Dynamic Modulus (E*) for Mix and Pavement Design

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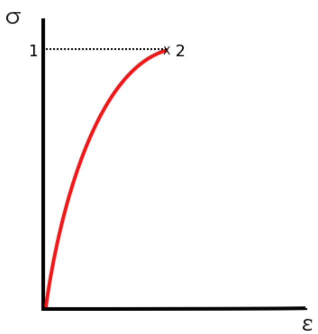
Outline

- What is E*?, Why E* not just E?
- How E* is measured?
- Model Development:
  - Mix parameters
  - Mathematical formulation
  - Regression analysis
  - Validation using field mixes
  - Analysis using MEPDG
- Application
  - Software

2

The Elastic Modulus, E

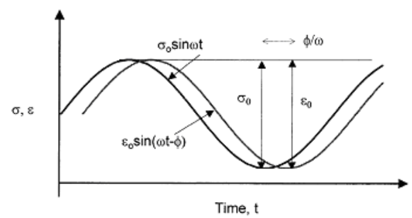


3

The Dynamic Modulus (E*)

The dynamic modulus is defined as the absolute value of the Complex Modulus (E*), which is the ratio of stress / strain for a linear **visco-elastic** material.

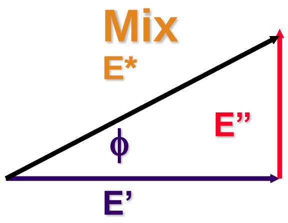
$$|E^*| = \frac{\sigma_o}{\varepsilon_o}$$



Why E* ?

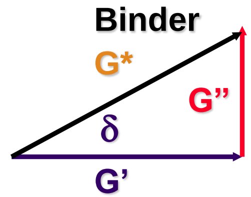
E* (Dynamic modulus) accounts for the viscous component as well.

E (elastic modulus) ≅ E' when the phase angle ϕ is zero.



Why E* ?

E* is a function of:
Binder G*, and
Aggregate properties



Most likely the viscous element will be affected by the binder, while the elastic component by both (binder and aggregates)

The Dynamic Modulus (E*) Test

- AASHTO TP 62-03 Test Protocol.
- Test Temperatures: 14, 40, 70, 100 and 130 °F.
- Loading frequencies: 0.1, 0.5, 1, 5, 10 and 25 Hz @ each temperature.

E* Sample Preparation

Dynamic Modulus Test

Typical Results

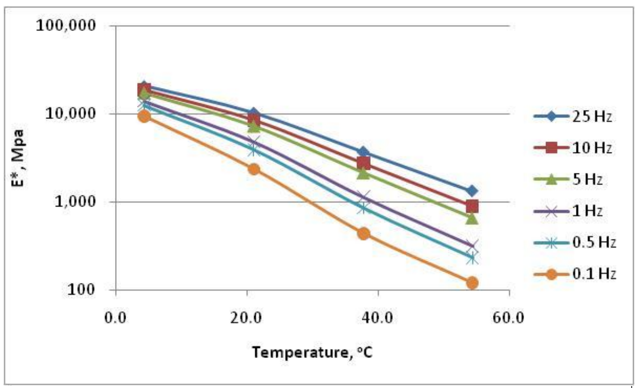
E* (MPa) vs. Temp and Frequency

Temp, °C	25 Hz	10 Hz	5 Hz	1 Hz	0.5 Hz	0.1 Hz
4.4	20,683	18,784	17,345	14,070	12,619	9,531
21.1	10,257	8,518	7,284	4,846	3,964	2,383
37.8	3,694	2,743	2,145	1,137	863	442
54.4	1,331	895	660	318	235	121

10

Typical Results

E* vs. Temp and Frequency



11

E* Modeling

12

Empirical Models

- Asphalt Institute Method (Shook and Kallas 1969)
- Witczak Models (Witczak 1978, Miller et al. 1983, Witczak and Fonesca 1996 & Bari and Witczak 2006)
- Christensen et al. (2003)

Witczak's 1996 Model

$$\log E^* = -1.25 + 0.029P_{200} - 0.0018(P_{200})^2 \ldots$$
$$+ 0.0028P_4 - 0.058V_a - 0.822\frac{V_{beff}}{V_{beff}+V_a} \ldots$$
$$+ \frac{3.872 + 0.0021P_4 + 0.004P_{38} - 0.000017(P_{38})^2 + 0.0055P_{34}}{1+\exp(-0.603313 - 0.313351\log f - 0.393532\log\eta)}$$

where,
E = dynamic modulus of mix, 10^5 psi.
P_{200} = percent aggregate passing #200 sieve.
P_4 = percent aggregate retained on #4 sieve.
P_{38} = percent aggregate retained on 3/8 inch sieve.
P_{34} = percent aggregate retained on 3/4 inch sieve.
V_a = percent of air voids in the mix by volume.
V_{beff} = percent of effective binder content by volume.
f = loading frequency, Hz.
η = asphalt viscosity at any temperature and degree of aging, 10^6 poises.

This Model is used in ME-PDG Level 3

Witczak's 2006 Model

$$\log_{10} E^* = -0.349 + 0.754\left(|G_b^*|^{-0.0052}\right) \ldots$$
$$\times \left(\begin{array}{l} 6.65 + 0.032P_{200} + 0.0027(P_{200})^2 + 0.011P_4 - 0.0001(P_4)^2 \\ + 0.006P_{38} - 0.00014(P_{38})^2 - 0.08V_a - 1.06\frac{V_{beff}}{V_{beff}+V_a} \end{array} \right) \ldots$$
$$+ \frac{2.56 + 0.03V_a + 0.71\frac{V_{beff}}{V_{beff}+V_a} + 0.012P_{38} - 0.0001(P_{38})^2 + 0.01P_{34}}{1+\exp(-0.7814 - 0.5785\log|G_b^*| + 0.8834\log\delta_b)}$$

where,
G_b^* = binder's dynamic shear modulus
δ_b = binder's phase angle

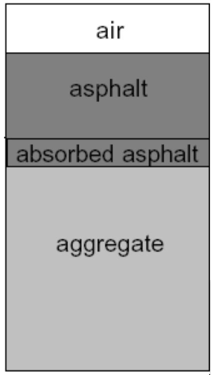
Our Goal

was to develop a **simple model** that predicts HMA Dynamic Modulus (E*) using the constituents of the asphalt mix and their interactions.

Factors Affecting the Dynamic Modulus of Asphalt Mixes

- Binder
- Aggregates
- Air voids

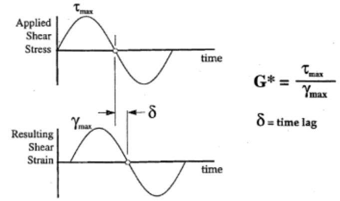
(Interaction?)

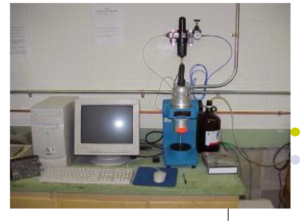


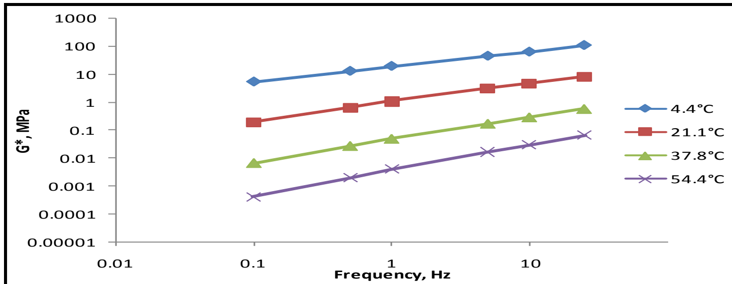
Asphalt Binder Properties

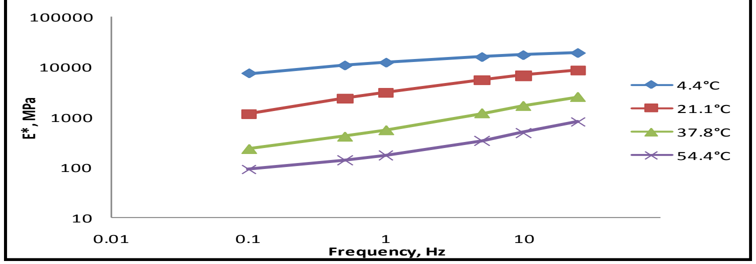
Asphalt Binder Shear Modulus (G*).

Measured by the Dynamic Shear Rheometer.







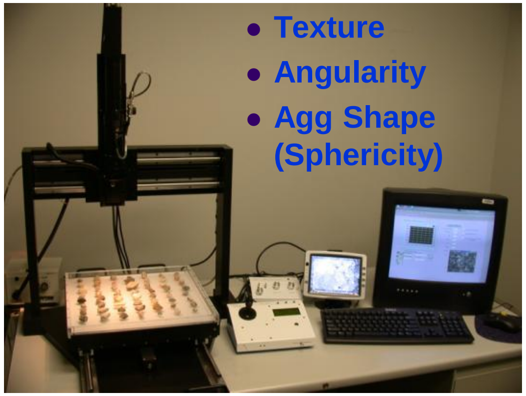


Aggregates Properties

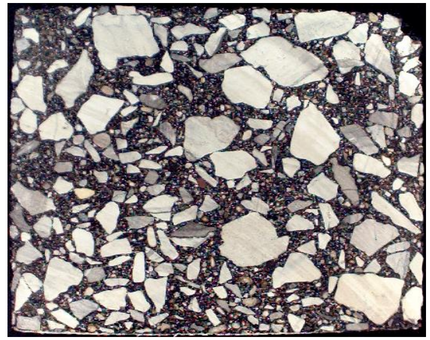
- Size,
- Shape (e.g. Angularity),
- Texture, and
- Structure.

Aggregate Shape Characteristics and CEI

- Texture
- Angularity
- Agg Shape (Sphericity)

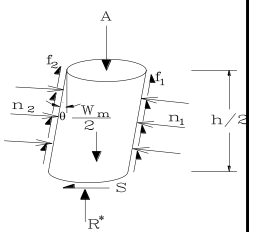


Mix Image



25

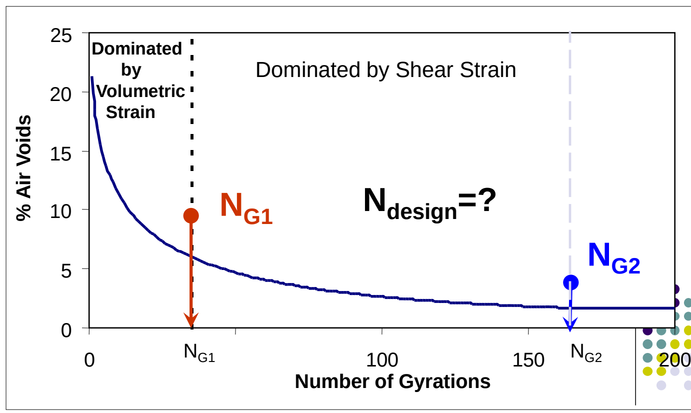
Aggregates Properties



Measured by the Gyratory Stability (GS)

$$\text{Gyratory Stability, } GS = \sum_{N_{G1}}^{N_{design}} S_{N\theta} \cdot d_e$$

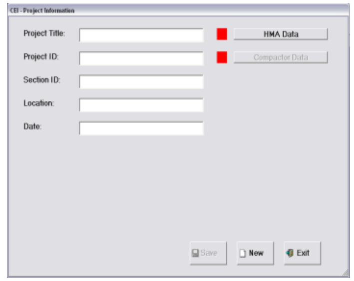
Analysis of the Compaction Curve



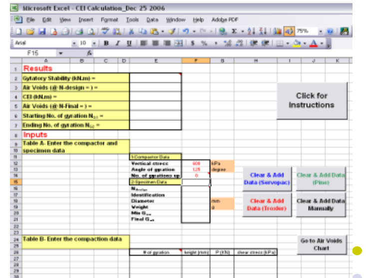
Gyratory Stability

$$GS = \sum_{N_{G1}}^{N_{design}} S_{N\theta} \cdot \Delta d_e$$

Gyratory Stability Software



Visual Basic Software



Excel File w/ Macros

Model Formulation

Variables	Units	Dimensions (L,M,T)
Asphalt Mix Dynamic Modulus, E*	MPa	$ML^{-1}T^{-2}$
Binder Dynamic Shear Modulus, G*	MPa	$ML^{-1}T^{-2}$
Gyratory Stability, GS (Compaction Energy)	kN.m	$ML^{2}T^{-2}$
Air voids, AV%	-	-
Binder Content, P_b Or Aggregates Content, P_s	-	-

n = 5 **m = 3**

PI Groups

Dimensional product = n - m = 5 - 3 = 2 (π_1 and π_2).

- Binder effects:

$$\pi_1 = \frac{P_b.E^*}{G^*} = \frac{ML^{-1}T^{-2}}{ML^{-1}T^{-2}}$$

- Aggregates effects:

$$\pi_2 = \frac{P_s.E^*}{GS} = \frac{ML^{-1}T^{-2}}{ML^{2}T^{-2}} = L^{-3}$$

PI Groups *(cont.)*

π_2 must be dimensionless. Therefore,

$$\pi_2 = \frac{P_s.E^*}{GS}.V = \frac{ML^{-1}T^{-2}}{ML^2T^{-2}}.L^3$$

$$V = V_{se} + V_b + V_v$$

$$V = \frac{P_s}{G_{se}.\rho_w} + \frac{P_b}{G_b.\rho_w} + AV\%.V$$

$$G_{mm} = \frac{1}{\frac{P_s}{G_{se}} + \frac{P_b}{G_b}}$$

$$V = \frac{1}{\rho_w G_{mm}.(1-AV\%)} = \frac{1}{\rho_w G_{mb}}$$

PI Groups *(cont.)*

In summary,

$$\pi_1 = \frac{P_b.E^*}{G^*}$$

$$\pi_2 = \frac{(1-P_b).E^*}{\rho_w.GS.G_{mb}}$$

$$\pi_1 = f(\pi_2) \rightarrow \frac{P_b.E^*}{G^*} = f\left(\frac{(1-P_b).E^*}{\rho_w GS.G_{mb}}\right) = \frac{1}{\frac{(1-P_b).E^*}{\rho_w GS.G_{mb}}}$$

$$E^* = a\left(\frac{G^*}{P_b}.\frac{\rho_w.GS.G_{mb}}{(1-P_b)}\right)^b$$

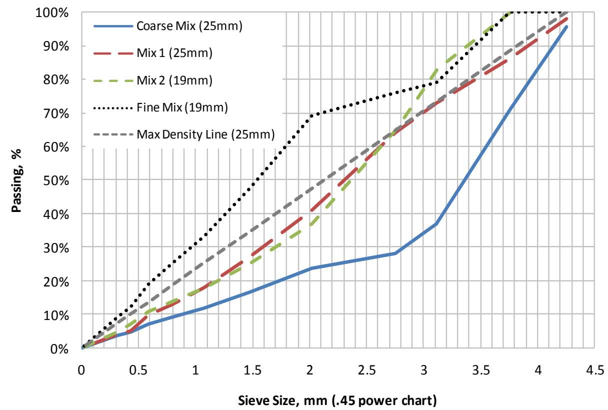
Lab Mix Matrix

Asphalt Content	-0.5	Opt	0.5	-0.5	Opt	0.5	-0.5	Opt	0.5
Binder Grade	PG 70-34			PG 70-28			PG 70-22		
Coarse Mix					√				
Mix 1		√		√	√	√		√	
Mix 2		√			√				
Fine Mix					√				
	PG 64-34			PG 64-28			PG 64-22		
Mix 1					√				
Mix 2	√	√	√		√			√	
	PG 58-34			PG 58-28					
Mix 1					√				
Mix 2		√							

34

Lab Mixes –

Selected Aggregate Structures



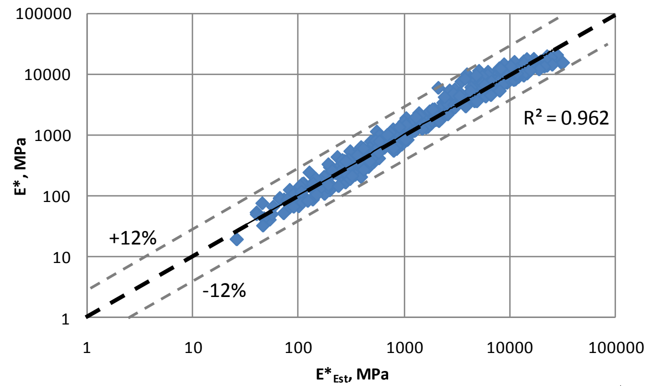
35

Proposed Model

$$E^* = 1.08\left(\frac{G^*.GS.G_{mb}}{P_b\,(1-P_b)}\right)^{0.5583}$$

where,
E*: Dynamic Modulus for Asphalt Mix, MPa,
G*: Dynamic Shear Modulus for RTFO Aged Binder, MPa,
P_b: Percent Binder Content,
GS: Gyratory Stability, kN.m,
G_{mb}: Bulk Specific gravity of Mix, $G_{mb} = G_{mm}$ (1-AV%),
G_{mm}: Maximum Specific gravity of Mix, and
AV%: Air Voids.

Data Analysis



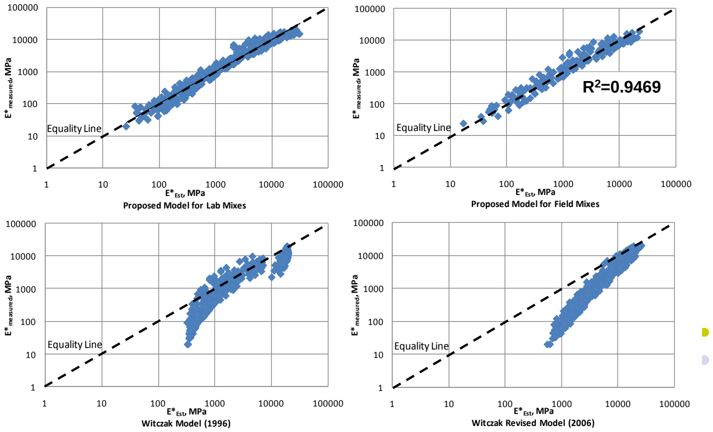
MODEL VALIDATION

Field Mixes

Mix ID	1	2	3	4	5	6	7
Class	SP4	SP3	SP3	SP2	SP3	SP3	SP3
ESALs	> $30x10^6$	3 - $30x10^6$	3 - $30x10^6$	0.3 - $3x10^6$	3 - $30x10^6$	3 - $30x10^6$	3 - $30x10^6$
N-design	125	100	100	75	100	100	100
Mix Properties							
PG	70-28	64-34	70-28	58-34	70-28	70-28	70-28
Gmm	2.449	2.424	2.568	2.480	2.448	2.581	2.460
Pb%	4%	4%	4%	4%	4%	3.5%	3.5%
Gb	1.021	1.025	1.034	1.009	1.021	1.036	1.036
Gsb	2.586	2.558	2.771	2.731	2.589	2.822	2.822
Sieves	%Passing						
25mm (1")	98%	100%	100%	100%	100%	100%	98%
19 mm (3/4")	86%	100%	97%	100%	100%	100%	90%
12.5mm (1/2")	73%	83%	83%	95%	79%	96%	74%
9.5mm (3/8")	64%	65%	71%	78%	66%	87%	66%
4.75mm (#4)	41%	37%	51%	53%	45%	58%	40%
2.36mm (#8)	27%	25%	34%	35%	32%	36%	25%
1.18mm (#16)	18%	18%	23%	22%	23%	22%	16%
600μm (#30)	13%	14%	16%	15%	16%	17%	12%
300μm (#50)	10%	11%	11%	12%	9%	13%	10%
150μm (#100)	5%	7%	8%	9%	5%	8%	7%
75μm (#200)	4.0%	4.7%	5.9%	6.8%	4.0%	6.4%	5.7%

39

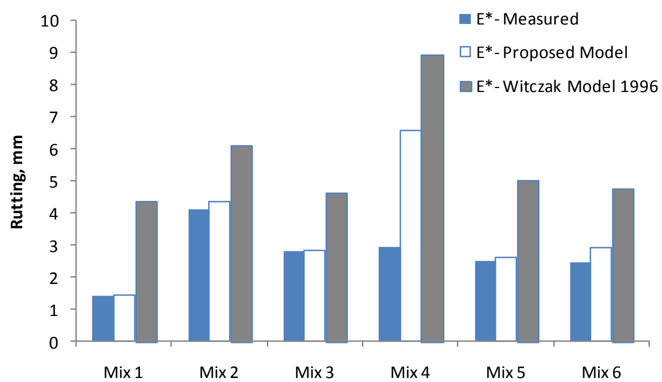
E* Predicted vs. Measured



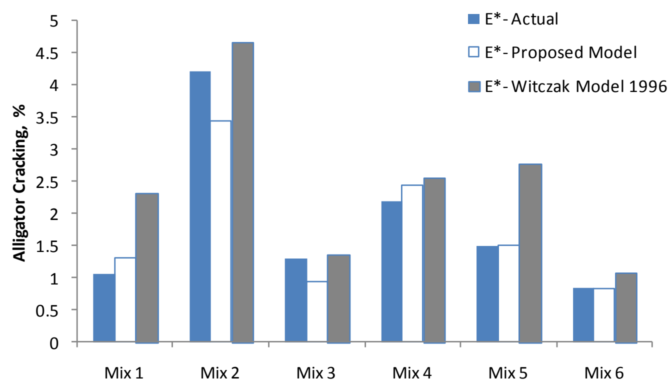
Application to M-E PDG

41

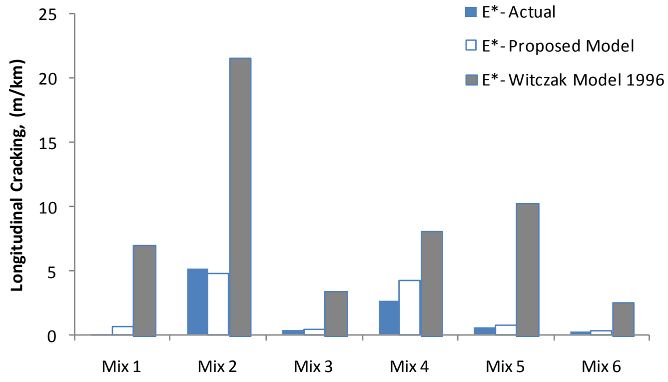
Prediction of Permanent Deformation Using MEPDG



Prediction of Alligator Cracking Using MEPDG



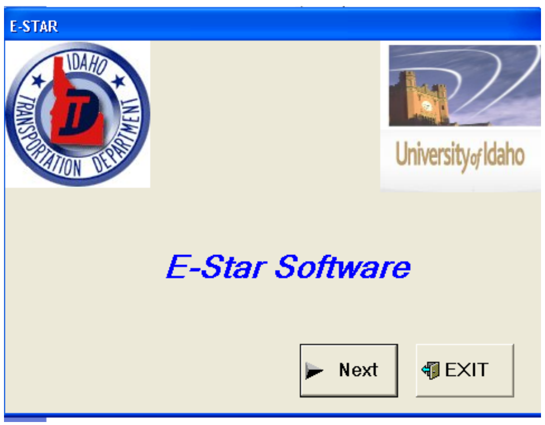
Prediction of Longitudinal Cracking Using MEPDG



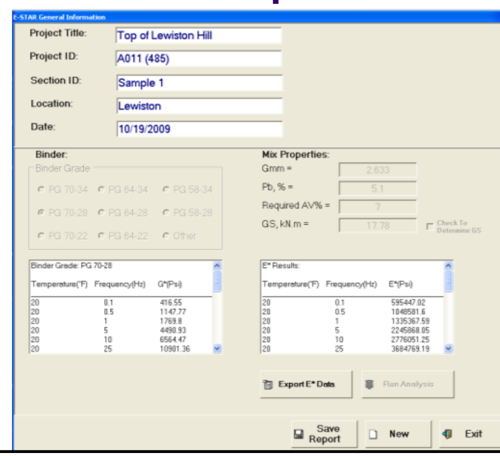
In Summary

1. E* is a mix property that depends on **binder grade** and **content**, **aggregates properties** and **mix structure**.
2. Dimensional analysis was used to develop the mathematical form of the E* model. The model was found to be dependent on: **GS**, **Pb**, **Gmb**, and **Binder G*.**
3. Regression analysis showed R^2 equal to 0.962.
4. MEPDG runs showed predicted distresses with E* from the model were closer to the measured values than Level 3.

E* Software



E* Software Output



47

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- We acknowledge support provided by all these organizations:
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  - UI – NIATT
  - UI – Civil Engineering

48

Project Team

- **Fouad Bayomy (PI),** Phase A – Deformation Studies, and overall project phases
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- **Richard Nielsen (Co-PI),** Reliability Studies
- **Thomas Weaver (Co-PI),** Constitutive Modeling
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  - Baek, Seung Il
  - Prashant Darveshi
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  - Ned Parrish (Research Mgr)
- **USDOT**
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  - Ed Weiner, COTR
  - Peter Belenky, COTR
  - Paul Ziman (FHWA, Boise Office)
- **External Testing**
  - Idaho Asphalt Supply, Inc.
- **NIATT and CE Support**
  - Judy LaLonde
  - Tami Noble
  - Don Parks
  - Undergraduate Students: Frank Eckwright

49

Questions?