Center for Integration of Composites into Infrastructure

Application of Geofoam in Thermal Encapsulation of Foundations

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PI: Anand J. Puppala
Professor | A.P. and Florence Wiley Chair
Director – Center for Infrastructure Renewal

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May 23, 2024

ThermaFoam LLC

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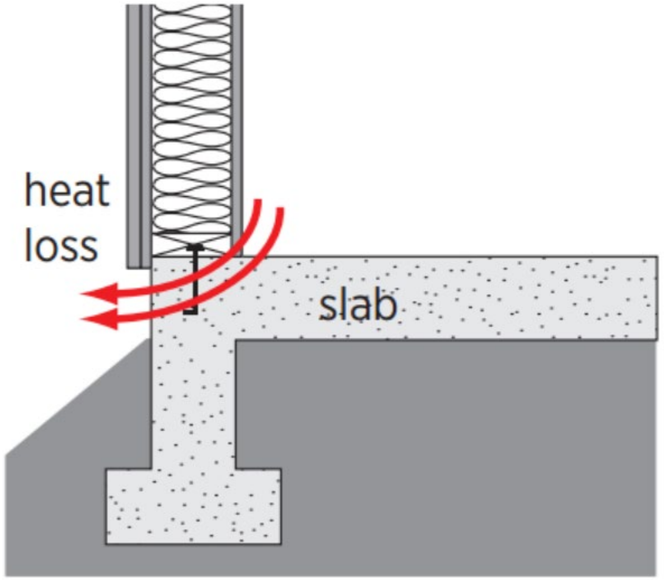
Zachry Department of Civil & Environmental Engineering

Presentation Outline

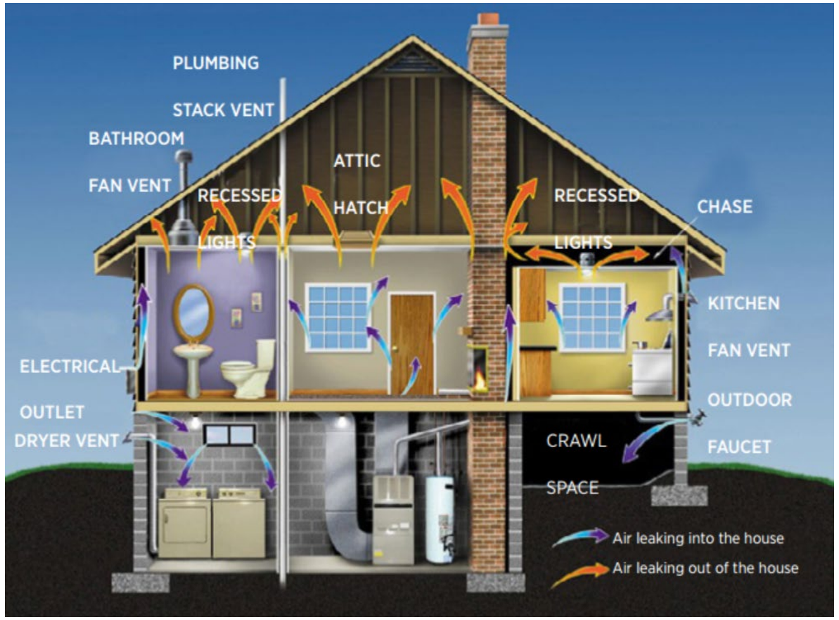
- Introduction
- Test Methodology
- Previous GBF & GAF Tests
- R-130 Geofoam Around Footing (GAF) Tests
  - GAF-2 in. R-130 Test
  - Indoor Temperature: Control vs GAF
  - Slab Temperature: Control vs GAF
- Results Summary
- Conclusions

Introduction

- Temperature fluctuations inside the dwellings typically occur from advection, diffusion and radiation at foundation superstructure joints
- About 15% of all heat loss in a home is through floors or basements
- Thermal Encapsulation using Geofoam
  - Research Plan
  - Laboratory Testing Setups



Heat loss



The stack effect

Source: EPA, US DOE (2011, 2012)

Test Methodology

Control Tests (Baseline)

*GBF Geofoam-R-250 (8, 4, and 2 in. thick)

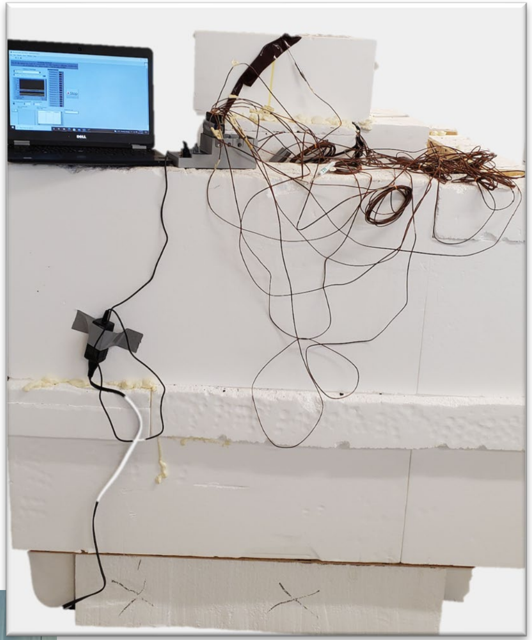
*GAF Geofoam-R-250 (8, 4, and 2 in. thick)

GAF-8 in. Geofoam-R-130

GAF-2 in. Geofoam-R-130

COMSOL Modeling of Laboratory Tests

Initial Setup



Final Setup

*GBF: Geofoam Below Foundation
GAF: Geofoam Around Foundation

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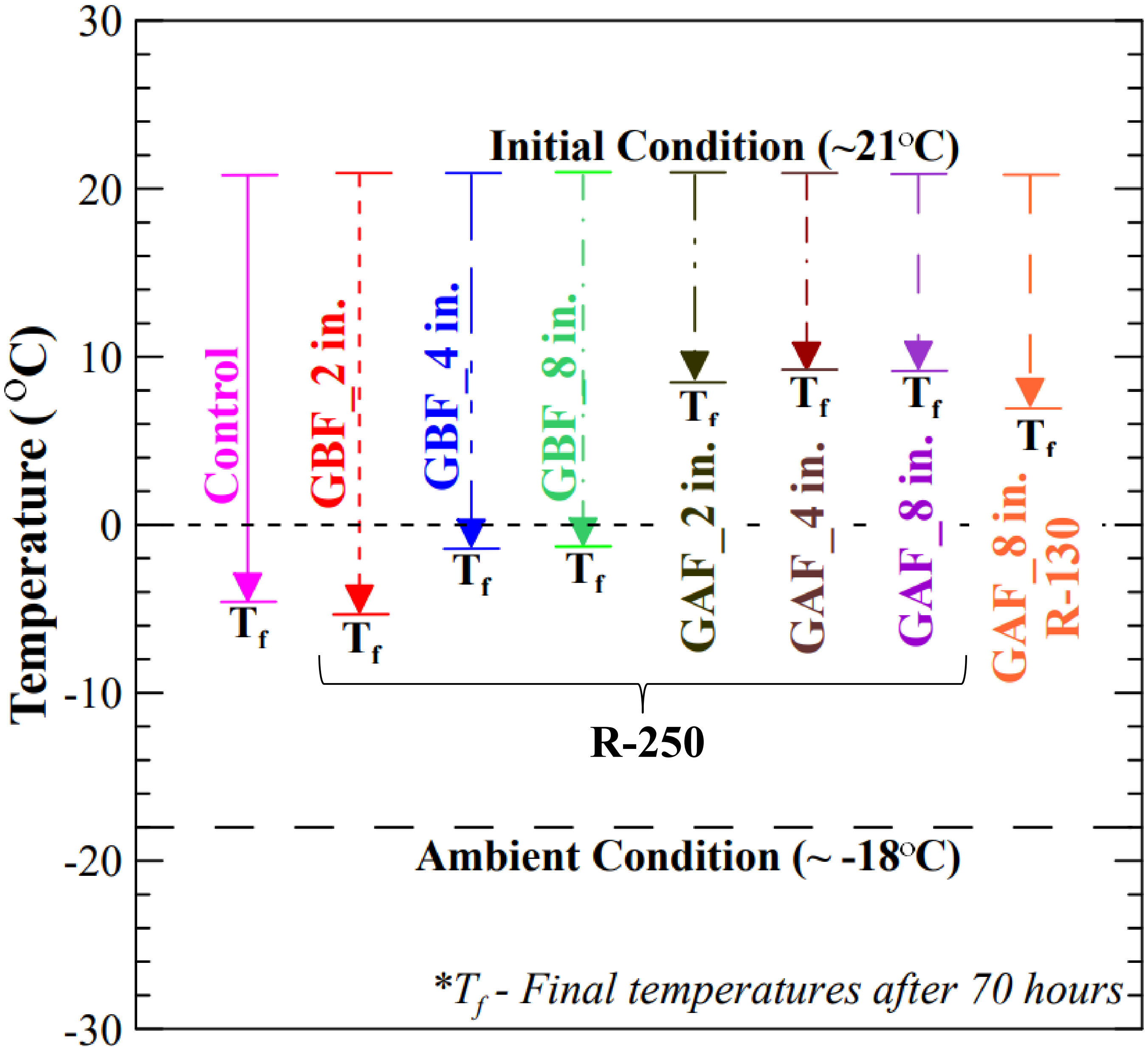
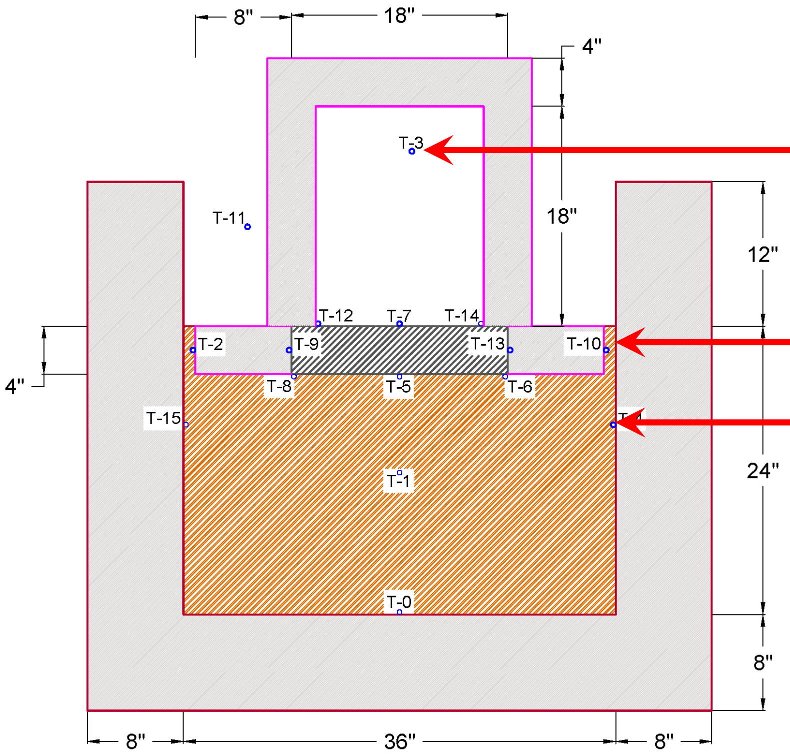
Previous GBF & GAF Tests

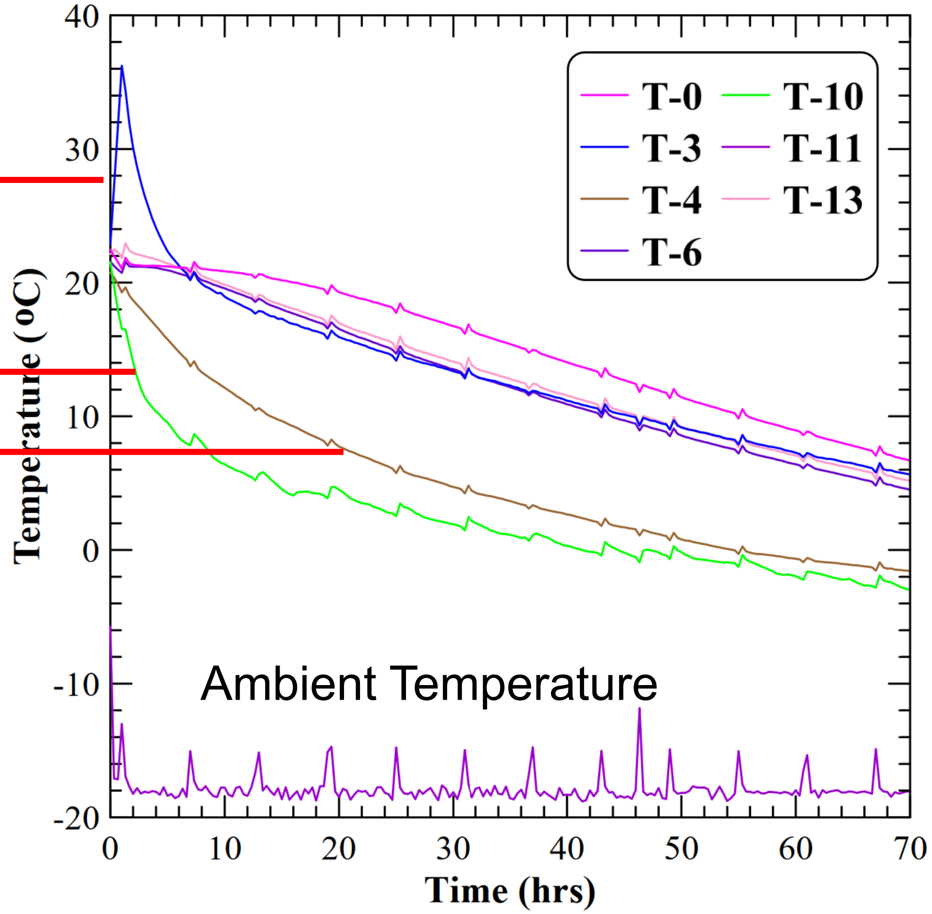
- GAF configurations significant outperform all GBF tests
- GAF sections >8˚C warmer indoor temperature than GBF sections and >10 ˚C warmer than Control section
- Not much difference in performance for thicker insulation ➔ 2 in. GAF most efficient



GAF-2 in. R-130 Test

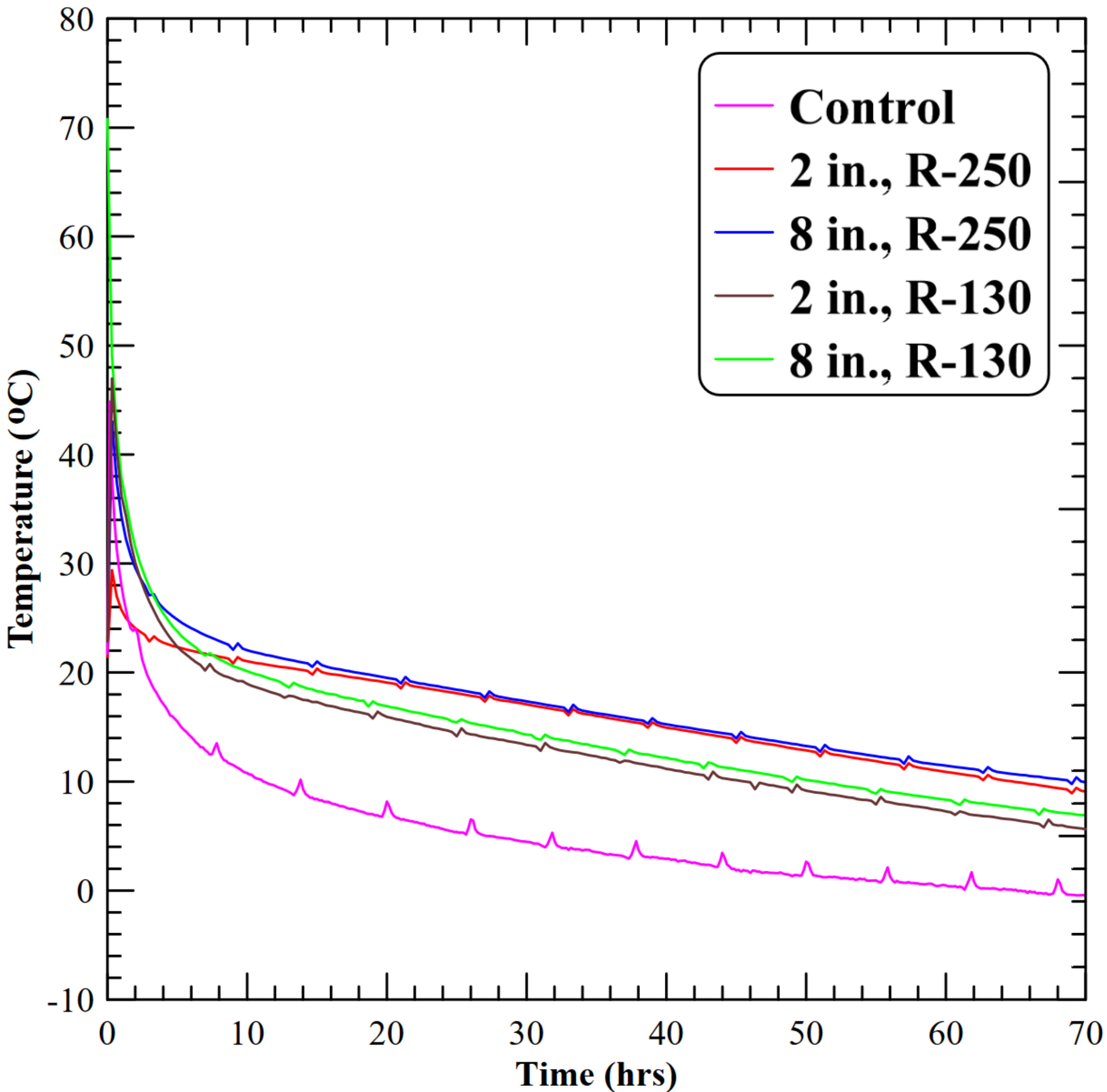
- Significantly warmer indoor temperature compared to control test (>5 ˚C) warmer
- Increased temperature observed within the slab and superstructure – reduced heat loss
- Side walls – coldest





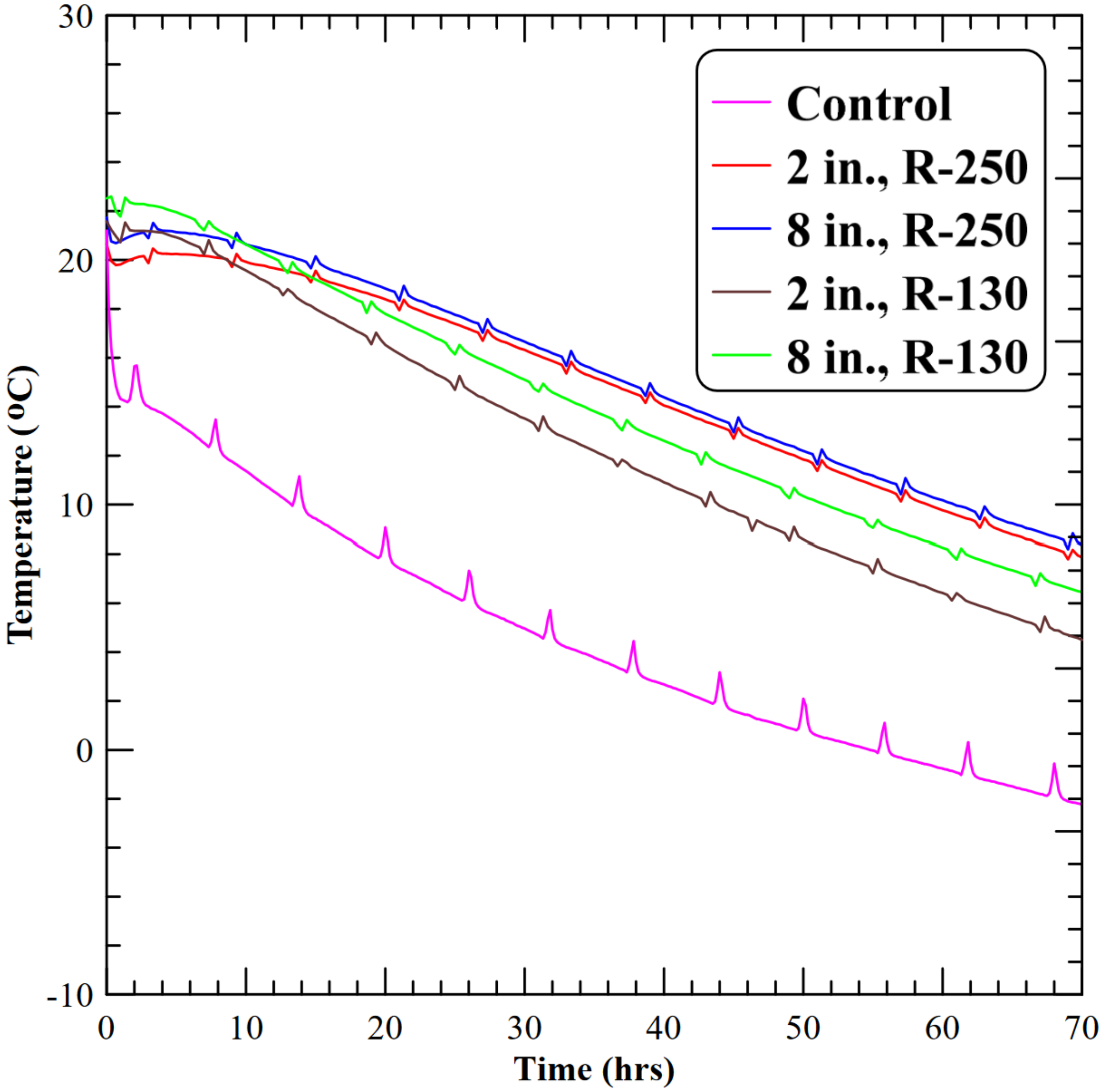
Indoor Air Temperature: Control vs GAF

- Similar trend of reduced heat loss observed in all 4 GAF tests
- Lower R-values led to cooler indoor temperatures
- R-250 sections > 1.5 ˚C warmer than R-130 section
- 2 in. thick R-130 geofoam may be least efficient GAF configuration



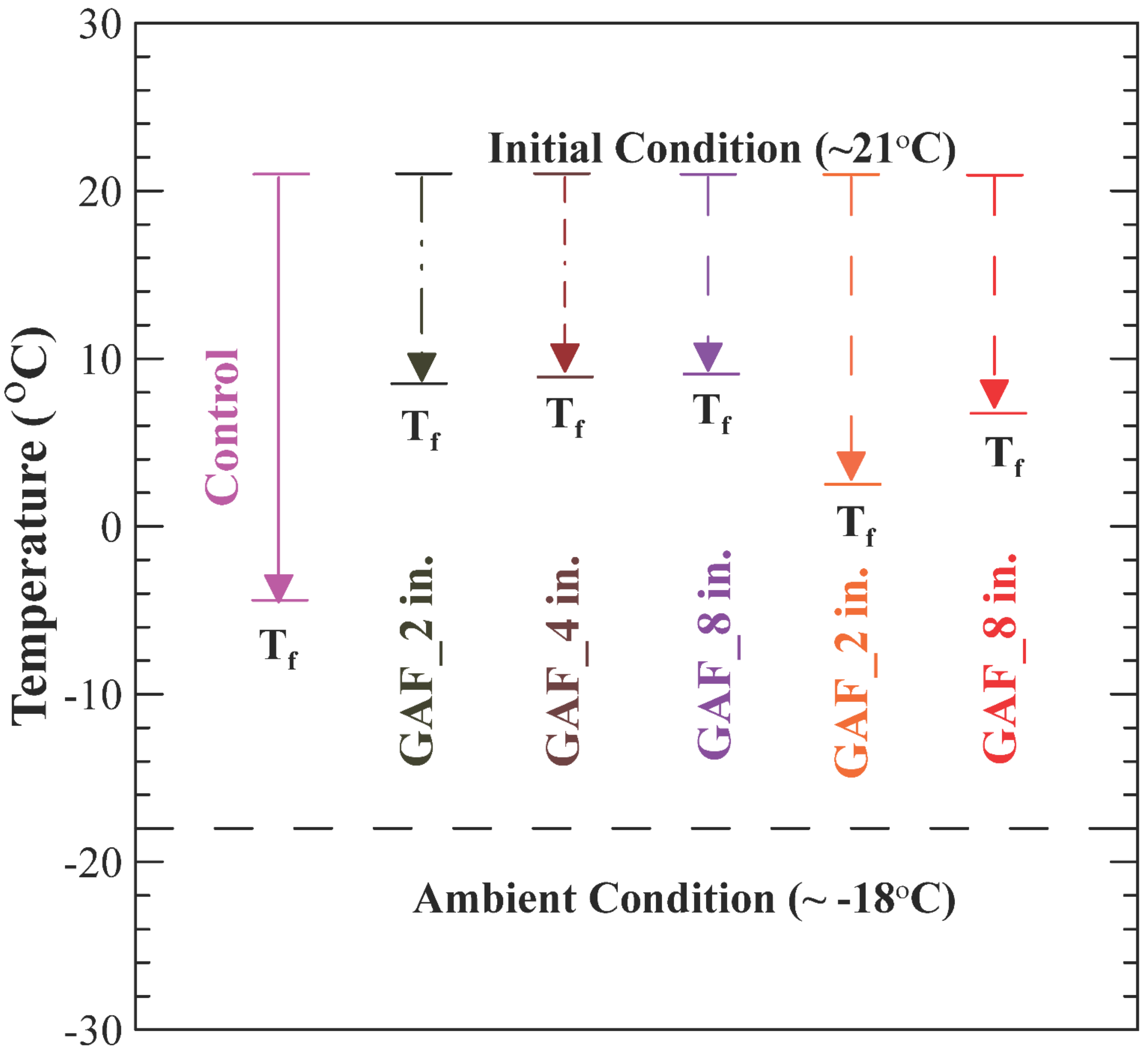
Slab Temperature: Control vs GAF

- ❑All GAF sections > 10 ˚C warmer slab temperature than Control
- ❑Lower R-values led to cooler slab temperatures
- ❑8 in. R-250 sections > 2 ˚C warmer than 8 in. R-130 section
- ❑2 in. R-250 sections > 6 ˚C warmer than 2 in. R-130 section



Results Summary

- ❑GAF-2 in. R-250 section had >4° C warmer slab temperature than GAF-2 in. R-130 section
- ❑GAF-8 in. R-250 section had >2°C warmer slab temperature than GAF-8 in. R-130 section
- ❑GAF- 8 in. R-250 section had >2°C warmer slab temperature than GAF-8 in. R-130 section



Conclusions

- Better performance of GAF → Heat lost to ambient air controlling factor
- Thinner insulation with higher R-value performed better than thicker insulation with lower R-value
- GAF-2 in. thick R-250 outperformed GAF-8 in. thick R-130
- Thermal properties and insulation configuration had more influence than thickness of geofoam
- Influence of insulation thickness was higher for lower grade geofoams
- 2 in. thick R-250 in GAF configuration could be an efficient option

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Design and Testing of IFI Geosynthetic Products

Project (Leader): Krishneswar Ramineni

Team: Nripojyoti Biswas, Avinash Gonnabathula, and Md Ashrafuzzaman Khan

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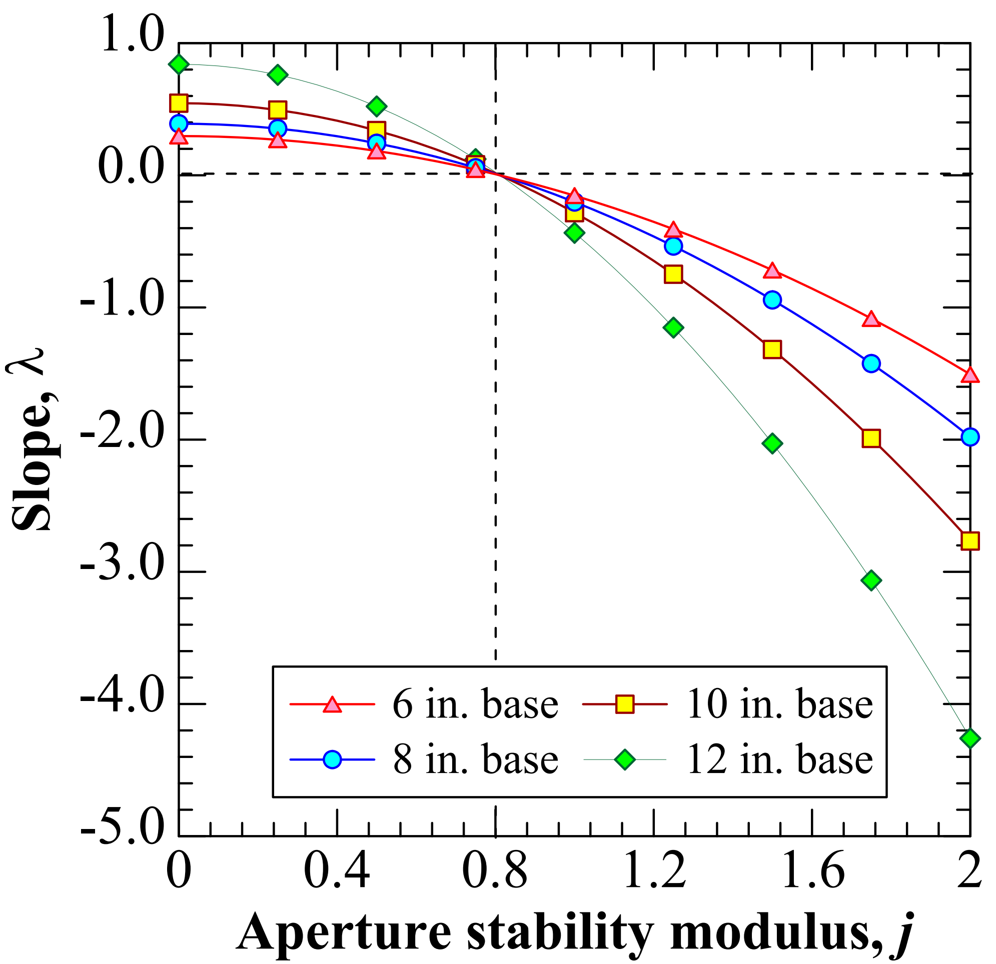
Presentation Outline

- Introduction and Background
- Objectives
- Experimental Program
- Test Results and Trends
- Unpaved Base Layer Design
- Design Charts
- Limitations
- Summary
- Future Work

Introduction and Background

- Pavements built over poor subgrade soils → low bearing capacity, distress and construction issues
- Geosynthetics → Improve pavement performance → High modulus geogrids can work on weak subgrades
- Limitations of existing design method (G-H method)
  - Applicable only to geogrids with aperture stability modulus , *j* below 0.8 m-N/deg (experimental values used in the development are less than this value!)
  - Assumes the initial stress distribution of first cycle as constant
- Need to update the calibration equation and develop design charts



Slope vs Aperture stability modulus graph **based on G-H equation**

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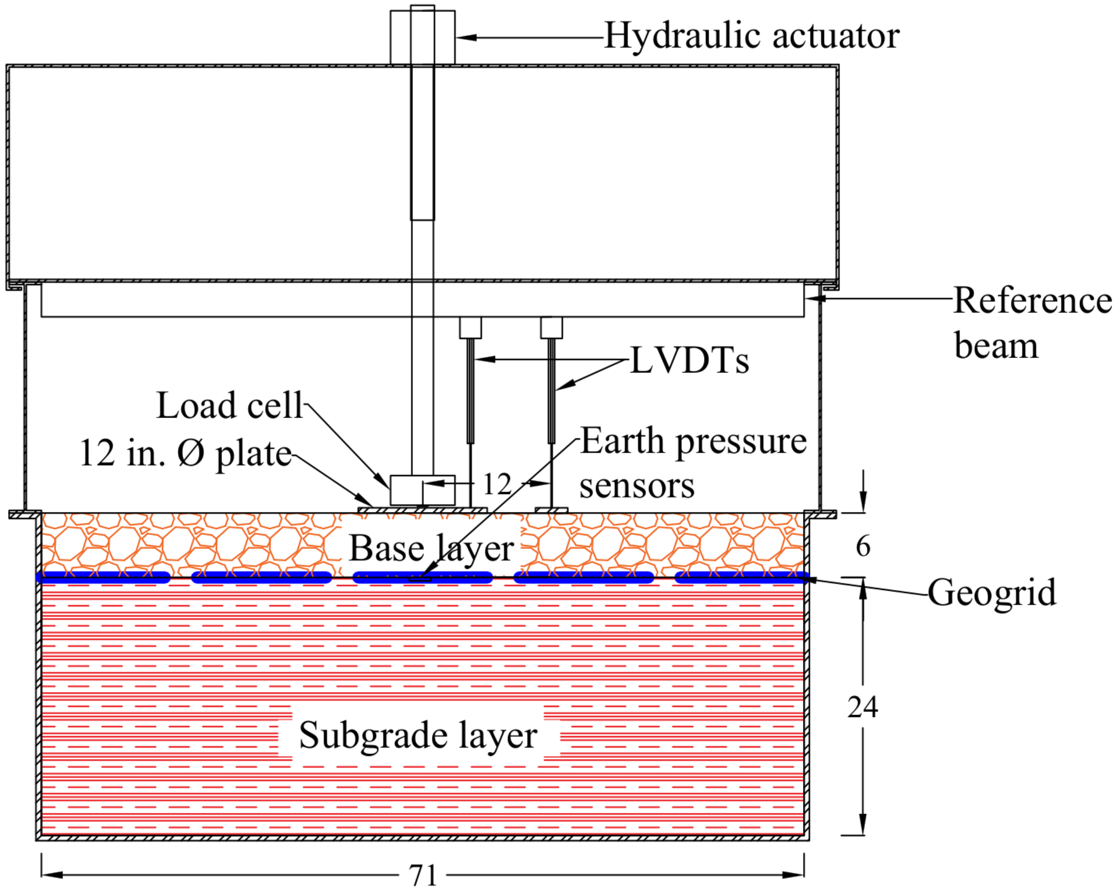
Objectives

The objectives of the current study are:

- Phase 1 Part 1 Objective I : Performing repeated load tests on geosynthetic reinforced base layers built on different weak subgrades (12-inch base sections)
- Phase 1 Part 2 Objective II: Development of various design charts and methods for IFI, Inc Geosynthetic Products based on Phase 1 Part 1 results
- Phase 1 Part 3 Objective III: Perform non-destructive tests on geosynthetic reinforced unpaved sections and develop numerical model to determine the stiffness properties of different pavement layers in the field.
- Phase 2 Part 1 Objective IV: Performing repeated load tests on geogrid reinforced base layers built on different weak subgrades (6-inch base sections)
- Phase 2 Part 2 Objective V: Development of various design charts and coefficients for IFI, Inc Geosynthetics products based on Phase 1 Part 1 and Phase 2 Part 1 results

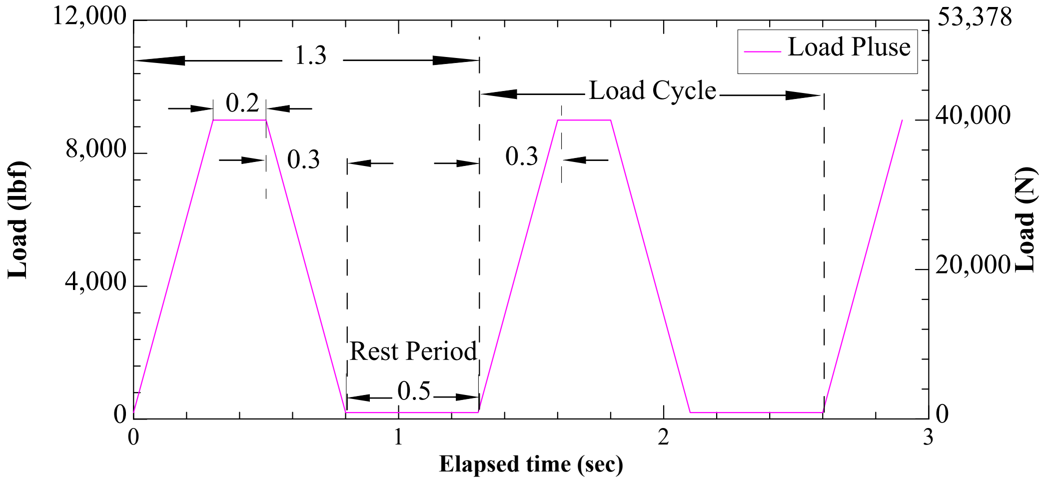
Experimental Program

Large-Scale Repeated Load Testing



Note: All dimensions are in in. (1 in. = 25.4 mm)

Schematic of the large-scale test box



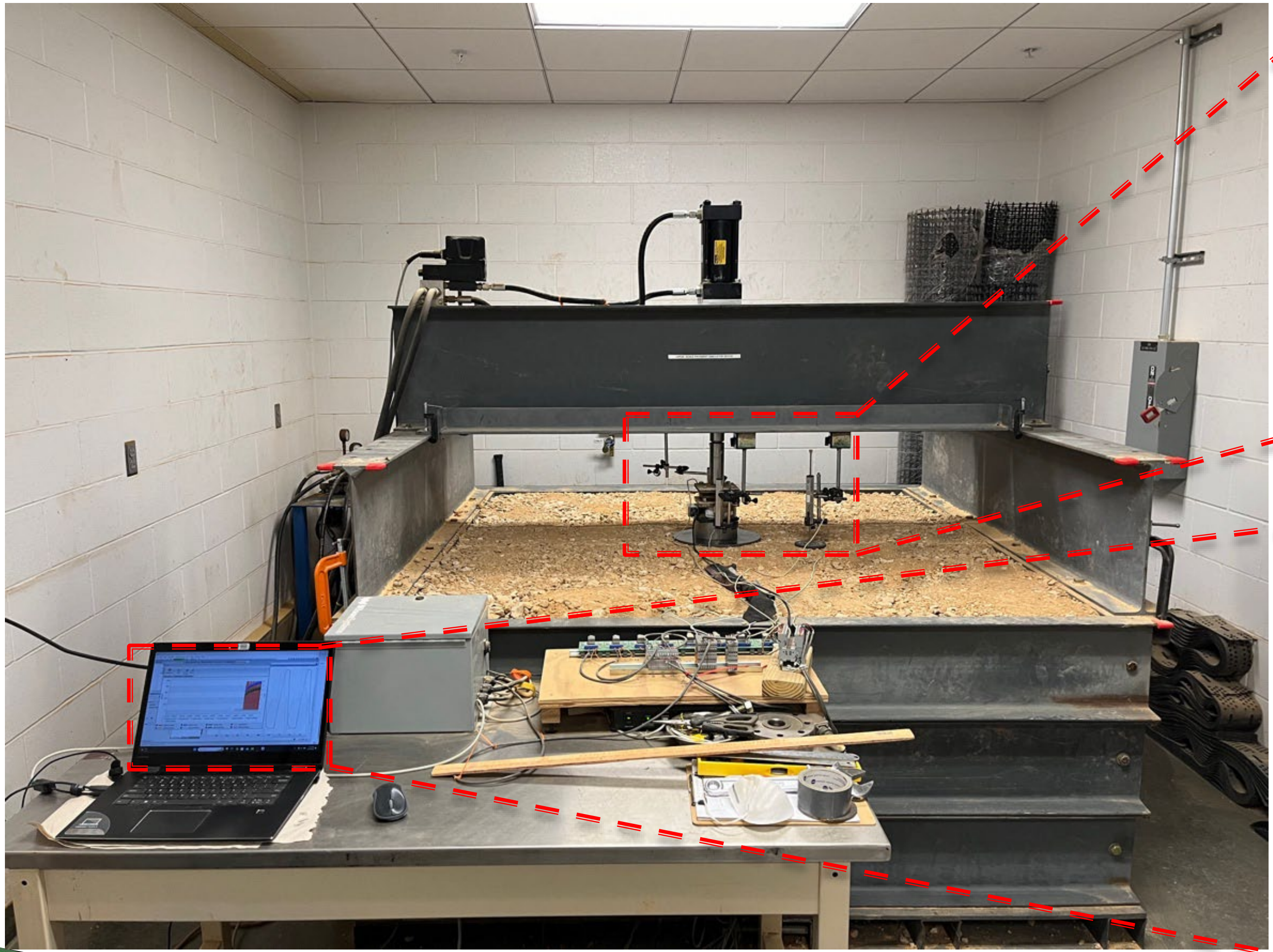
Repeated load pulse

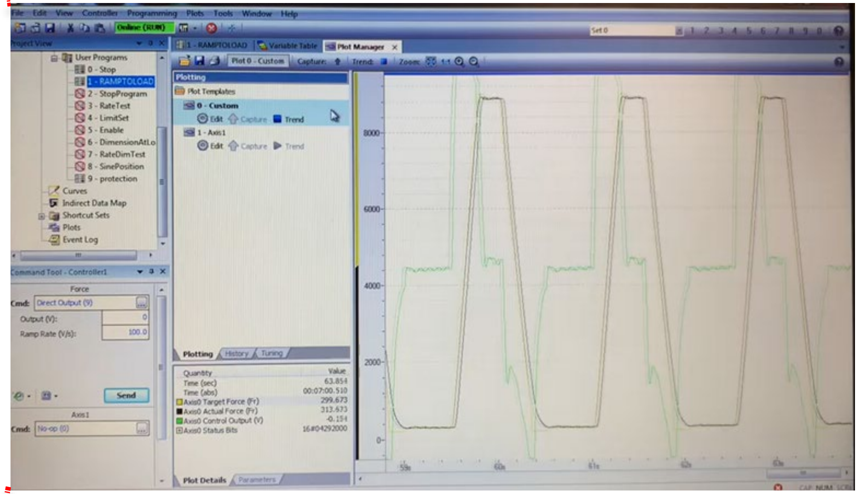
- Frequency of loading: 0.77 Hz
- Peak load: 9000 lbf
- Loading plate diameter: 12 in.
- Instrumentation: Load cell, pressure sensors, Multiple LVDTs

Reinforcement layer was placed at the interface of base and subgrade layers

Experimental Program

Large-Scale Repeated Load Testing





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Experimental Program

Large-Scale Repeated Load Tests Performed on Geocell/Geocomposites

Test ID	(h)	(CBR_{sg})	Geosynthetic type	Geosynthetic material property
12_1_FG6	12 in.	CBR 1	Geocomposite (FG6)	j = 0.80 m-N/deg + Non-woven
12_1_GCSP4			Geocell (GCSP4)	4 in. height
12_1_GCSP6			Geocell (GCSP6)	6 in. height
12_1_BL6_GCSP4			Geogrid (BL6) + Geocell (GCSP4)	j = 0.98 m-N/deg + 4 in. height
12_1_BL6_GCSP6			Geogrid (BL6) + Geocell (GCSP6)	j = 0.98 m-N/deg + 6 in. height
12_3_FG6		CBR 3	Geocomposite (FG6)	j = 0.80 m-N/deg + Non-woven
12_3_GCSP4			Geocell (GC4)	4 in. height
12_3_GCSP6			Geocell (GC6)	6 in. height
12_3_BL6_GCSP4			Geogrid (BL6) + Geocell (GCSP4)	j = 0.98 m-N/deg + 4 in. height
12_3_BL6_GCSP6			Geogrid (BL6) + Geocell (GCSP6)	j = 0.98 m-N/deg + 6 in. height

“Test ID” nomenclature: “Base thickness_CBR of Subgrade_Primary Reinforcement type_Secondary Reinforcement type”

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Experimental Program

Large-Scale Repeated Load Testing on Geogrid Reinforcements

Test ID	*h*	CBR_{sg}	Geosynthetic type	Geosynthetic material property
12_1_UR	12 in.	CBR 1	-	-
12_1_BL5			Geogrid (BL5)	*j* = 0.80 m-N/deg
12_1_BL6			Geogrid (BL6)	*j* = 0.98 m-N/deg
12_1_BL7			Geogrid (BL7)	*j* = 1.50 m-N/deg
12_3_UR		CBR 3	-	-
12_3_BL5			Geogrid (BL5)	*j* = 0.80 m-N/deg
12_3_BL6			Geogrid (BL6)	*j* = 0.98 m-N/deg
12_3_BL7			Geogrid (BL7)	*j* = 1.50 m-N/deg
6_1_UR	6 in.	CBR 1	-	-
6_1_BL6			Geogrid (BL6)	*j* = 0.98 m-N/deg
6_1_BL7			Geogrid (BL7)	*j* = 1.50 m-N/deg
6_3_UR		CBR 3	-	-
6_3_BL6			Geogrid (BL6)	*j* = 0.98 m-N/deg
6_3_BL7			Geogrid (BL7)	*j* = 1.50 m-N/deg

"Test ID" nomenclature: "Base thickness_CBR of Subgrade_Primary Reinforcement type_Secondary Reinforcement type"

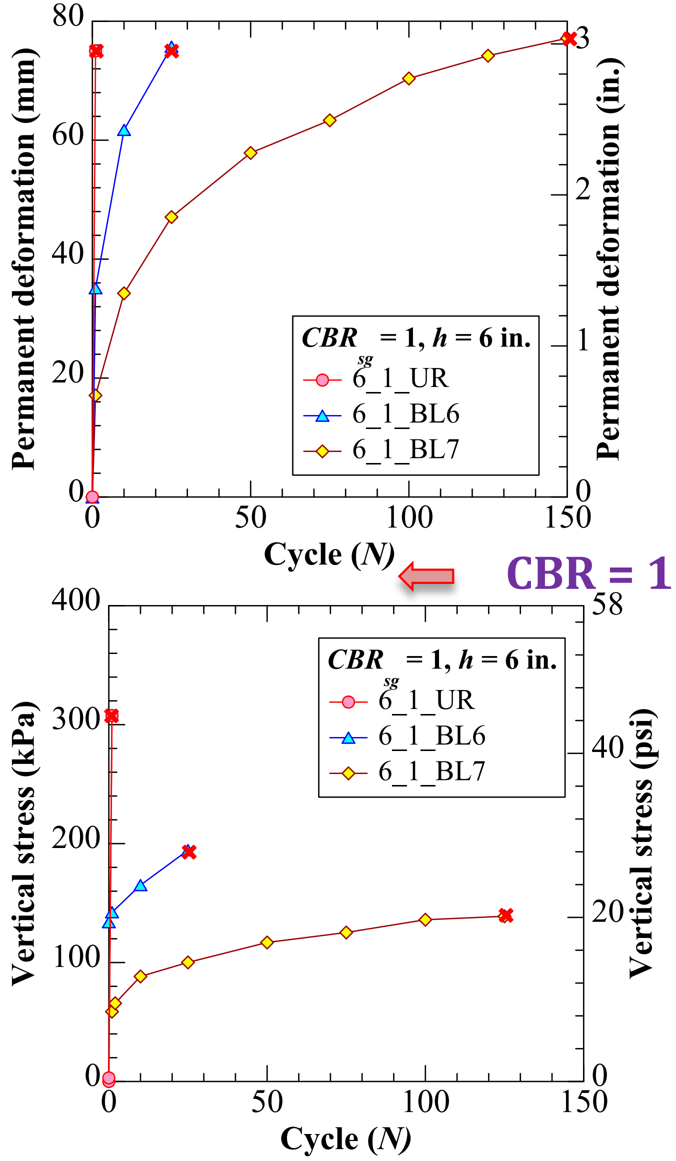
Test Results and Trends

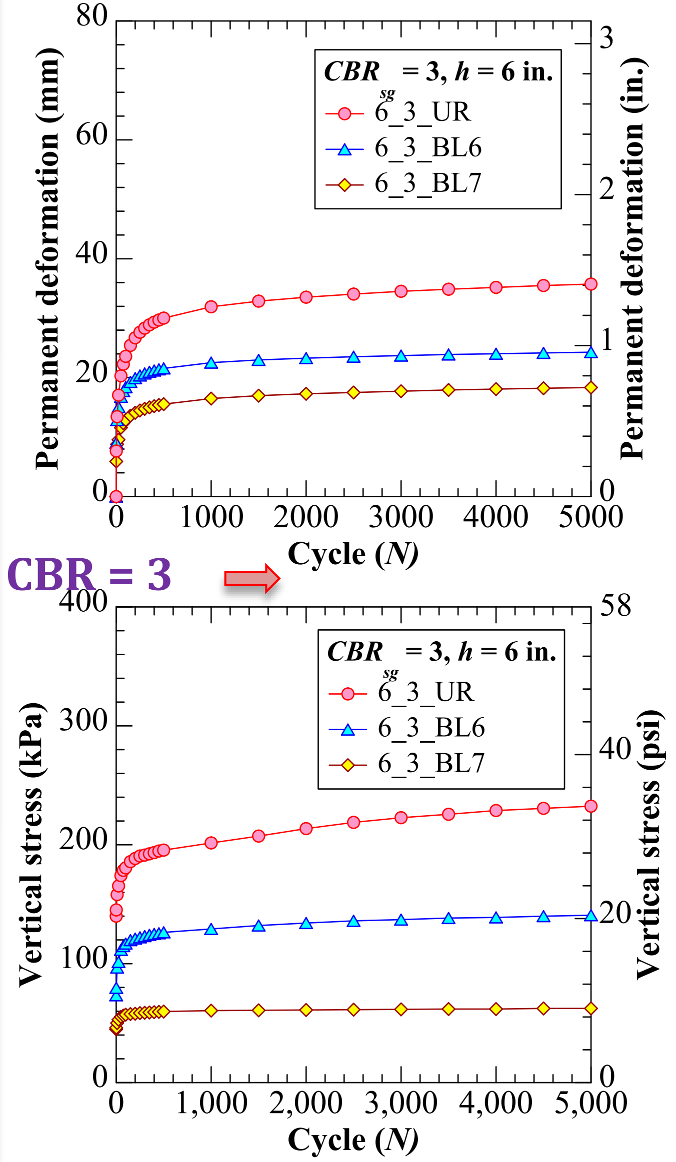
Surface Deformation:

- Permanent deformation ↓ ⇒ subgrade strength ↑, base thickness ↑ and geogrid stiffness *j* ↑
- CBR_{sg} = 1; 6 in. base layer test sections failed (3 in. or 75 mm) before reaching 150 loading cycles

Vertical stresses

- Vertical stresses at top of subgrade reduced with geosynthetic reinforcement
- The key influencing factors: Geogrid stiffness *(j)*, Subgrade strength *(CBR_{sg})*, *r/h* ratio





Unpaved Base Layer Design – Theory

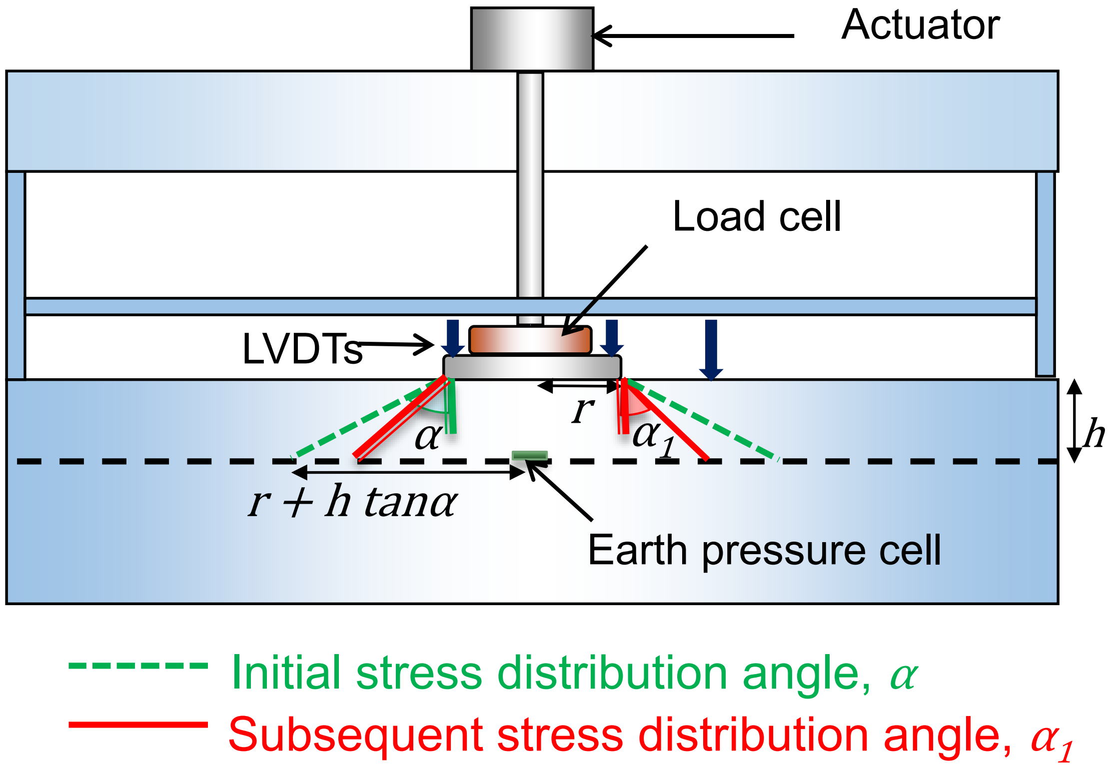
Stress at interface, $p_i = \dfrac{P}{\pi\,(r + h\tan\alpha)^2}$

$$h = \frac{1}{\tan\alpha} \times \left(\sqrt{\frac{P}{\pi r^2 p_i}} - 1 \right) \times r$$

Stress on subgrade should be less than mobilized bearing capacity

$$p_i \leq mN_c c_u$$

$$\boxed{h \geq \frac{1}{\tan\alpha} \left(\sqrt{\frac{P}{\pi r^2 \left(\frac{s}{f_s}\right)\left\{1 - 0.9exp\left[-\left(\frac{r}{h}\right)^2\right]\right\} N_c c_u}} - 1 \right) \times r}$$



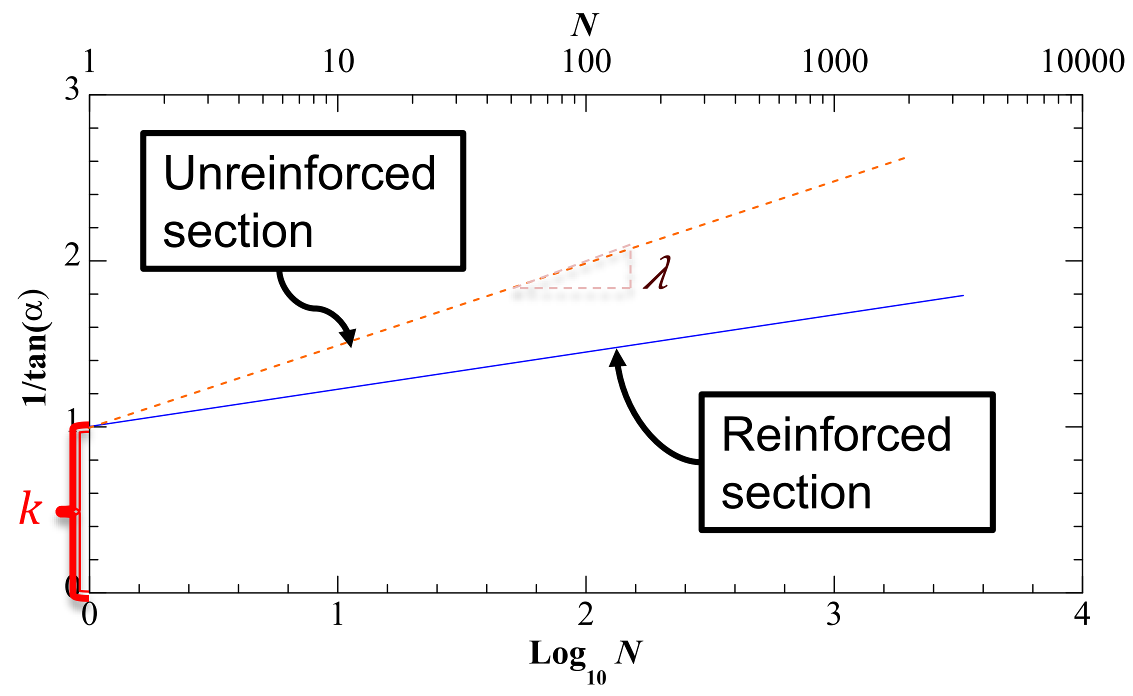
Where, P = vehicular load applied, r = the loading plate of radius, h = the thickness of the base layer, α = stress distribution angle, m = bearing capacity mobilization coefficient, N_c = bearing capacity factor; c_u = undrained cohesion of the subgrade soil (kPa), f_s = factor equal to 75 mm rut depth and s= rut depth (mm)

Unpaved Base Layer Design – Theory

Geogrid-reinforced unpaved roads

- Stress distribution angle (α) → improvement with geogrids → generate $1/\tan(\alpha)$ vs. $\log_{10}N$ graphs
- Intercept is k and Slope is λ
- Giroud and Han (2004b, 2004a) Method → α depends on
  - Ratio of loading plate radius to base layer thickness (*r/h*)
  - Types of geosynthetics (*j*)
  - Number of loading cycles (*N*)
  - Parameter *k* is a constant value of 1.1

$$\boxed{\frac{1}{\tan(\alpha)} = k + \lambda \times \log_{10} N}$$



r = Radius of the plate, *h* = Base thickness, *N* = Number of loading cycle, *j* = Aperture stability modulus

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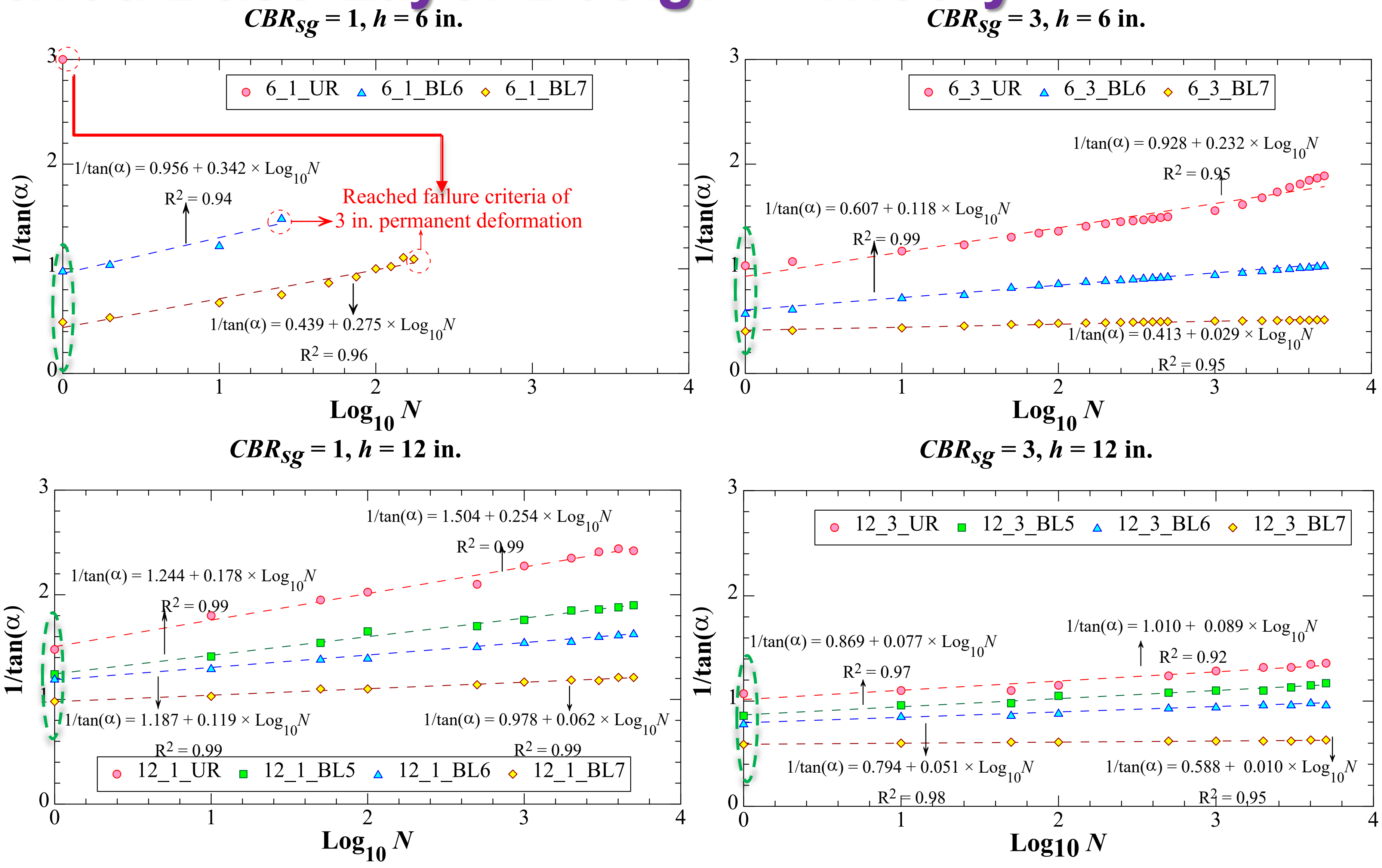
Unpaved Base Layer Design – Theory

Geogrid-reinforced unpaved roads

- ❑ k is not constant
- ❑ The slope of the line decreases
  - ➢ Geogrid stiffness (j)⬆
  - ➢ Subgrade strength (CBR_{sg})⬆



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Unpaved Base Layer Design

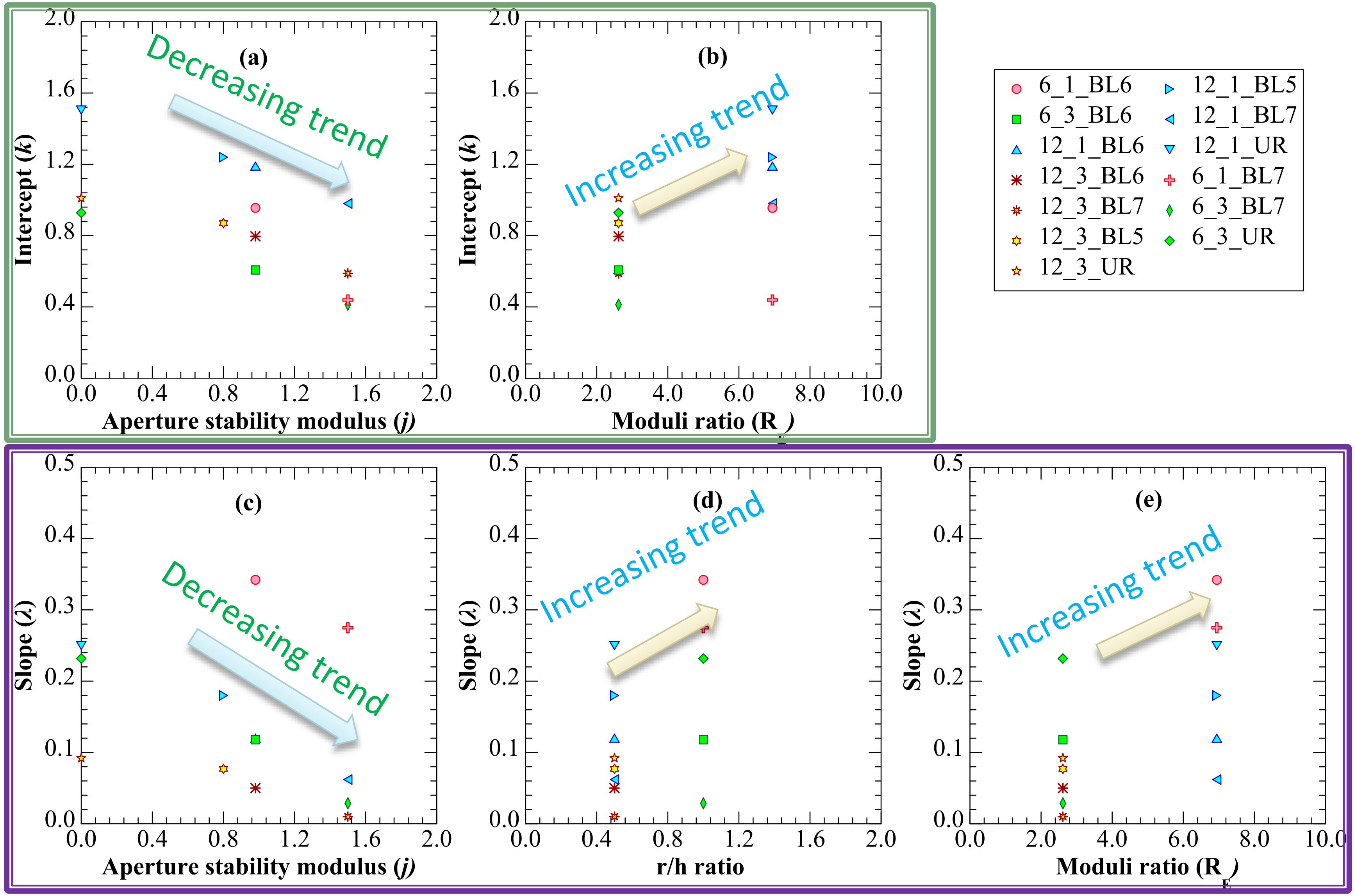
Base Thickness	Subgrade CBR	Reinforcement Type	λ	k	R^2
6 in.	1	Unreinforced	-	-	-
	1	BL6	0.342	0.956	0.94
	1	BL7	0.275	0.439	0.96
	3	Unreinforced	0.232	0.928	0.95
	3	BL6	0.118	0.607	0.99
	3	BL7	0.029	0.413	0.96
12 in.	1	Unreinforced	0.254	1.504	0.99
	1	BL5	0.178	1.244	0.99
	1	BL6	0.119	1.187	0.99
	1	BL7	0.062	0.978	0.99
	3	Unreinforced	0.089	1.010	0.93
	3	BL5	0.077	0.869	0.97
	3	BL6	0.051	0.794	0.98
	3	BL7	0.010	0.588	0.95

Unpaved Base Layer Design

- Effect of different variable on design parameters, (k and λ)
  - Effect of k
    - k↓ ⇒ Geogrid j↑
    - k↑ ⇒ moduli ratio R_E↑
  - Effect of λ
    - λ↓ ⇒ Geogrid j↑
    - λ↑ ⇒ moduli ratio R_E↑
    - λ↑ ⇒ r/h ratio↑

$$k = f(E_1, E_2, j)$$

$$\lambda = f(E_1, E_2, r, h, j)$$



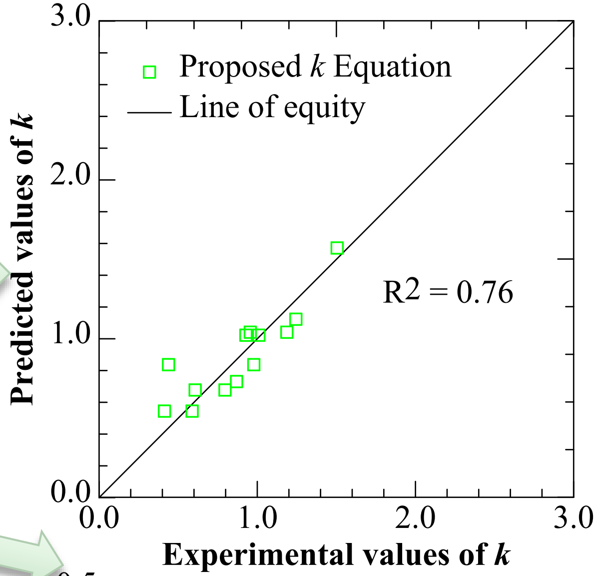
r = radius of the plate, h = base thickness, E_1 = Modulus of base, E_2 = Modulus of subgrade, j = aperture stability modulus

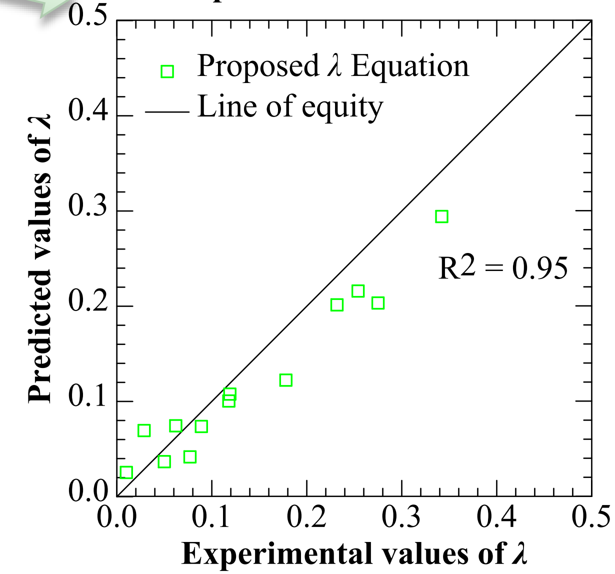
Unpaved Base Layer Design

- The coefficients for *k and λ* obtained from performing multiple variable regression modeling on the TAMU laboratory test results

$$k = 0.67e^{(-0.42\times j)}(R_E)^{0.43};\ \mathrm{R}^2 = 0.76$$

$$\lambda = 0.07e^{(-0.71\times j)}(R_E)^{1.1}(r/h)^{1.45},\ \mathrm{R}^2 = 0.95$$





- Generalized form of the $1/\tan(\alpha)$ by substituting *k and λ* parameters is

$$\boxed{\frac{1}{\tan\alpha} = [0.67e^{(-0.42\times j)}(R_E)^{0.43}] + 0.07e^{(-0.71\times j)}(R_E)^{1.1}(r/h)^{1.45}\times log_{10}\,(N)}$$

r = radius of the plate, *h* = base thickness, E_1 = Modulus of base, E_2 = Modulus of subgrade, *j* = aperture stability modulus

Unpaved Base Layer Design

Proposed Design Equation

$$h_{lab} = \frac{0.67\, e^{-0.42\, j}\, (R_E)^{0.43} + \left(0.07\, e^{-0.71\, j}\right)\left(\frac{r}{h}\right)^{1.45} (R_E)^{1.1}\, log_{10}(N)}{\{1 + 0.204\, [R_E - 1]\}} \left\{ \sqrt{\frac{\frac{P}{(\pi r^2)}}{\left(\frac{s}{f_s}\right)\left\{1 - 0.9\, exp\left[-\left(\frac{r}{h}\right)^2\right]\right\} N_c c_u}} - 1 \right\} \times r$$

- G-H method developed a laboratory to field calibration factor based on field tests conducted by Hammitt (1970). The average value of the field calibration factor (f_{cal}) is 0.69

$$h_{field} = h_{lab} \times 0.69$$

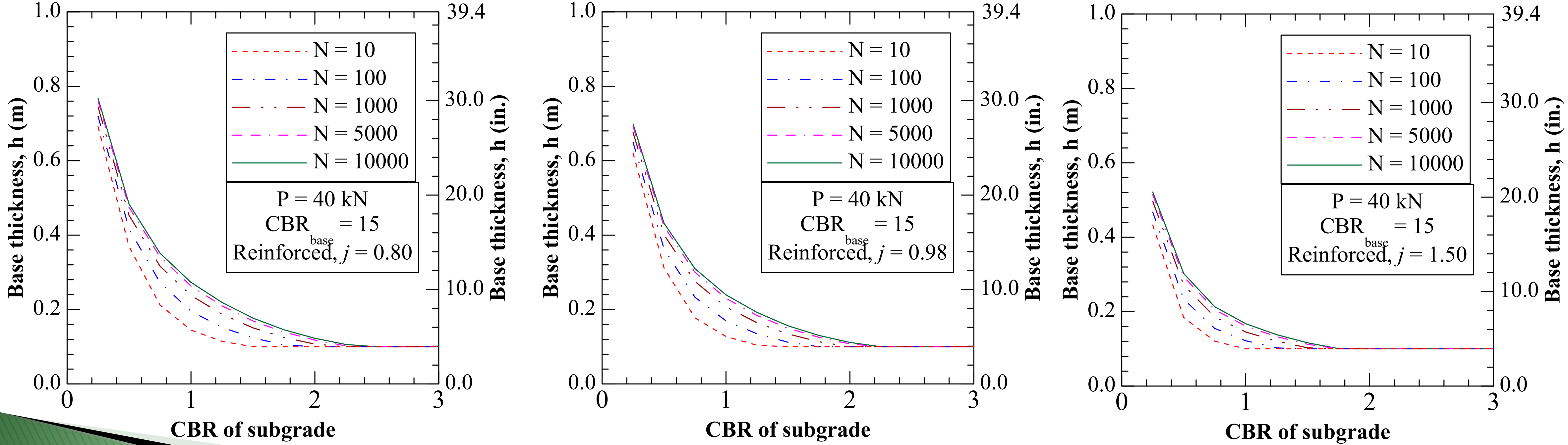
$$h_{field} = \frac{0.46\, e^{-0.42\, j}\, (R_E)^{0.43} + \left(0.048\, e^{-0.71\, j}\right)\left(\frac{r}{h}\right)^{1.45} (R_E)^{1.1}\, log_{10}(N)}{\{1 + 0.204\, [R_E - 1]\}} \left\{ \sqrt{\frac{\frac{P}{(\pi r^2)}}{\left(\frac{s}{f_s}\right)\left\{1 - 0.9\, exp\left[-\left(\frac{r}{h}\right)^2\right]\right\} N_c c_u}} - 1 \right\} \times r$$

Note: Further validation with full-scale field testing on high stiffness geogrids of IFI may yield different calibration factor.

Design Charts

Proposed Design Charts

- Design charts shows base thickness for a range of subgrade strength (CBR_{sg}) and for different loading cycles for different geogrids with different *j* properties
- A minimum base thickness of 6 in. is recommended when the design equation in the chart yields thickness lower than 6 in.



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Limitations

- The current proposed design method's validity is limited to the assumptions made and the testing conditions followed in the research

  - Proposed design methodology validity is constrained to testing variables:

    - ***R_E* values** ranging between **2.6 to 6.9**
    - ***CBR* values** of subgrade soils within the range of **1 and 3**
    - Biaxial geogrids with ***j* values** ranging from **0.8 m-N/deg to 1.5 m-N/deg**

  - Developed equation → for stiff subgrade yields lower design base thickness, < 6 in. → Recommend a **minimum thickness of 6 in.** for practical considerations and insights from the laboratory data.

  - **An average field calibration factor of 0.69 (from previous design methods) was followed**

  - **Future field studies on high strength materials may yield different field calibration factors**

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Summary

- Current laboratory studies showed the addition of geosynthetics significantly enhances the performance of the unpaved section sections constructed on weak subgrades.
- G-H equation has been updated to include stiffer geogrids and the proposed method is recommend for geogrids with *j* values ranging from 0.8 m-N/deg to 1.5 m-N/deg
- Design charts were developed for IFI geosynthetic products

Future Works

- Field testing and long-term performance of the high modulus geogrids
- For paved layer coefficients, we recommend large box test on 3-layered system with upper layer simulating asphalt concrete

Center for Integration of Composites into Infrastructure

Performance of pavement sections with H_2Ri geosynthetics

Project Leader: Nripojyoti Biswas

Team members: Avinash Gonnabathula, Krishneswar Ramineni and Gustavo Hernandez Martin

PI: Anand J. Puppala

Professor | A.P. and Florence Wiley Chair

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Texas Department of Transportation

TENCATE

May 23, 2024

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Presentation Outline

- ❖ Introduction
- ❖ Task Plan
- ❖ Life Cycle Analysis
- ❖ Field Test Sections
- ❖ Large Scale Lab testing
- ❖ Summary

Introduction

❖ Objective

- ❑ Evaluate the feasibility/efficiency of using H_2Ri geosynthetic for improving drainage and strength of pavement sections built on high-plastic expansive soil

❖ Field Studies indicated efficacy of application

❖ Laboratory studies

- ❑ Control Section
- ❑ Reinforced Sections

Control Section

Reinforced Section

Task Plan

Task 1

- ✓ Literature Review
- ✓ Geomaterial Characterization
- ✓ Construction of Test Sections
- ✓ Instrumentation and Monitoring

Task 2

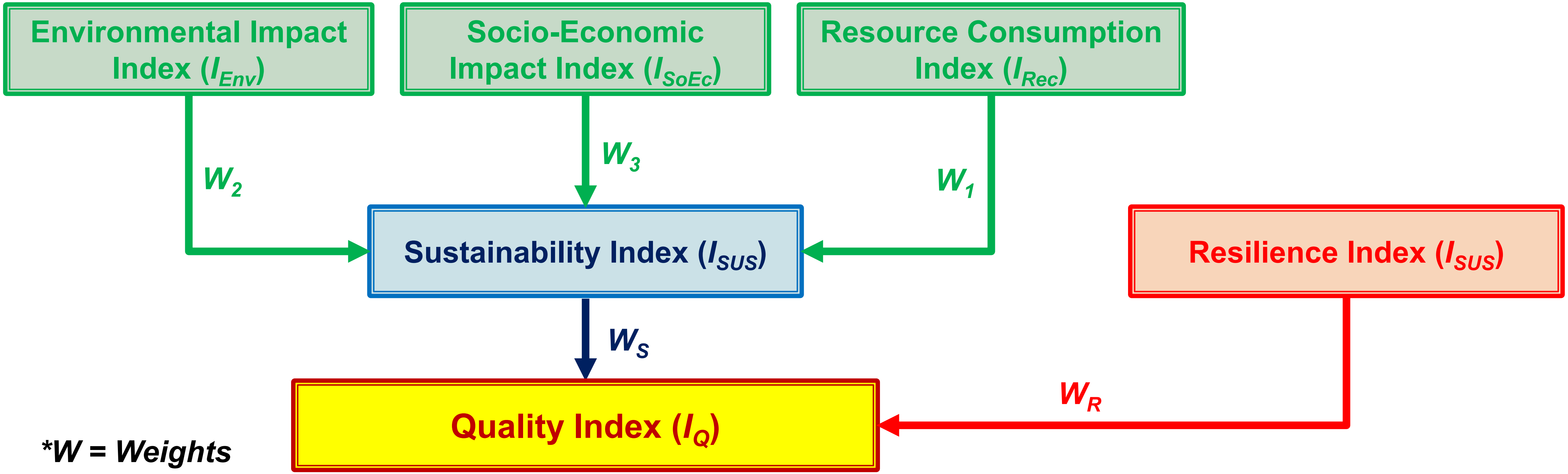
- ✓ Laboratory Studies (H_2Ri)
- ✓ Wicking Tests
- ✓ Parametric Study

Task 3

- Life Cycle Analysis
- Carbon Footprint Analysis
- Design & Construction Guidelines

Life Cycle Analysis

Combined Assessment Framework (Das 2018)



***W = Weights**

$$^*\sum W = 1$$

$$I_{SUS} = W_1 \times I_{Env} + W_2 \times I_{SoEc} + W_3 \times I_{Rec}$$

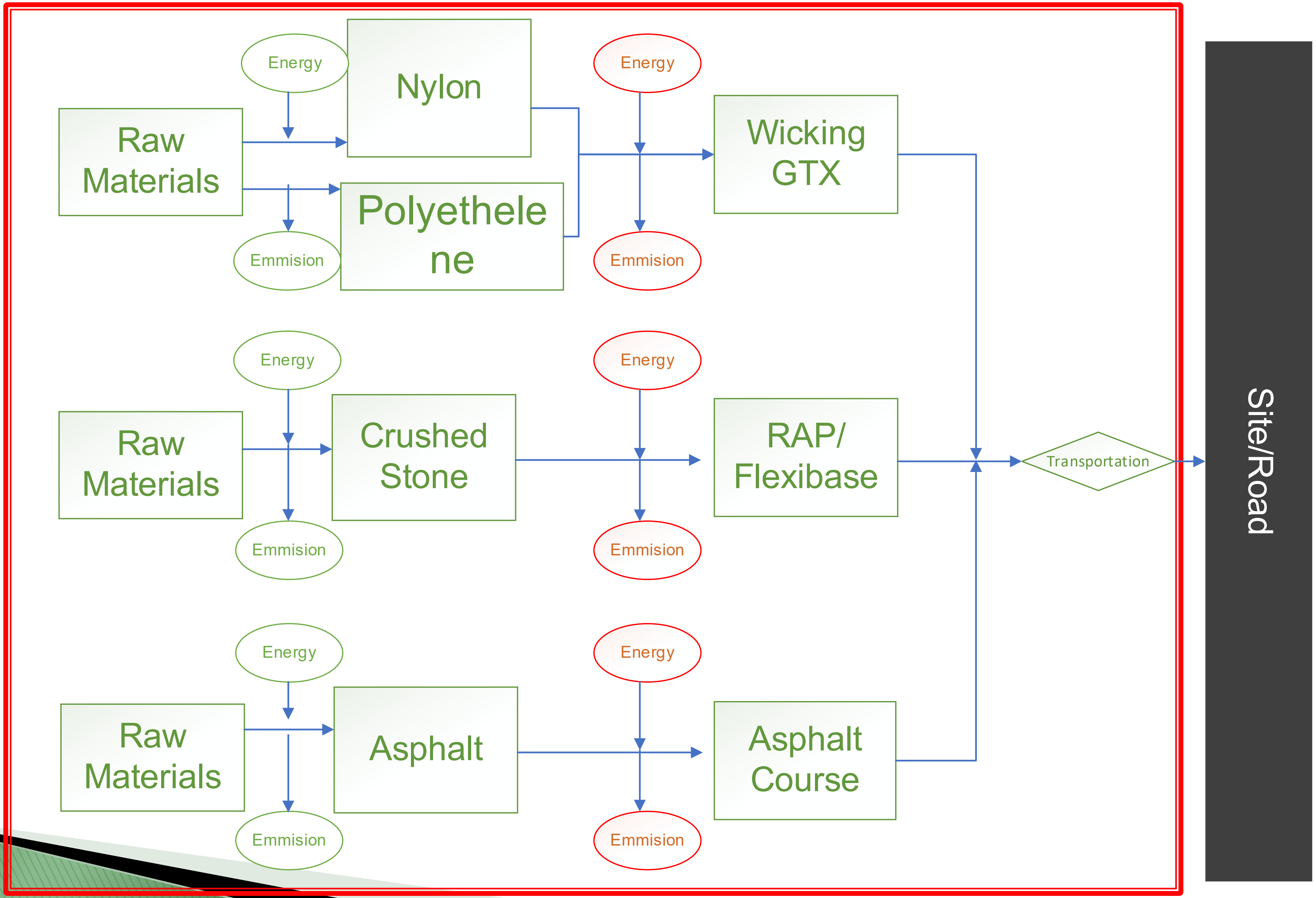
$$I_Q = W_s \times I_{SUS} + W_R \times I_{Res}$$

Lower value indicates better alternative

Life Cycle Analysis Outline

- Boundary condition is considered as cradle to gate + transportation to site
- Construction machinery costs and impacts are ignored
- The database costs are market costs for the products
- Cost and Impact analysis was done per meter length of road
- Sustainability analysis for environmental impact was performed using OpenLCA
- ReCiPe 2016 Midpoint method was used for calculation

Process Flow



Sustainability Analysis – Test Parameters

$$I_{Rec} = w_{1a} \times E_{E\,(material\,production)} + w_{1b} \times E_{E\,(Transportation)}$$

$$I_{Env} = w_2 \times GW_P$$

$$I_{SoEc} = w_3 \times C$$

Where,

w_i = Weight factors

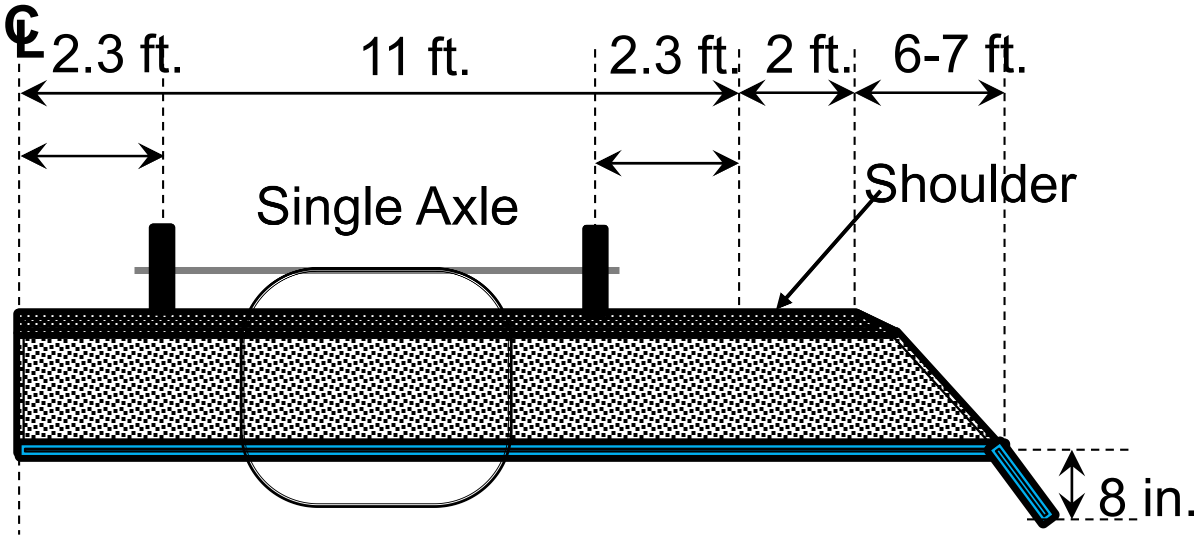
E_E = Embodied Energy

GW_P = Global Warming Potential

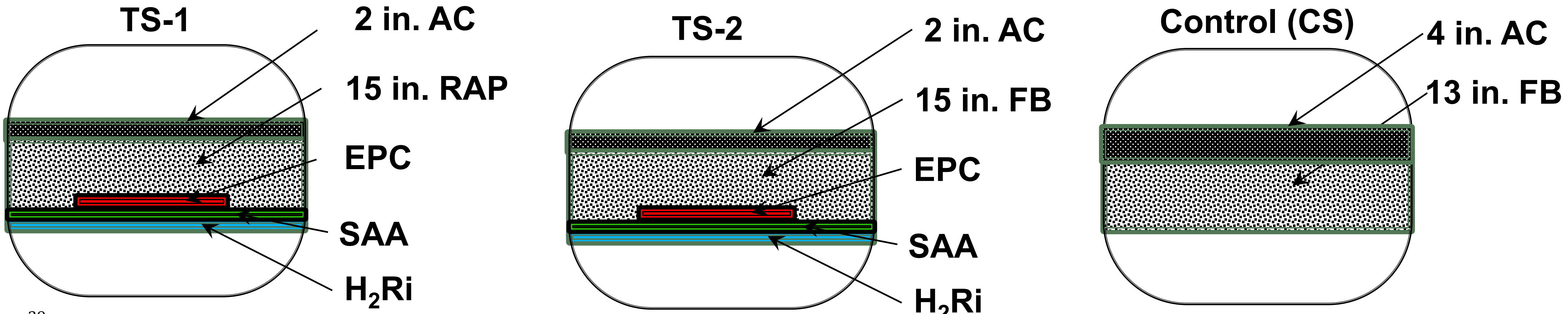
C = Cost of the process

Test ID	A	B	C
Section ID	TS-1	TS-2	Control
Section Parameters	15 in. RAP + 2 in. AC + H_2Ri gtx	15 in. FB + 2 in. AC + H_2Ri gtx	13 in. FB + 4 in. AC
Section Length	3.3 m	3.3 m	3.3 m
Section Width	15 ft.	15 ft.	15 ft.

Field Test Sections – FM1807 Venus, Texas



AC – Asphalt Concrete RAP - Reclaimed Asphalt Pavement Aggregates FB - Flex Base
EPC - Earth Pressure Cells SAA - Shape Array Sensors



Field Test (In-situ Observations)

- ❖ Section A & B shows no surface distresses except for some cracks on shoulders.
- ❖ Section C has some visible distresses on the outer wheel path.

Section A

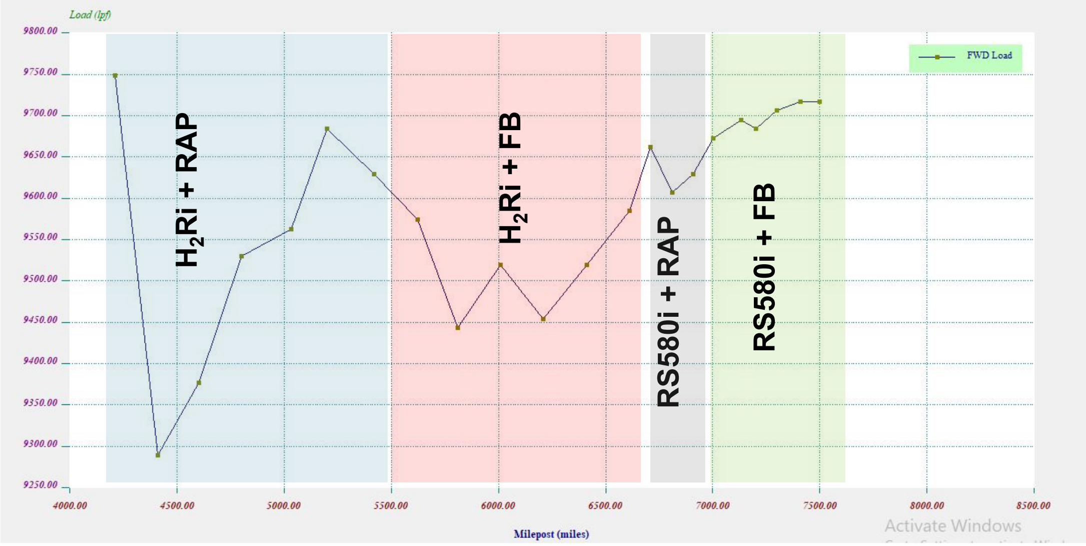
Section B

Section C

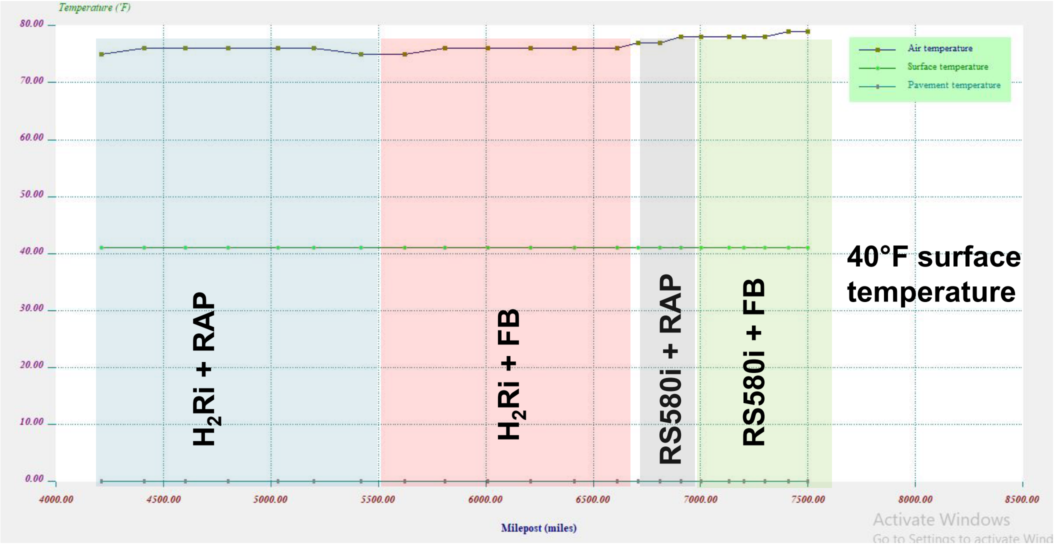
Falling Weight Deflectometer Tests – February 2024

FWD Test on Field Test Sections

Drop Weight at each Station (lbf)



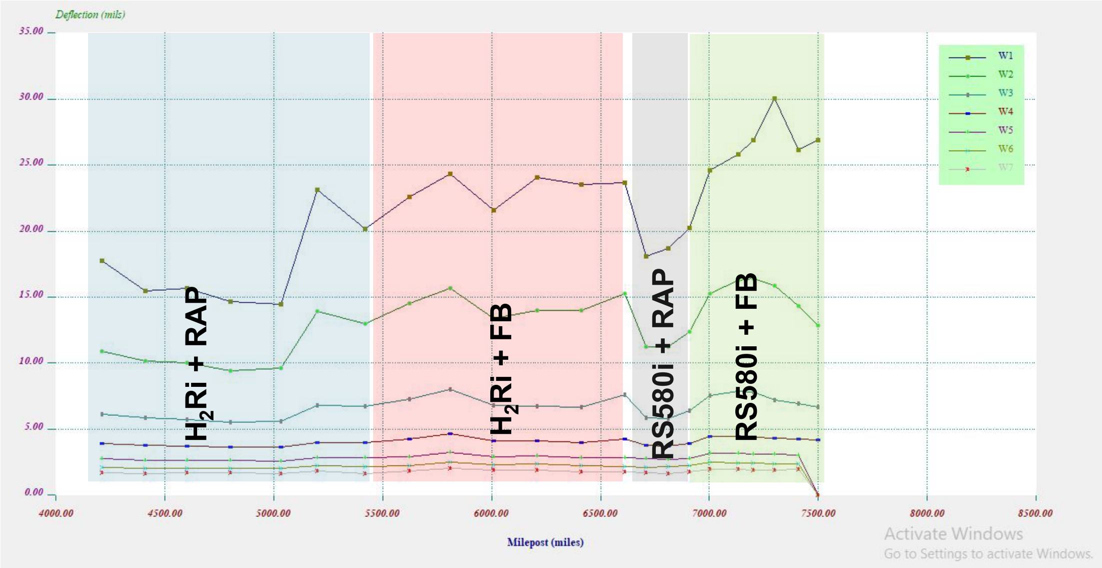
Pavement and Air Temperature



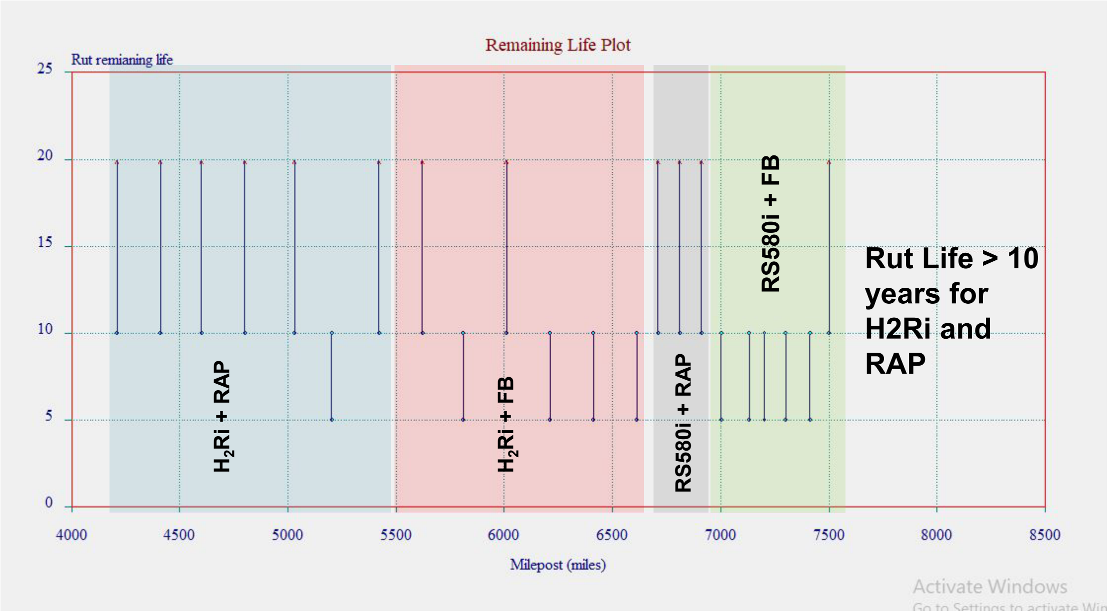
❖ Deformations measured using 7 sensors (D1-D7)

Falling Weight Deflectometer Tests - Results

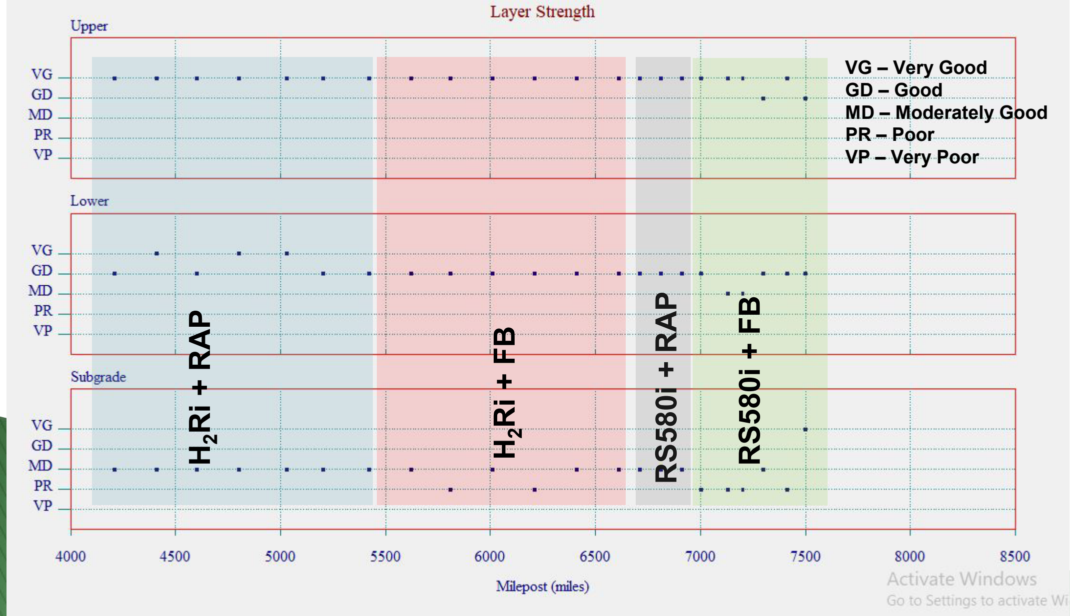
Deformation for sensors (D1-D7)



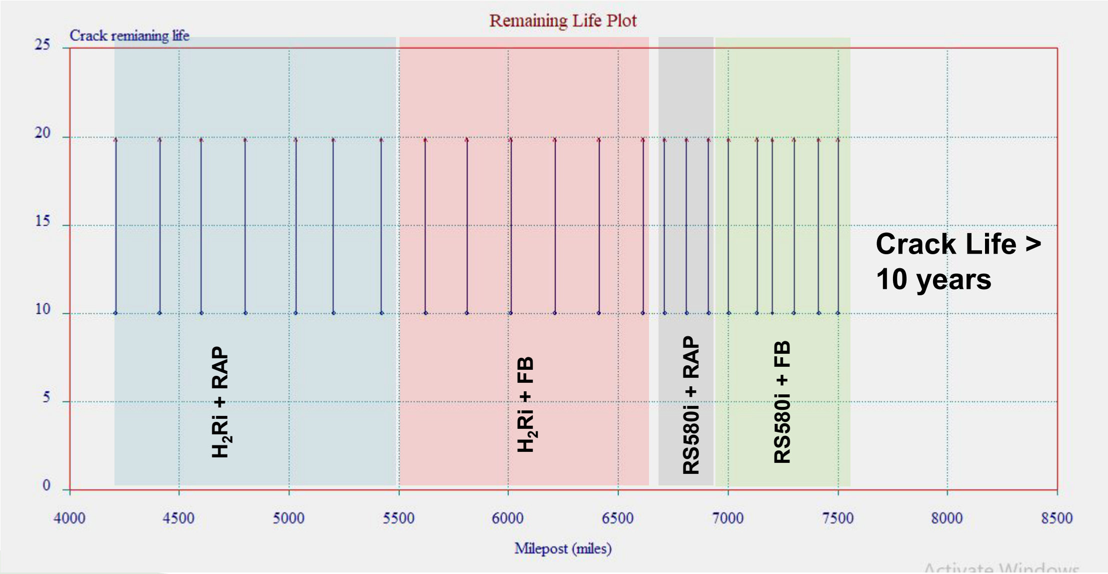
Remaining Rut-Life



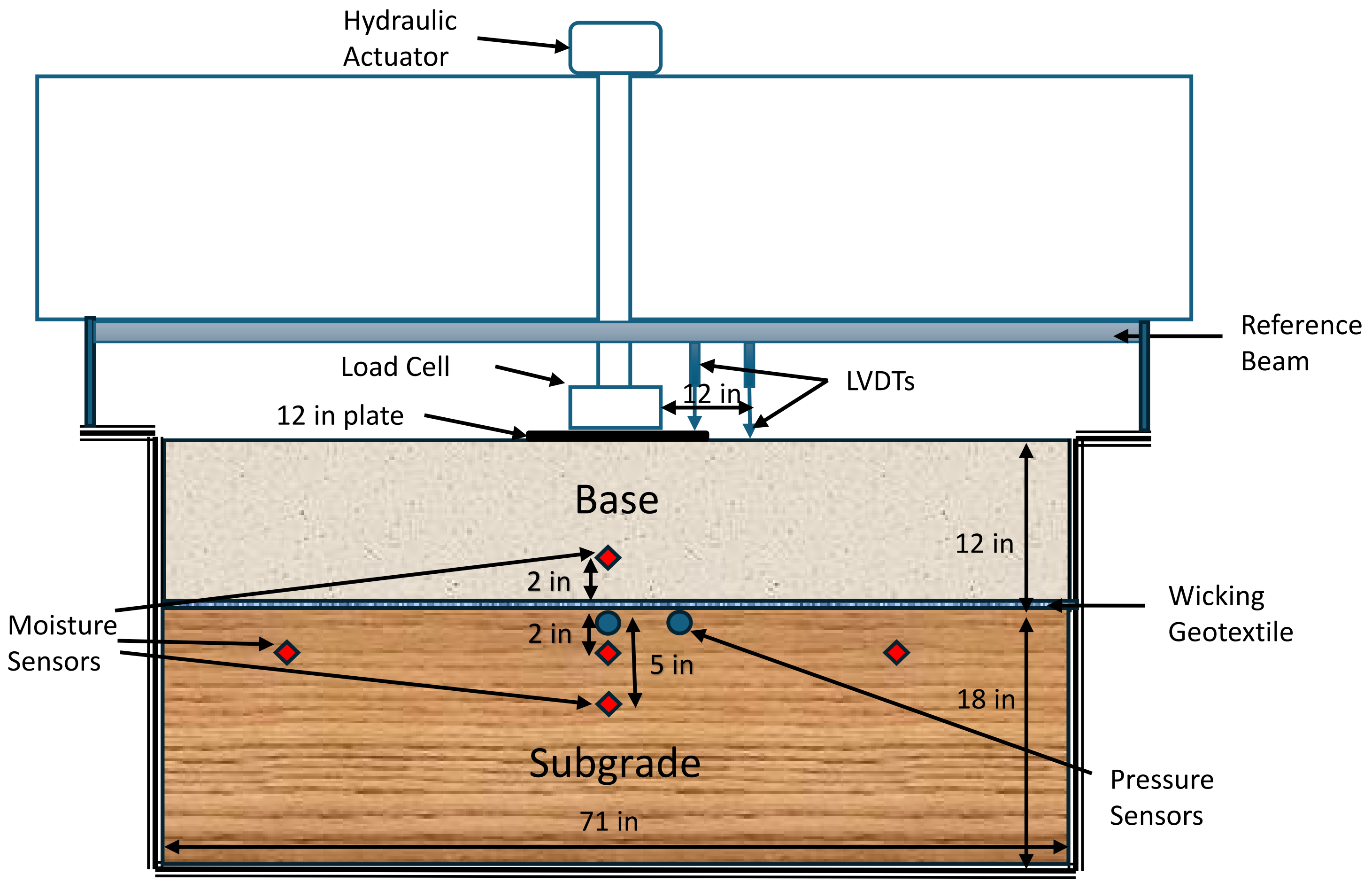
Layer Conditions



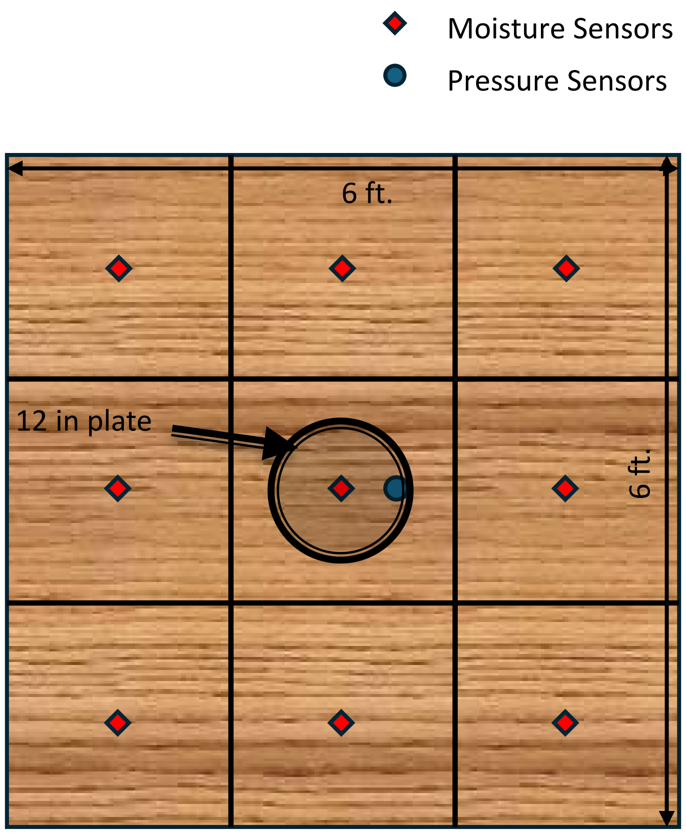
Remaining Crack-Life



Schematic of Large Box Setup

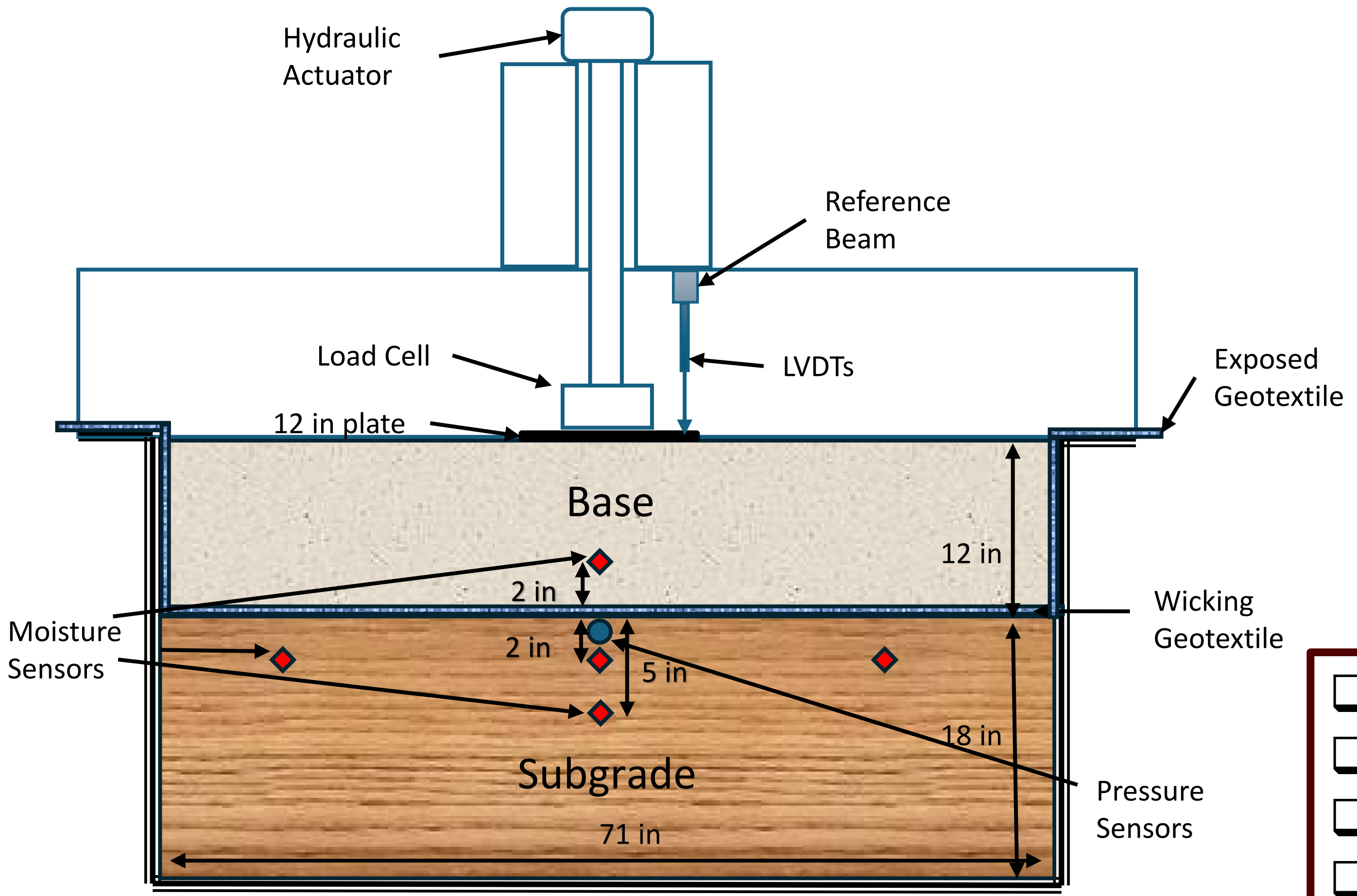


Front View

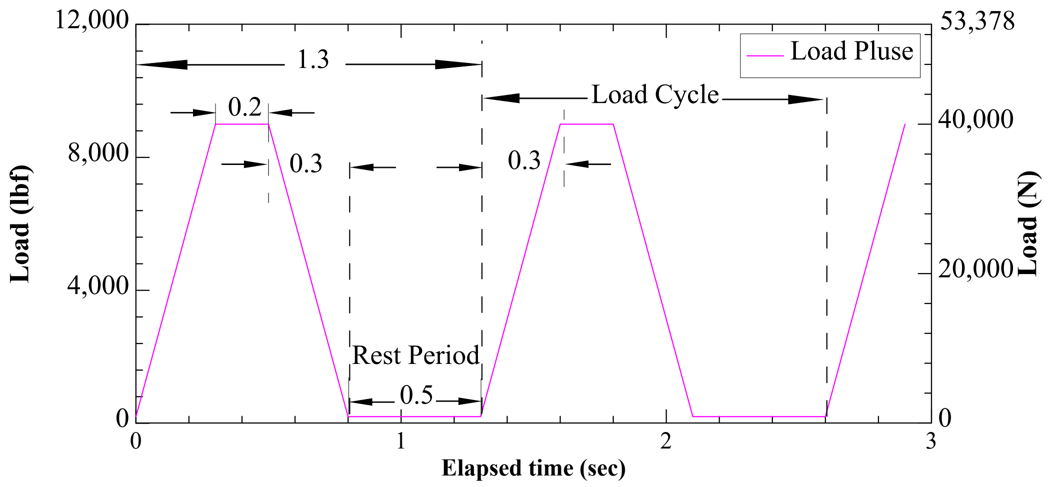


Top View

Schematic of Large Box Setup



Side View



Repeated load pulse

- ❑ Frequency of loading: 0.77 Hz
- ❑ Peak load: 9000 lbf
- ❑ Loading plate diameter: 12 in.
- ❑ Instrumentation: Load cell, pressure sensors, Multiple LVDTs and strain gauges

Box Construction

- ❖ The box will be filled with subgrade and compacted in layers after mixing the soil at OMC and saturated after the construction
- ❖ Geotextile → interface of subgrade and base layers
- ❖ The test sections will equipped with moisture sensors and LVDTs
- ❖ Quality control during construction:
    - ➢ Soil core specimens will be collected
    - ➢ Variable energy dynamic cone penetration test (VE-DCP) or traditional DCP
    - ➢ Light Weight Deflectometer (LWD) tests are performed

Box Preparation

❖ **The box is waterproofed at the bottom from the inside and geo membrane is installed for additional protection.**

Future Works

- Need to develop a comprehensive Life Cycle Cost Analysis (LCCA) for the H2Ri geotextile (cradle-to-gate + End-of-life)
- Large Scale Testing is to be performed.