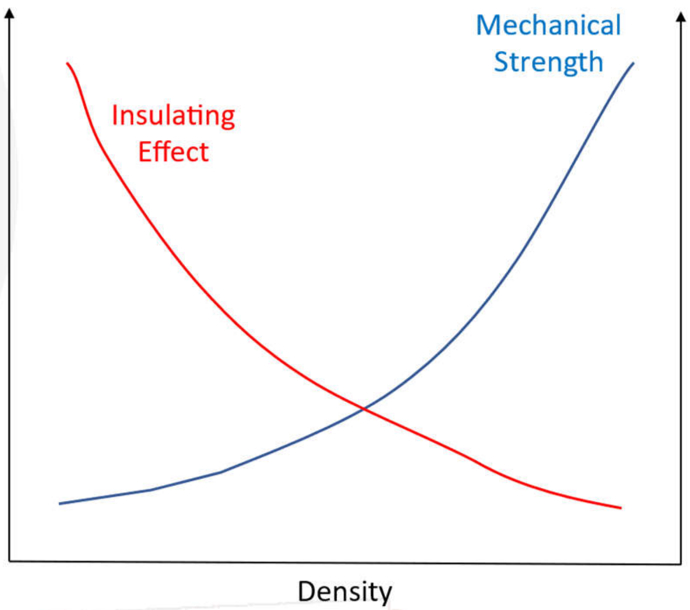
Background

- Problem 1:

The potential of using foamed concrete as an insulation layer was not well investigated.

- Problem 2:

The methodology of selecting optimum parameters that balance the mechanical strength and insulating effect was not established.



Research Objectives

- Establish the relationship between foamed concrete density and thermal/mechanical properties through laboratory testing.
- Develop a thermal-mechanical (TM) coupled finite element (FE) model to predict the thermal and mechanical performance of insulated pavements.
- Conduct large-scale testing of foamed concrete insulated pavement structure to calibrate and validate the FE model.
- Perform a parametric study to investigate the influence of different factors of a foamed concrete layer on the thermal and mechanical performance of pavement structures.

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Foamed Concrete Laboratory Test

- Cylinder sample size: 3 in. (diameter) by 6 in. (height)
- 4 density groups: 30 lb/ft^3, 40 lb/ft^3, 50 lb/ft^3, 60 lb/ft^3
- 7 samples per group (28 samples in total)
- 4 samples were used for the compressive strength test, 3 samples were used for thermal conductivity test

compressive strength test

thermal conductivity test

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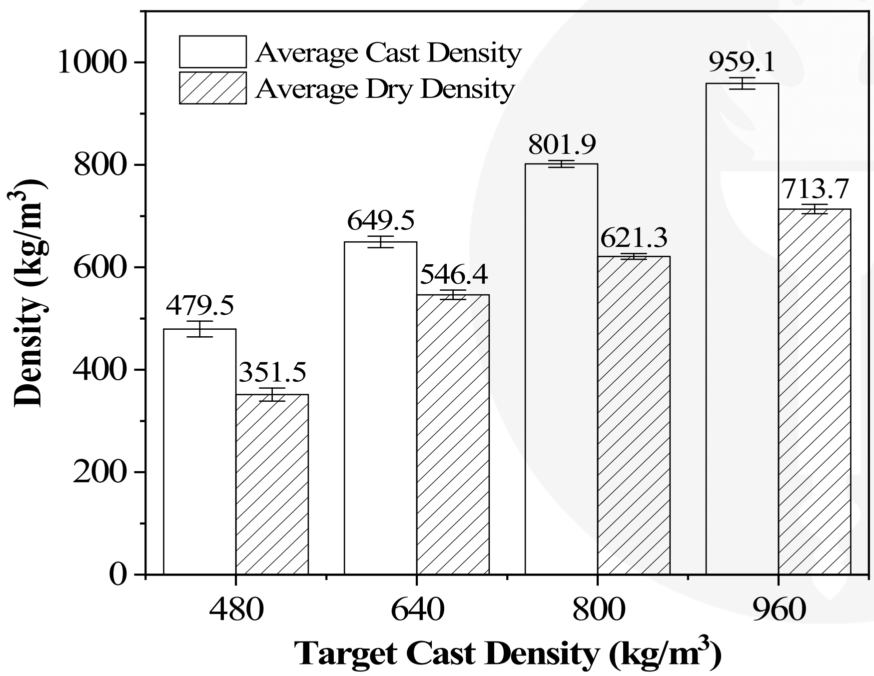
Foamed Concrete Laboratory Test



- Samples were prepared based on ASTM C796-97
- The samples were demolded 3 days after molding
- Then the samples were maintained in a humid room with a controlled temperature of 23 °C and relative humidity of 50%
- Samples were tested on day 28 after molding

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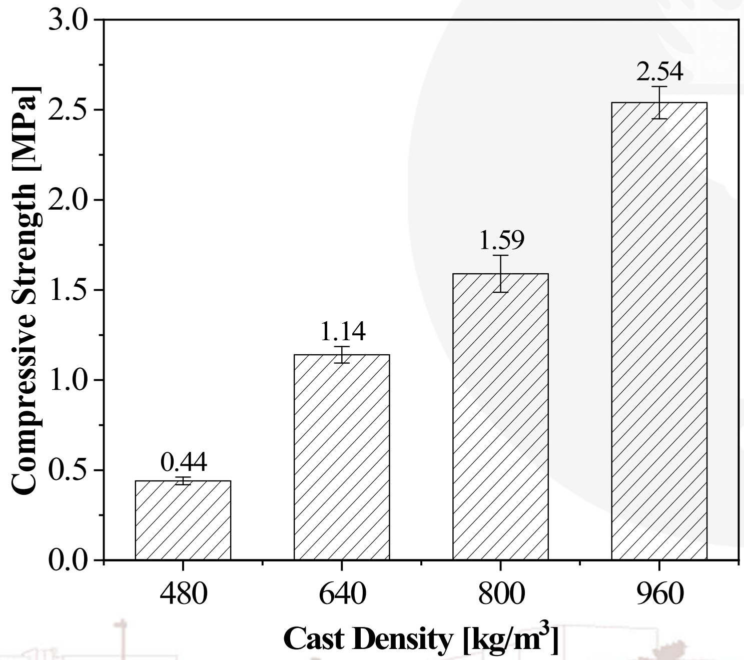
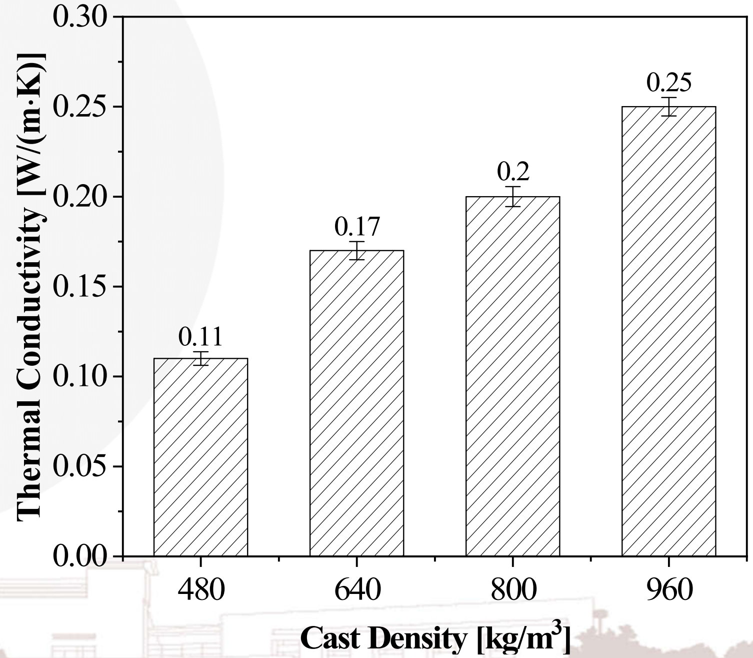
Foamed Concrete Laboratory Test

- Relations between mechanical/thermal properties and density





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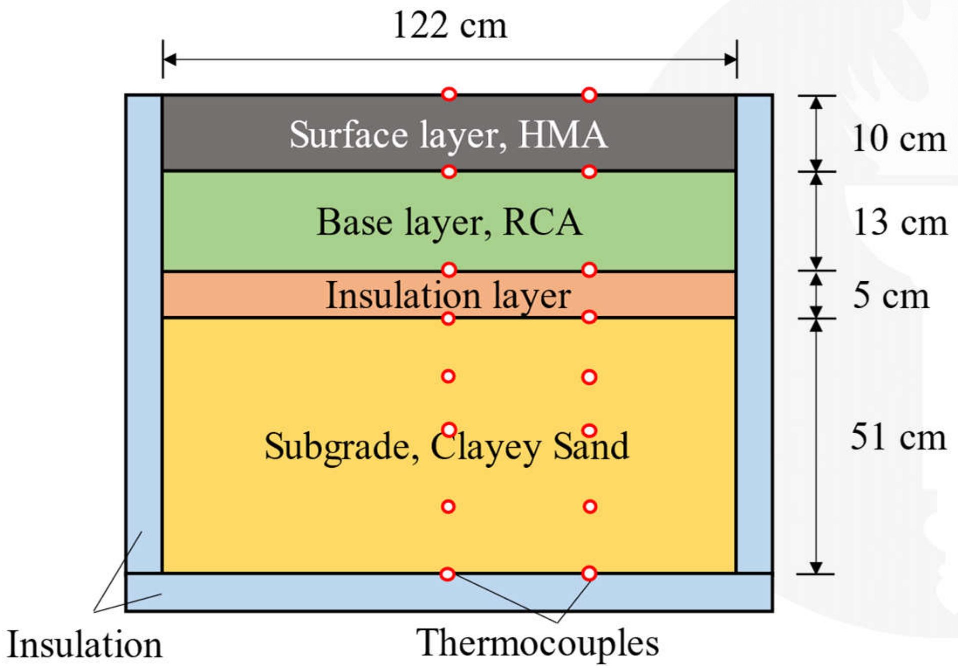
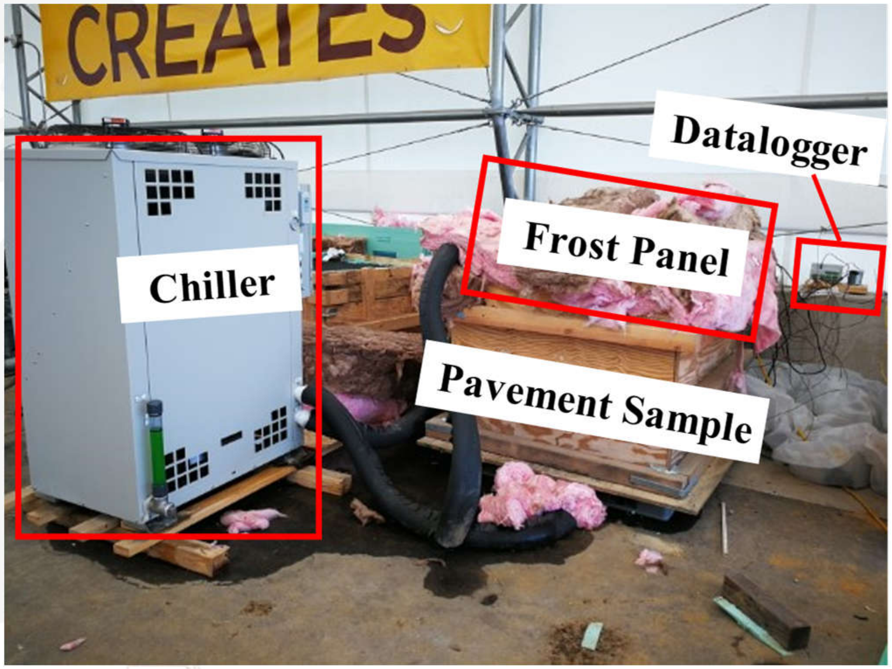
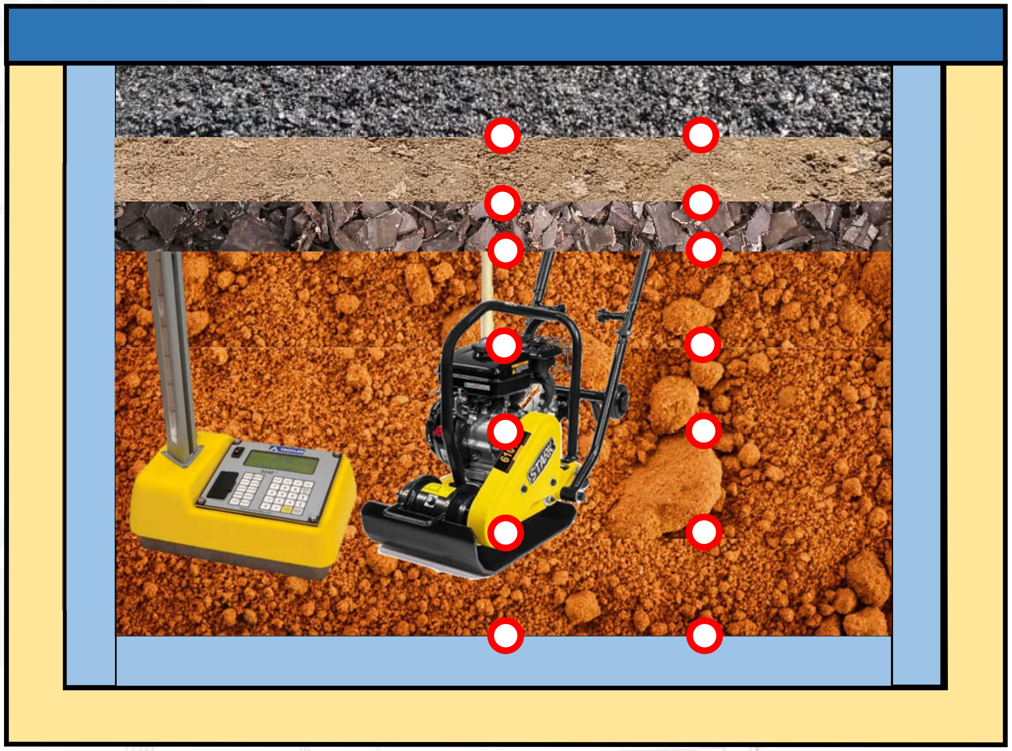
Large Pavement Boxes (Structure)





Construction Procedure



Materials Used

- **Hot Mix Asphalt (HMA)–Surface Layer:**
  - NMAS: 9.5 mm;
  - Design: NJDOT specifications;
  - Binder Content and Type: 5.8% & PG 64-22.
- **Recycled Concrete Aggregates (RCA)–Base Layer:**
  - Coarse Proportion: 56%,
  - Sand Proportion: 35%,
  - Fine Proportion: 9%,
  - Proctor OMC: 12.1%.
- **Clayey Sand–Subgrade Layer:**
  - Fine Proportion: 35.2%,
  - Frost Susceptible;
  - Proctor OMC: 12.4%.

Build the Box

Fill the Subgrade Soil Layer

Compact & Measure

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Insulation Layer and Base Layer

Foamed Concrete

Recycled Concrete Aggregates

Hot Mix Asphalt Layer

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Cooling System

Frost Panel

Chiller

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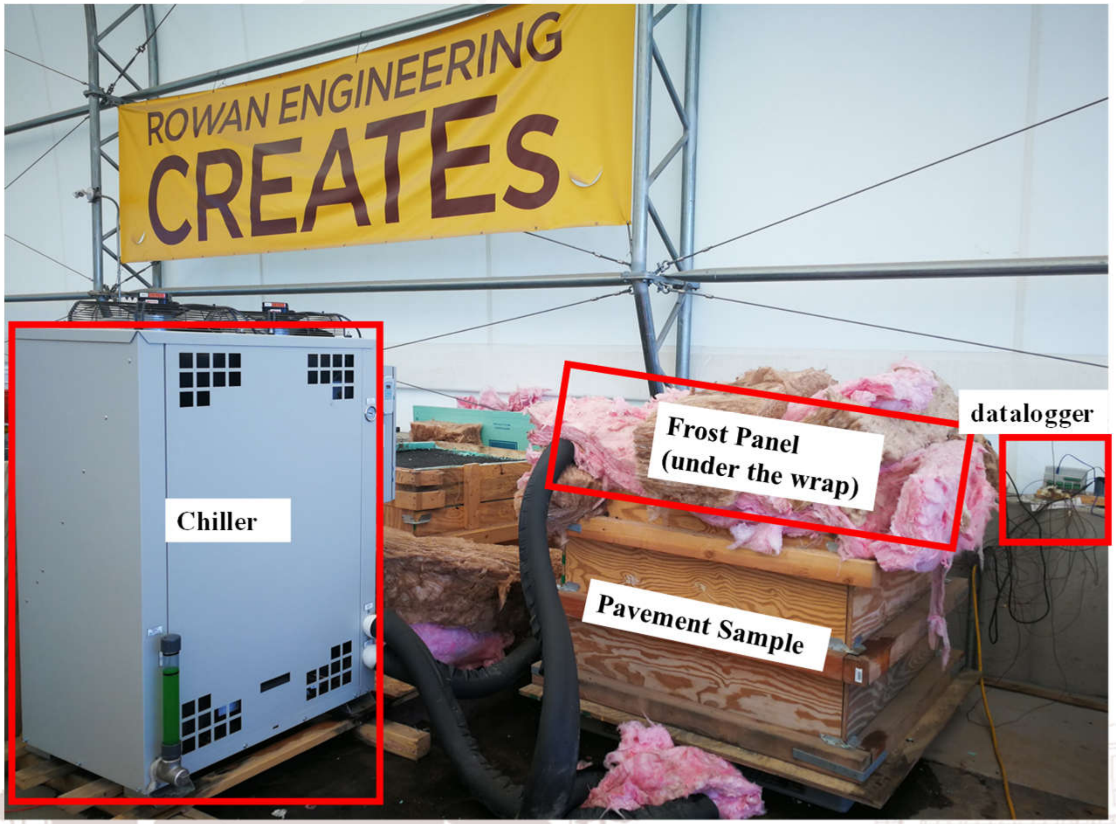
Test Setup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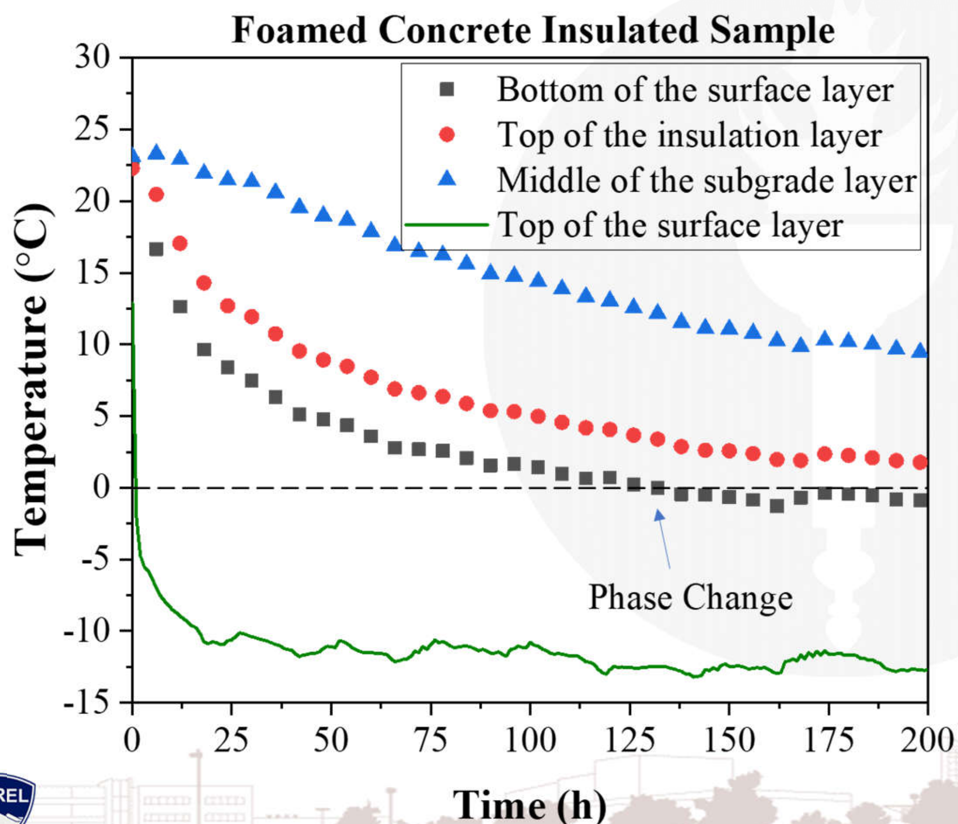
CREATES
Chiller
Frost Panel
(under the wrap)
datalogger
Pavement Sample

Temperature Distribution within the Pavement Box



- This result was used to calibrate the parameters of FE model

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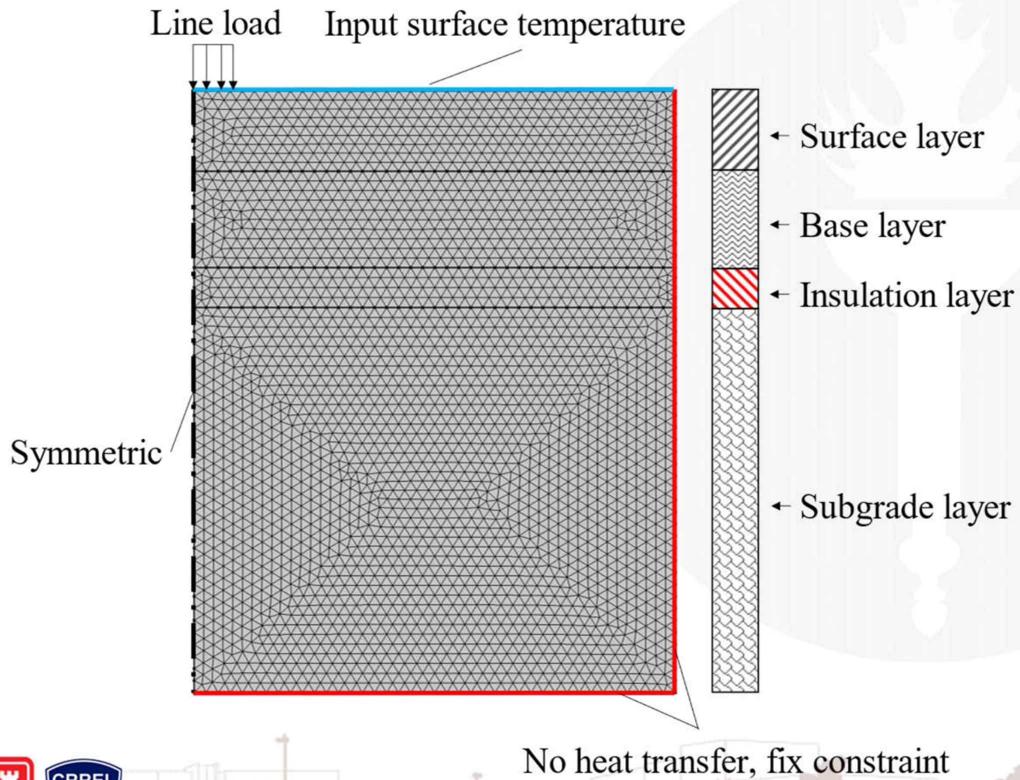
Model Geometry & Loading



- 2D symmetric
- Thermal-mechanical coupled model
- Same size with the large-scale pavement sample

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Governing Equations

Mechanical Field

Surface: Visco-elastic model
Others: Linear elastic model

$$E = E_0(1 + \theta_i)$$

$$(\rho C)_{eq}\frac{\partial T}{\partial t} + \nabla \cdot (-k_{eq}\nabla T) = Q$$

$$(\rho C)_{eq} = \begin{cases} \rho_s C_s & \text{Surface and insulation layer} \\ \rho_s C_s v_s + \rho_w C_w v_w & \text{Base and subgrade layer} \end{cases}$$

$$k_{eq} = \begin{cases} k_s & \text{Surface and insulation layer} \\ k_s v_s + k_w v_w & \text{Base and subgrade layer} \end{cases}$$

$$C_w = \frac{1}{\rho_w}(\theta_i \rho_i C_i + \theta_{uw}\rho_{uw}C_{uw}) + L\frac{\partial \alpha_m}{\partial t}$$

$$\rho_w = \theta_i \rho_i + \theta_{uw}\rho_{uw}$$

$$\alpha_m = \frac{1}{2}\frac{\theta_{uw}\rho_{uw} - \theta_i \rho_i}{\theta_i \rho_i + \theta_{uw}\rho_{uw}}$$

$$k_w = \theta_i k_i + \theta_{uw}k_{uw}$$

$$\theta_i + \theta_{uw} = 1$$

Thermal Field

Hydraulic Field

Richard's equation

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial x}\left[D(\theta)\frac{\partial \theta}{\partial x}\right]$$

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Performance Prediction

- Based on the Mechanistic-empirical Pavement Design Guide (MEPDG):
  - For pavement rutting:

$$\Delta_{p(HMA)} = \beta_{1r} k_z \varepsilon_{r(HMA)} 10^{k_{1r}} n^{k_{2r}\beta_{2r}} T^{k_{3r}\beta_{3r}}$$

$$\Delta_{p}\left(_{base/subgrade}\right) = \beta_{s1} k_1 \varepsilon_v \left(\frac{\varepsilon_0}{\varepsilon_r}\right) e^{-\left(\frac{\rho}{N}\right)^{\beta}}$$

  - For pavement cracking:

$$N_{f-HMA} = k_{f1}(C)(C_H)\beta_{f1}(\varepsilon_t)^{k_{f2}\beta_{f2}}(E_{HMA})^{k_{f3}\beta_{f3}}$$

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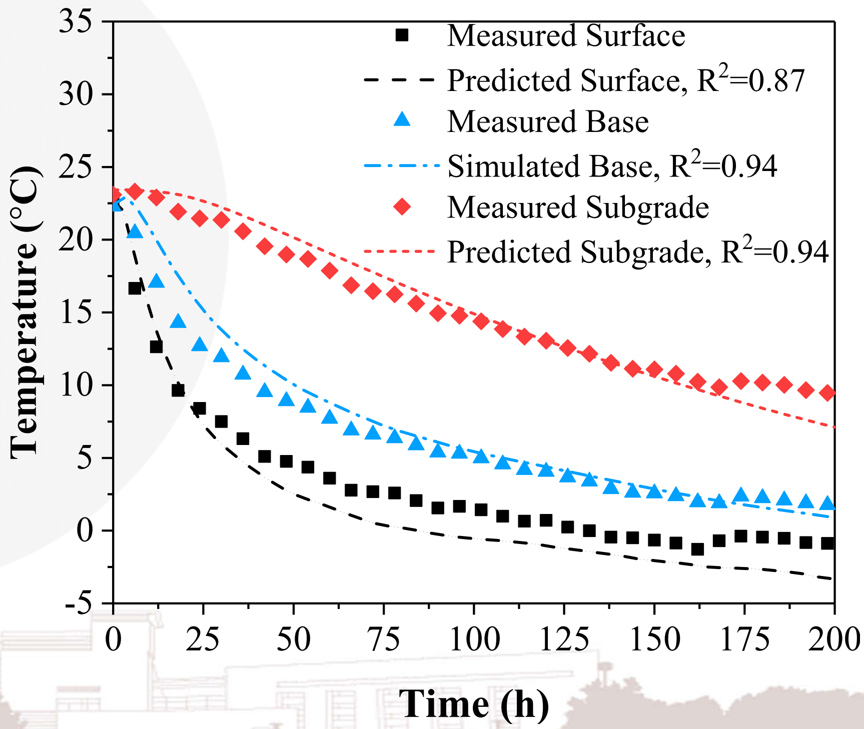
Calibration based on the large-scale test

Layer	Density [kg/m³]	Thermal Conductivity [W/(m·K)]	Heat Capacity [J/(kg·K)]	Young's Modulus [MPa]
Surface	1905	1.00	3963	500
Base	2007	2.20	1838	200
Subgrade	1948	2.81	2941	80

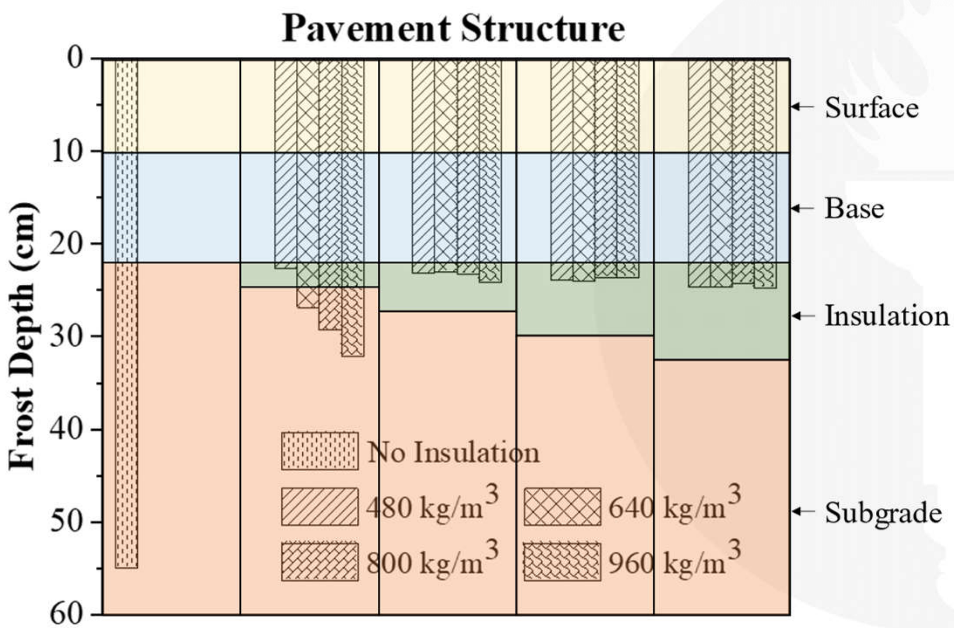


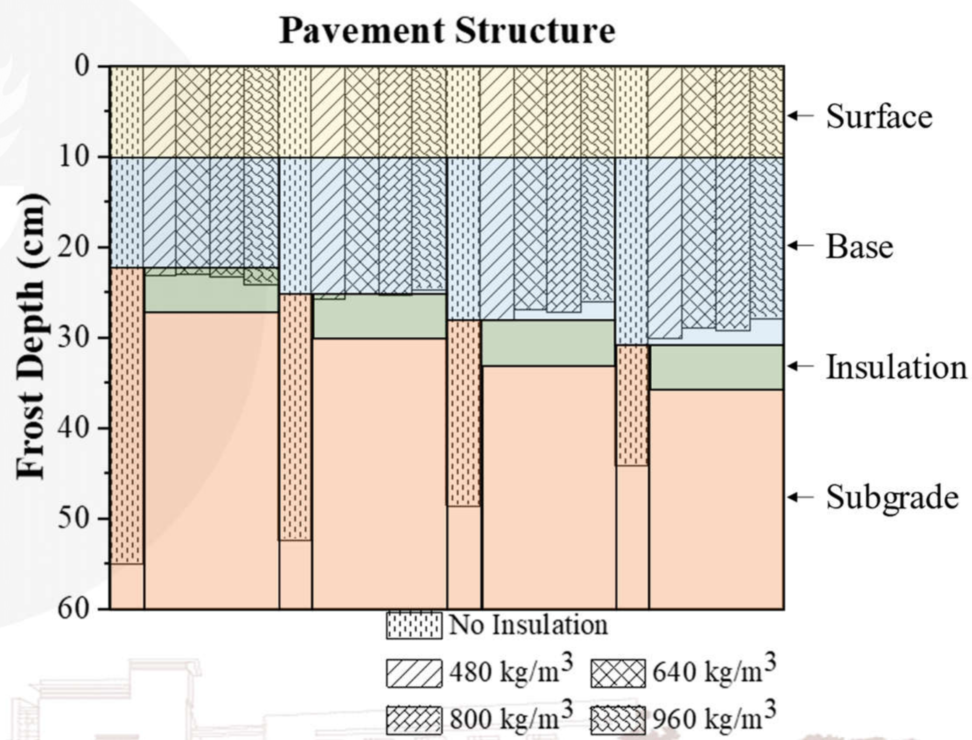
Parametric Study Based on the FE Model

Group	Surface (cm)	Base (cm)	Insulation (cm)	Subgrade (cm)
1	10	12	0,2.5,5,7.5,10	100
2	10	12,15,18,21	0,5	100

- Group 1: Investigate the influence of the insulation thickness on the pavement performance
- Group 2: Investigate the influence of the insulation depth on the pavement performance

Influence on the Frost Depth





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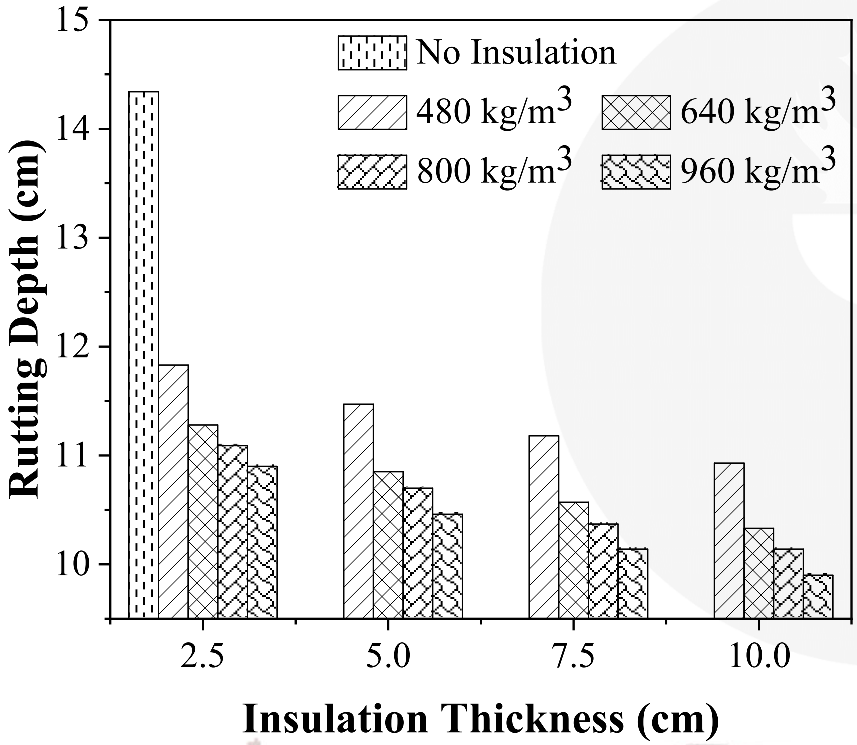
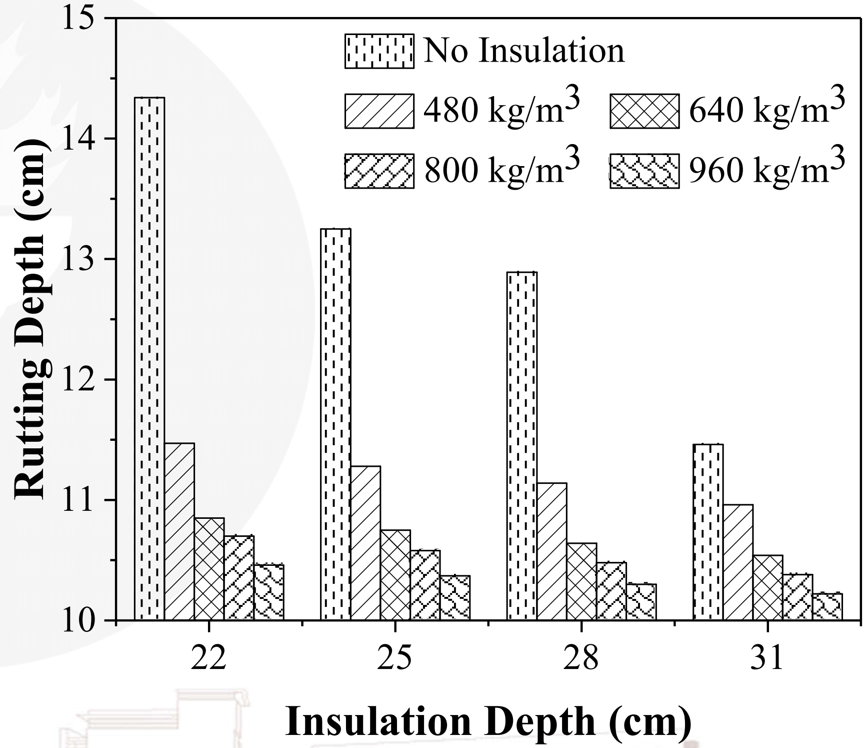
Influence on the Rutting Depth





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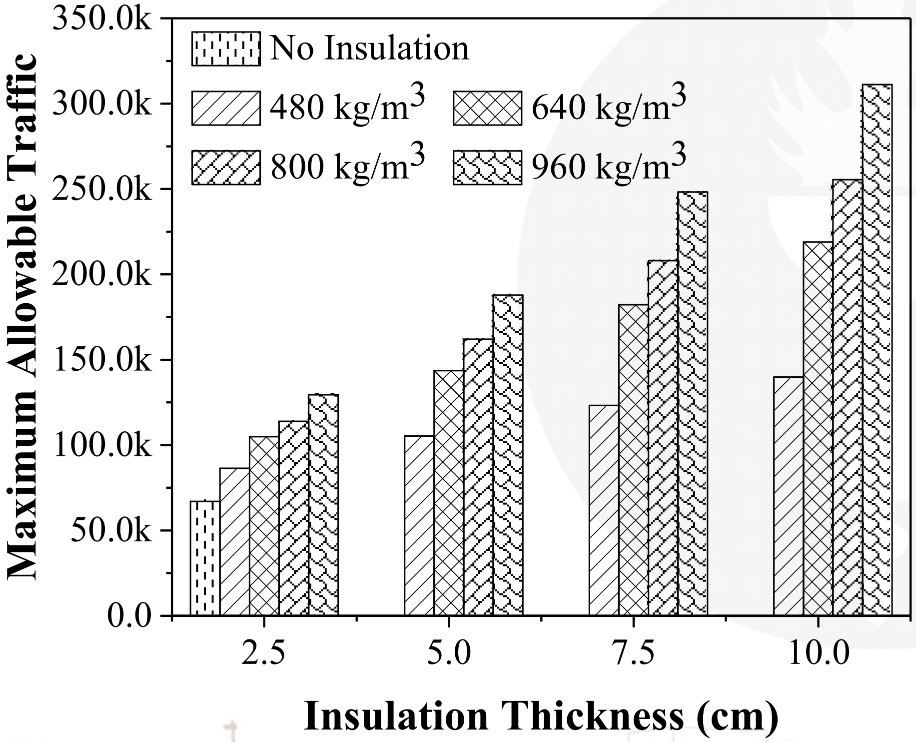
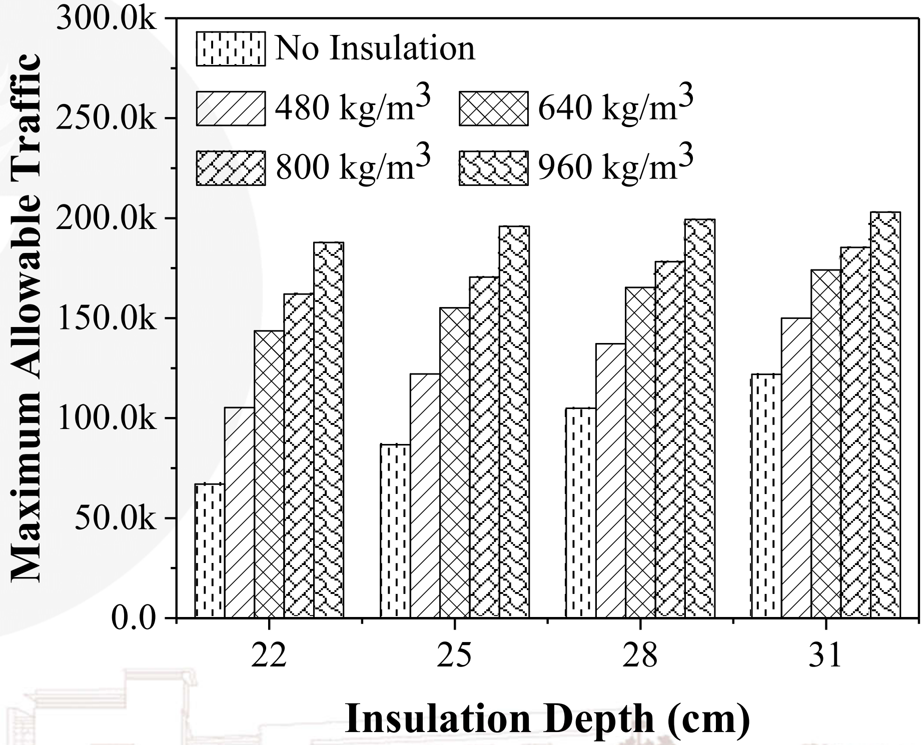
Influence on the Maximum Allowable Traffic





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Conclusions

- Foamed concrete with higher density has a higher compressive strength, thermal conductivity, and a lower porosity.
- Compared with the performance of uninsulated pavements, the foamed concrete insulated pavement has better performance in resisting frost effect and traffic loading.
- To ensure the subgrade layer unfrozen, there is a minimum insulation thickness for a foamed concrete layer. In this study, for a foamed concrete layer with a density larger than 480 kg/m^3, the minimum thickness was 5 cm.
- Increasing the depth of the insulation layer will achieve a better mechanical performance, while also increasing the frozen depth. Using a foamed concrete with a higher density results in a better mechanical performance.

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Thank you!

Contact: zhuc@rowan.edu