Evaluation of Resilient Modulus from Basic Soil Properties

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Contents

- ❑ Objectives
- ❑ Background
- ❑ Testing Program
- ❑ Analysis & Results
- ❑ Conclusions
- ❑ Questions

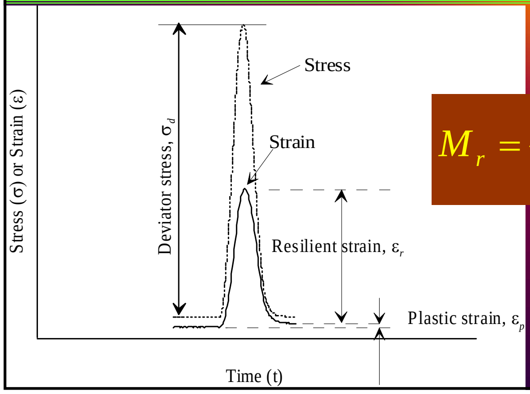
Objectives

- ❑ To develop a methodology for estimating the resilient modulus of various Wisconsin subgrade soils from basic soil properties for use/implementation in the Mechanistic-Empirical pavement design

Methods of Determining the Resilient Modulus of Subgrade Soils

- ❑ Laboratory tests
  - ❑ Repeated load triaxial test (recommended by AASHTO)
- ❑ In-situ nondestructive test (NDT) methods
  - ❑ Dynaflect
  - ❑ Falling Weight Deflectometer (FWD)
  - ❑ Light Drop Weight (LDW)

Resilient Modulus - Repeated Load Triaxial



$$M_r = \frac{\sigma_d}{\varepsilon_r}$$

Resilient Modulus – Flexible Pavement Design

AASHTO 1986 and 1993 design guides recommended the use of the resilient modulus to characterize subgrade soils

$$\log_{10} W_{18} = Z_R S_o + 9.36 \log_{10}(SN+1) - 0.20 + \frac{\log_{10}\left(\frac{\Delta PSI}{4.2-1.5}\right)}{0.40 + \frac{1094}{(SN+1)^{5.19}}} + 2.32 \log_{10} M_R - 8.07$$

AASHTO Mechanistic-Empirical Pavement Design Input Parameters

Level 1
- ❑ Most accurate
- ❑ Highest reliability and lowest uncertainty
- ❑ Conduct laboratory/field testing for project specified
- ❑ Extensive effort
- ❑ Increased cost

Level 2
- ❑ Intermediate accuracy
- ❑ Development of correlations

Level 3
- ❑ Lowest accuracy
- ❑ Highest uncertainty
- ❑ Based on average values in the region
- ❑ Low traffic volume

AASHTO Mechanistic-Empirical Pavement Design

MATERIAL	INPUT LEVEL 1	INPUT LEVEL 2	INPUT LEVEL 3
Asphalt concrete	Measured dynamic modulus	Estimated dynamic modulus	Default dynamic modulus
Portland cement concrete	Measured elastic modulus	Estimated elastic modulus	Default elastic modulus
Stabilized materials	Measured modulus	Estimated modulus	Default modulus
Granular materials	Measured resilient modulus	Estimated resilient modulus	Default resilient modulus
Subgrades	Measured resilient modulus	Estimated resilient modulus	Default resilient modulus

AASHTO Mechanistic-Empirical Pavement Design

Universal nonlinear model for unbound pavement materials from clayey subgrade to granular bases (NCHRP 1-28A)

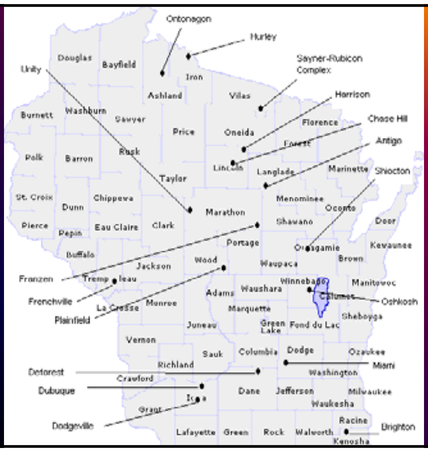
$$M_r = k_1 p_a \left(\frac{\sigma_b}{p_a}\right)^{k_2} \left(\frac{\tau_{oct}}{p_a} + 1\right)^{k_3}$$

Research Methodology

- ❑ Literature Review on Resilient Modulus of Subgrade Soils
  - ❑ Fundamental aspects of resilient modulus
  - ❑ Factors affecting resilient modulus
  - ❑ Resilient modulus models
  - ❑ AASHTO mechanistic-empirical pavement design
  - ❑ LTPP resilient modulus investigation

Research Methodology

- ❑ Selection of a Wide Spectrum of Subgrade Soils that Comprise Core Soil Types in Wisconsin
  - ❑ Identified by WisDOT
  - ❑ 19 different soil samples were collected



Soil Samples

Research Methodology

- ❑ Evaluate the Effects of Soil Properties and Stress Levels on the Resilient Modulus of Wisconsin Subgrade Soils
  - ❑ Soils were subjected to laboratory testing:
    - ➢ Physical properties
    - ➢ Compaction characteristics
    - ➢ Repeated load triaxial test (resilient modulus)

Laboratory Testing – Physical Properties

- Particle Size Distribution
  - Sieve Analysis
  - Hydrometer Analysis
- Atterberg Limits
  - Plastic Limit
  - Liquid Limit
- Soil Classification
  - Unified Soil Classification System
  - AASHTO Soil Classification (Group Index)
- Specific Gravity
- Organic Content

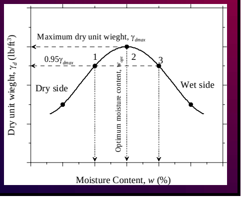
Laboratory Testing – Compaction

- Standard Proctor Compaction Test (AASHTO T 99)
  - Maximum Dry Unit Weight (γ_{dmax})
  - Optimum Moisture Content (w_{opt})

Laboratory Testing – Physical Properties

Laboratory Testing – Repeated Load Triaxial Test (Resilient Modulus)

- Repeated Load Triaxial Test (AASHTO T307)
- Each soil was subjected to testing at:



- γ_{dmax} and w_{opt}
- 95% γ_{dmax} ➔ on the dry side
- 95% γ_{dmax} ➔ on the wet side

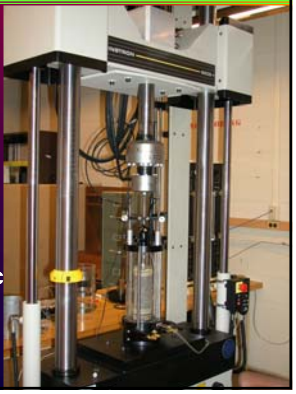
Repeated Load Triaxial Test System

Sample Preparation – AASHTO T 307
1.4, 2.8 and 4.0” Diameter

Preparation of Soil Specimens

Preparation of Soil Specimens

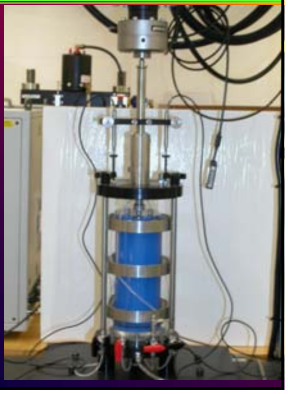
Repeated Load Triaxial Test System



UWM System:

- 8802 Instron closed loop servo-hydraulic dynamic materials test system
- 56-kip 6 inch stroke actuator
- 1,000 and 250 lb dynamic load cells
- Environmental chamber

Repeated Load Triaxial Test System



UWM System:

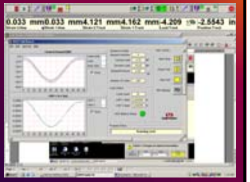
- 1.4, 2.8 and 4.0” diameter samples
- High accuracy LVDTs
- Pore pressure transducers
- Pressure panel and volume change measurements

Repeated Load Triaxial Test System

UWM System: Computer Controlled Testing & Resilient Modulus Software

Repeated Load Triaxial Test System

UWM System: Computer Controlled Testing & Resilient Modulus Software



Investigated Soils

Location of investigated soil and horizon	Passing Sieve #200 (%)	Liquid Limit LL (%)	Plastic Limit PL (%)	Plasticity Index PI (%)	Specific Gravity G_s	Optimum Moisture Content $w_{opt.}$ (%)	Maximum Dry Unit Weight		Unified Soil Classification System (USCS)	Group Index (GI)	AASHTO Soil Classification
							γ_{dmax} (kN/m^3)	γ_{dmax} (pcf)			
Brighton township, Kenosha Co., series BcA	48	29	17	12	2.67	13.9	18.3	116.5	SC (Clayey sand)	3	A-6 (Clayey soil)
Franzen, Marathon Co., B horizon	29	NP	NP	NP	2.67	8.5	20.1	128.0	SM (Silty sand)	0	A-2-4 (Silty or clayey gravel and sand)
Antigo, Langlade Co.	91	30	19	11	2.63	14.5	17.5	111.4	CL (Lean Clay)	9	A-6 (Clayey soil)
Chase Hill, Lincoln Co.	15	NP	NP	NP	2.62	10.5	19.1	121.6	SM (Silty sand with gravel)	0	A-2-4 (Silty or clayey gravel and sand)
Unity, Marathon Co.	35	35	16	19	2.59	15.7	17.4	110.8	SC (Clayey sand)	2	A-2-6 (Silty or clayey gravel and sand)
Shiocton, Outagmie Co., series ShA, C horizon	41	NP	NP	NP	2.69	11.2	15.9	101.3	SM (Silty sand)	0	A-4 (Silty soil)
Harrison, Lincoln Co., series PeB.	22	NP	NP	NP	2.66	8.5	19.1	121.6	SM (Silty sand with gravel)	0	A-2-4 (Silty or clayey gravel and sand)
Hurley, Iron County	32	NP	NP	NP	2.61	19.0	15.5	98.7	SM Silty sand	0	A-2-4 (Silty or clayey gravel and sand)

Investigated Soils

Soil Type, Location and Horizon	Passing Sieve #200 (%)	Liquid Limit LL (%)	Plastic Limit PL (%)	Plasticity Index PI (%)	Specific Gravity G_s	Optimum Moisture Content $w_{opt.}$ (%)	Maximum Dry Unit Weight		Unified Soil Classification System (USCS)	Group Index (GI)	AASHTO Soil Classification
							γ_{dmax} (kN/m^3)	γ_{dmax} (pcf)			
Dodgeville silt loam, series DhB2, Iowa Co., B	97	37	25	12	2.55	18.8	16.1	102.5	CL (Lean clay)	13	A-6 (Clayey soil)
Miami silt loam, series MyC2, Dodge Co., B	96	39	22	17	2.57	18.1	16.6	105.7	CL (Lean clay)	18	A-6 (Clayey soil)
Ontonagon clay1 Ashland Co., C	31	42	20	22	2.63	17.5	17.5	111.4	SC (Clayey sand)	2	A-2-7 (Silty or clayey sand and gravel)
Ontonagon clay2 Ashland Co., C	26	47	22	25	2.64	22.0	16.0	101.9	SC (Clayey sand)	2	A-2-7 (Silty or clayey sand and gravel)
Plainfield sand, Wood Co., C	2	NP	NP	NP	2.65	X	X	X	SP (Poorly graded sand)	0	A-3 (Fine sand)
Deforest, Dane Co., PnB, C horizon	27	NP	NP	NP	2.66	7.8	20.5	130.5	SM (Silty sand)	0	A-2-4 (Silty or clayey sand and gravel)
Oshkosh, Winnebago Co., series KmB, B horizon	30	NP	NP	NP	2.64	12.7	18.2	115.9	SM (Silty sand)	0	A-2-4 (Silty or clayey sand and gravel)
Oshkosh, Winnebago Co., series KmB, C horizon	48	28	14	14	2.69	13.5	19.0	121.0	SC (Clayey sand)	3	A-6 (Clayey soil)

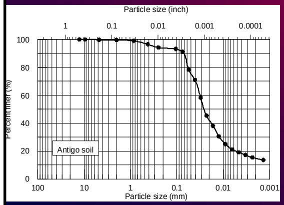
Investigated Soils

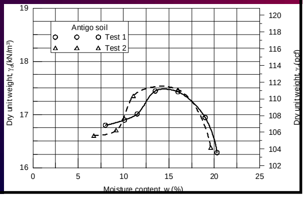
Soil Type, Location and Horizon	Passing Sieve #200 (%)	Liquid Limit LL (%)	Plastic Limit PL (%)	Plasticity Index PI (%)	Specific Gravity G_s	Optimum Moisture Content $w_{opt.}$ (%)	Maximum Dry Unit Weight		Unified Soil Classification System (USCS)	Group Index (GI)	AASHTO Soil Classification
							γ_{dmax} (kN/m^3)	γ_{dmax} (pcf)			
Dubuque, Iowa Co.	72	35	23	12	2.55	18.0	16.6	105.7	CL (Lean clay)	8	A-6 (Clayey soil)
Frenchville, Trempealeau Co.	20	NP	NP	NP	2.64	7.3	20.4	129.9	SM (Silty sand)	0	A-2-4 (Silty or clayey gravel and sand)
Sayner-Rubicon Complex, Vilas Co.	1	NP	NP	NP	2.65	X	X	X	SP (Poorly graded sand with gravel)	0	A-1 (Stone fragments, gravel and sand)

Laboratory Testing Program

- Tests were repeated to insure consistency of the results
- When test results differ ➔ a third test was conducted
- Resilient modulus was repeated 4 to 5 times on samples to insure test repeatability

Investigated Soils

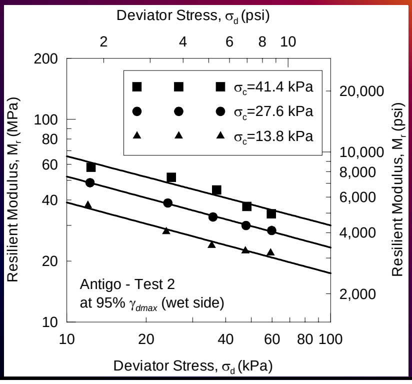




Resilient Modulus Test Results

Test Sequence No.	Confining Stress σ_c (kPa)	Deviator Stress σ_d (kPa)	Antigo wet #1 M_r (MPa) Mean	SD	CV (%)	Deviator Stress σ_d (kPa)	Antigo wet #2 M_r (MPa) Mean	SD	CV (%)
1	41.4	12.45	49.65	0.30	0.60	12.35	57.96	0.24	0.41
2	41.4	24.91	43.30	0.45	1.04	24.92	51.74	0.14	0.28
3	41.4	36.71	36.72	0.08	0.21	36.94	44.83	0.16	0.36
4	41.4	47.90	30.55	0.08	0.25	48.11	37.13	0.07	0.19
5	41.4	59.36	28.33	0.07	0.24	59.67	34.18	0.05	0.15
6	27.6	12.29	40.79	0.17	0.43	12.24	48.69	0.19	0.39
7	27.6	23.98	30.23	0.09	0.28	24.15	38.65	0.18	0.46
8	27.6	35.51	26.00	0.09	0.34	35.82	32.97	0.11	0.33
9	27.6	48.44	24.22	0.07	0.29	47.79	29.92	0.03	0.11
10	27.6	60.25	23.31	0.03	0.14	59.80	28.28	0.04	0.15
11	13.8	12.08	30.67	0.16	0.53	12.02	37.60	0.19	0.51
12	13.8	23.37	21.42	0.05	0.24	23.83	27.92	0.13	0.46
13	13.8	35.81	18.80	0.06	0.31	35.41	23.88	0.11	0.47
14	13.8	48.43	18.57	0.04	0.20	47.53	22.44	0.05	0.22
15	13.8	60.18	18.68	0.05	0.29	59.22	21.91	0.05	0.24

Resilient Modulus Test Results

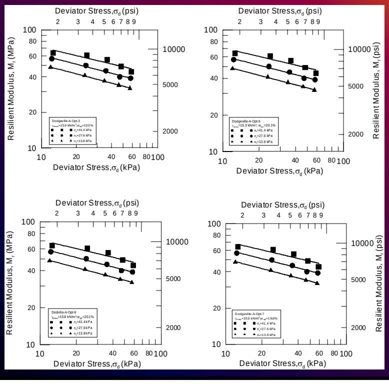


Repeatability of Resilient Modulus Test Results

Dodgeville soil tested at 95% of maximum dry unit weight and moisture content greater than the optimum moisture content (dry side)

Test Sequence	σ_c (kPa)	Test #1 σ_d (kPa)	Test #1 M_r (MPa)	Test #2 σ_d (kPa)	Test #2 M_r (MPa)	Test #4 σ_d (kPa)	Test #4 M_r (MPa)	Mean σ_d (kPa)	Mean M_r (MPa)	CV(σ_d)	CV(M_r)
1	41.4	12.8	109.2	11.9	130.3	12.8	142.3	12.5	127.3	4.4	13.2
2		25.2	126.8	25.4	133.5	25.5	146.4	25.4	135.6	0.5	7.3
3		37.7	133.6	37.6	133.3	38.0	146.5	37.8	137.8	0.6	5.5
4		50.5	133.5	49.7	133.7	50.5	145.7	50.2	137.6	0.9	5.1
5		62.7	131.6	62.2	131.0	63.1	145.3	62.7	136.0	0.7	6.0
6	27.6	12.8	105.0	11.7	125.1	12.2	134.9	12.2	121.7	4.4	12.5
7		25.3	118.7	25.0	126.1	25.3	138.9	25.2	127.9	0.7	8.0
8		37.8	125.1	37.4	125.7	37.7	138.5	37.6	129.8	0.5	5.8
9		50.2	127.1	49.6	124.2	50.3	138.4	50.0	129.9	0.7	5.8
10		62.6	126.8	62.1	123.2	63.3	138.8	62.7	129.6	1.0	6.3
11	13.8	12.4	99.5	11.8	110.8	12.0	123.8	12.1	111.4	2.8	10.9
12		25.0	104.6	24.7	112.4	25.2	126.7	25.0	114.6	1.0	9.8
13		37.3	109.8	37.1	112.2	37.5	127.3	37.3	116.4	0.6	8.2
14		50.0	113.0	49.4	111.7	50.2	127.7	49.9	117.5	0.8	7.5
15		62.4	114.5	61.9	111.5	63.1	128.8	62.5	118.3	1.0	7.8

Repeatability of Resilient Modulus Test Results



Research Methodology

- ❑ **Analyses of Test Results and Development of Models to Predict Resilient Modulus**
  - ❑ **Established accurate resilient modulus test database**
  - ❑ **Selected resilient modulus model**
  - ❑ **Identified main variables for analysis**
  - ❑ **Selected software for the analysis**
  - ❑ **Conducted comprehensive statistical analysis/regression**

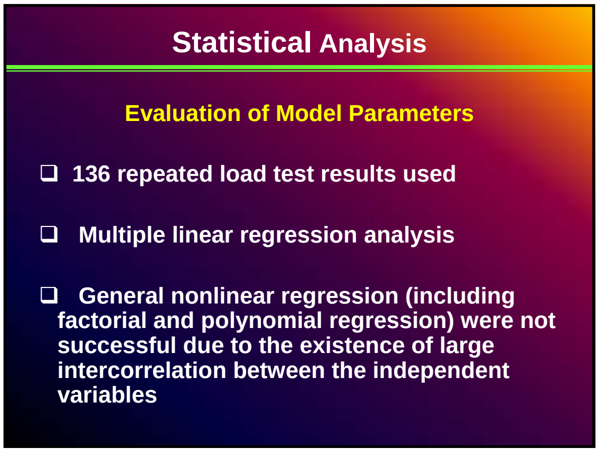
Statistical Analysis

Resilient Modulus Constitutive Model

- ❑ **Project NCHRP 1-28A start the test**
- ❑ **AASHTO M-E Pavement Design**

$$M_r = k_1 p_a \left(\frac{\sigma_b}{p_a}\right)^{k_2} \left(\frac{\tau_{oct}}{p_a} + 1\right)^{k_3}$$

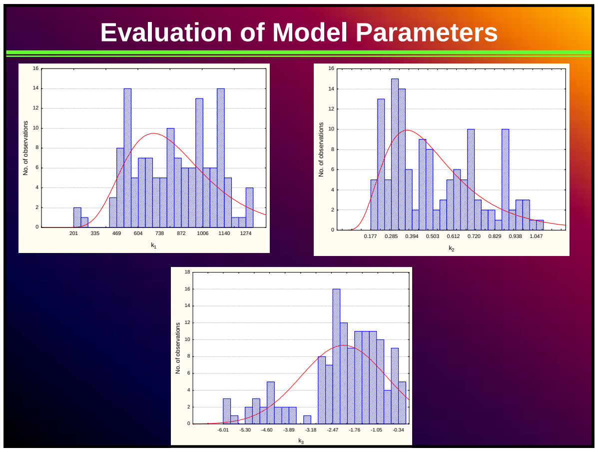
$$\log\left(\frac{M_r}{P_a}\right) = \log k_1 + k_2 \log\left(\frac{\sigma_b}{P_a}\right) + k_3 \log\left(\frac{\tau_{oct}}{P_a} + 1\right)$$



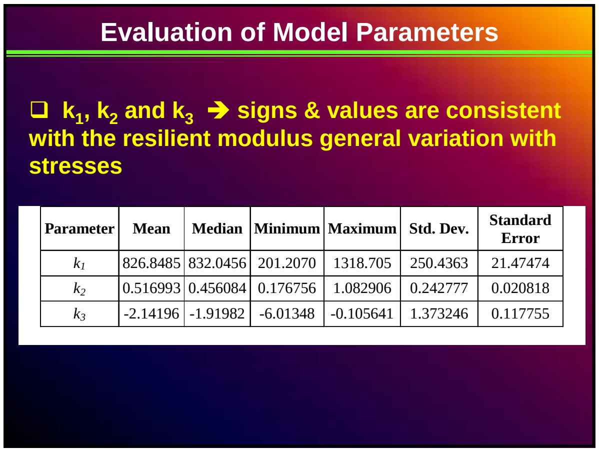
Statistical Analysis

Evaluation of Model Parameters

- ❑ 136 repeated load test results used
- ❑ Multiple linear regression analysis
- ❑ General nonlinear regression (including factorial and polynomial regression) were not successful due to the existence of large intercorrelation between the independent variables



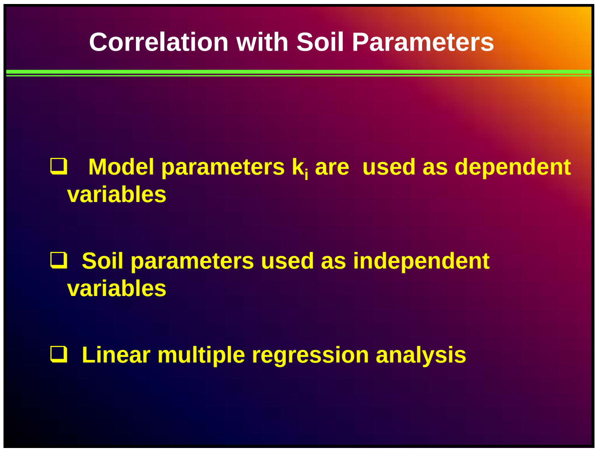
Evaluation of Model Parameters



Evaluation of Model Parameters

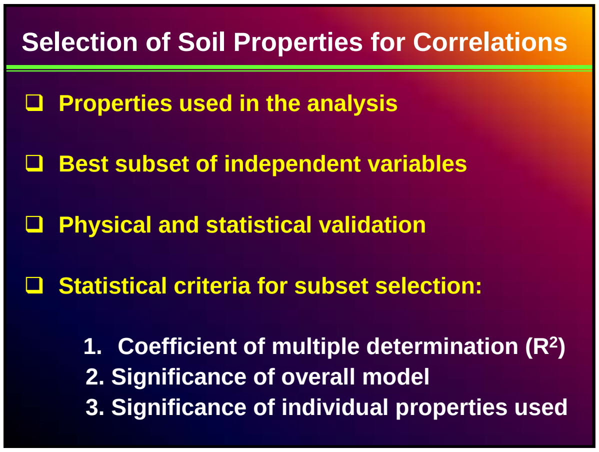
- ❑ k_1, k_2 and k_3 ➔ signs & values are consistent with the resilient modulus general variation with stresses

Parameter	Mean	Median	Minimum	Maximum	Std. Dev.	Standard Error
k_1	826.8485	832.0456	201.2070	1318.705	250.4363	21.47474
k_2	0.516993	0.456084	0.176756	1.082906	0.242777	0.020818
k_3	-2.14196	-1.91982	-6.01348	-0.105641	1.373246	0.117755



Correlation with Soil Parameters

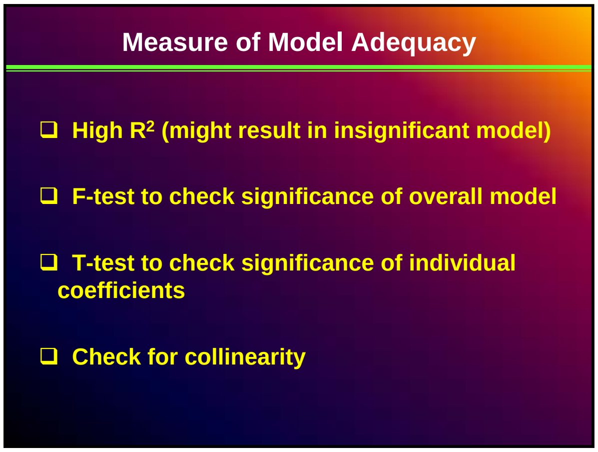
- ❑ Model parameters k_i are used as dependent variables
- ❑ Soil parameters used as independent variables
- ❑ Linear multiple regression analysis



Selection of Soil Properties for Correlations

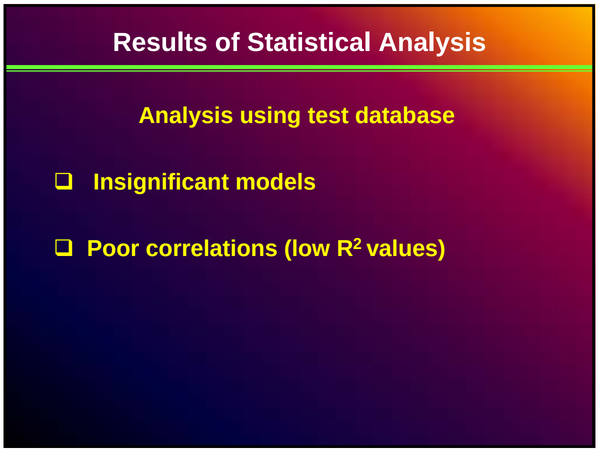
- ❑ Properties used in the analysis
- ❑ Best subset of independent variables
- ❑ Physical and statistical validation
- ❑ Statistical criteria for subset selection:

1. Coefficient of multiple determination (R^2)
2. Significance of overall model
3. Significance of individual properties used



Measure of Model Adequacy

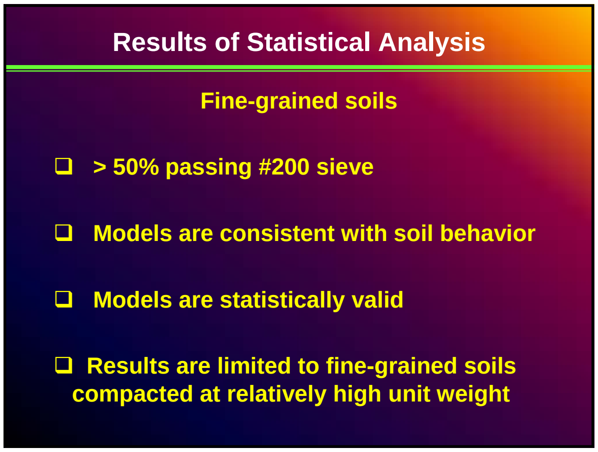
- ❑ High R^2 (might result in insignificant model)
- ❑ F-test to check significance of overall model
- ❑ T-test to check significance of individual coefficients
- ❑ Check for collinearity



Results of Statistical Analysis

Analysis using test database

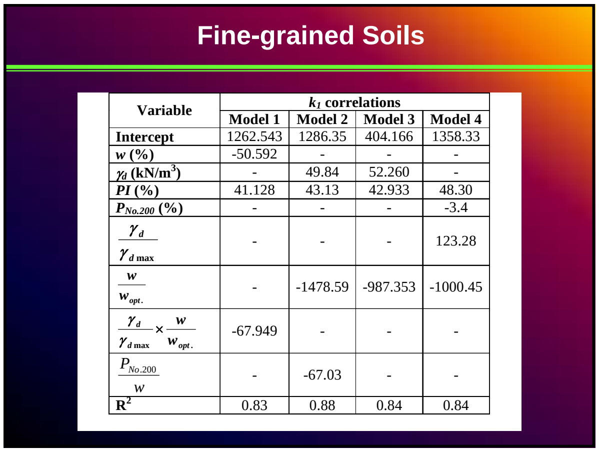
- ❑ Insignificant models
- ❑ Poor correlations (low R^2 values)



Results of Statistical Analysis

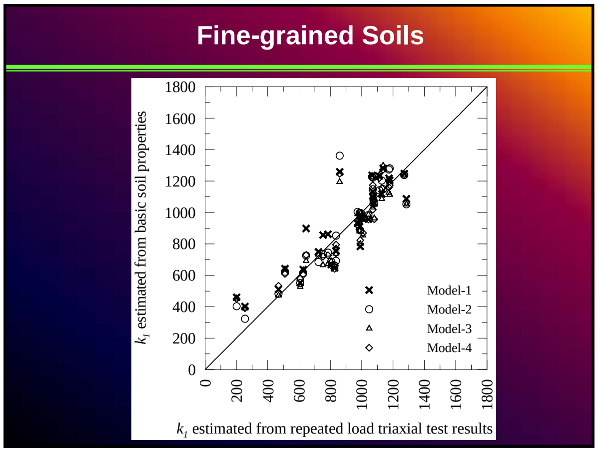
Fine-grained soils

- ❑ > 50% passing #200 sieve
- ❑ Models are consistent with soil behavior
- ❑ Models are statistically valid
- ❑ Results are limited to fine-grained soils compacted at relatively high unit weight

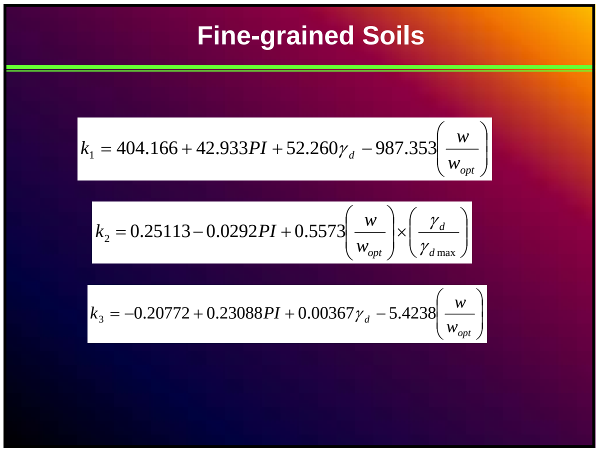


Fine-grained Soils

Variable	***k_1* correlations**			
	Model 1	**Model 2**	**Model 3**	**Model 4**
Intercept	1262.543	1286.35	404.166	1358.33
w (%)	-50.592	-	-	-
γ_d (kN/m^3)	-	49.84	52.260	-
PI (%)	41.128	43.13	42.933	48.30
$P_{No.200}$ (%)	-	-	-	-3.4
$\frac{\gamma_d}{\gamma_{d\,\max}}$	-	-	-	123.28
$\frac{w}{w_{opt.}}$	-	-1478.59	-987.353	-1000.45
$\frac{\gamma_d}{\gamma_{d\,\max}} \times \frac{w}{w_{opt.}}$	-67.949	-	-	-
$\frac{P_{No.200}}{w}$	-	-67.03	-	-
R^2	0.83	0.88	0.84	0.84



Fine-grained Soils

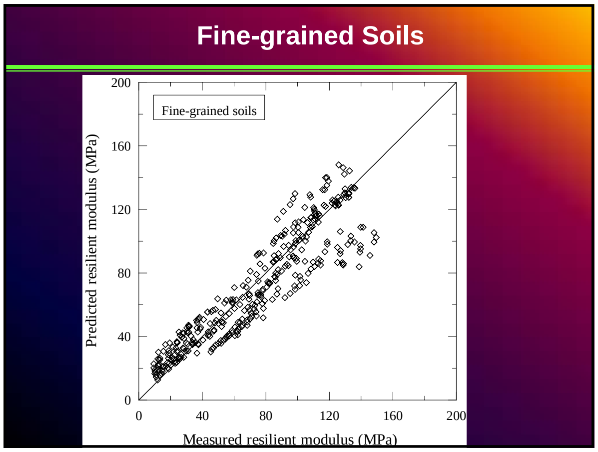


Fine-grained Soils

$$k_1 = 404.166 + 42.933PI + 52.260\gamma_d - 987.353\left(\frac{w}{w_{opt}}\right)$$

$$k_2 = 0.25113 - 0.0292PI + 0.5573\left(\frac{w}{w_{opt}}\right)\times\left(\frac{\gamma_d}{\gamma_{d\max}}\right)$$

$$k_3 = -0.20772 + 0.23088PI + 0.00367\gamma_d - 5.4238\left(\frac{w}{w_{opt}}\right)$$



Fine-grained Soils

Coarse-grained Soils

- ❑ < 50% passing sieve #200
- ❑ Poor correlations (low R^2 values)
- ❑ Insignificant models

Non-plastic Coarse-grained Soils

- ❑ Analysis of non-plastic coarse-grained soils
- ❑ D_{10}, C_u and C_c did not improve the models
- ❑ Developed models are consistent with natural soil behavior
- ❑ Developed models are statistically valid
- ❑ Results are limited to non-plastic coarse-grained soils compacted at relatively high unit weight

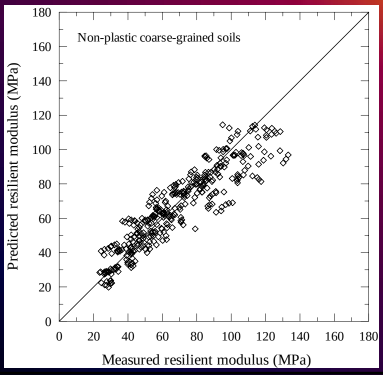
Non-plastic Coarse-grained Soils

$$k_1 = 809.547 + 10.568 P_{No.4} - 6.112 P_{No.40} - 578.337 \left(\frac{w}{w_{opt}} \right) \times \left(\frac{\gamma_d}{\gamma_{d\max}} \right)$$

$$k_2 = 0.5661 + 0.006711 P_{No.40} - 0.02423 P_{No.200} + 0.05849 (w - w_{opt}) \\ + 0.001242 (w_{opt})(\gamma_{d\max})$$

$$k_3 = -0.5079 - 0.041411 P_{No.40} + 0.14820 P_{No.200} - 0.1726 (w - w_{opt}) \\ - 0.01214 (w_{opt}) \times (\gamma_{d\max})$$

Non-plastic Coarse-grained Soils



Plastic Coarse-grained Soils

- ❑ Developed models are consistent with natural soil behavior
- ❑ Developed models are statistically valid
- ❑ Results are limited to plastic coarse-grained soils compacted at relatively high unit weight

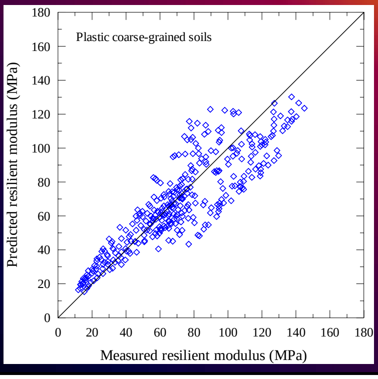
Plastic Coarse-grained Soils

$$k_1 = 8642.873 + 132.643 P_{No.200} - 428.067 (\%Silt) - 254.685 PI + 197.230 \gamma_d \\ - 381.400 \left(\frac{w}{w_{opt}} \right)$$

$$k_2 = 2.3250 - 0.00853 P_{No.200} + 0.02579 LL - 0.06224 PI - 1.73380 \left(\frac{\gamma_d}{\gamma_{d\max}} \right) \\ + 0.20911 \left(\frac{w}{w_{opt}} \right)$$

$$k_3 = -32.5449 + 0.7691 P_{No.200} - 1.1370 (\%Silt) + 31.5542 \left(\frac{\gamma_d}{\gamma_{d\max}} \right) - 0.4128 (w - w_{opt})$$

Plastic Coarse-grained Soils



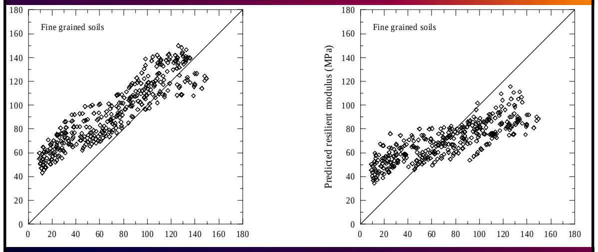
LTPP Study

- Based on LTPP database
- Resilient modulus obtain using SHRP Protocol P46
- The database variability ➔ data were obtained using various testing and sampling procedures

WHRP Study

- Based on AASHTO T 307
- Same sampling technique and testing procedure
- Verified for repeatability
- The proposed model showed better results when compared to LTPP models

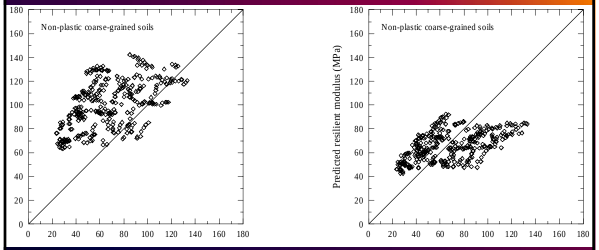
LTPP Study



(a) LTPP silt model

(b) LTPP all subgrade soils model

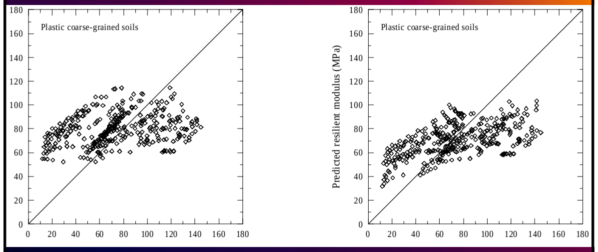
LTPP Study



(c) LTPP sand model

(d) LTPP all subgrade soils model

LTPP Study



(e) LTPP sand model

(f) LTPP all subgrade soils model

Conclusions

- **Representative Wisconsin subgrade soils were subjected to experimental testing program to determine their:**
  - **Physical properties and compaction characteristics**
  - **Resilient modulus**
- **Testing program resulted in the development of high quality database**
- **Laboratory testing program was used to develop correlations for estimating the resilient modulus from basic soil properties**

Conclusions

- **The resilient modulus constitutive equation selected by NCHRP Project 1-37A was adopted**
- **The model parameters k_i were correlated with basic soil properties**
- **The correlations proposed by this study were able to estimate the resilient modulus of compacted soils with reasonable accuracy**
- **The models developed herein outperformed the LTPP models**

Publications

- **Published: *Evaluation of Resilient Modulus of Typical Wisconsin Soils*, ASCE Geotechnical Practice Publication No. 1**
- **Published: *Effect of Sample Size on the Resilient Modulus of Cohesive Soils*, *The 16th International Conference on Soil Mechanics and Geotechnical Engineering* (*ICSMGE*), Osaka, Japan**

Publications

- **TRB 2006: *Evaluation of Resilient Modulus Model Parameters for Mechanistic Empirical Pavement Design, TRR 1967***

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Questions