FHWA Task Order #11
Contract No. DTFH61-05-D-00017

ASSESSMENT OF THE DATABASE FROM THE PAVEMENT SUBGRADE PERFORMANCE STUDY

January 24, 2011

Engineering & Software Consultants Inc.

Test Matrix

Subgrade Moisture Content	AASHTO Soil Type				
	A-2-4	A-4	A-6	A-6/ A-7-6*	A-7-5
Optimum	**10 %** TS 701	**17 %** TS 702	**16 %** TS 709 **CBR=13**		**20%** TS 712 **CBR=53**
Wet of Optimum 1	**12 %** TS 707	**19 %** TS 704	**19 %** TS 708	**21%** TS 710 **CBR=2.3**	
Wet of Optimum 2	**15 %** TS 703	**23 %** TS 705 **CBR=1**	**22 %** TS 706		**25%** TS 711 **CBR=13**

** This soil was borderline between AASHTO A-6 and A-7-6*

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Soil Properties

	AASHTO Soil Class				
	A-2-4	A-4	A-6	A-6/ A-7-6*	A-7-5
Maximum Dry Density (kg/m^3)	1,934	1,780	1,791	1,800	1,700
OMC (%)	10	16.5	16	17	20.5
Liquid Limit	30	28	33	40.2	55
Plasticity Index	3	8	15	21	21
Percent < #10	71.8	98	99	99	100
Percent < #200	31.2	85	92	99	88
Specific Gravity	2.72	2.72	2.7	2.72	2.72
USCS	SM	ML	CL	CL/CH	MH

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Objectives

- To review in detail the PSPS data, to check for completeness and for quality and consistency with the pavement engineering principles and with other similar field and laboratory studies conducted in the United States and overseas;
- To assemble additional available data, including laboratory test results, to enhance the current database;
- To obtain construction quality assurance testing and forensic testing from all cells

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Objectives - continued

- To convert the enhanced database in a new format (ACCESS) which will allow easy import in statistical or other analytical software packages;
- To develop the catalog and dictionary for the data assembled in the enhanced database;
- To prepare a detailed work plan for future data analysis and modeling, to facilitate the development of Second Generation Design Models for subgrade materials for pavements from the data and results of the Pavement Subgrade Performance Study.

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WORK PLAN

1. **Literature Search**;
2. **Review of Data and Results from the Pavement Subgrade Performance Data**;
3. **Assembling of Additional Data** –Additional available laboratory test results and missing data will be assembled
4. **Development of a New and Enhanced Database** in a new format and the catalog and dictionary for the data;
5. **Preparation of the Work Plan** for future data analysis and modeling;
7. **Resilient Modulus Testing** of subgrade soil and granular materials.

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Task 1: Literature Search

1. DTRM reports on permanent deformation in subgrade soil and effects of freeze-thaw cycles
2. Paper on an HVS project in Sweden
3. Conceptual models from South Africa and the University of Arkansas
4. Paper by Whu et al. (2009).
5. Investigate permanent deformation models for HMA

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Task 2: Review of Data from PSPS
Task 3: Assembling of Additional Data

1. Review of Research Reports
2. Review of Data Availability
3. Identify needed data
4. Request for additional available data
5. Develop rules for data check
6. Mark bad data
7. Add the additional assembled data to the database

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Task 3: Assembly of Additional Data

- Visit to CRREL on Nov. 3, 2008
- Met with Dr. Edel Cortez and discussed about data collection process and material tests
- Obtained samples of base and 3 subgrade soils (about 5 buckets each) and transported them to NYSDOT Geotech Lab
- Visited with the paving contractor for 711 and 712 and obtained mix designs.

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Task 3: New Data from Dr. Cortez

- Submitted a request in Feb 2009 based on the review of the reports
- After no answer, second requested for data used to build charts /statistic in the reports
- Requested and received Word version of reports
- Received some data, mainly from 701 to 706

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TASK 4: Database Assembly
Data Availability – Excel Database

One Excel file for each test cell. It contains in table format:

- Load data
- Soil properties (MDD, OMC, LL, PL, classification)
- Surface rutting data
- Layer-by-layer Vertical Permanent deformation
- Permanent Strains (z,x,y)
- Resilient (dynamic) strains (z,x,y)
- Stress (z, x, y)

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Rules for Response Data Check

A. The stresses and strains (vertical, longitudinal and transverse) in the subgrade soil must decrease with depth.
B. The vertical stresses and strains must be compressive
C. The permanent strains and deformations must increase with the number of loading passes applied
D. When similar wheel loads were used, the corresponding stresses and strains should be higher for the test window with the higher moisture content in the subgrade soil.
E. For any given test window, the stresses and strains must keep the same sign throughout the APT loading.
F. No data should be retained for pavement structures that failed in less than 5,000 load repetitions.
G. Observe and record other anomalies

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Rule A: *The stresses and strains (vertical, longitudinal and transverse) in the subgrade soil must decrease with depth.*

Flag the data recorded for:

- the entire test cell 705
- test windows C2 and C6 of cell 706
- test window C4 of test cell 708,
- test windows C3 and C5 of cell 709
- test windows C2, C4 and C6 of cell 710

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Rule A: *Stresses and strains in the subgrade must decrease with depth*

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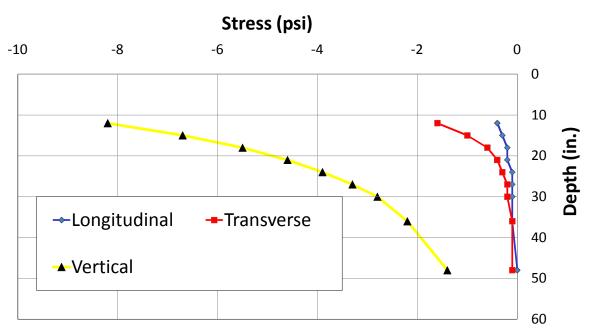
Rule B: *Vertical Stresses and strains must be compressive*



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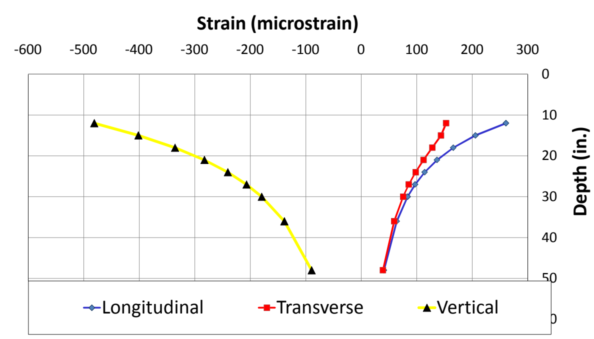
Rule B: *Vertical Stresses and strains must be compressive, horizontal strains may be tensile*



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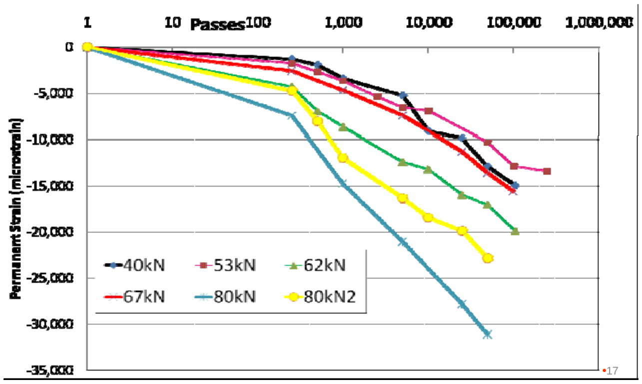
Rule C: *Permanent strain must increase with number of passes*

Depth=0.45m TS707 A-2-4@12%MC



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Proposed Rules D and E

- When similar wheel loads were used, the corresponding stresses and strains should be higher for the test window with the higher moisture content in the subgrade soil.
- For any given test window, the stresses and strains must keep the same sign throughout the APT loading.

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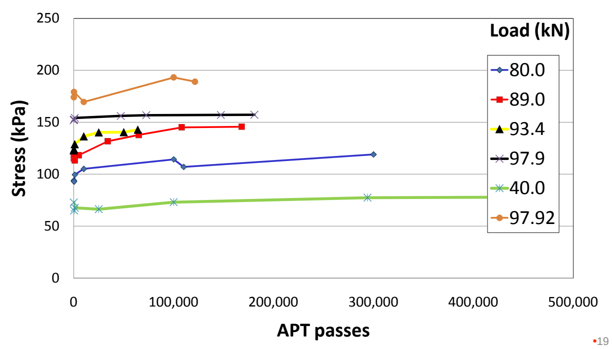
712 A-7-5@20%MC

Vertical Stress at 76mm below top of subgrade



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Rule F: *No data should be retained for test windows that failed in less than 5,000 passes*.

Flag in the database the data recorded for:

- the entire test cell 705
- test windows C2 and C6 of cell 706
- test window C4 of test cell 708,
- test windows C3 and C5 of cell 709
- test windows C2, C4 and C6 of cell 710
- test window C6 of cell 711

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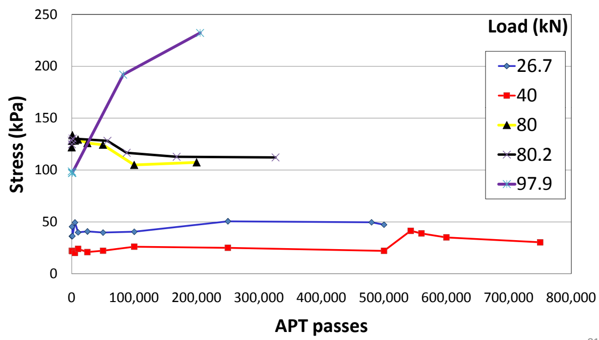
Rule G: Observe anomalies
711 A-7-5@25%MC

Vertical Stress at 76mm below top of subgrade

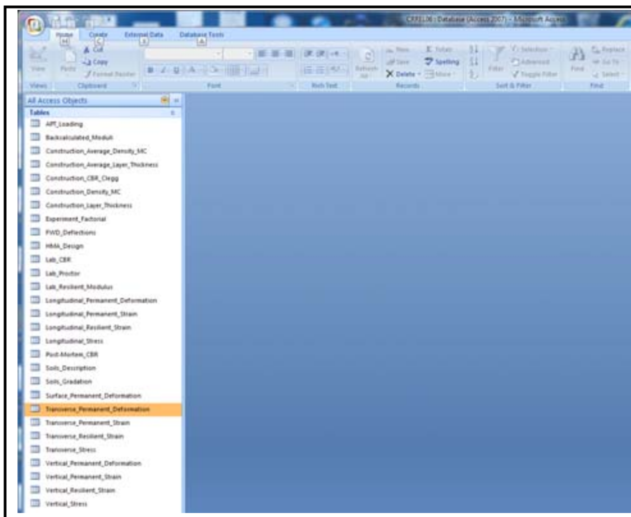


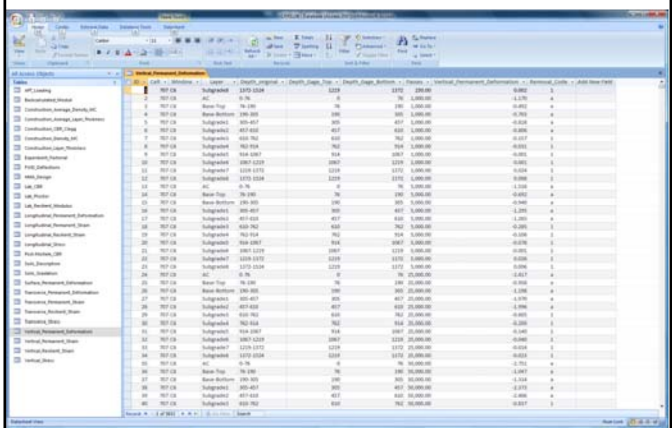
Task 4: New and Enhanced Database

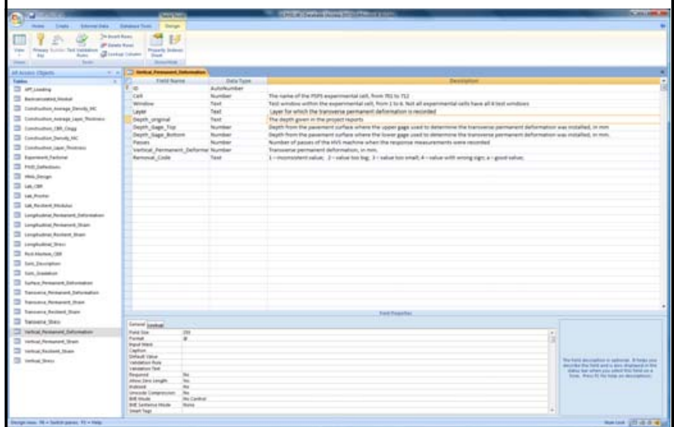
- All data in the Excel database and the more recently added data was assembled in an ACCESS database
- All original data was kept
- Erroneous data was marked
  - 1 – inconsistent value 2 – value too big;
  - 3 – value too small 4 – value with wrong sign
  - a – good value
- Remarks were added to ease understanding
- Data dictionary included in Final Report - App B

ACCESS Database

- Easy to navigate
- Contains all data organized in 29 tables
- Description and units of measure are included for each variable
- Variables and tables are named such that they can be easily identified
- The format of all variables was adjusted to reduce the size of the database
- The variable description facilitates data extraction by most statistical software



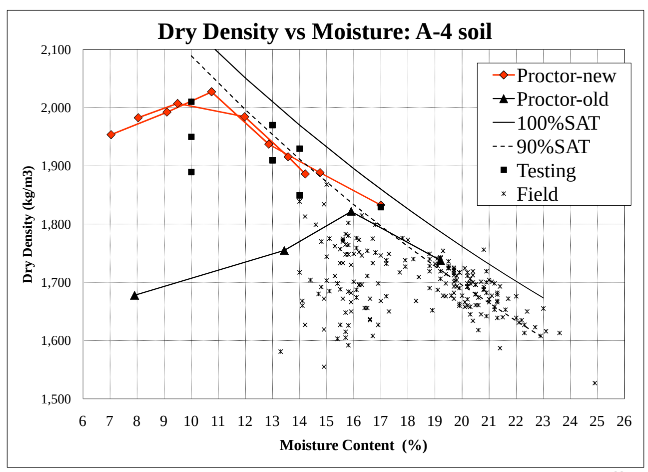


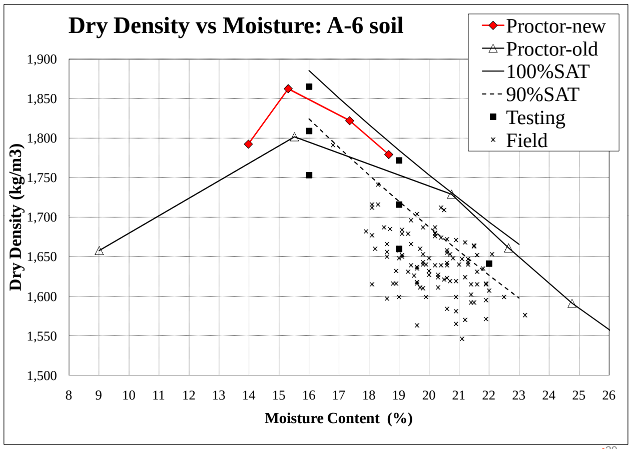


Task 7: Laboratory Material Testing

Performed only on 3 Subgrade soils

- Proctor tests (OMC, MDD) AASHTO T99
- Resilient Modulus at nominal moisture contents and three density levels (90, 95, 100% MDD)





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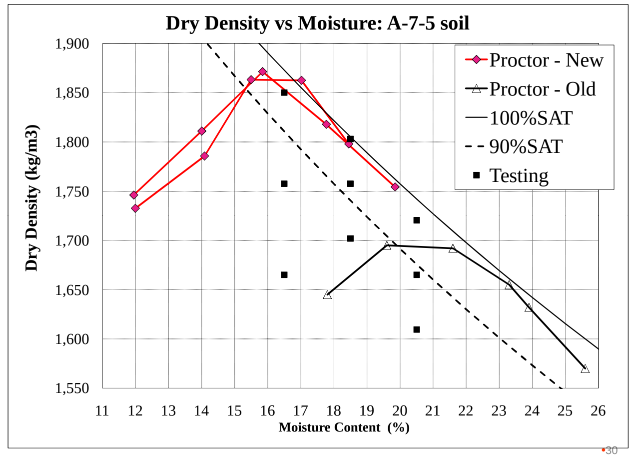

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Original vs New Proctor results (T 99)

MDD (kg/m³)

Soil	Original	New
A-2-4	1,935	
A-4	1,780	2,010
A-6	1,791	1,865
A6/A-7-6	1,800	
A-7-5	1,700	1,850

OMC (%)

Soil	Original	New
A-2-4	10.0	
A-4	17.0	10.0
A-6	16.1	16.1
A6/A-7-6	17.0	
A-7-5	20.5	16.5

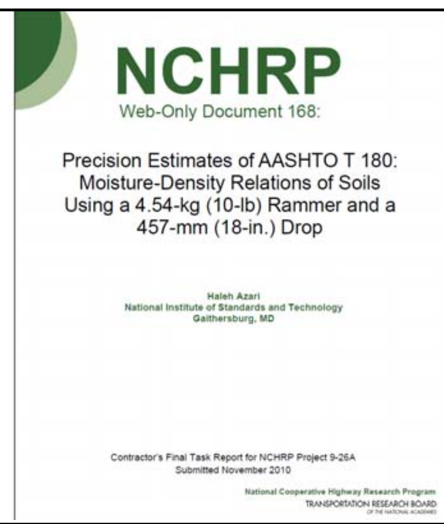

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Table 2-4. Optimum moisture content and maximum density values from the preliminary study

Soil-Aggregate Type	Dry Density, lb/ft^3	Moisture, %
Fine-Graded w/ Clay	136.4	5.6
Fine-Graded w/ Silt	136.1	6.2
Coarse-Graded w/ Clay	147.6	4.3
Coarse-Graded w/ Silt	149.3	5.4

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Figure 3-1. Maximum density values (pcf) and their corresponding error bands

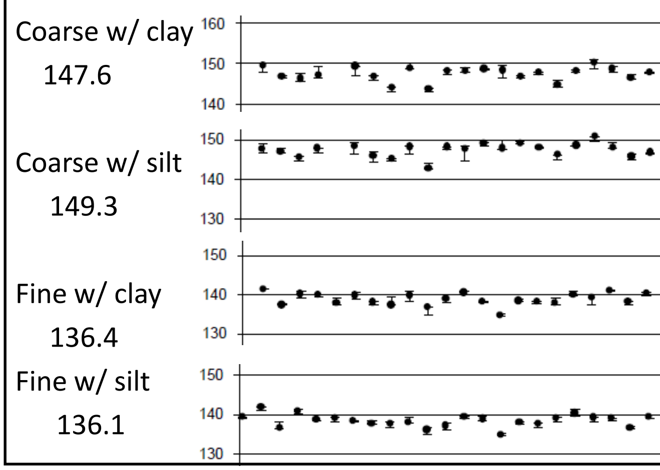
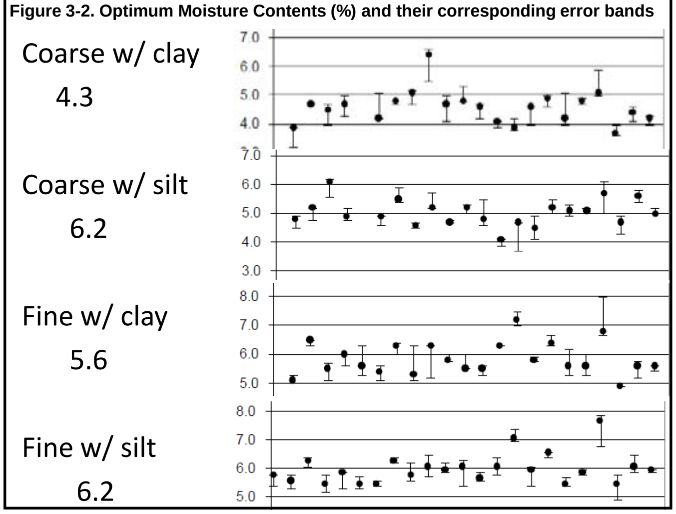


Figure 3-2. Optimum Moisture Contents (%) and their corresponding error bands



Data Availability - Construction

		A-2-4			A-4			A-6			A-6 / A-7-6	A-7-5	
		701	707	703	702	704	705	709	708	706	710	712	711
Paving Date		N	N	N	N	N	N	N	N	N	N		
Density	Subgrade	R	A	R	R	R	R	S	S	R	S	S	S
	Base	R	A	R	R	R	R	S	S	R	S	S	S
	HMA		A				R	S	S	R	S		S
MC	Subgrade	R	A	R	R	R	R	S	S	R	S	S	S
	Base	R	A	R	R	R	R	S	S	R	S	S	S
Elevations or thickness	Subgrade	R		R	R				S	N	N	N	
	Base	R	S	R	R			S	S	N	N	N	
	HMA	R	S	R	R		N	S	S	N	N	N	
Clegg Hammer		R			R	R				R			
VANE SHEAR							S						
DCP		R											
FWD on	Base	N		N	N	N							
	HMA	E	E	E	E	E	E	E	E	E	E	E	E
backcalculated		N	R	N	N	N	R	N	N	N	N		

D – database	R - report	S - statistic / graph	- not recorded
E – electronic / DVDs	A – from Dr. Cortez	N - not reported/ likely measured/known	

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Resilient Modulus Testing

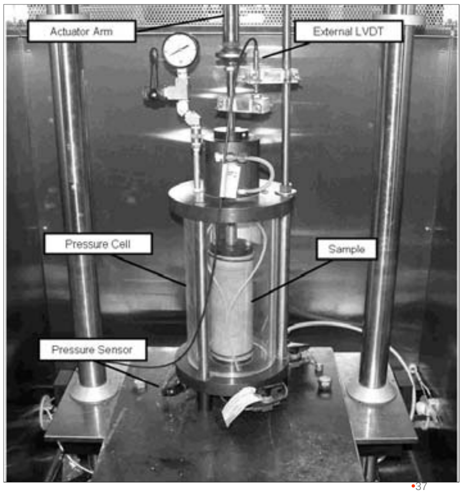

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Table 8.3 Loading Sequence in the AASHTO T 307-07

Sequence	Confining Pressure (kPa)	Maximum Stress (kPa)	Number of cycles
0 - conditioning	41.4	27.6	1000
1	41.4	13.8	100
2	41.4	27.6	100
3	41.4	41.4	100
4	41.4	55.2	100
5	41.4	68.9	100
6	27.6	13.8	100
7	27.6	27.6	100
8	27.6	41.4	100
9	27.6	55.2	100
10	27.6	68.9	100
11	13.8	13.8	100
12	13.8	27.6	100
13	13.8	41.4	100
14	13.8	55.2	100
15	13.8	68.9	100

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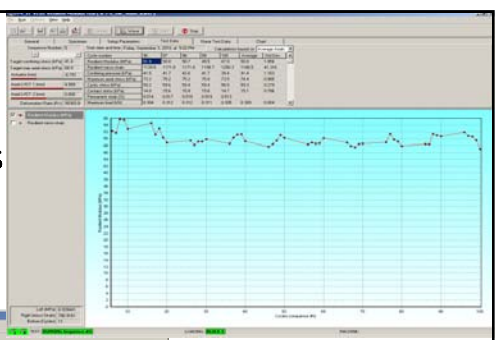
Resilient Modulus Testing



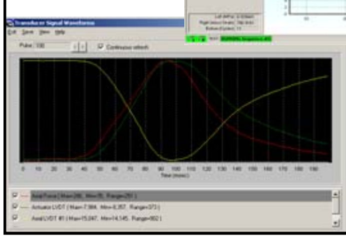


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Table 8.2 Resilient Modulus Test Factorial

	MC (%)	Relative Density (%)	Remarks
A-4	10	94	
		97	
		100	
OMC=10%	13	95	
		98	Problems with some samples
MDD=2,010 (kg/m^3)	14	92	
		96	Problems with some samples
	17*	91	Test did not work. Soil too wet and soft
A-6	16*	92	
		95	
		98	
OMC=16.10%	19	89	
		92	
MDD=1,865		95	
(kg/m^3)	22	88	Test did not work. Soil too wet and soft
	16.5	90	
		95	
		100	
	18.5	92	
		95	
A-7-5		98	
OMC=16.5%	20.5*	87	
MDD=1,850		90	This was the original OMC for this soil.
(kg/m^3)		93	Several samples were too soft.

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Deformed Samples at High Moisture Content

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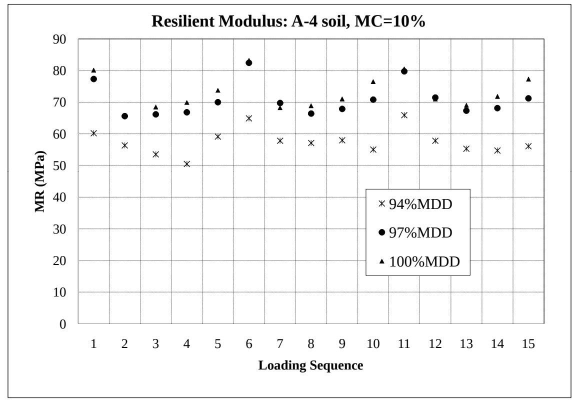

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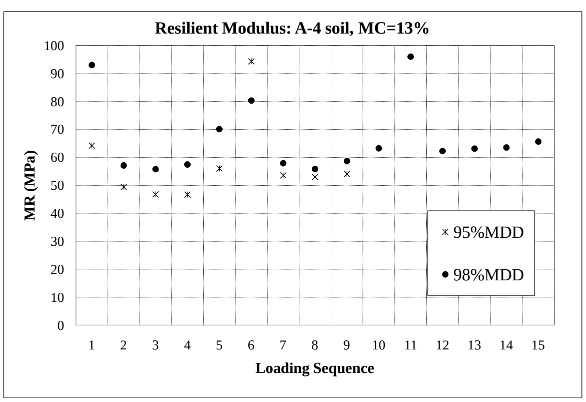

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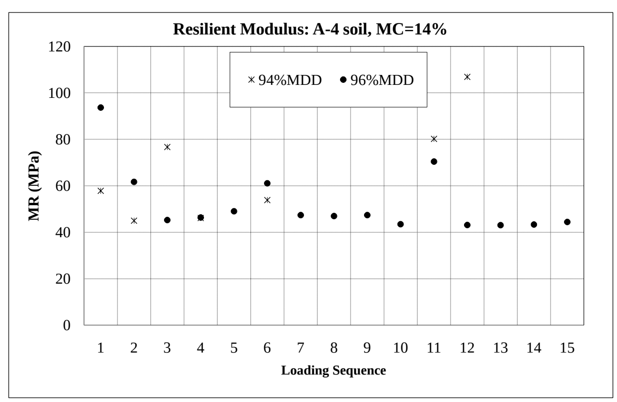

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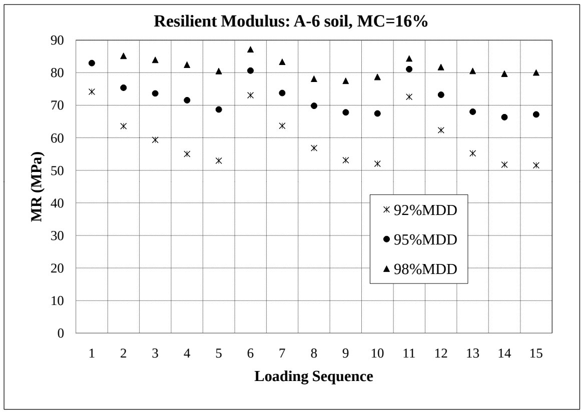
Resilient Modulus: A-6 soil, MC=16%
MR (MPa)
Loading Sequence
92%MDD
95%MDD
98%MDD

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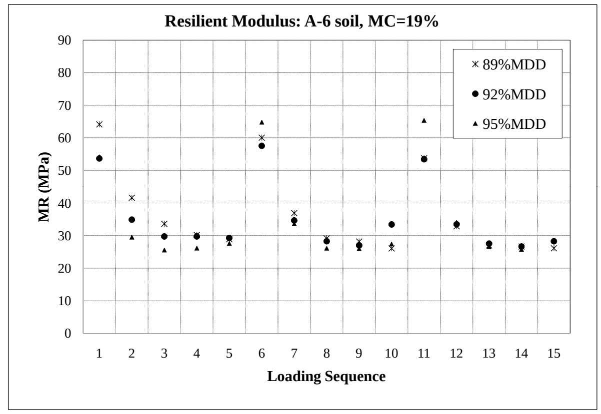
Resilient Modulus: A-6 soil, MC=19%
MR (MPa)
Loading Sequence
89%MDD
92%MDD
95%MDD

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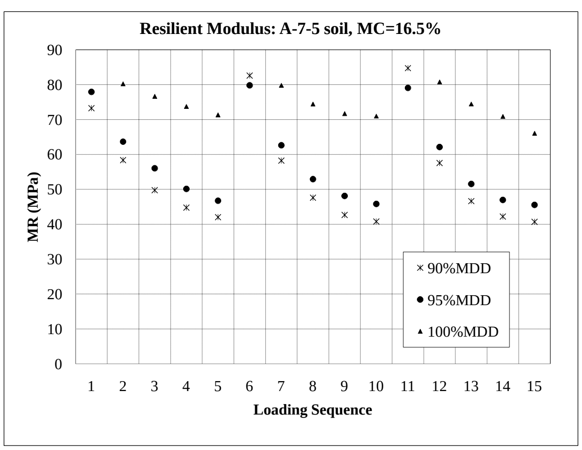
Resilient Modulus: A-7-5 soil, MC=16.5%
MR (MPa)
Loading Sequence
90%MDD
95%MDD
100%MDD

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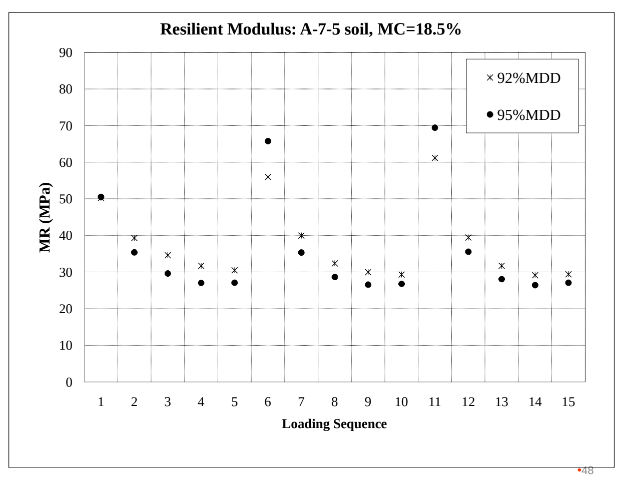
Resilient Modulus: A-7-5 soil, MC=18.5%
MR (MPa)
Loading Sequence
92%MDD
95%MDD

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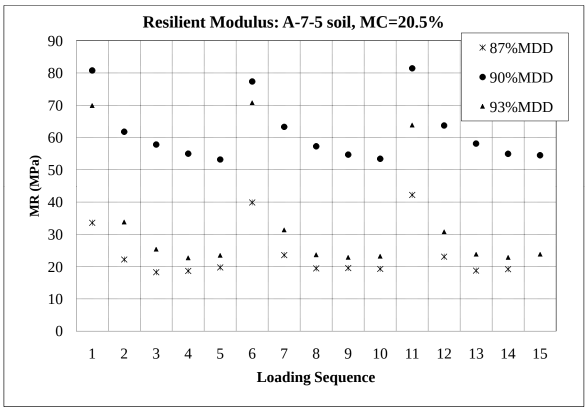

Non-linear Stiffness Model for Soil

$$M_R = K_1 \cdot p_a \cdot (\theta / p_a)^{K_2} \cdot [(\tau_{oct} / p_a) + 1]^{K_3}$$

M_R = Resilient Modulus,
K_1, K_2, and K_3 = Regression Constants,
Θ = bulk stress = $\sigma_v + 2*\sigma_3$
ρ_a = normalizing stress (atmospheric pressure)
σ_3 = Confining Stress
τ_{oct} = Octahedral Shear Stress = $\{[2*(\sigma_v - \sigma_3)^2]^{0.5}\}/3$
σ_v = Maximum Axial Stress

Non-Linear Model Parameters

	Moisture Content (%)	Relative Density (%)	K_1	K_2	K_3	R^2
A-4		94	617.773	-0.0544	-0.4499	**0.475**
		97	759.427	-0.0488	-0.4489	**0.400**
	10	100	744.397	-0.0435	-0.1497	**0.107**
OMC=10%		95	807.466	-0.6297	-1.0196	0.737
MDD=2,010	13	98	826.279	-0.1020	-1.2701	**0.362**
(kg/m^3)		94	820.985	-0.4282	-0.5128	**0.323**
	14	96	845.029	0.2847	-3.2208	0.629
A-6		92	790.102	0.0439	-1.7676	0.941
		95	840.573	0.0520	-0.9872	0.871
OMC=16.10%	16	98	899.899	0.0674	-0.6404	0.729
		89	746.436	0.2228	-4.7687	0.870
MDD=1,865		92	612.746	0.0383	-3.5385	0.719
(kg/m^3)	19	95	708.516	-0.1624	-4.5251	0.750
		90	920.632	-0.0578	-3.3029	0.911
		95	897.121	0.0253	-2.7462	0.950
	16.5	100	973.1	0.0097	-1.3889	0.898
		92	624.104	-0.0894	-3.1204	0.865
A-7-5	18.5	95	720.403	-0.1931	-4.3754	0.809
OMC=16.5%		87	433.624	-0.1388	-3.8242	0.759
MDD=1,850		90	836.326	-0.0254	-1.8626	0.858
(kg/m^3)	20.5	93	972.138	0.0889	-7.1036	0.837

Task 5: DRAFT PLAN FOR FUTURE DATA ANALYSYS

PROPOSED WORK PLAN
for future data analysis and modeling

1. **Review of the PSPS products**;
2. **Development of Empirical Models for Permanent Deformation in Soils**;
3. **Advanced Laboratory Testing of Subgrade Soils**
4. **Finite Element Modeling of Permanent Deformation Accumulation**;
5. **Final Report**.

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Task 1: Literature Search

1. DTRM reports on permanent deformation in subgrade soil and effects of freeze-thaw cycles
2. Paper on an HVS project in Sweden
3. Conceptual models from South Africa and the University of Arkansas
4. Paper by Whu et al. (2009).
5. Investigate permanent deformation models for HMA

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Task 2: Development of Empirical Models for PD

- Use multi-linear and non-linear regression analysis to derive models for incremental vertical permanent deformation PD:
  - The model currently incorporated in M-E PDG
  - All other empirical models
  - New models that will include the effect of:
    - the already accumulated permanent deformation
    - the resilient vertical strain
    - the vertical and horizontal stresses
- The influence of soil type, moisture content and relative dry density should be studied

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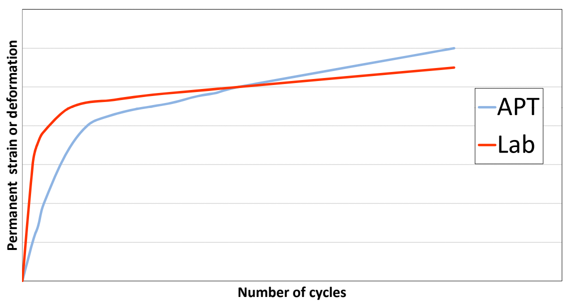
Task 3: Advanced Laboratory Testing

- Repeated triaxial test with pulsating confining pressure and with suction measurements to determine the accumulation of permanent deformation in order to:
  - Determine if the deformation accumulates in the laboratory tests in similar way as in the APT test.
  - It will allow the determination of parameters for mechanistic model that calculate PD in the subgrade soils using FEM.

Soils	MC	Density	Confining stress	Deviatoric stress
3 A-4 first	OMC, OMC+3%	95% and 100%	2	2

Lab vs. In-service Permanent



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Task 4: FE Modeling of PD Accumulation

STEPS:

1. Modeling of the accumulation of permanent deformation in laboratory tested samples.
2. Derivation of the coefficients of the mechanistic models through back-estimation. These coefficients will be different for different soils, moisture contents and relative dry densities.
3. FEM modeling of the accumulation of permanent deformation in the APT experiment
4. Comparison of deformations computed with FEM analysis and the corresponding ones measured in the APT experiment to validate the mechanistic models.

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