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16. Abstract

This five-year project was initiated to collect materials and pavement performance data on a minimum of 100 highway test sections around the State of Texas, incorporating flexible pavements and overlays. Besides being used to calibrate and validate mechanistic-empirical (M-E) design models, the data collected will also serve as an ongoing reference data source and/or diagnostic tool for TxDOT engineers and other transportation professionals. Towards this goal, this interim report provides a documentation of the comprehensive data analysis plans that were developed to analyze the collected data. The data collection plans are documented elsewhere as Report 0-6658-P1.

As documented here, the data analysis plans were designed to cover various key aspects, including the following: (1) the tools and test methods used to measure/collect the data, (2) the type and format of the data measured/collected, (3) the raw data reduction processes for each data type, (4) the software used to process and analyze the measured/collected data, (5) the analytical methods and models used to analyze the measured/collected data, (6) the dimensional and/or quantitative units of the measured/computed parameters, and (7) the data reporting format including how the data will be accessed and displayed from the MS Access Data Storage System (i.e., tables, graphs, bar charts, etc.). Specifically, the data to be analyzed included the following: (1) laboratory and field test data including asphalt-binders, hot-mix asphalt (HMA) mixes, base, and subgrade soil materials; (2) traffic data; and (3) environmental and climatic data.

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The United States Government and the State of Texas do not endorse products or manufacturers. Trade or manufacturers' names appear herein solely because they are considered essential to the object of this report. The researcher in charge was Lubinda F. Walubita.

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LIST OF NOTATIONS AND SYMBOLS

AASHTO	American Association of State Highway and Transportation Officials
AC	Asphalt-binder content
AV	Air voids
Avg	Average
CV	Coefficient of variation
CTB	Cement-treated base
CTIS	Center for Transportation Infrastructure Systems
DCP	Dynamic cone penetrometer
EB	Eastbound direction
FHWA	Federal Highway Administration
FWD	Falling weight deflectometer
IRI	International roughness index
GIS	Geographical Information System
GPS	Geographical positioning system
FWD	Falling weight deflectometer
HMA	Hot-mix asphalt
LTB	Lime-treated base
LTPP	Long-Term Pavement Performance
M-E	Mechanistic Empirical
MEPDG	Mechanistic Empirical Pavement Design Guide
MS	Microsoft©
MR	Resilient modulus
NB	Northbound direction
PD	Permanent deformation
PMIS	Pavement Management Information System
PP	Perpetual Pavement
PSI	Pavement serviceability index
PSPA	Portable seismic property analyzer
PVMNT	Pavement
QA	Quality assurance

QC	Quality control
SB	Southbound direction
SPS	Specific pavement studies
TFPDB	Texas Flexible Pavement Database
TSFP	Texas Successful Flexible Pavement
TTI	Texas Transportation Institute
TxDOT	Texas Department of Transportation
UT	University of Texas at Austin
UTEP	University of Texas at El Paso
WB	Westbound direction
WP	Wheel path

CHAPTER 1: INTRODUCTION

Proper calibration of pavement design and rehabilitation performance models to conditions in Texas is essential for cost-effective flexible pavement designs. The degree of excellence with which TxDOT's pavement design models is calibrated will determine how optimally literally billions of dollars of future roadway investment capital will be spent. The magnitude of benefits and consequences involved makes this research project one of the more important research efforts that the department has undertaken in recent memory.

Collection of quality and reliable pavement performance data on a sustained basis will thus be the main goal of this project. Inevitably, this presents a perfect opportunity to calibrate and validate the currently design methods and models for both flexible pavements and overlays. The calibration of these models to Texas local conditions will result in pavement designs that are more economical, with superior performance expectation, in the long term.

OBJECTIVES AND SCOPE OF WORK

The primary goal of this five-year project is to collect materials and pavement performance data on a minimum of 100 highway test sections around the State of Texas. The data collected is being used to calibrate and validate the mechanistic-empirical (M-E) design models. It will also serve as an ongoing reference source and/or diagnostic tools for TxDOT engineers and other transportation professionals.

Towards this goal and as documented here, the specific objective of this task was to develop sound data analysis plans and, among others, to address the following key aspects of the data collection process:

- The tools and test methods used to collect the data.
- The type and format of the data that is being measured and collected.
- The raw data reduction process for each data type.
- The software being used to process and analyze the measured/collected data.
- The analytical methods, techniques, and models being used to analyze the measured/collected data.
- The dimensional and/or quantitative units of the measured/computed parameters.

- The data reporting format including how the data will be accessed and displayed from the MS Access Data Storage System (i.e., tables, graphs, bar charts, etc.).

Having sound data analysis plans is a very critical aspect and an integral part of the data collection plan to ensure quality data. It is meaningless to have robust data collection plans without sound data analysis plans or appropriate data analysis models. Data collection plans are documented elsewhere as Report 0-6658-P1 (Walubita et al. 2011).

This report, denoted here as Product 0-6658-P3, documents the data analysis plans that were formulated in the early stages of this project to process and analyze the laboratory, field, traffic, environmental, and climatic data. The scope and contents of the report covers the following items:

- Chapter 2: Lab test data analysis: part I (asphalt-binders).
- Chapter 3: Lab test data analysis: part II (HMA mixes).
- Chapter 4: Lab test data analysis: part III (base and subgrade soil materials).
- Chapter 5: Field test data analysis: part I (cracking, rutting, profiles, skid, etc.).
- Chapter 6: Field test data analysis: part II (PSPA, DCP, and FWD).
- Chapter 7: Field test data analysis: part III (forensics—GPR and coring).
- Chapter 8: Traffic data analysis.
- Chapter 9: Environmental and climatic data analysis.
- Chapter 10: Summary and recommendations.

Some appendices of important data are included at the end of the report, along with a CD of some models, analysis demonstrations, and example results.

SUMMARY

This introductory chapter discusses the background and research objectives along with the scope and content of the report. Specifically, this report, denoted here as Product 0-6658-P3, documents the data analysis plans that were formulated to process and analyze the laboratory, field, traffic, environmental, and climatic data that is being collected.

CHAPTER 2: LAB TEST DATA ANALYSIS PART I

The data analysis plans discussed in this chapter and denoted as Part I pertain to the asphalt-binder tests that were recommended to generate the required rheological and engineering properties as well as PG grading of the extracted binders, These tests include the following:

- The specific gravity (SG).
- The viscosity.
- The dynamic shear rheometer (DSR).
- The bending beam rheometer (BBR).
- The MSCR.
- The elastic recovery (ductility).
- PG grading of the asphalt-binders.

In general, the data analysis plans incorporate the following aspects: the test specification, the analysis procedure, and the reporting format. The unit of measurement and interpretation of each data type along with typical or threshold values are also indicated.
A summary of key points concludes the chapter.

MATERIAL SAMPLING AND QUANTITIES

As documented in the data collection plans (Report 0-6658-P1), all the above tests are based on binder extractions (Tex-210-F) from the plant-mix hauled from: a) the production plant, b) directly from the site, or c) from cores; all sources that represent in-situ field conditions. If hauled from the site, which is preferred, the plant-mix should be sampled from a minimum of three different trucks but not more than five, precisely at the location of the test section (see Figure 2-1). In a nutshell, the plant-mix or field cores should be sampled/cored from a minimum of three locations within the test section. The Texas method Tex-210-F will be used for extracting the binders (TxDOT 2011).

Figure 2-1. Plant-Mix Sampling from the Construction Site.

The approximate material (plant-mix/cores) requirement to conduct all these asphalt binder tests per mix type or HMA layer is 100 lb. Thus, about 34 lb of material or cores should be sampled per sampling location. TxDOT recommended that the number of replicate samples for most of these tests be reduced from three to one, due to repeatable results when dealing with homogeneous asphalt-binder materials and the need to optimize resources.

TEST SPECIFICATIONS AND DATA ANALYSIS METHODS

Table 2-1 lists the test specifications, analysis methods, and the output data along with the expected typical values or thresholds. In general, all the analysis procedures and methods are based on pre-existing standard specifications for asphalt-binders, incorporating Texas and US national standards. Test plan proposals for the asphalt-binders are included in Appendix A.

Table 2-1. Test Specification and Data Analysis Methods for Asphalt-Binders (Extracted).

#	Test	Spec	*Sample Replicate	Data Analysis Method/ Procedure	Output Data and Unit of Measurement	Typical Value/ Threshold
1	SG	T 228	1	T 228	Specific gravity	
2	Viscosity	T 316	1	T 316	Viscosity (Pa.s)	≤ 3.00 Pa.s
3	DSR	T 315	1	T 315	– Shear modulus, G* (kPa) – Phase angle,δ (°) – G*/Sin δ (kPa) – True temperature grade	G*/Sin (δ) ≥ 2.20 kPa
4	MSCR	TP 70	9 (3 × 3 temps)	TP 70	– R100, R3200 – J_{nr}100, J_{nr}3200 – R_{diff}, $J_{nr\text{-}diff}$ (%)	
5	BBR	T 313	2 (1 × 2 temps)	T 313	– Flexural stiffness, S (MPa) – m-value	– S ≤ 300 MPa – m-value ≥ 0.3
6	Elastic recovery	D 6084-A & Item 300	3 (@ 50°F)	Item 300 (pg 212)	% age recovery	
7	Binder PG grading	M 320, Item 300, MP 19		M 320, Item 300, MP 19	Asphalt-binder PG grade	

*Number of replicate samples based on TxDOT recommendations.

Appendix A shows the detailed test specifications and thresholds, specifically the TxDOT specification Item 300 and the AASHTO TP 70. Table 2-2 shows an example of the computations and analyzed results for the DSR test based on the T 315 specification.

Table 2-2. DSR (T 315) Test Results: Extracted PG 64-22, US 59 (Atlanta District, TX).

Sample	T#1 = 58°C			T#2 = 64°C			T#3 = 70°C			True Grade Temp (°C)
	G* (kPa)	δ (°)	G*/Sin(δ) (kPa)	G* (kPa)	δ (°)	G*/Sin(δ) (kPa)	G* (kPa)	δ (°)	G*/Sin(δ) (kPa)	
Sample# 1	7.14	82.90	7.20	3.24	84.90	3.25	1.59	86.40	1.59	67.26
Sample# 2	7.00	82.90	7.06	3.13	85.00	3.14	1.50	86.40	1.51	66.90
Sample# 3	6.03	83.30	6.08	2.67	85.20	2.68	1.25	86.60	1.25	65.55
Avg	6.72	83.03	6.78	3.01	85.03	3.02	1.45	86.47	1.45	66.57
Stdev	0.604	0.230	0.610	0.302	0.153	0.302	0.176	0.116	0.178	0.901
CV	8.99%	0.28%	9.00%	10.03%	0.18%	10.00%	12.18%	0.13%	12.26%	1.35%

Clearly, Table 2-2 shows that the PG 64-22 asphalt-binder meets the T 315 high temperature requirements at 64°C. However, the true temperature grade based on Table 2-2 is actually 66.6°C. The table also shows good repeatability with low variability for this test, hence the TxDOT recommendation to consider only one replicate test sample.

DATA REPORTING FORMAT AND ACCESS

In general, most of the asphalt-binder test data are reported and may be accessed in one or more of the following formats from the MS Access Data Storage System:

- Numerical listing.
- Tabular listing.
- Bar chart.
- Graphical format (i.e., plots, curves, etc.).

Currently, investigations are also under way to facilitate direct data exporting from the MS Access Data Storage System. Figures 2-2 through 2-6 show examples of some of the asphalt-binder data extracted from the MS Access Data Storage System.

	SpecificGravity_ID	MaterialProp_ID	Sample1	Sample2	Sample3	AVG	CV
	SG_TTI-00001	MP_TTI-00001	1.057	1.055	1.054	1.055	0.10%
*	SG-						

Specific Gravity

Figure 2-2. Specific Gravity Data for PG 64-22 (US 59, Atlanta District, TX).

DSR-RTFO

	DSR-RTFO_ID	MaterialProp_ID	Item	T#1 @58°C (G*)	T#1 @58°C (δ)	T#1 @58°C (G*/Sin (δ))	T#2 @64°C (G*)	T#2 @64°C (δ)	T#2 @64°C (
	DSRR_TTI-000001	MP_TTI-00001	Sample1	6.52	84.7	6.55	2.69	86.5	
	DSRR_TTI-000002	MP_TTI-00001	Sample2	6.48	84.9	6.5	2.75	86.6	
	DSRR_TTI-000003	MP_TTI-00001	Sample3	6.46	84.9	6.48	2.8	86.6	
	DSRR_TTI-000004	MP_TTI-00001	Average	6.49	84.83	6.51	2.75	86.57	
	DSRR_TTI-000005	MP_TTI-00001	CV(%)	0.47	0.14	0.55	2.01	0.07	
*	DSRR-								

Figure 2-3. DSR Data for PG 64-22 (US 59, Atlanta District, TX).

RTFO-MSCR

	RTFO-MSCR_ID	MaterialProp_ID	Item	T#1 @52°C (R100)	T#1 @52°C (R3200)	T#1 @52°C (R_diff(%))	T#1 @52°C (J_nr 100)	T#1 @52°C (J
	MSCR_TTI-000001	MP_TTI-00001	Sample1	6.9	5.6	18.8	7.207E-06	
	MSCR_TTI-000002	MP_TTI-00001	Sample2	7.4	5.7	23.3	6.809E-06	
	MSCR_TTI-000003	MP_TTI-00001	Sample3	6.9	6	12.9	6.290E-06	
	MSCR_TTI-000004	MP_TTI-00001	Average	7.07	5.76	18.33	6.768E-06	
	MSCR_TTI-000005	MP_TTI-00001	CV(%)	3.85	3.44	28.58	6.790E+00	
*	MSCR-			0	0	0	0.000E+00	

Figure 2-4. MSCR Test Data for PG 64-22 (US 59, Atlanta District, TX).

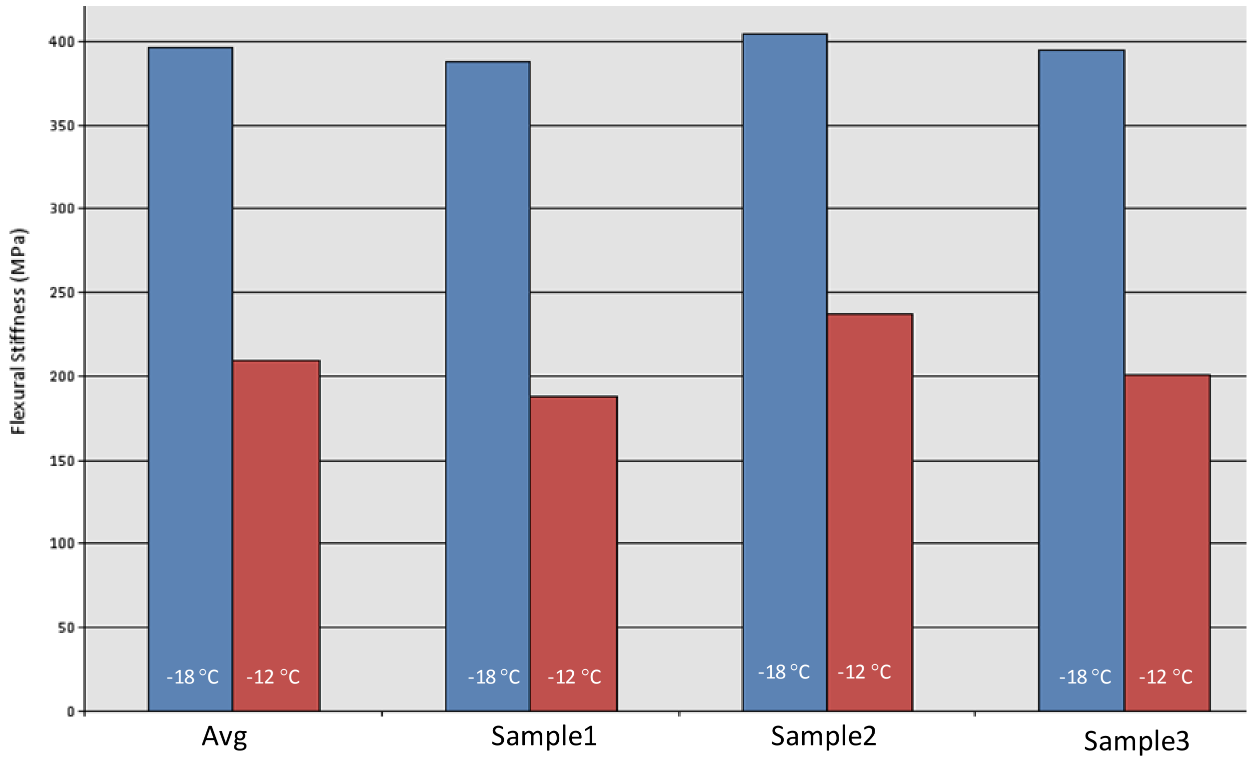

Figure 2-5. BBR-Flexural Stiffness Bar Chart for PG 64-22 (US 59, Atlanta District, TX).

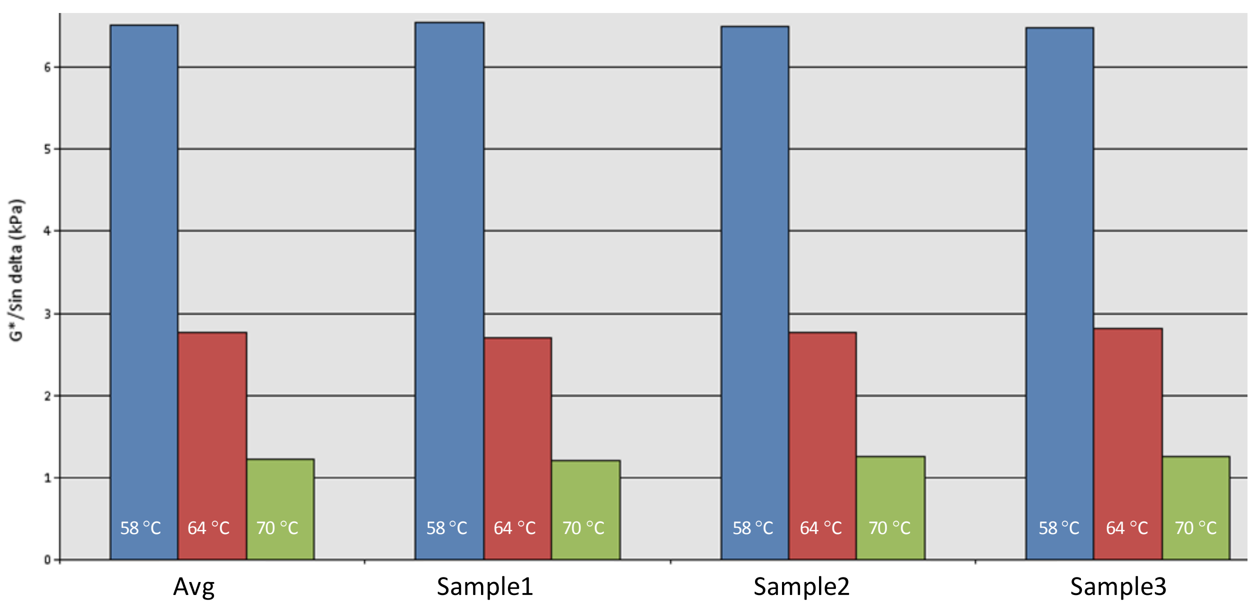

Figure 2-6. DSR Bar Chart for PG 64-22 (US 59, Atlanta District, TX).

SUMMARY

This chapter presented the data analysis plans for the asphalt-binders including the test specifications, analysis procedures, and the data reporting format. Overall, all the data analysis procedures and methods were consistent with Texas and US national standards for testing, analyzing, reporting, and interpretation of the asphalt-binder test data. Demonstration examples of the test results and extracts from the MS Access Data Storage System were also discussed. Test plan proposals for asphalt-binders are included in Appendix A.

CHAPTER 3: LAB TEST DATA ANALYSIS: PART II

Part II of the laboratory test data analysis plans covers the data collection format, raw data reduction process, and analysis procedure for the following HMA mixes:

- Asphalt-binder extractions and gradations.
- The Hamburg rutting test.
- The Overlay Tester (OT).
- The OT for measuring fracture properties.
- The dynamic modulus (DM).
- The repeated load permanent deformation (RLPD) test.
- The Indirect-tension (IDT) test.
- The HMA thermal coefficient test.

As discussed in the subsequent sections of this chapter, the data analysis plans also includes the analysis models and software used. The unit of measurement and interpretation of each data type along with typical or threshold values are also indicated. A summary of key points concludes the chapter.

MATERIAL SAMPLING AND QUANTITIES

As documented in the data collection plans (Report 0-6658-P1), all the above tests will be based only on plant-mix materials and field cores that represent in-situ field conditions (Walubita et al. 2011). Unless otherwise circumstances do not permit, then raw materials can be considered. The plant-mix material will either be hauled from the production plant or directly from the site. If hauled from the site, which is preferred, the plant-mix should be sampled from a minimum of three but not more than five different trucks, precisely at the location of the test sections (see Figure 2-1). In a nutshell, the plant-mix or field cores should be sampled/cored from a minimum of three locations within the test section. Where extraction tests such as determining the asphalt-binder content and aggregate gradation are required, the Texas method Tex-210-F will be used (TxDOT 2011).

The approximate material (plant-mix/cores) requirement to conduct all these HMA tests per mix type or HMA layer is 500 lb. Thus, about 167 lb of material or cores should be sampled per sampling location. Except for the Hamburg test, a minimum of three replicate samples will be used per test per material type.

TEST SPECIFICATIONS AND DATA ANALYSIS METHODS

Table 3-1 lists the test specifications and data analysis procedures (based on Texas as well as national standards), and output data for the HMA mixes along with some typical thresholds. Test plan proposals for the HMA mixes are included in Appendix B.

Table 3-1. Test Specification and Data Analysis Procedures for HMA Mixes.

#	Test	Spec	*Sample Replicate	Data Analysis Method/ Procedure	Output Data and Unit of Measurement	Typical Value/ Threshold
1	AC extractions & gradations	Tex-210-F	3	Tex-210-F	- Asphalt content (%) - Gradation & particle size distribution	–
2	Hamburg	Tex-242-F	1 (1 set of 2)	Tex-242-F	Rut depth (mm)	< 12.5 mm
3	Overlay Test (OT)	Tex-248-F @ 77°F	5	Tex-248-F	- Maximum load (lbf) No. of cycles to failure	≥ 300 (typical mixes) ≥ 750(CAM)
4	OT fracture properties	Report 0-5798-2, PP 97	5	Report 0-5798-2, PP 97	Fracture parameters, *A & n*	–
5	Dynamic modulus (DM)	AASHTO TP 62-03	3	AASHTO TP 62-03	Dynamic modulus ,|E*| (ksi)	–
6	Repeated Load Permanent Deformation test (RLPD)	Report 0-5798-2 a) 104°F @ 20 psi & b) 122°F @ 10 psi; for 10 0000 cycles.	6 (3 x 2 temps)	Report 0-5798 (New)	– Permanent strains (in/in) – Viscoelastic properties, alpha (α) & mu (μ)	–
7	Indirect-tension test (IDT)	Tex-226-F @ room temp.	3	Tex-226-F	Indirect tensile strength σ, (psi)	85–200 psi
8	HMA thermal coefficient	Apeagyei et al. 2008	3	Apeagyei et al. 2008	Thermal coefficient (α)	1.137–3.512 E-05

*Number of replicate samples based on TxDOT recommendations.

Asphalt Binder Extractions and Gradations

The asphalt-binder extractions and gradations for the Type D plant mix from US 59 (Atlanta District, TX) were carried out as per the TxDOT specification Tex-210-F (TxDOT 2011). Table 3-2 has MS Excel® calculations that show that the results were very repeatable; hence, three replicates are sufficient for asphalt-binder extractions and gradations.

Table 3-2. Asphalt-Binder Extractions and Gradations for Type D Plant-Mix from US 59 (Atlanta District, TX).

Sieve Size	Specification		Design	Tex-210-F					
	Lower Limit	Upper Limit		Sample #1	Sample #2	Sample #3	Avg	Stdev	CV
3/4	100.0	100.0	100.0	100.0	100.0	100.0	100.0	0.00	0.0%
1/2	98.0	100.0	99.1	98.9	99.4	98.6	99.0	0.40	0.4%
3/8	85.0	100.0	93.4	90.5	94.0	92.3	92.3	1.75	1.9%
No.4	50.0	70.0	58.6	57.4	60.1	57.2	58.3	1.62	2.8%
No.8	35.0	46.0	36.8	35.5	36.9	35.2	35.9	0.91	2.5%
No.30	15.0	29.0	22.0	21.6	22.2	21.5	21.8	0.38	1.8%
No.50	7.0	20.0	18.7	19.0	19.4	18.8	19.1	0.31	1.8%
No.200	2.0	7.0	5.6	6.0	6.1	5.9	6.0	0.10	1.9%
AC				5.4%	5.5%	5.4%	5.4%	0.00	1.06%

The Hamburg Rutting Test

Table 3-3 shows that the rutting tests conducted on samples molded from the plant-mix hauled from highway US 59 (Atlanta) during construction as per Tex-242-F (TxDOT 2011) gave very repeatable results; CV < 10 percent. In general, the Hamburg test has historically exhibited good repeatability with low variability, and therefore, one replicate set is considered sufficient. Analysis of the Hamburg rutting data is typically carried out using ordinary MS Excel spreadsheets.

Table 3-3. Hamburg Test Results for Type D Plant-Mix from US 59 (Atlanta District, TX).

	AV (7±1%)	Rut Depth (mm) @ Various Load Passes				
		0 000	5 000	10 000	15 000	20 000
Sample set# 1	7.2%	0.0	2.6	3.4	4.0	4.3
Sample set# 2	7.5%	0.0	2.5	3.3	3.9	4.2
Sample set# 3	6.9%	0.0	2.8	3.4	3.9	4.3
Avg	7.2%	0.0	2.6	3.4	3.9	4.3
Stdev	0.003	0.000	0.153	0.058	0.058	0.058
CV	4.2%	0.0%	5.8%	1.7%	1.5%	1.4%

The Overlay Tester (OT)—Cracking Resistance Potential

The OT will be used to characterize the HMA cracking susceptibility based on the Tex 248-F specification (TxDOT 2011). Analysis of the OT data is typically accomplished using ordinary MS Excel spreadsheets or macros. Table 3-4 shows an example of the OT results obtained after testing samples prepared from the plant mix sampled from US 59 (Atlanta District).

Table 3-4. Overlay Test Results for Type D Plant-Mix from US 59 (Atlanta District, TX).

	AV (7±1%)	Peak Load (lb)	OT Cycles
Sample # 1	6.8%	695	309
Sample # 2	6.1%	700	121
Sample # 3	6.4%	773	334
Sample #4	6.3%	757	269
Sample #5	6.6%	839	240
Avg (all)	6.4%	753	255
Stdev (all)	0.270	59.129	82.966
CV (all)	4.3%	7.9%	32.6%
Avg (best 3)	6.4%	716	304
Stdev (best)	0.153	32.025	32.787
CV (best 3)	2.4%	4.5%	11.0%

Five replicate samples will be used and results input into the MS Access® Data Storage System. However, only the best three results with the lowest CV will be used in M-E analysis and/or performance analysis/predictions. Researchers developed an MS Excel macro to do the analysis (i.e., picking the best three) and can be found in the included CD (Walubita et al. 2011).

OT Fracture Properties

To determine the fracture properties (*A* and *n*) of the HMA mixes, researchers used the enhanced OT test procedure for fracture properties (*A* and *n*) (Zhou et al. 2010). Appendix B provides a detailed explanation of the procedure and data analysis method. MS Excel macros for performing the analysis can be found in the included CD. Like the regular OT, five replicate samples will be utilized and entered into the MS Access Data Storage System. The user can then pick the best three, based on the lowest CV using an MS Excel macro (refer to the included CD).

A step-by-step description of the enhanced OT Test procedure for measuring and computing the fracture parameters, *A* and *n* is presented below (Zhou et al. 2010):

- Specimen size is 6 inches (150 mm) long by 3 inches (75 mm) wide by 1.5 inches (38 mm) high, and it can be cut from a sample prepared on the SGC or from a field core.
- Step 1, OT-modulus (E) test: The OT-E test is carried out using the OT machine with certain modifications (discussed in detail in Appendix B), to determine the HMA modulus E.
- Step 2, OT test: To determine the fracture properties (*A* and *n*), a modified version of Tex-248-F is used (see Appendix B).
- After performing these two steps, the fracture properties *A* and *n* can be calculated using an MS Excel macro, which is given in the included CD.

Table 3-5 shows an example of the computed results, and Appendix B has other examples. Clearly, Table 3-5 shows high variability for the fracture parameter *A* based on the higher CV magnitude. An acceptable CV for this test would be 30 percent or less (i.e., CV ≤ 30%).

Table 3-5. OT Fracture Properties Results for Type D Plant-Mix from US 59 (Atlanta District, TX).

	AV (7±1%)	*A*	*n*
Sample # 1	6.0 %	4.45E-08	4.90
Sample # 2	6.3 %	1.67E-08	5.46
Sample # 3	6.0 %	1.78E-08	5.37
Sample #4	6.0 %	5.03E-08	5.18
Sample #5	6.0 %	9.88E-08	5.26
Avg (all)	6.1 %	4.56E-08	5.23
Stdev (all)	0.134	3.34E-08	0.215
CV (All)	2.0 %	73.2%	4.1%
Avg (best 3)	6.0 %	3.75E-08	5.27
Stdev (best)	0.000	1.73E-08	0.095
CV (best 3)	0.0 %	46.2%	2.0%

The Dynamic Modulus (DM) Test

The DM test will be carried out as per the AASHTO TP 62-03 standard test procedure at five different temperatures and six loading frequencies. Analysis and interpretation of the results is also based on the AASHTO TP 62-03 specification (AASHTO 2001), with some analysis templates given in the included CD. Table 3-6 shows an example of the test results for two temperatures and two loading frequencies, with a master-curve shown in Figure 3-1. Appendix B includes examples of detailed DM test results.

Table 3-6. |E*| Results for Type D Plant-Mix from US 59 (Atlanta District, TX)

	**AV (7±1%)**	**|E*| @ 77°F, 10 Hz (ksi)**	**|E*| @ 130°F, 5 Hz (ksi)**
Sample # 1	8.0%	817	48
Sample # 2	7.9%	848	40
Sample # 3	7.3%	875	49
Avg	7.7%	847	46
Stdev	0.379	29.023	4.933
CV	4.90%	3.43%	10.80%

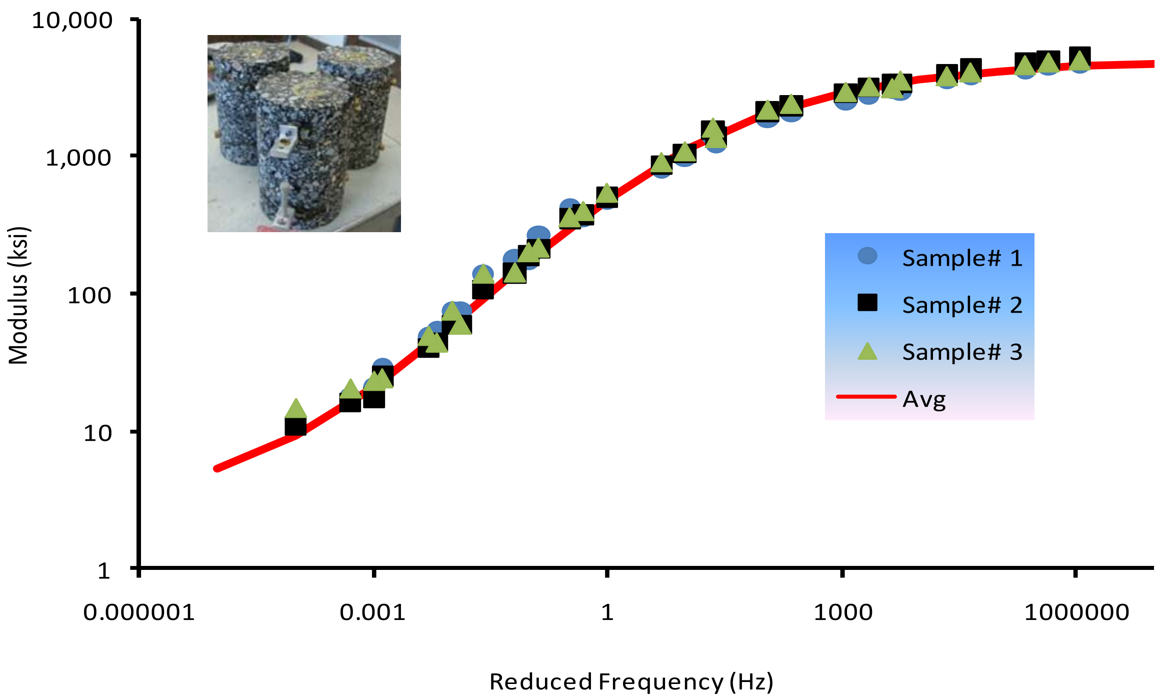

Figure 3-1. |E*| Master-Curve for Type D Plant-Mix (US 59, Atlanta District).

The Repeated Load Permanent Deformation (RLPD) Test

Researchers used the RLPD test, which is based on TTI Report 0-5798 (Zhou et al. 2010) to determine the HMA permanent deformation properties, namely the viscoelastic parameters alpha (α) and mu (μ). As included in Appendix B, both the test procedure and the data analysis method are based on the recommendations of Zhou et al. (2010). MS Excel macros for analyzing the data are provided in the included CD. A step-by-step procedure for the RLPD test and data analysis is described below:

- Specimen size is 4 inches (100 mm) in diameter by 6 inches (150 mm) high.
- Test without confining pressure, with 0.1 second loading and 0.9 second rest period.
- Conduct test at two temperatures (to simulate the Texas climate), 104°F/40ºC and 122°F/50ºC.
- Apply the loads corresponding to each temperature as per Table 3-1(i.e., 20 psi for 104°F and 10 psi for 122°F).
- To determine the viscoelastic rutting parameters, the accumulative permanent deformation (or strain) versus the number of load repetitions (N) is plotted on a log-log scale. This is expressed by the classical power law model given in Equation 3-1:

$$\boldsymbol{\varepsilon}_{\mathbf{p}} = aN^{b} \qquad \text{(Equation 3-1)}$$

Where

a = intercept that represents permanent strain at N = 1.

b = slope that represents the rate of change in permanent strain as a function of the change in load repetitions (*log N*).

Table 3-7 shows an example of the results obtained from RLPD test and shows that the mu parameter has high variability, particularly at the high temperature. In general and as theoretically expected, variability is often high at the high temperature domain partially due to the increasing elasticity of the HMA mix.

Table 3-7. RLPD Results for Type D Plant-Mix from US 59 (Atlanta District, TX).

	**Sample Set#1, T=40°C (20 psi, 10,000 load cycles)**			**Sample Set#2, T=50°C (10 psi, 10,000 load cycles)**		
	AV (7±1%)	**Alpha (α)**	**mu (μ)**	**AV (7±1%)**	**Alpha (α)**	**mu (μ)**
Sample#1	8.0%	0.6436	0.58	7.2%	0.5912	0.31
Sample#2	7.9%	0.6218	0.51	6.9%	0.6872	0.49
Sample#3	7.3%	0.6145	0.50	7.5%	0.7073	0.65
Avg.	7.7%	0.6266	0.53	7.2%	0.6619	0.48
Stdev	0.379	0.015	0.044	0.300	0.062	0.170
COV	4.9%	2.4%	8.2%	4.2%	9.4%	35.2%

The Indirect Tensile (IDT) Test

Both the IDT test and data analysis procedures will be conducted according to Tex-226-F (TxDOT 2011). As shown in Table 3-8, results of the IDT test (Tex-226-F) for samples molded from plant mix sampled from US 59 (Atlanta District, TX) as well as those prepared from raw materials shown in Table 3-8, fall within the typical range of 85–200 psi (TxDOT 2011). Additionally, the results for both the raw materials and plant mix are comparable and consistent.

Table 3-8. IDT Results for Type D Plant-Mix from US 59 (Atlanta District, TX).

	**AV (7±1%)**		**IDT Strength (psi)**	
	Raw Materials	**Plant-Mix**	**Raw Materials**	**Plant-Mix**
Sample#1	7.3%	7.2%	131	135
Sample#2	7.1%	7.8%	133	129
Sample#3	6.9%	7.8%	136	129
Avg	7.1%	7.6%	133	131
Stdev	0.200	0.346	2.517	3.464
CV	2.8%	4.6%	1.9%	2.6%

Based on the example given, Table 3-8 also shows that the IDT test, which is run in monotonic single-shot loading mode, is very repeatable with CV less than 5 percent. This level of variability is not surprising but incomparable with the results shown previously for the repeated load OT test. Notice also that the samples from the plant-mix exhibited relatively lower IDT strength and higher variability.

HMA Thermal Coefficient

In the improvised TTI test method for the HMA thermal coefficient, changes in the sample dimensions (length) were measured from three radial equidistant points for a temperature range of 14 to 104°F, changing at a rate of 0.2°F/min. The steps are summarized below:

- Original sample dimensions = 4-inch diameter by 6-inch length or height.
- Measure initial (original) length at room temperature (77°F); average = 6 inches
- Measure the sample length after dropping the temperature to 14°F at a rate of 0.2°F/min.
- Measure the sample length after raising the temperature from 14 to 104°F at a rate of 0.2°F/min.
- Calculate the average change in length to determine the HMA thermal coefficient. The model for calculating the thermal coefficient was based on the following equation (Apeagyei et al. 2008):

$$\alpha = \frac{\varepsilon}{\Delta T} \qquad \text{(Equation 3-2)}$$

Where

α = thermal coefficient (in/in/°F).

ε = thermal strain per unit length.

ΔT = change in temperature.

Example test results for the Type D plant-mix from US 59 (Atlanta, TX) are shown in Table 3-9 and are comparable with the data found in the literature (Apeagyei et al. 2008). However, variability as measured in terms of the CV is relatively high, which is partially explained by the fact that there is no direct control of the thermal loading with this test.

Table 3-9. TTI HMA Thermal Coefficient Results for Type D US 59 (Atlanta District, TX).

	**AV (7±1)**	**α (in/in/°F)**
Sample# 1	7.4%	1.05E-05
Sample# 2	6.9%	1.92E-05
Sample# 3	7.3%	0.93E-05
Avg	7.2%	1.30E-05
Stdev	0.003	5.40E-06
CV	3.3%	41.5%

The α range found in the literature was 1.137–3.512 E-05, from which the above average value falls within range (Apeagyei et al. 2008). The MEPDG uses a default α value of 1.300E-05 in/in/°F, which coincidentally, is equivalent to the value shown in Table 3-10. However, as TxDOT recommended, there is still a need to compare with the Tex-428-A (TxDOT 2011) and then, assess as to which method is more practical with repeatable and realistic results. This is currently ongoing; but as Table 6-6 shows, the results from the improvised TTI test method are not unreasonable.

DATA REPORTING FORMAT AND ACCESS

In general, most of the HMA materials test data are reported and/or may be accessed in one or more of the following formats from the MS Access Data Storage System; see Figures 3-2 through 3-5:

- Numerical listing.
- Tabular listing.
- Bar chart.
- Graphical format (i.e., plots, curves, etc.).

Hamburg_ID	MaterialProp_ID	LoadPass	Sample1(mm)	Sample2(mm)	Sample3(mm)	AVG	CV	Click to Add
HWTT_TTI-000001	MP_TTI-00001	0	0	0	0	0	0.00%	
HWTT_TTI-000002	MP_TTI-00001	5000	2.6	2.5	2.8	2.6	5.80%	
HWTT_TTI-000003	MP_TTI-00001	10000	3.4	3.3	3.4	3.4	1.70%	
HWTT_TTI-000004	MP_TTI-00001	15000	4	3.9	3.9	3.9	1.50%	
HWTT_TTI-000005	MP_TTI-00001	20000	4.3	4.2	4.3	4.3	1.40%	
HWTT_TTI-000006	MP_TTI-00001	AV (7±1%) (%)	7.2	7.5	6.9	7.2	4.20%	

Figure 3-2. Hamburg Test Data for US 59 Plant Mix (Atlanta District).

OT_ID	MaterialProp_ID	Item	AV(7±1) (%)	PeakLoad(lbs)	OT_Cycles
OT_TTI-000001	MP_TTI-00001	Sample1	6.8	695	309
OT_TTI-000002	MP_TTI-00001	Sample2	6.1	700	121
OT_TTI-000003	MP_TTI-00001	Sample3	6.4	773	334
OT_TTI-000004	MP_TTI-00001	Sample4	6.3	757	269
OT_TTI-000005	MP_TTI-00001	Sample5	6.6	839	240
OT_TTI-000006	MP_TTI-00001	Average (all)	6.4	753	255
OT_TTI-000007	MP_TTI-00001	CV (all (%))	4.3	7.9	32.6
OT_TTI-000008	MP_TTI-00001	Average (best3)	6.4	717	304
OT_TTI-000009	MP_TTI-00001	CV (best3 (%))	2.4	5	11

Figure 3-3. Overlay Test Data for US 59 Plant Mix (Atlanta District).

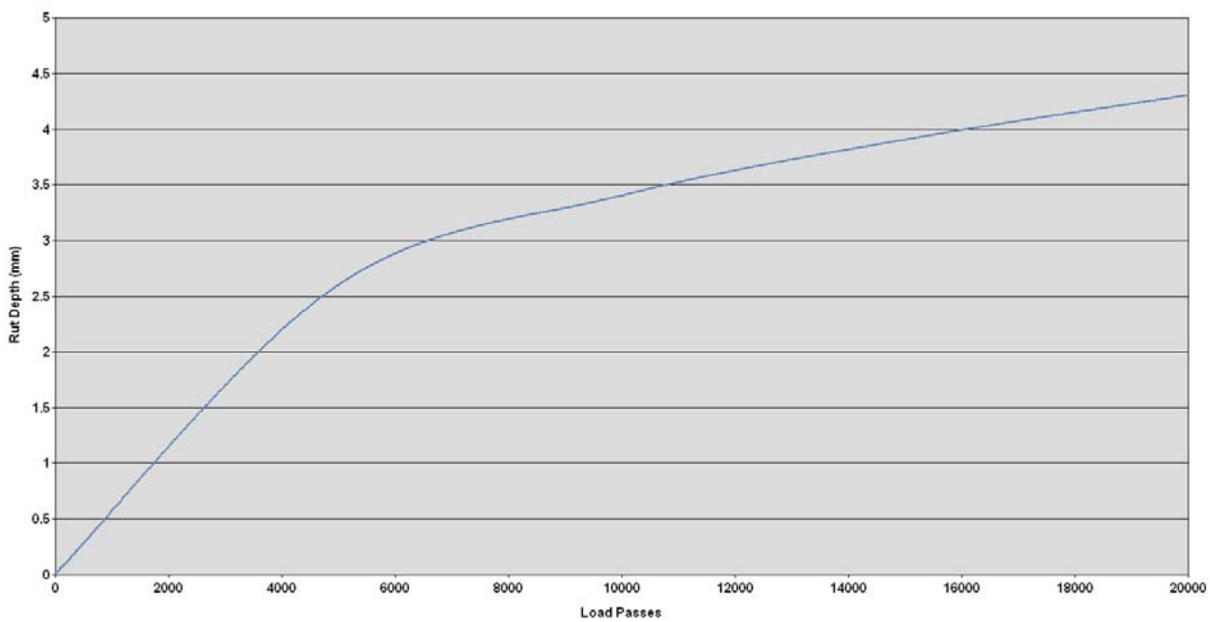

Figure 3-4. Plot of Rut Depth vs. Load Passes Obtained from US59 Hamburg Data.

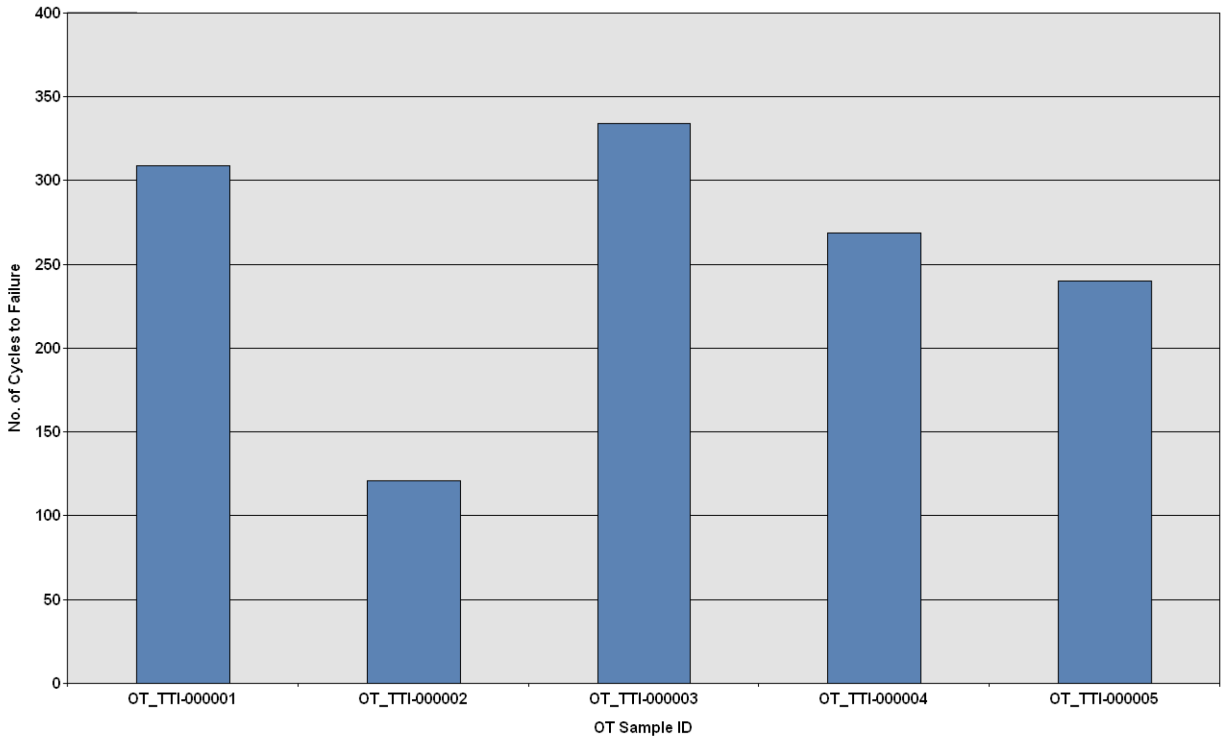

Figure 3-5. OT Results from US 59 (Atlanta District).

Clearly, Figures 3-2 through 3-5 show that the MS Access Data Storage System has potential to display data in any desired format. Appendix B shows more examples of data extract from the MS Access Data Storage System. Currently, investigations are under way to facilitate direct data exporting from the MS Access Data Storage System or vice versa.

SUMMARY

This chapter presented the data analysis plans for the HMA mixes including the test specifications, analysis procedures, and the data reporting format. Overall, all the data analysis procedures and methods are consistent with the Texas and US national standards for testing, analyzing, reporting, and interpreting the HMA test data, except for the following:

- OT fracture properties.
- RLPD test data.
- HMA thermal coefficient.

Examples of the test results and data extracts from the MS Access Data Storage System were also presented. Test plan proposals for HMA mixes are included in Appendix B.

CHAPTER 4: LAB TEST DATA ANALYSIS: PART III

Part III of the laboratory data analysis plans pertain to the base and subgrade soil materials, both untreated and treated. These data analysis plans are discussed in this chapter and include the data collection format, raw data reduction process, and analysis procedure for the untreated and treated base and subgrade materials. The following tests are common among all the treated and untreated bases and subgrade soils:

- Sieve analysis.
- Atterberg limits.
- Soil Classification.
- Moisture density curves.

MATERIAL SAMPLING AND QUANTITIES

At each site, the required materials should be sampled at a minimum of three locations at the test section. For flexible bases the material should be sampled from the windrow. For treated materials, the materials should be gathered before the stabilizing agent is added. For plant-mix treated materials, the material should be sampled from the plant at three distinct locations within the stock pile. Overall, a minimum of 600 lb of material (200 lb per sampling point) should be collected for bases and 450 lb (150 lb per sampling point) for the subgrade soils.

TEST SPECIFICATIONS AND DATA ANALYSIS METHODS

Test plan proposals for the base and subgrade soil materials are included in Appendix C.

Sieve Analysis

Materials collected from each location should be subjected to sieve analysis as per Tex 110-E and Tex-111-E (TxDOT 2011). These tests include:

- Dry sieving with the addition of No. #100 and #200 to the sieve stack on the entire materials retrieved from the site. The values to be reported are percent passing Sieves 2 1/2 in., 1-3/4 in., No. 7/8 in., 3/8 in., No. 4, No. 40, No. 100, and No. 200.

- Wash sieve on representative samples of adequate weight as described in Tex-110-E. The values to be reported are percent passing on sieves No. 40, No. 100. and No. 200.
- Hydrometer tests on representative samples using the materials passing No. 40 sieve. The values to be reported are percent passing 0.02 mm, 0.002 mm, and 0.001 mm.

The average gradations from Item 1 should always be compared with what TxDOT reports in the QC/QA charts. If the two gradations on each sieve are within 5 percent for sieves coarser than No. 40 or 3 percent on sieves equal or finer than No. 40, the sampled materials will be considered different. Figures 4-1a to 4-1c show the average gradation from the three tests will be used for subsequent tests.

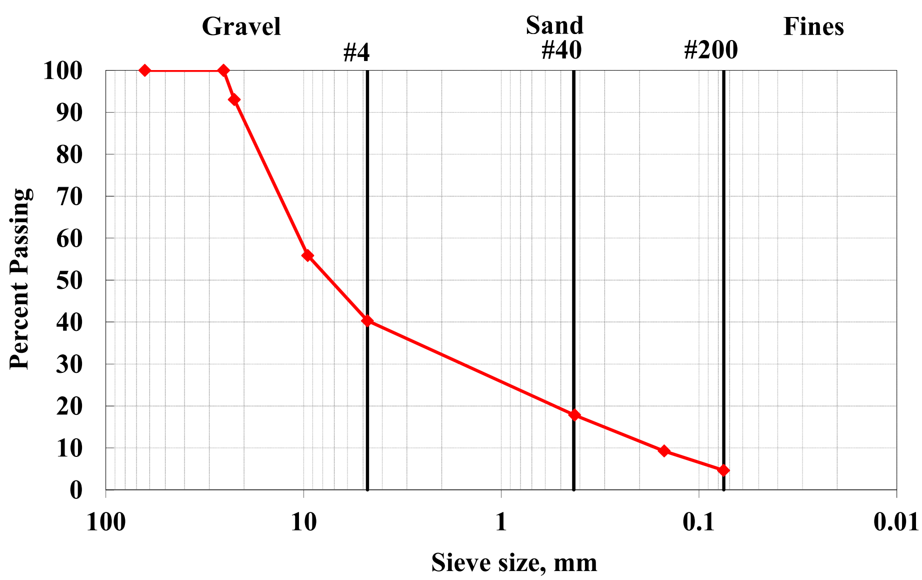

Figure 4-1a. Typical Average Gradation Curve from an El Paso Base.

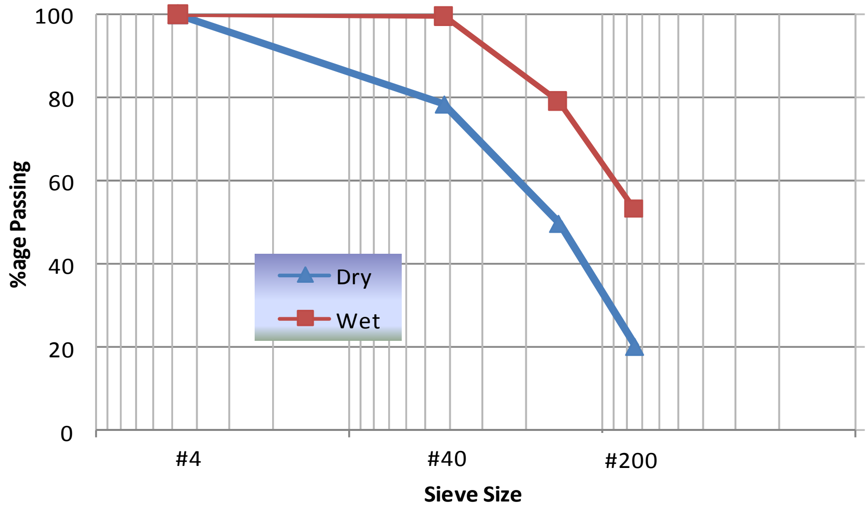

Figure 4-1b. Typical Average Gradation Curves for Raw Subgrade Soil (Loop 480, Laredo).

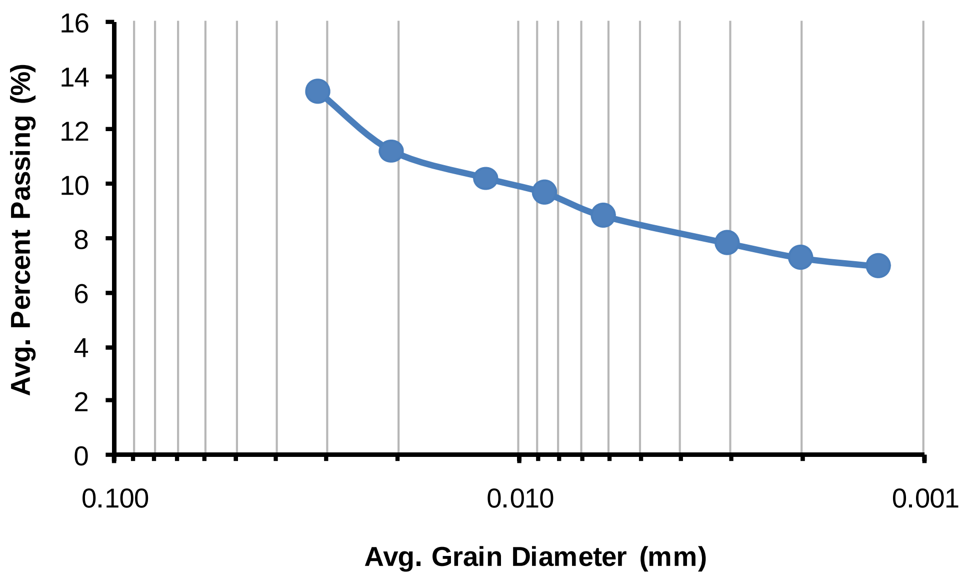

Figure 4-1c. Hydrometer Test Results for Raw Subgrade Soil (Loop 480, Laredo).

Atterberg Limits

Atterberg Limits tests consist of the Liquid Limit, Plastic Limit, and Plasticity Index tests and are conducted as per Tex-104-E through Tex-106-E (TxDOT 2011). One test will be carried out on the representative sample from the stock for comparison with TxDOT results if available.

If the two results are different (i.e., the liquid limits differ by more than 15 percent and the Plasticity Index by more than 20 percent), the research team will conduct a second series of tests. It should be mentioned that the treated materials should be also tested once after treatment. Table 4-1 includes the typical results from the test on the material shown in Figure 4-1. The results seem quite repeatable, justifying the reduction in the number of replicates.

Table 4-1a. Typical Index Test Results from an El Paso Base.

Material Properties			Sample			Avg	Stdev	COV
			#1	#2	#3			
Atterberg Limits	Tex-104-E	LL	22	23	24	23	1.000	4%
	Tex-105-E	PL	13	15	15	14	1.155	8%
	Tex-106-E	PI	9	8	9	9	0.577	7%

Table 4-1b. Typical Index Test Results for Raw Subgrade Soil (Loop 480, Laredo).

Material Properties			Sample			Avg	Stdev	COV
			#1	#2	#3			
Atterberg Limits	Tex-104-E	LL	15	15	16	15	0.577	3.8%
	Tex-105-E	PL	10	11	10	10	0.577	5.6%
	Tex-106-E	PI	5	5	6	5	0.577	10.8%

Soil Classification

The average results from the sieve analysis and the Atterberg Limits should be used to classify the materials as per Unified Soil Classification System and AASHTO Classification System. The supporting information that should be extracted is percent gravel, percent sand, and percent passing No. 200. In addition, the Coefficients of Uniformity (Cu), and Coefficient of Curvature (Cc), should be calculated by estimating and reporting the diameters associated with 10 percent, 30 percent, and 60 percent passing, d_{10}, d_{30} and d_{60}, respectively. Table 4-2 shows an example of such an analysis for the El Paso base.

Table 4-2. Typical Results for Soil Classification of an El Paso Base.

Material Properties		Value
PL		22%
LL		13%
Cu		65
Cc		2.9
% Gravel		60
% Sand		36
% Fines =		4
d10 =		0.167 mm
d30 =		2.284 mm
d60 =		10.891 mm
Classification	Tex 142-E	GW
	AASHTO	A 1-b

Moisture Density Curves

The next step is to perform a moisture density test as per Tex-113-E for the bases and Tex 114-E for the subgrade soils. Four specimens at different moisture contents are prepared. For treated materials, the design dosage of the stabilizer will be added to the material. The reported outcomes of these tests are the optimum moisture content (OMC) and the maximum dry density (MDD). The results from one series of tests should be compared with those from TxDOT (if available). If the two results are different (i.e., the two OMCs differ by more than 1 percent and the MDD by more than 2 pcf), the researchers will conduct a second set of tests. Table 4-3 shows typical results from such an activity on an El Paso base. The results are quite repeatable, suggesting that replicate tests may not be necessary.

Table 4-3. Typical Moisture Density Test Results from an El Paso Base.

Material Properties	Samples		Average	Stdev	COV
	#1	#2			
MDD (pcf)	144	145	145	0.707	0%
OMC (%)	6.5	6.6	6.6	0.071	1%

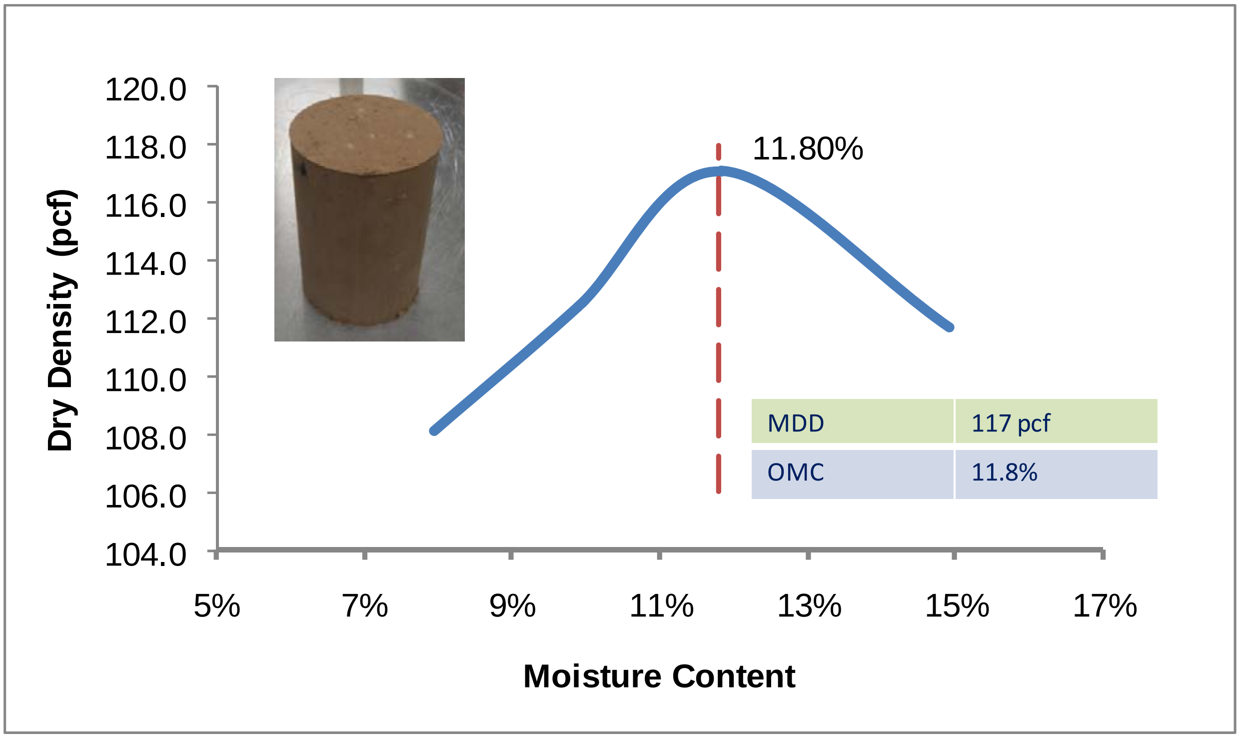

Figure 4-2. Example of MD for Raw Subgrade Soil (Loop 480, Laredo).

Strength Tests on Untreated Bases and Subgrades

The strength tests that are necessary for the untreated materials include the Texas Triaxial Tests (Tex-117-E) and Standard Triaxial Test (Tex-143-E) (TxDOT 2011). These tests are described below.

The Texas Triaxial Tests

The Texas Triaxial tests will be performed on six specimens prepared at the OMC and MDD and moisture conditioned for 10 days. The specimens will be subjected to six confining pressures varying between 0 to 15 psi, as described in Tex-117-E. The values to be reported are the angle of internal friction, ϕ, cohesion, c, and the classification, TTC. As the results of these tests are less critical to the design, they will be carried out on one set of specimens. Table 4-4 shows the typical results on two sets of specimens. The variations between the Texas Triaxial Class and the angle of internal friction are rather small. The higher variation in the cohesion can be attributed to the small values associated with them and the nature of curve fitting associated with these tests.

Table 4-4. Typical Results from Strength Tests on an El Paso Base.

Material Properties			Sample		Avg	Stdev	COV
			#1	#2			
Texas Triaxial	Tex-117-E	Class	3.1	2.8	3.0	0.212	7%
		Cohesion, psi	7.2	5.6	6.4	1.131	18%
		Φ, degree	48	54	51	4.243	3%
Standard Triaxial	Tex-143-E	Cohesion, psi	8.9	7.4	8.2	1.061	13%
		Φ, degree	51	53	52	1.414	3%

The Standard Triaxial Tests

The Standard Triaxial tests will be performed on three specimens prepared at the OMC and MDD. These specimens are tested about 24 hrs after preparation without moisture conditioning. The specimens will be subjected to three confining pressures varying between 3 to 10 psi, as described in Tex-143-E. The values to be reported are the angle of internal friction (ϕ) and cohesion (c). This test will be carried out on two sets of specimens. If the results from the two sets are different (i.e., the angles of internal friction differ by more than 10 percent or the cohesions by more than 20 percent), a third set of tests will be performed. Table 4-4 shows typical results on two sets of base specimens. This test seems to be slightly more repeatable than the Texas Triaxial Tests.

Strength Tests on Treated Bases and Subgrades

The unconfined compressive strength (UCS) test will be carried out on the bases and subgrade soils that are treated with stabilizers in triplicate. Researchers at the OMC and MDD will prepare three specimens with the design dosage of stabilizer, then cure these for seven days before testing. The test protocol in general is similar to that of Tex-117-E. The reported values are the individual and average values of the UCS as well as corresponding COV.

Deformation Tests on Untreated Bases and Subgrades

The deformation tests that are necessary for the untreated materials include the resilient modulus (MR) tests and the permanent deformation (PD) tests. These tests are described below.

Resilient Modulus Tests

The resilient modulus tests will be performed as per NCHRP 1-28A procedure as included in Appendix C. The parameters to be reported for each specimen are the three fit parameters (k_1 through k_3) and the coefficient of correlation (R^2) values of the best fit curve. These tests will be carried out in duplicate on specimens prepared at the OMC and MDD. If the results from the two resilient modulus tests (as the representative modulus values judged at representative confining pressure and deviatoric stress as the MEPDG prescribed) differ by more than 20 percent, a third test will be performed. Table 4-5 shows an example for the El Paso base.

Table 4-5. Typical Results for Resilient Modulus Parameters on El Paso Base.

Target Moisture Content (%)	**Nominal Moisture Content (%)**	**Dry Density (pcf)**	**K_1**	**K_2**	**K_3**	**R^2**
6.0	5.8	143	718	0.58	−0.28	0.98
6.0	6.0	143	669	0.52	−0.28	0.98
Avg	5.9	143	694	0.55	−0.28	0.98
Stdev	0.141	0.000	34.648	0.042	0.000	0.000
CV	2%	0%	5%	8%	0%	0%

Permanent Deformation Tests

The permanent deformation tests will be performed as per procedure included in Appendix C. The parameters to be reported for each specimen are the resilient strain, ε_r, permanent deformation parameters α and μ and the R^2 values of the best fit curve. These tests will be carried out in duplicate on specimens prepared at the OMC and MDD. If the results from the two PD tests (as judged by the parameters α and μ) differ by more than 20 percent, a third test will be performed. Table 4-6 shows an example for the El Paso base.

Table 4-6. Typical Permanent Deformation Parameters for El Paso Base Material.

Target Moisture Content, %	Nominal Moisture Content, %	Resilient Strain, ε_r	α	μ	R^2
6	5.6	0.011	0.04	0.96	0.99
6	5.8	0.009	0.03	0.94	0.96
Avg	5.7	0.010	0.04	0.950	--
Stdev	0.1	0.001	0.01	0.01	--
COV	2%	14%	20%	1%	--

Deformation Tests on Treated Bases and Subgrades

The deformation tests that are necessary for the treated materials include modulus tests and the permanent deformation (PD) tests. These tests are described below.

Modulus Tests

The resilient modulus (M_R) tests will be performed similar to the untreated materials but at zero confining pressure. The deviatoric stresses applied to the specimens will be 10 percent, 20 percent, 30 percent, and 40 percent of the UCS of the material determined before. Three specimens with the design dosage of stabilizer will be prepared at the OMC and MDD and will be cured for seven days prior to testing. The parameters to be reported for each specimen are the representative resilient modulus since parameters k_2 and k_3 will be zero for these materials. Figure 4-3 shows an example for the El Paso base.

As part of this activity, free-free resonant column (FFRC) tests will be performed on each specimen before M_R tests. According to Hilbrich and Scullion (2007), these tests are more robust and repeatable than the M_R tests. The moduli from the FFRC and M_R tests will be correlated.

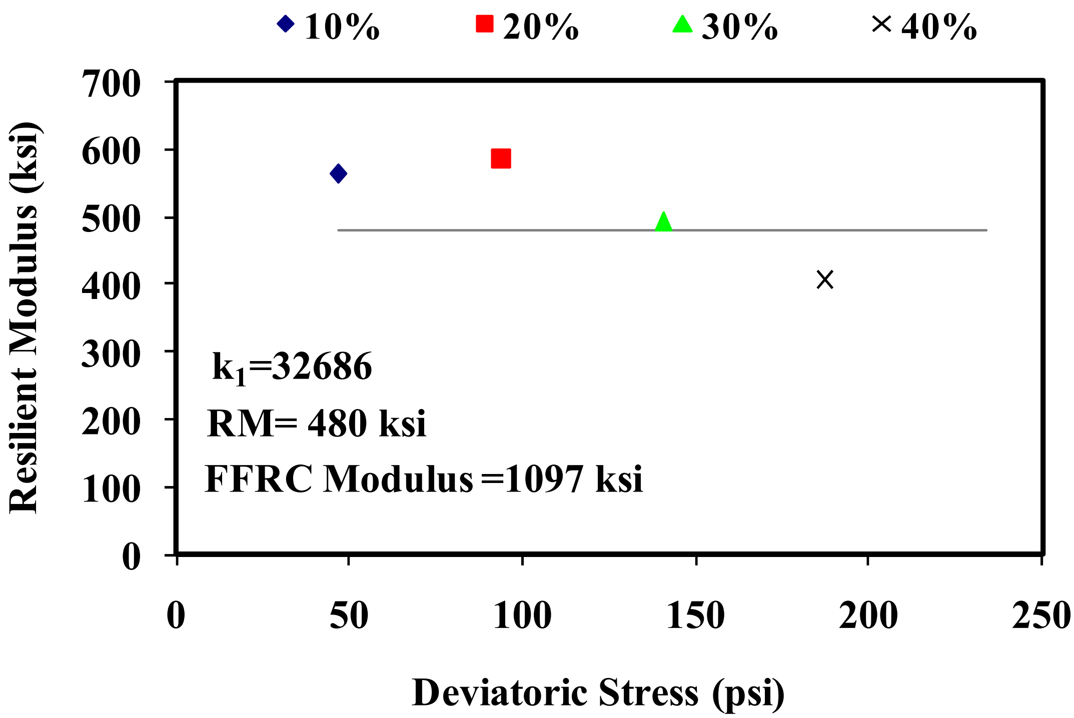

Figure 4-3. Typical Resilient Modulus Test Results.

Permanent Deformation Tests

The permanent deformation tests will be carried out only if the percent stabilizer is less than 2 percent as per procedure included in Appendix C. The parameters to be reported for each specimen are the resilient strain, ε_r, permanent deformation parameters α and μ, and the R^2 values of the best fit curve. These tests will be carried out in duplicate on specimens prepared at the OMC and MDD. If the results from the two PD tests (as judged by the parameters α and μ) differ by more than 20 percent, a third test will be performed.

Moisture Characteristics Tests

The moisture characteristics tests include the establishment of soil water characteristic curves of untreated bases and subgrade soils. In addition, since the specific gravities of these materials are also needed to establish the volumetric moisture contents, these values will also be measured.

Soil Water Characteristic Tests

These tests will be carried out using the filter paper method as described by Bulut et al. (2001). The results reported are the variations in the soil matric suction, ψ, with volumetric moisture content, θ. One of the models that will be considered to fit to the measured data is,

$$\theta = \left[1 - \frac{\ln\left(1+\frac{\psi}{\psi_r}\right)}{\ln\left(1+\frac{10^6}{\psi_r}\right)}\right] \times \frac{\theta_{sat}}{\left[\ln\left[e + (\alpha\psi)^n\right]\right]^m} \qquad \text{(Equation 4-1)}$$

Where

ψ_r = matric suction at residual volumetric water content.

θ_{sat} = volumetric water content at full saturation.

α, n, m = the model fitting parameters.

These tests will be conducted on one sample at different moisture contents.

Specific Gravity Tests

To assess the degree of saturation, hence the volumetric moisture content at saturation, the specific gravity of the material, G_s, should be known since the degree of saturation, S_r, is estimated from the gravimetric moisture content, ω, using the equation,

$$S_r = \omega\, G_s\, \rho_d / (G_s\, \rho_w - \rho_d) \qquad \text{(Equation 4-2)}$$

Where

ρ_d = dry mass density.

ρ_w = mass density of water.

The specific gravity of the bases will be estimated as per ASTM C-127 and C-128, while the specific gravity of the subgrade soils will be estimated from Tex-108-E. Due to the uncertainties in the measurement of the specific gravity and the narrow range of specific gravity that most bases and subgrade soils fall within, it is not uncommon to estimate this value.

In this study, these tests will be carried out in duplicate on several materials. Based on the evaluation of these results, a decision on reducing the number of tests or eliminating them will be made. Table 4-7 is an example of the specific gravity results for the raw subgrade soil from Loop 480 in Laredo District.

Table 4-7. Specific Gravity Results for Raw Subgrade Soil (Loop 480, Laredo).

	Item	**Specific Gravity**
	Sample# 1	2.57
	Sample# 2	2.62
	Sample# 3	2.60
	Avg	2.60
	Sdtev	0.02
	CV	0.94%

SUMMARY

This chapter discussed the data analysis plans for the base and subgrade soil materials, both untreated and treated. Criteria for material sampling, test procedures, and data analysis methods/models along with the data reporting format were all discussed. Test plan proposals for the base and subgrade soil materials are included in Appendix C.

CHAPTER 5: FIELD TEST DATA ANALYSIS: PART I

The data analysis plans discussed in this chapter pertain to the field tests that were recommended to evaluate some of the key distresses and performance characteristics of the HMA flexible pavements and overlays. As discussed here, Part I of these data analysis plans includes the following:

- Test section characteristics.
- Crack survey.
- Rutting.
- Surface profiles.
- Skid number.

The data analysis plans also include descriptions of the parameters to be measured, test methods, test equipment, target number of sections to be tested per year, frequency of tests, proposed time of the year, and example of the data collected. A summary of key points is then presented to conclude the chapter.

TEST SECTION CHARACTERISTICS

As per TxDOT recommendation, researchers will use one 500-ft test section per homogeneous highway project and homogeneous pavement structure, preferably in the outside lane. Figure 5-1 shows that the selection of the test sections will be conducted in conjunction with Study 0-6622 subject to TxDOT approval. To ensure that all influencing variables are accounted for, the factors listed in Table 5-1 will be considered when selecting the test sections.

In summary, the test sections should not, for instance, be only Overlays or new construction. The coverage should be as broad as possible to cover all the factors in Table 5-1. Otherwise, it will be very difficult to calibrate the M-E models. So, it is very critical that the researchers ensure that the 100 test sections, if possible, cover an equal number of variables listed in Table 5-1, including the associated distresses as Study 0-6622 (2011) stipulates.

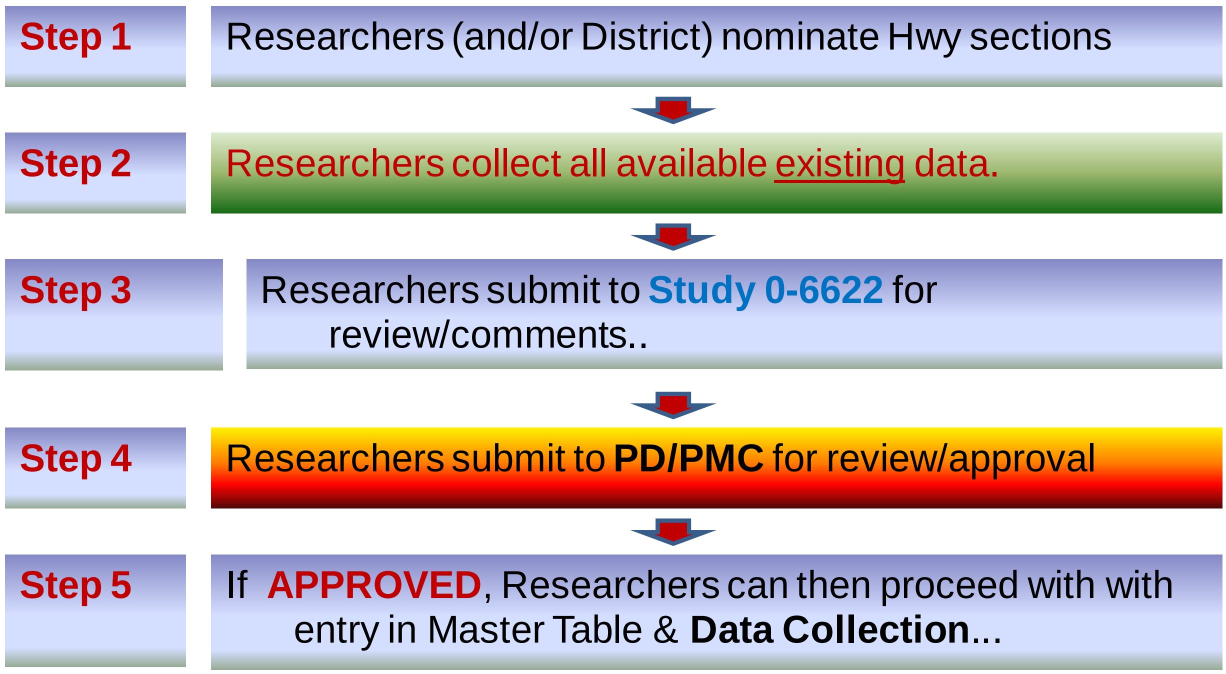

Figure 5-1. Steps for Selecting Field Test Sections.

Table 5-1. Variables to Consider when Selecting Test Sections.

#	Variable	Minimum	Description	Comment
1	Pavement type	4	a) HMA on HMA, b) HMA on untreated granular bases, c) HMA on treated base, and d) surface treatment on untreated and/or treated base.	WMA, RAP, RAS, and perpetual pavements will also be considered.
2	Pavement category	4	a) perpetual, b) typical flexible HMA, c) HMA overlay over HMA, and d) HMA overlay over PCC	
3	Thickness	2	a) thin (≤ 3 inches) and b) thick (> 3 inches)	
4	Traffic levels	2	a) low and b) high volume	Include Intestate, State, and Farm roads
5	Environmental types	5	a) dry-warm, b) dry-cold, c) wet-warm, d) wet-cold, and e) moderate (mixed).	
6	Age conditions	2	a) new construction and b) existing	

In cases where the pavement structure is homogeneously the same, but other variables such as traffic or age are different, then more than one different 500-ft test sections may be utilized from such a highway project. For instance, if the pavement structure such as the number of layers, layer thicknesses, or materials on the same highway is different, then more than one 500-ft test sections may be utilized. Examples of these scenarios include the following:

- SH 114 (Fort Worth District)—same traffic level, environment, and perpetual pavement structure but two different materials. Two test sections were thus selected: one with SFHMA mix designs, and the second with traditional dense-graded mix designs.
- US 59 (Atlanta District)—same traffic level and environment but different overlay structures: one with Petromat interlay, another with Truepave interlayer, and the third, without any interlayer material (denoted as Control). Therefore, three test sections were selected representing Petromat, Truepave, and Control, respectively.

To ensure homogeneity when selecting the test sections, particularly in the case of the existing pavement structures and overlays, both the GPR and FWD will be utilized to locate homogeneous sections. Once a test section has been identified, the start and end points are marked using the following identifiers:

- Painting (white or orange paint) on the shoulders—test section start and end points.
- GPS coordinates—test section start and end points.
- Existing mile marker signs—test section start and end points.
- Physical landmarks such as intersections, etc.—test section start and end points.
- Road signs—at test section start and end points; see Figure 5-2.

Once marking of the test sections is completed, field testing can then be conducted. Table 5-2 lists the test procedures and data characteristics for cracking, rutting, surface profiles, and skid number; see Appendix D for more details.

Figure 5-2. Road Signs for the Test Sections.

Table 5-2. Field Test Procedures and Data Characteristics—Part I.

#	Test	Test Procedure (Spec)	Frequency	Analysis Method	Output Data (Units)	Typical Value/ Threshold
1	Cracking	Visual-walking surveys (manual counts and tape measurements) – Alligator cracking – Longitudinal cracks – Transverse cracks	At test section selection and/or just after construction, and thereafter, twice per year (just after winter and summer)	MS Excel	Number of cracks; %age cracking; crack length, interspacing of cracks, crack width (severity), crack density	≤ 25% (alligator) ≤ 1000 ft/mi (longitudinal)
2	Surface rutting	Straightedge, wedge, and ruler; ≥ 6 pts @ 100 ft interval; both WPs		MS Excel	Rut depth (inch)	≤ 0.5
3	Surface profiles	TTI high-speed profiler; in both WPs		TxDOT RideQuality Software	IRI (inch/mi) and PSI	30 ≤ IRI≤ 172; 2.5 ≤ PSI ≤ 5.0
4	Texture and skid	From TxDOT PMIS	From TxDOT PMIS	From TxDOT PMIS	-	-

CRACKING

As indicated in Table 5-2, crack evaluation is done via visual-walking surveys:

- At the time of test section selection in case of existing pavements and overlays.
- Just after construction in case of overlays and new pavements.
- Thereafter twice per year, just after winter and just after summer.

Types of cracking assessed include the following:

- Alligator cracks.
- Longitudinal cracks.
- Transverse cracks.

Figure 5-3 has photographical examples of these cracks. As Figure 5-4 and Appendix D both show, the data to measure, record, and report on the crack survey map should be the following:

- Date and time of the crack survey.
- Taking photographs.
- The air and pavement temperature (°F) at the time of crack survey.
- The lane width (ft).
- The number of cracks.
- The crack lengths (ft).
- The crack widths (inch) and spacing (ft).

From these data, researchers can either manually compute the percentage cracking of the test section or use MS Excel, after which they can then determine the crackdensity. Although some thresholds are given in Table 3-1, the ideal situation is to have zero cracking. While the measured parameters may be reported as tabular listing, the computed crack density can be tabulated or graphed as function of time so as to visually monitor the rate of deterioration. A similar reporting format will be used in the MS Access Data Storage System.

Figure 5-3. Cracking on US 59 (Atlanta District) and SH 121 (Paris District) Prior to Overlay Placement in Spring 2011.

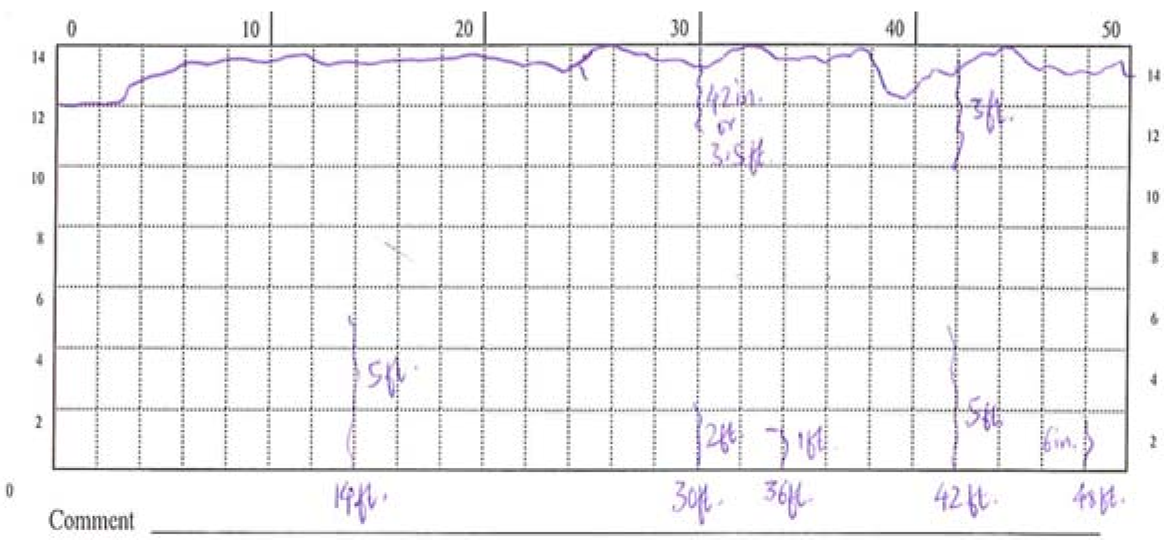

Figure 5-4. Example of Crack Survey Map for US 59, Atlanta District (Spring 2011).

SURFACE RUTTING

For this distress, researchers measured the rut depth at every 100-ft interval using the measuring wedge and a straightedge as shown in Figure 5-5. Thus, they did measurements on a total of six points, both in the right and left WP of the lane. Like for the crack survey, rut measurements were conducted as follows:

- At the time of test section selection in the case of existing pavements and overlays.
- Just after construction in the case of overlays and new pavements.
- Thereafter, twice per year, just after winter and just after summer.

Figure 5-5. Surface Rut Measurements on SH 114 (Fort Worth, Summer 2011).

During field rut measurements, the data to measure, record, and report on the field rut survey sheet or crack map should be the following:

- Date and time of the crack survey.
- Taking photographs.
- The air and pavement temperature (°F) at the time of crack survey.
- The lane width (ft).
- The surface rut depth every 100 ft interval (inch).

From these data, the average rut depth, Stdev, and CV can be computed using MS Excel and reported in a tabular, bar chart, or graphical format as a function of time. A similar reporting format will be used in the MS Access Data Storage System. Tables 5-3 and 5-6 have examples of these analyses, include the measured temperatures.

Table 5-3. Tabulation of Rut Measurements for SH 114—Superpave (Fort Worth).

Interval (ft)	Avg Rut Depth (inch)			
	Summer2006 (Construction)	Summer2007	Summer2009	Summer2011
0	0.00	0.04	0.050	0.103
100	0.00	0.04	0.056	0.088
200	0.00	0.06	0.080	0.125
300	0.00	0.06	0.075	0.100
400	0.00	0.05	0.076	0.100
500	0.00	0.05	0.065	0.094

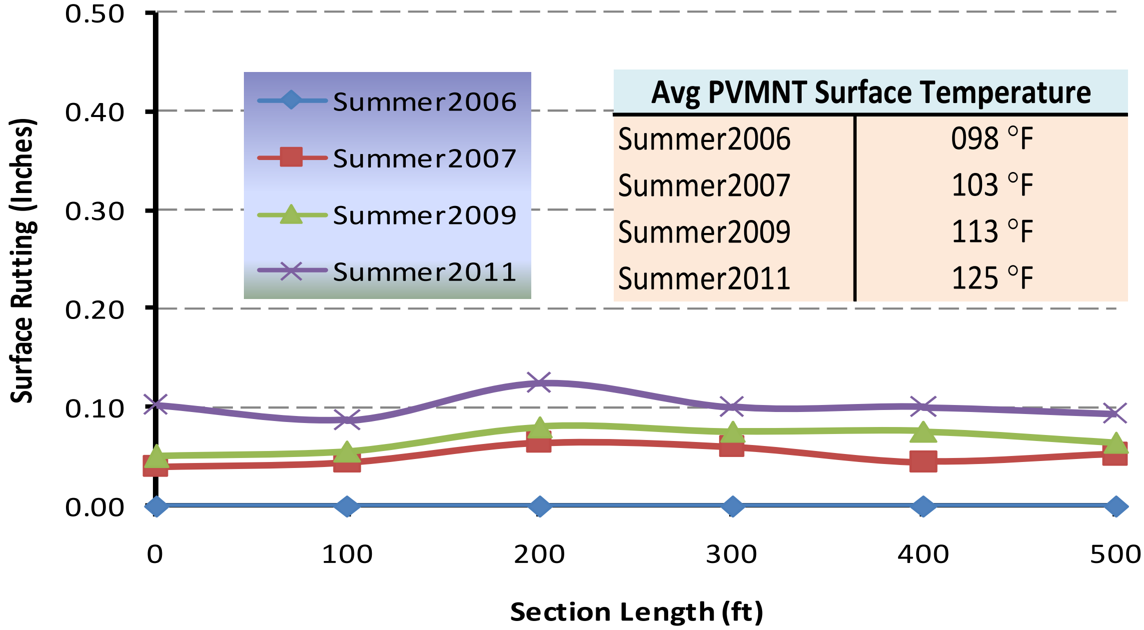

Figure 5-6. Graphical Plot of Rut Measurements on SH 114—Superpave (Fort Worth).

SURFACE PROFILES

Like the preceding distresses, surface profiles to evaluate the pavement smoothness and ride quality were conducted as follows:

- At the time of test section selection in case of existing pavements and overlays.
- Just after construction in case of overlays and new pavements.
- Thereafter twice per year, just after winter and just after summer. Measurements were conducted both in the right and left WPs using the TTI high-speed profiler vehicle; see Figure 5-7.

The desired output data from the high-speed surface profile measurements is the IRI (inch/mi) and PSI. Reduction and analysis of the raw profile data to compute these parameters is accomplished using the TxDOT *RideQuality* software based on the Texas Specification 585 (TxDOT 2011). Both the IRI and PSI results can then further be analyzed and reported as tabular listings, bar charts, or graphical plots using MS Excel or Access as a function of time. A similar reporting format will be used in the MS Access Data Storage System. Examples of the IRI and

PSI results are illustrated in Figures 5-7 and 5-8. Typical ranges and thresholds of these parameters are given below:

- 30 ≤ IRI≤ 172 inch/mi (the smaller the IRI value, the better).
- 2.5 ≤ PSI ≤ 5.0 (the higher the PSI value, the better).

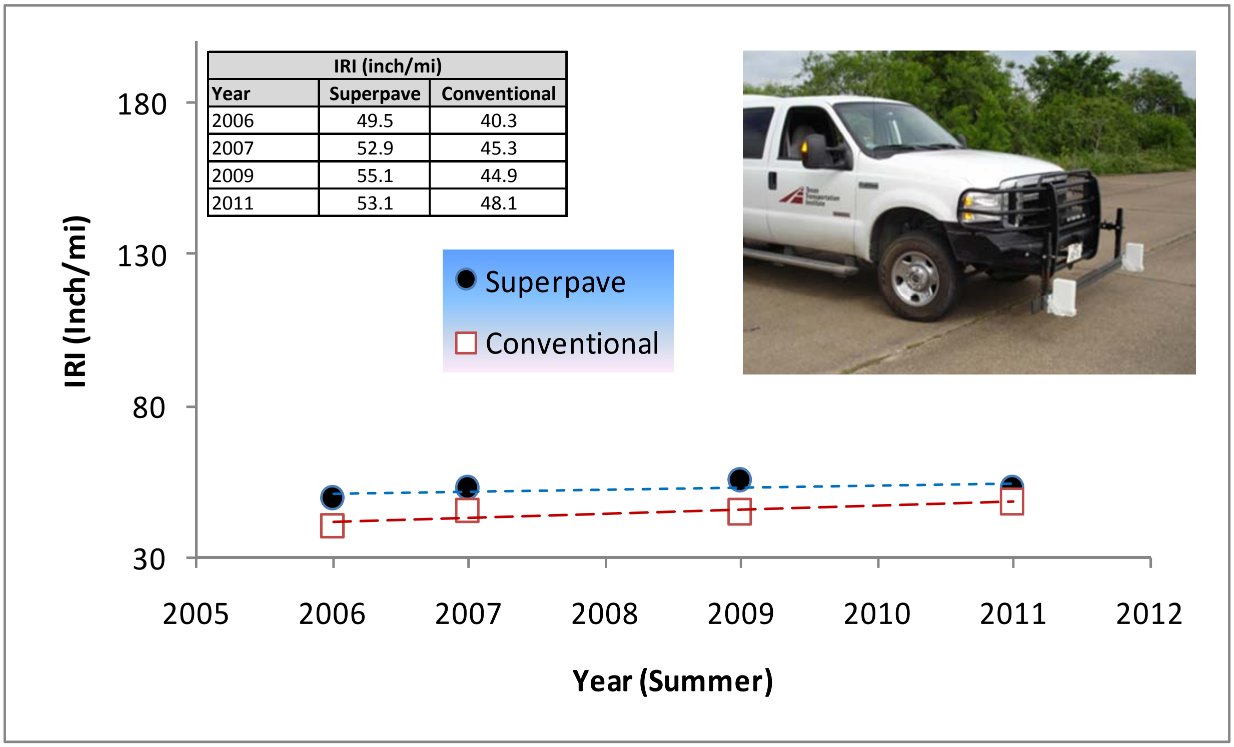

Figure 5-7. Example of IRI Data for SH 114 (Fort Worth) as a Function of Time.

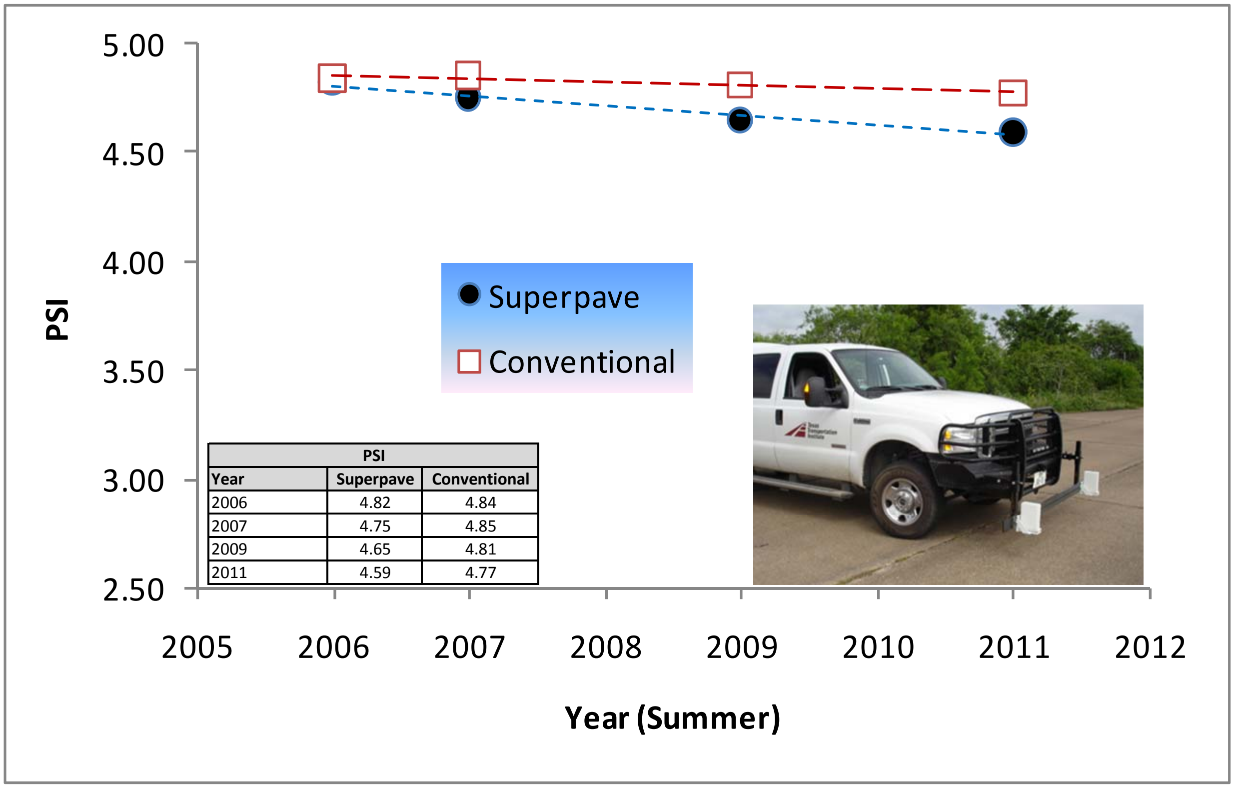

Figure 5-8. Example of PSI Data for SH 114 (Fort Worth) as a Function of Time.

TEXTURE AND SKID NUMBER

As per TxDOT recommendations, these data will be periodically obtained from the PMIS and reported as tabular listings, bar charts, or graphical plots. Analysis to generate the tables, charts, and/or plots will be accomplished using MS Excel or Access. The texture and skid data are particularly more critical for overlays; hence, the necessity to collect these data.

SUMMARY

This chapter presented and discussed the various aspects of the Part I field data analysis plans incorporating the following: 1) field test section characteristics, 2) cracking, 3) rutting, 4) surface profiles, and 5) texture and skid data. The test procedure, frequency measurements, data analysis methods, the output data, units of measurement, and the format of reporting it were also discussed. Typical values and thresholds for each distress and data type were also presented.

CHAPTER 6: FIELD TEST DATA ANALYSIS: PART II

Part II of the field data analysis plans deals with the PSPA, DCP, and FWD. Table 6 lists the field test procedures and data characteristics. Detailed discussions for each test method are provided in the subsequent sections.

Table 6-1. Field Test Procedures and Data Characteristics—Part II.

#	Test	Test Procedure (Spec)	Frequency	Analysis Method	Output Data (Units)	Typical Value/ Threshold
1	PSPA		At test section selection &/or just after construction, and thereafter, twice per year (just after Winter and summer)			
2	DCP	Min 6 pts (≥3 in WP and ≥3 in-between WP)		MS Excel	Layer thickness (inch), and modulus (ksi or psi)	
3	FWD	Every 25 ft, 9 kips, ≥ 1 drop, WP		Modulus 6.1 software and MS Excel	Surface deflections (mls), curvature indices, and modulus (ksi)	

PORTABLE SEISMIC PAVEMENT ANALYZER TESTS

The Portable Seismic Property Analyzer (PSPA) uses the Spectral-Analysis-of-Surface-Waves (SASW) method that is based on measuring surface waves propagating in layered elastic media. The SASW test is a non-intrusive seismic test method that relies on the measurement of Rayleigh type surface waves; see Figure 6-1 for a photographical view of the PSPA and SASW devices.

Figure 6-1. The PSPA Device.

The key point in the SASW method is the measurement of the dispersive nature of the surface waves, which are used to determine the shear wave velocity of the pavement, the base, and the subgrade. An impact source and two receivers (or accelerometers) placed on the pavement surface control the generation and detection of surface waves. The two vibration transducers are located at known distances from the source; the software conducts the automated data analysis. The method provides qualitative variation of modulus with depth. The parameter reported at each test point is the average seismic modulus of the layer. The PSPA is recommended to be used to measure the modulus of the HMA at each site, an option to measure the variations in the modulus of the base and subgrade. Figure 6-2 presents the typical results from an HMA, base and subgrade layer.

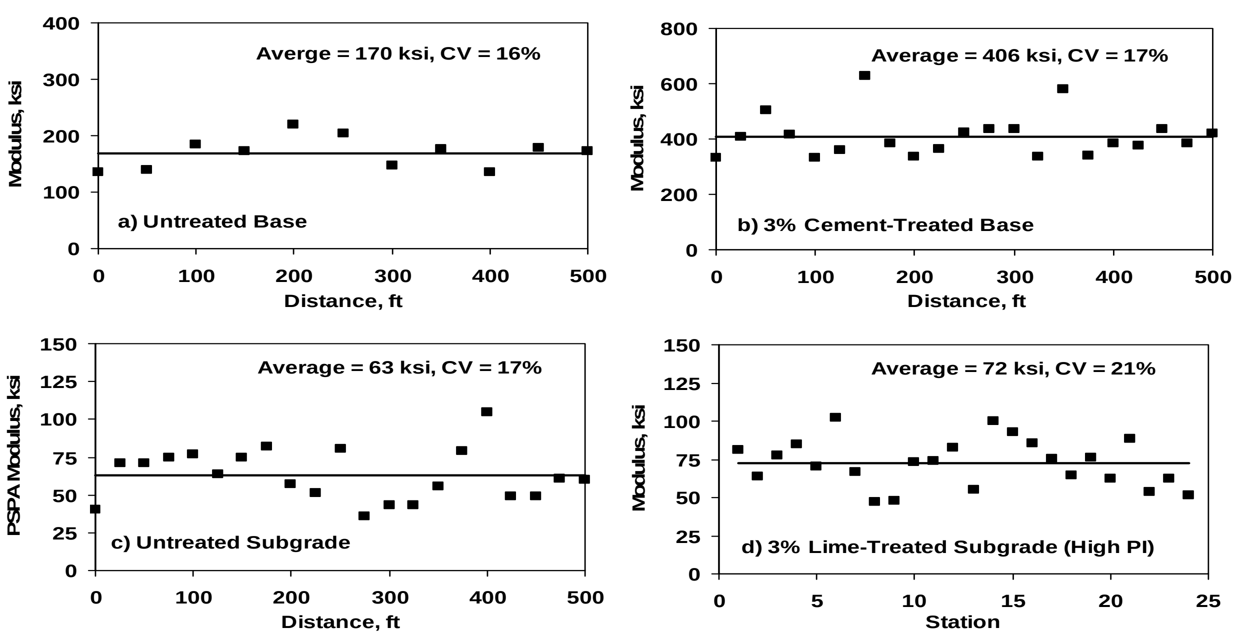

Figure 6-2. PSPA Data from Untreated and Treated Base and Subgrade.

DYNAMIC CONE PENETROMETER (DCP) TEST

The DCP consists of a 5/8-inch-diameter steel rod with a steel cone attached to one end which is driven into the pavement layers by means of a sliding dual-mass hammer; see Figure 6-3. During DCP testing in the field, the following information should be recorded and/or calculated:

- Date and time of DCP testing.
- Taking photographs.
- Location of DCP hole (i.e., in WP, outside WP, in shoulder, etc.).
- Drilling depth (if this was done).
- Number of blows.
- Penetration depth (inch or mm).
- Penetration rate (mm/blow)—calculated manually or using MS Excel.

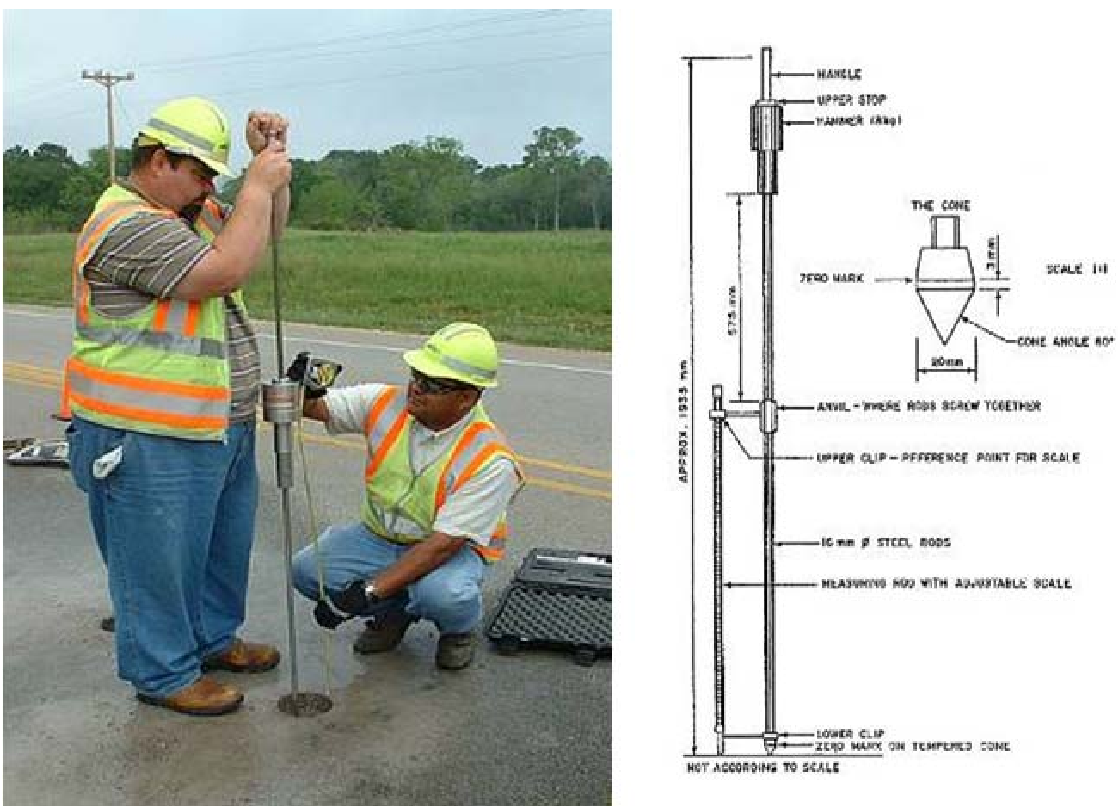

Figure 6-3. Illustration of DCP Testing.

The DCP has been widely used to measure the soil strength and correlating DCP index with California Bearing Ratio (CBR) strength values. The DCP index is based on the average penetration depth resulting from one blow of the 17.6-lb hammer. The M-E PDG program employs a correlation equation (Equation 6-1) to estimate resilient moduli in cases where only the DCP data are available.

$$M_r = 2555\left(\frac{292}{DCPI^{1.12}}\right)^{0.64} \qquad \text{(Equation 6-1)}$$

Where

M_r = resilient modulus in psi.

$DCPI$ = DCP Index (penetration rate in mm/blow).

The research team will conduct the DCP test at several locations based on interpretation of GPR and FWD data along a section segment. As minimum however, this will be done at six location points within the test section, with a minimum three points in the WP and three outside the WP. The following procedure to analyze and report DCP data will be employed:

- Generate a plot that shows the relationship between penetration depth in inches and number of blows as shown in Figure 6-4.
- Determine the segment that exhibits different slope, indicating the presence of different layers as shown in Figure 6-4. From this analysis, the layer thickness can be approximated.
- Obtain DCPI for each segment by calculating the slope. Note that the unit conversion should be done into SI unit (mm/blow) to use Equation 6-1.
- Use Equation 6-1 to compute resilient layer modulus in psi.
- Provide a summary table that reports the layer thickness (inch), DCP index (mm/blow), and resilient layer modulus (ksi); see Table 6-2.
- Report the final layer thickness and moduli results as tabular listing or bar chart.
  A similar reporting format will be used in the MS Access Data Storage System.

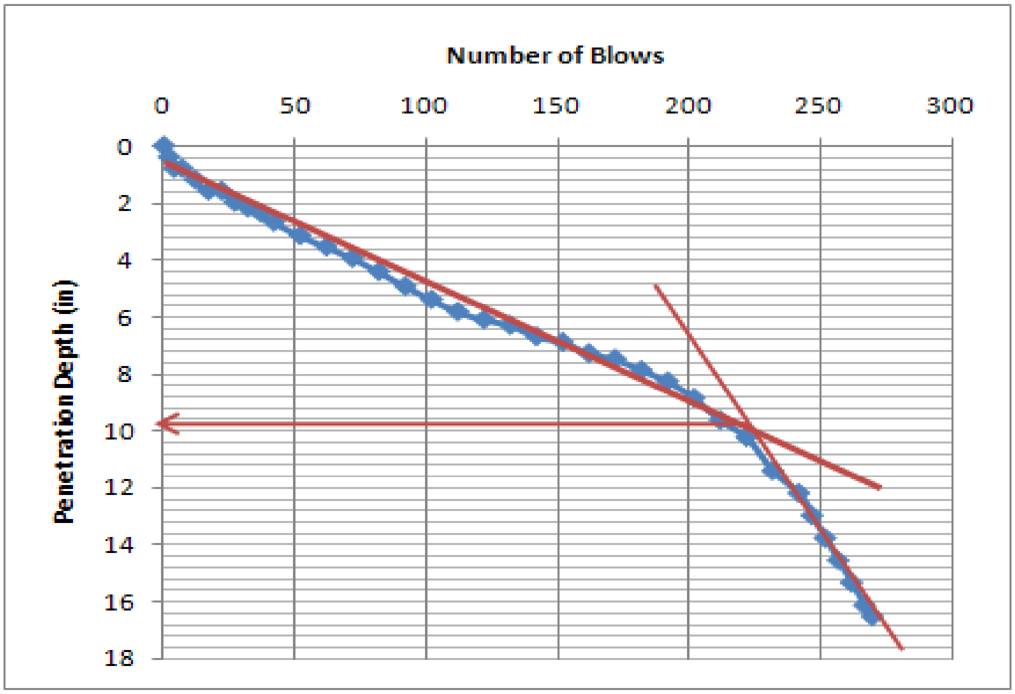

Figure 6-4. Example of DCP Data Collected from US 59, Atlanta District.

Table 6-2. Example of DCP Processed Data (US 59, Atlanta District).

Cumulative Blow Number	Penetration Depth (cm)	Penetration Depth (inch)	Penetration Depth (mm)	DCPI (mm/blow)	M_R (ksi)
0	0	0.00	0	0	
2	1	0.39	10	5.00	30.43
4	2	0.79	20	5.00	30.43
7	2	0.79	20	2.86	45.45
12	3	1.18	30	2.50	50.02
17	4	1.57	40	2.35	52.24
22	4	1.57	40	1.82	62.85
27	5	1.97	50	1.85	62.02
32	5.5	2.17	55	1.72	65.43
37	6	2.36	60	1.62	68.22
42	6.8	2.68	68	1.62	68.29
52	8	3.15	80	1.54	70.84
62	9	3.54	90	1.45	73.85
72	10	3.94	100	1.39	76.23
82	11.2	4.41	112	1.37	77.15
92	12.5	4.92	125	1.36	77.44
102	13.7	5.39	137	1.34	78.08
112	14.8	5.83	148	1.32	79.00
122	15.5	6.10	155	1.27	81.26
132	16	6.30	160	1.21	84.04
142	17	6.69	170	1.20	84.79
152	17.5	6.89	175	1.15	87.20
162	18.5	7.28	185	1.14	87.71
172	19	7.48	190	1.10	89.83
182	20	7.87	200	1.10	90.16

FALLING WEIGHT DEFLECTOMETER (FWD) TEST

FWD is one of the representative non=-destructive tests (NDTs) used in pavement evaluation to estimate layer moduli. The test uses the backcalculation procedure to evaluate the existing condition and predict the remaining life of the pavement by interpreting the deflection basin to come up with surface curvature index (SCI), base curvature index (BCI), and subgrade condition index in terms of w7 (i.e., deflection sensor# 7) Figure 6-5 shows an example of FWD testing on SH 114 (Fort Worth) in summer 2011.

Figure 6-5. Example FWD Testing on SH 114 (Fort Worth, Summer 2011).

Researchers will conduct FWD tests in the outside wheel path at 25-ft intervals targeting a 9000-lb load. They will measure pavement temperature at the beginning and end of section at 1-inch depth below. More importantly, they will be especially cautious to avoid any severely cracked area that could adversely affect the data interpretation during the data collection. In general, FWD testing will follow this procedure:

- Every 25 ft interval in the outside WP.
- 9 kips load.

- Minimum one load drop.
- Avoid severely cracked areas.
- Where possible, also test in outside WP (i.e., in-between WPs).
- Record the date and time of FWD testing.
- Take photographs.
- Record the air and pavement temperature at 1-inch depth (°F).

Use MODULUS 6.1 software for the raw data reduction and backcalculation analyses to generate the layer moduli values. Then use Equation 6-2 to normalize the backcalculated FWD modulus to 77 °F.

$$E_{77F} = TCF\,(E_{FWD});\; TCF = (T^{2.81})/200{,}000 \qquad \text{(Equation 6-2)}$$

Where

E_{77F} = normalized modulus to 77°F in ksi.

E_{FWD} = backcalculated FWD modulus in ksi without any temperature corrections.

TCF = HMA modulus temperature correction factor to 77°F.

T = HMA pavement temperature at the time the FWD data were collected.

Other parameters that can be used from the FWD data include the surface deflections, SCI, and BCI. All these data may be reported and displayed as a tabular listing, bar chart, or graphical plots. A similar reporting format will be used in the MS Access Data Storage System. Table 6-3 and Figures 6-6 through 6-7 show examples of processed and analyzed FWD. More examples of FWD data analyses can be found in Appendix D.

Table 6-3. FWD Moduli Results from US 59, Atlanta District (Spring 2011).

Layer/Material	Layer Thickness (Inch)	Uncorrected FWD Modulus (ksi)
Existing HMA layer	≅ 11	657
Base# 1 (LTA)	≅ 10	129
Base# 2 (LTA)	≅ 08	69
Subgrade	∞	28

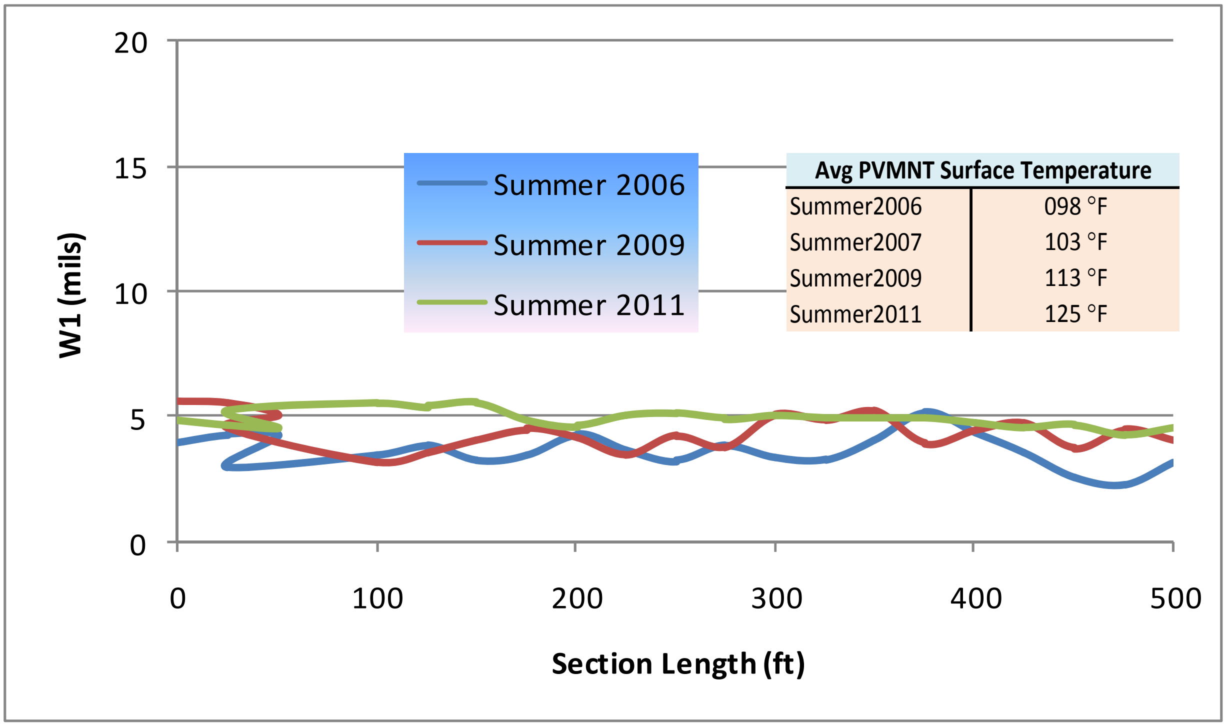

Figure 6-6. FWD W1 Deflection on SH 114 Superpave (Fort Worth).

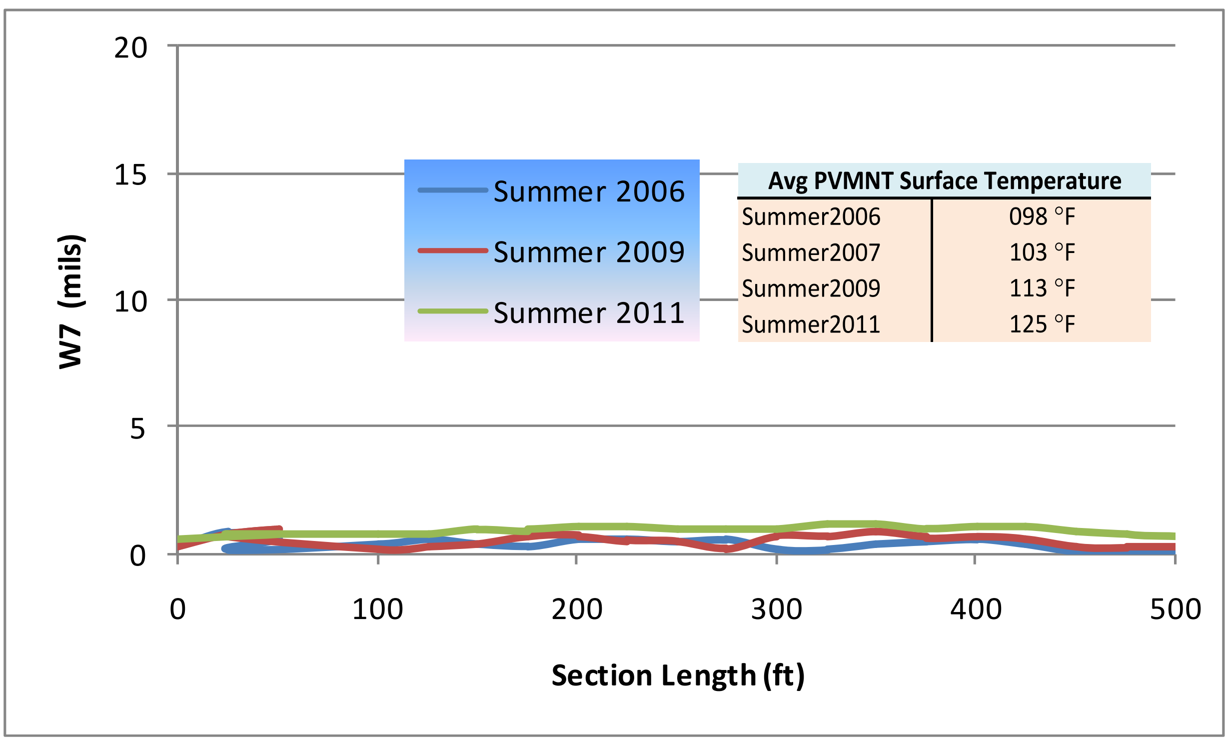

Figure 6-7. FWD W7 Deflection on SH 114 Superpave (Fort Worth).

SUMMARY

This chapter presented and discussed the various aspects of the Part II field data analysis plans, namely the PSP, DCP, and FWD test methods. The test procedure, frequency measurements, data analysis methods, the output data, units of measurement, and the format of reporting it were also discussed. Where available and applicable, typical values and thresholds for each data type were also presented.

CHAPTER 7: FIELD TEST DATA ANALYSIS: PART III

Part III of the field test data analysis plans involves forensic evaluation, namely the GPR and coring. Table 7-1 summarizes the test procedure and data characteristics. Detailed discussions are provided in the subsequent text.

Table 7-1. Field Test Procedures and Data Characteristics—Part III.

#	Test	Test Procedure (Spec)	Frequency	Analysis Method	Output Data (Units)	Typical Value/ Threshold
1	GPR	TTI-TxDOT reports; in outside or right WP	Prior to test section selection and/or just after construction, and thereafter, as needed	Pavecheck software	Layer thickness, forensic defects, etc.	N/A
2	Coring	6 inch diameter, minimum 10 cores (≥ 4 from WP; ≥ 4 in-between WP; ≥ 2 from cracked area)	At test section selection and/or just after construction, and thereafter, as needed	N/A	Layer thickness, forensic defects, core density, lab tests, etc.	N/A

GROUND PENETRATING RADAR (GPR)

The GPR data and synchronized video were collected using the following MRADAR data acquisition system, on the outside or right WP:

1) On the entire highway project length prior to test section selection to aid in selecting a section with a homogeneous pavement structure and approximating the layer thicknesses. This step is very critical as it has a long-term impact on the performance expectation of the test sections. Therefore, it is recommended that this task be conducted prior to selecting the test section and conducting any tests, particularly on existing pavement sections and overlays.
2) Just after construction as needed to aid in assessing and documenting the construction quality and HMA layer compaction uniformity.
3) During performance monitoring as needed.

The minimum data items that should be collected and that which the GPR system requires are:

- GPR data from test section.
- Metal plate GPR file collected prior to and after data collection.
- Zipped image file.
- The GPS file.

Thereafter, the data are processed and analyzed using the Pavecheck software. The GPR data is typically analyzed and displayed as image files from which the layer thicknesses, layer interfaces, and forensic defects can be visually determined. Figure 7-1 shows an example of the processed GPR data.

Figure 7-1. Processed GPR Data for SH 114 Conventional (SH 114, Fort Worth).

CORING

From each test section, a minimum of 10 6-inch diameter cores should be extracted, with at least four cores from the outside WP, four cores in between the WP, and at least two from cracked areas. Coring is a very critical aspect of this study primarily for the following reasons:

- Layer thickness determination.
- Forensic evaluation
- Determination of the depth-extent of distresses such as cracking
- Documentation of the existing pavement structure.
- Verifying the homogeneity of the pavement structure.
- Lab testing including in-situ density determination.

Like for GPR testing, coring should be conducted as follows:

1) At the instance of test section selection to determine the layer thicknesses and extent of distresses such as cracking on existing pavement sections and overlays.
2) Just after construction for in-situ density evaluation and laboratory testing.
3) During performance monitoring as needed.

Figures 7-2 through 7-5 show some examples of both defective and non-defective cores from various field test sections..

Figure 7-2. Defective Cores from US 59 (Atlanta District) Prior to Overlay.

Figure 7-3. Intact Cores from SH 114 Conventional (Fort Worth).

Figure 7-4. Cores from SH 121 (Paris District) Prior to Overlay.

Figure 7-5. Cores from US 271 (Paris District) Prior to Overlay.

SUMMARY

This chapter presented and discussed Part III of the field data analysis plans, namely forensic evaluation incorporating GPR testing and coring. The test procedure, frequency measurements, data analysis method (GPR), and the expected output data were also discussed. Demonstrative examples of both GPR data and field cores were given.

CHAPTER 8: TRAFFIC DATA ANALYSIS

Maintaining and processing accurate and timely traffic data is one of the central issues in achieving successful mechanistic-empirical (M-E) pavement designs. The research team made an effort to collect and analyze traffic data with the assistance of Mr. Jim Neidigh of Southern Traffic Services (STS) using traffic tubes. This chapter documents the procedures adapted to analyze traffic data, including the reporting format.

RAW DATA FORMAT

Figure 8-1 shows an example of the raw data that STS collected on US 59. The raw data are arranged thus: the header section first provides information on the section location, section direction, survey duration, data type, and so on. The following data are then reported below the header section:

- Date.
- 24-hour time in (0000–2359) format.
- Total number of counted vehicles per time step.
- Vehicle count number per class.
- Average speed.
- Percentile of speed.

DATA ANALYSIS PROCEDURE

Researchers analyzed the traffic data to come up with the following items for the MS Access Data Storage System:

- Average Daily Traffic (ADT): averaged the total number of vehicle counts for two days (48 hours).
- Vehicle Class Distribution: generated the vehicle class distribution by dividing vehicle count of each class by the total number of vehicle counted.

- Percent of Truck: computed the percentage of trucks by taking a ratio of the summation of vehicle counts corresponding to Class 4 through 13 to the total number of vehicles counted.
- Average Daily Truck Traffic (ADTT): computed by multiplying ADT to the percent of truck.
- Average Vehicle Speed: averaged vehicle speeds collected for two days.

```
Southern Traffic Services
Class

US59 ONE MILE SCUTH OF MILE MARKER 308          SB SLOW

Datasets:
Site:   [C6027] C6027
Direction:      1 - North bound, A hit first., Lane: 0
Survey Duration:        13:34 Monday, June 06, 2011 => 10:53 Wednesday, June 15, 2011
File:   G:\DATA\2011\Private\11062\C602715JUN2011.EC0 (Plus)
Identifier:     S539WSX5 MC56-L5 [MC55] (c)Microcom 19Oct04
Algorithm:      Factory default
Data type:      Axle sensors - Paired (Class, Speed, Count)

Profile:
Filter time:    14:00 Monday, June 06, 2011 => 14:00 Wednesday, June 08, 2011
Included classes:       1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13
Speed range:    5 - 100 mph.
Direction:      North (bound)
Separation:     All - (Headway)
Name:   Factory default profile
Scheme: Vehicle classification (Scheme F2)
Units:  Non metric (ft, mi, ft/s, mph, lb, ton)

Column Legend:
 0  [Time]      24-hour time (0000 - 2359)
 1  [Total]     Number in time step
 2  [Cls]       Class totals
 3  [Mean]      Average speed
 4  [Vpp]       Percentile speed

Monday, June 06, 2011
```

Time	Total	Cls 1	Cls 2	Cls 3	Cls 4	Cls 5	Cls 6	Cls 7	Cls 8	Cls 9	Cls 10	Cls 11	Cls 12	Cls 13	Mean	Vpp 85
1400	52	1	19	16	2	6	1	0	3	2	1	1	0	0	71.7	77.8
1415	67	0	25	23	0	3	2	0	1	9	2	1	1	0	72.5	77.2
1430	60	0	24	22	0	5	1	0	3	5	0	0	0	0	71.6	79.4
1445	67	0	33	17	0	6	0	0	1	10	0	0	0	0	73.5	77.2
1500	60	0	20	21	0	5	0	0	1	12	1	0	0	0	71.7	78.7
1515	46	0	11	18	0	6	0	2	4	5	0	0	0	0	74.7	81.4
1530	69	2	26	20	0	11	0	0	3	5	0	1	0	1	72.5	77.2
1545	57	0	30	21	0	3	0	0	2	1	0	0	0	0	70.6	75.2
1600	66	0	32	19	1	9	0	0	2	2	0	1	0	0	72.7	77.8
1615	66	0	26	16	0	12	0	0	3	9	0	0	0	0	73.8	80.1
1630	55	0	17	26	0	6	1	1	1	2	1	0	0	0	71.9	77.6
1645	56	0	21	23	0	0	0	0	1	11	0	0	0	0	74.8	80.1
1700	69	1	27	19	2	9	1	0	0	9	0	1	0	0	73.4	78.7
1715	50	1	17	12	0	9	0	0	0	11	0	0	0	0	73.7	80.1
1730	45	0	15	13	2	7	3	0	0	5	0	0	0	0	73.4	77.4
1745	49	0	15	23	0	6	0	0	1	3	0	1	0	0	75.0	79.6
1800	49	0	19	17	2	7	0	0	0	4	0	0	0	0	73.4	80.1
1815	48	0	13	12	0	6	1	1	1	14	0	0	0	0	73.0	77.8
1830	43	0	21	14	0	3	0	0	0	5	0	0	0	0	71.7	76.5
1845	42	0	18	12	1	1	0	0	2	7	0	1	0	0	75.1	79.9
1900	29	0	8	7	1	8	1	0	0	4	0	0	0	0	70.2	79.0
1915	38	0	11	12	0	1	0	0	2	11	1	0	0	0	74.9	79.6
1930	43	0	16	10	0	0	0	0	3	12	0	2	0	0	70.9	77.2
1945	27	0	5	7	1	2	0	0	1	9	0	2	0	0	73.1	79.4
2000	34	0	15	9	0	7	0	0	0	3	0	0	0	0	72.0	79.4
2015	31	0	6	12	0	5	0	0	2	5	1	0	0	0	74.2	77.8
2030	34	0	10	6	0	2	1	0	0	13	2	0	0	0	69.7	74.5
2045	28	0	13	5	0	1	0	0	0	9	0	0	0	0	69.8	72.7
2100	20	0	9	5	0	1	0	0	0	5	0	0	0	0	69.4	74.3
2115	31	0	7	9	0	4	0	0	1	8	0	1	1	0	69.7	74.3
2130	17	0	8	5	0	0	0	0	0	3	0	1	0	0	71.2	74.7

Figure 8-1. An Example of Raw Traffic Data Collected on US 59 (Atlanta District).

As noted, there are 13 vehicle classes identified in accordance with the Federal Highway Administration (FHWA) classifications shown in Figure 8-2 (FHWA, 2001).

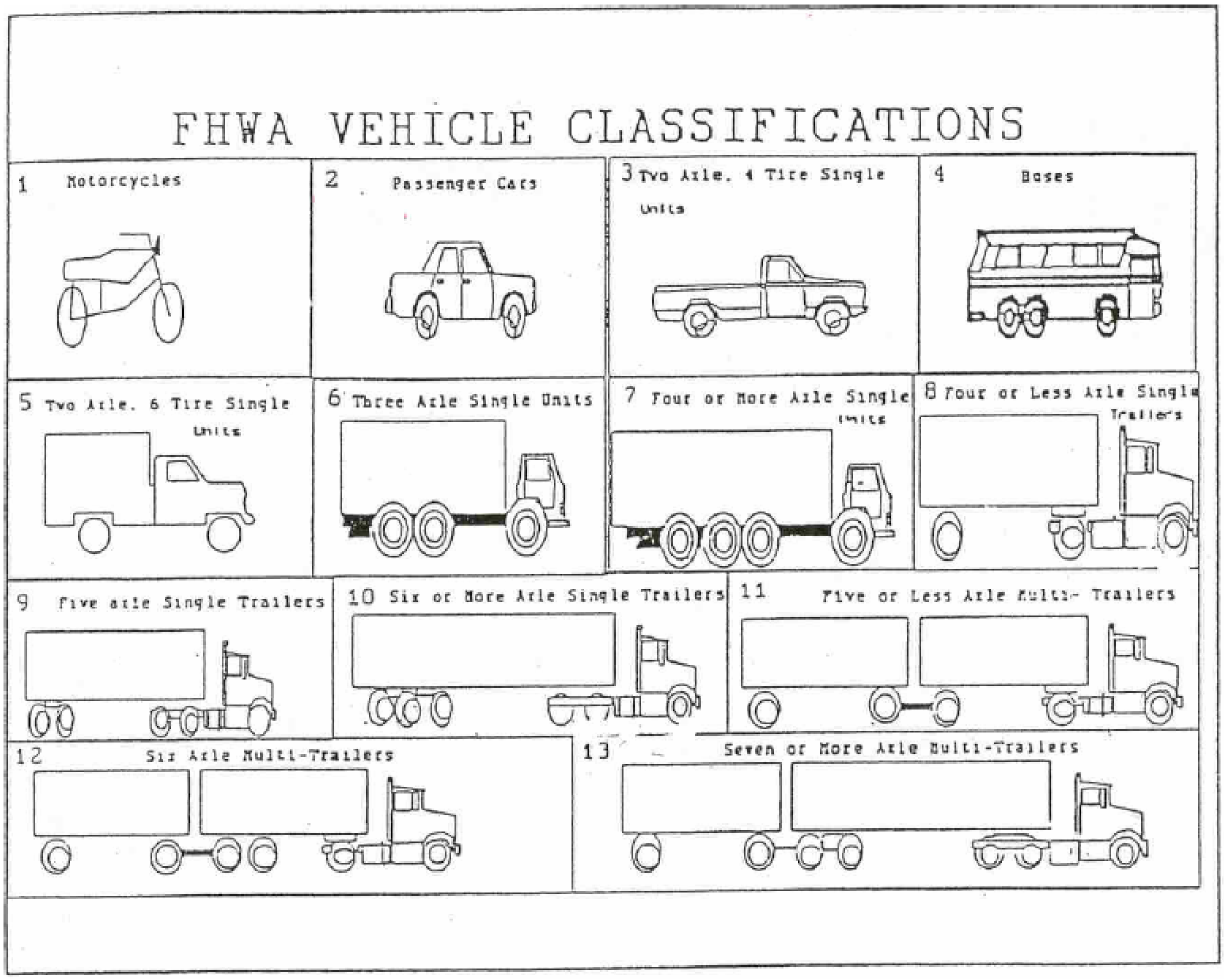

Figure 8-2. FHWA Vehicle Classifications.

With respect to computing the percentage of trucks, researchers considered Class 4 to 13 as heavy traffic in accordance with the Mechanistic-Empirical Pavement Design Guide (M-E PDG) software. For an example, Figure 8-3 shows the distributions of vehicle classification of US 59, and Table 8-1 presents the processed key traffic data.

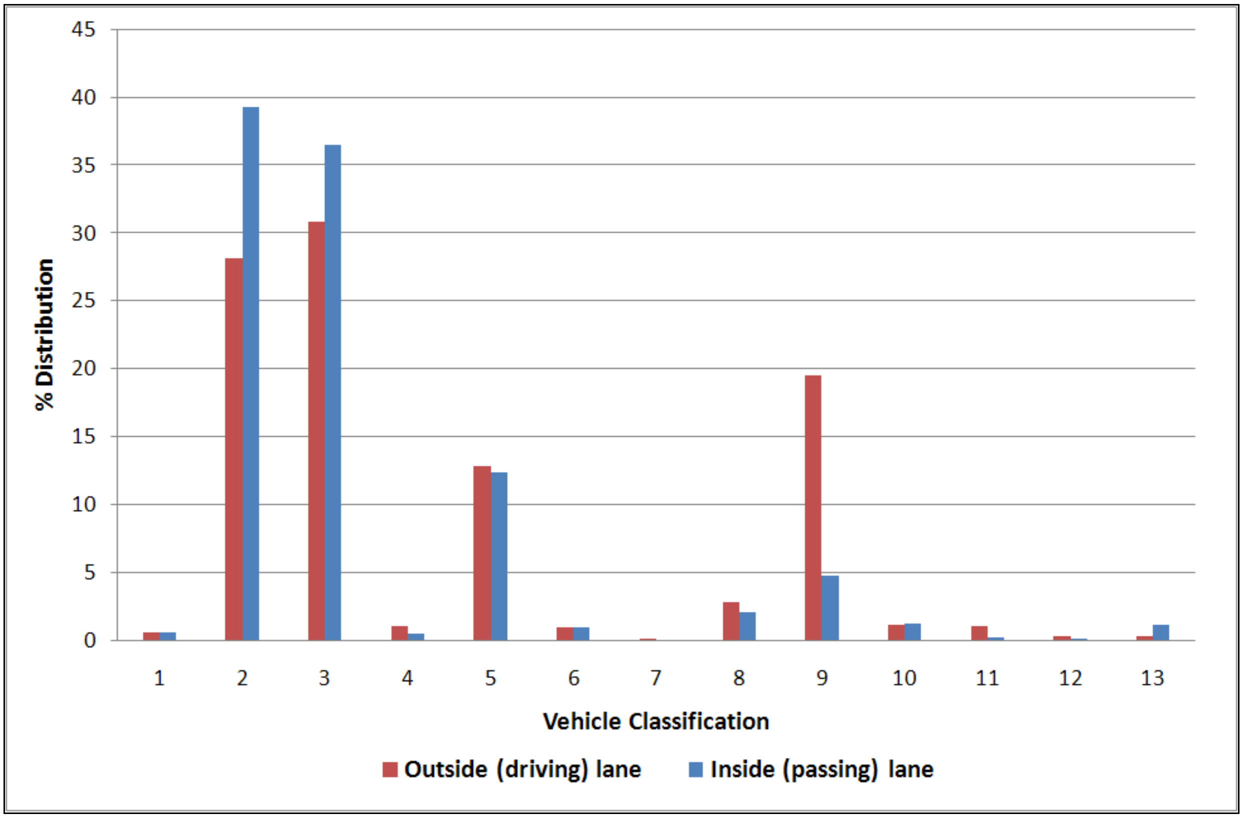

Figure 8-3. Vehicle Class Distribution of US 59 (Atlanta District).

Table 8-1. Summary of Traffic Data Analysis for US 59 (Atlanta)

Section	Lane	ADT	% Truck	ADTT	Avg. Speed (mph)
US 59	Outside SB	3710.5	40.4	1500.5	72.6
	Inside SB	1116.5	23.6	264.0	75.1

SUMMARY

This chapter presented and discussed the traffic data analysis plans including the method used and format in which it was collected. The analysis procedure was then described along with the reporting format. A demonstration example was also presented for US 59 in Atlanta District.

CHAPTER 9: ENVIRONMENTAL AND CLIMATIC DATA ANALYSIS

Climatic data is one of the core inputs in calibrating pavement performances based on the mechanistic-empirical (M-E) pavement design. This is because pavement materials are susceptible to the change with changes in climatic and environmental factors such as temperature, moisture, and humidity, which is directly associated with pavement response. The research team made an effort to collect and analyze climatic and environmental data using available web resources. This chapter documents the analyzed climatic data along with discussions on several issues that have been identified up to this point.

CLIMATIC DATA GENERATION

Researchers generated climatic data file using the M-EPDG program so that the generated file will be readily used for the Texas M-E program, which is being developed in Study 0-6622 (Zhou 2011). Note that the Texas M-E is also incorporating the weather station data available in the M-EPDG. The following steps were taken to generate the climatic files:

- Identify latitude and longitude coordination of the test section.
- Input of the coordination into the M-E PDG program and conduct interpolation to generate climatic input files like the one shown in Figure 9-1.
- Generate the climatic file and save it as 'Road ID.icm.' Run the M-E PDG using the generated climatic file to produce 'MonthlyClimateSummary.csv' file to check if there are abnormal values to be corrected. For the quality check, the most recent version of climatic data is also extracted from the web browser http://www7.ncdc.noaa.gov in order to compare with the processed climatic data using M-E PDG if the corresponding weather station data from the resource is available.

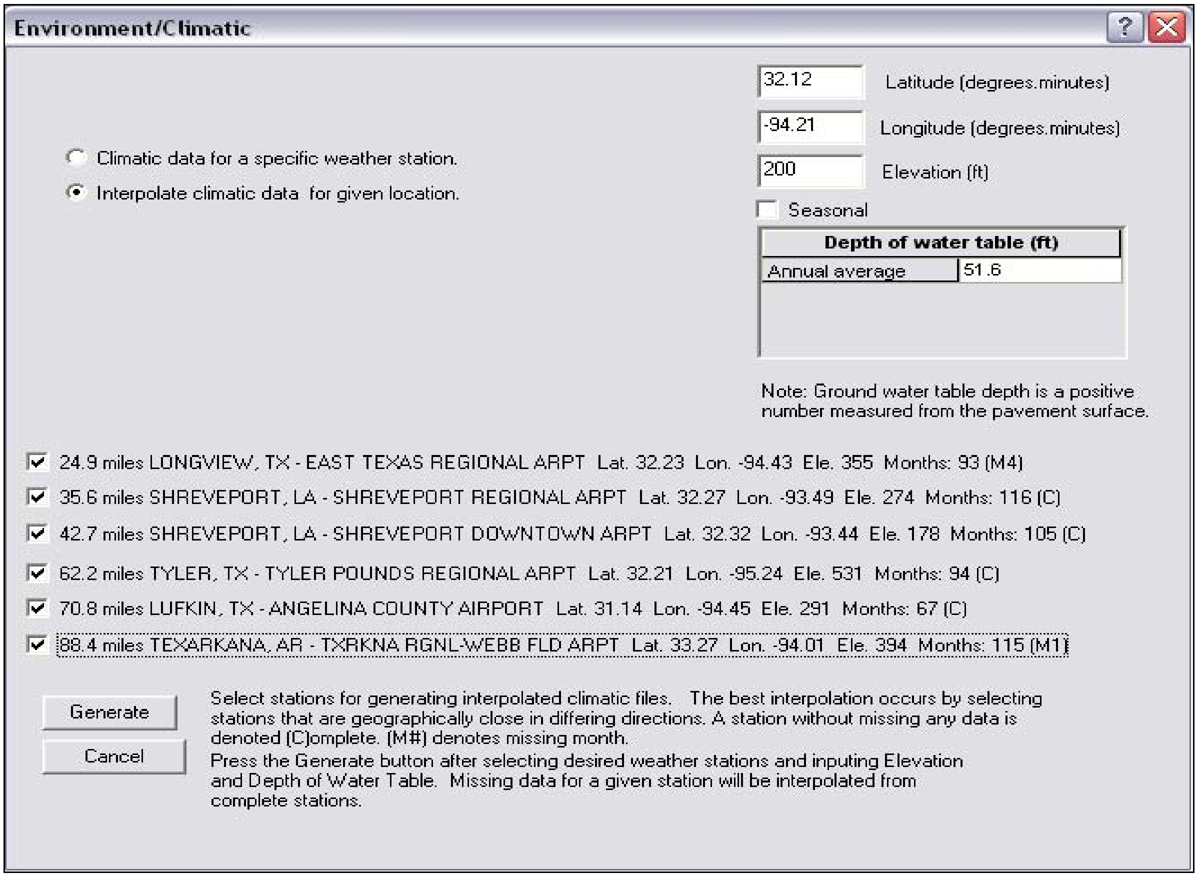

Figure 9-1. M-E PDG Climatic Data Generation Screen.

Using the MonthlyClimateSummary.csv file, researchers generated a summary table along with two charts showing the monthly variation of air temperature and precipitation for the purpose of establishing a database. Researchers will upload the '*.icm' file of each section into the database system for future flexible pavement performance calibration using the Texas M-E program. Figures 9-2 to 9-4 show an example of the processed climatic data forUS 59 in Atlanta District.

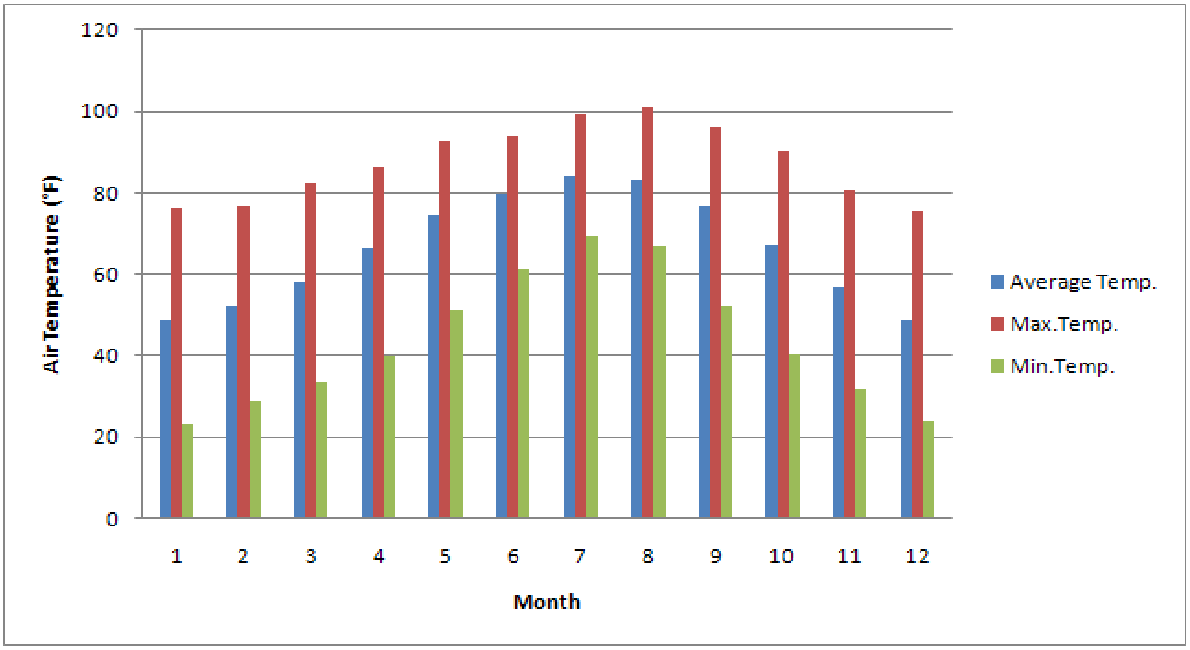

Figure 9-2. Air Temperature Monthly Variation Using M-E PDG Weather Station Data.

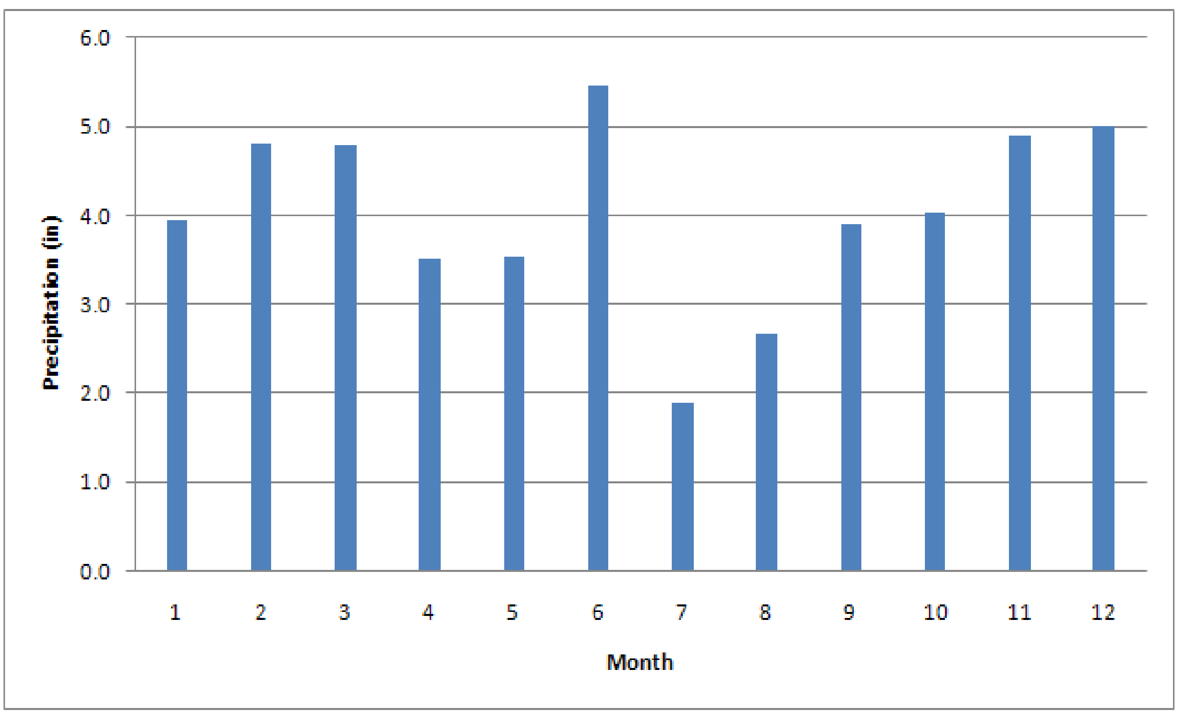

Figure 9-3. Precipitation Monthly Variation Using M-E PDG Weather Station Data.

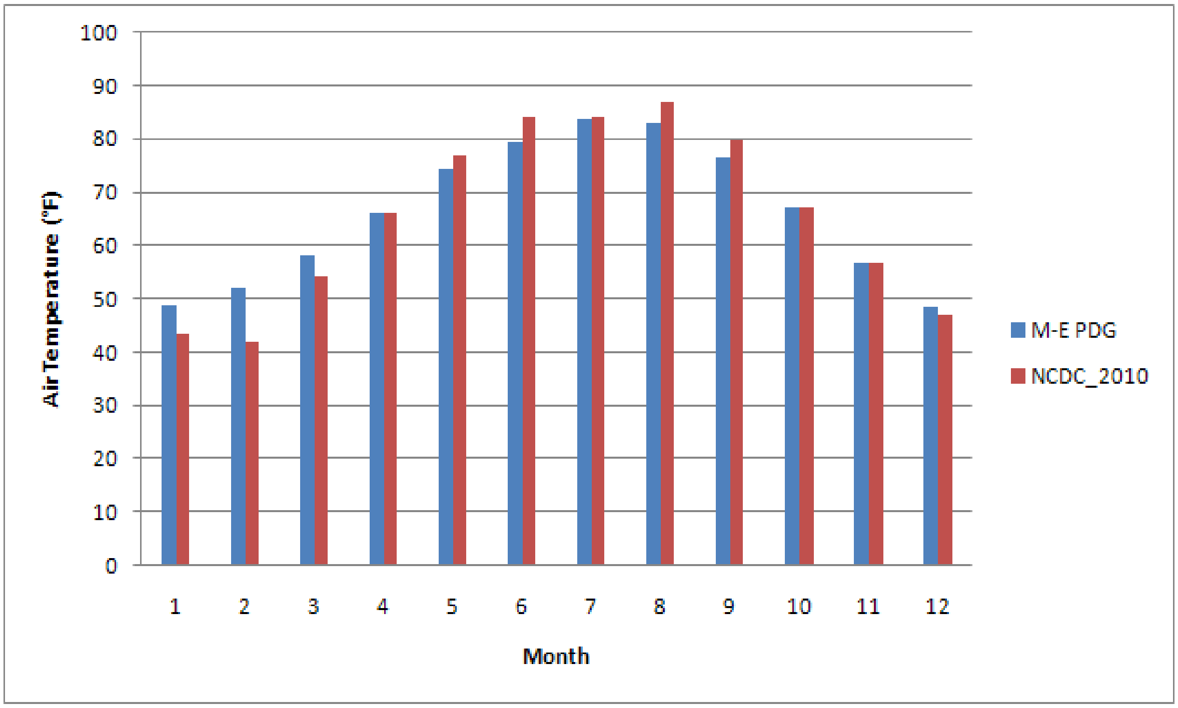

Figure 9-4. Comparison of Monthly Air Temperature Variation between M-E PDG and NCDC Weather Station Data.

GROUNDWATER TABLE DATA

Researchers collected groundwater table data from the web browser http://nwis.waterdata.usgs.gov.tx.nwis/gwlevels. From this search, they come to recognize the limitation of the available data, corresponding to the test section. The search was initially conducted by county level. Later, the researchers selected the closest location to the test section in terms of latitude and longitudinal coordinates for providing the groundwater table depth. To determine the distance between the well location and the test section based on latitude-longitude coordinates, the coordinates were first converted from degrees to radians using the following equations (Oh and Fernando, 2008):

$$\text{Latitude(rad)} = \frac{\tan^{-1}(1)}{45}\text{Latitude}(°)$$
$$\text{Longitude(rad)} = \frac{\tan^{-1}(1)}{45}\text{Longitude}(°) \qquad \text{(Equation 9-1)}$$

Then, if X_1 and Y_1 are the longitude and latitude, respectively, of a test section in radians, and X_2 and Y_2 are the corresponding coordinates for a given well location, the *Great Circle*

Distance Formula given by Equation 10.2 can be used to calculate the distance in miles between two pairs of latitude/longitude values specified in radians:

$$D = 3949.99\cos^{-1}\left\{\sin Y_1 \sin Y_2 + \cos Y_1 \cos Y_2 \cos\left(X_1 - X_2\right)\right\} \quad \text{(Equation 9-2)}$$

If the county-level data corresponding to the test section is not available, the adjacent counties were investigated to identify alternative locations. Table 9-1 presents an example of the groundwater table depth data. From the table, the highlighted locations are deemed to be representative due to its geographical vicinity to the test section for providing groundwater table depth data.

Table 9-1. Groundwater Table Depth Data.

Section	Section Location	County of Well	Well Location	Distance (mile)	G.W.T. (ft)	Years Collected
US 59 (Panola County)	Lat 32°12′14″ Long 94°20′33″	Panola	Lat 32°01′28″ Long 94°15′12″	13.4	44.8	Sept. 2004
		Panola	Lat 32°03′54″ Long 94°31′03″	14.0	126.35	Sept. 2004
		Panola	**Lat 32°12′14″ Long 94°21′30″**	**0.9**	**51.6**	**Sept. 2004**
		Panola	Lat 32°17′22″ Long 94°28′52″	10.0	42.9	Sept. 2004

SUMMARY

This chapter discussed the environmental and climatic data analysis plans. The plans also incorporated the climatic data generation methods, data analysis methods, and data reporting format.

CHAPTER 10: SUMMARY AND RECOMMENDATIONS

The primary goal of this five-year project is to collect materials and pavement performance data on a minimum of 100 highway test sections around the State of Texas. Therefore, the specific objective of this interim report, named here as Product 0-6658-P3, was to outline the following data analysis plans for each data item to be collected:

- Laboratory testing (asphalt-binders, HMA mixes, bases, and subgrade soils).
- Field performance testing (cracking, rutting, profiles, FWD, DCP, PSPA, etc).
- Forensic evaluation (GPR and coring).
- Traffic data.
- Environmental and climatic data.

While it should be noted that these data analysis plans are subject to change or modification in the course of the study, the following key aspects were nonetheless presented and discussed in this interim report for each data type:

- The tools and test methods used to collect the data.
- The type and format of the data measured and collected.
- The raw data reduction process
- The analytical methods, techniques, models, and software used to analyze the data.
- The dimensional and/or quantitative units of each parameter.
- The data reporting format including how the data will be accessed and displayed from the MS Access Data Storage System (i.e., tables, graphs, bar charts, etc.).

Key challenges that still need to be addressed are: 1) the MR and PD tests for bases and subgrade soils, and 2) traffic data collection and analysis method. At the time of this report, consensus agreement had not been reached on the MR and PD test parameters as well the data analysis methods and number of replicate samples. Liaison and consensus agreement on the traffic data collection and analysis method must also be addressed.

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APPENDIX A: LAB TEST DATA ANALYSIS (ASPHALT-BINDERS)

Table A-1. Test Plans for Asphalt-Binders (Extracted Binders Only).

#	Test	Spec	Test Parameters	Output Data	Sample Replicates			Time (hrs)		Material Requirement (grams)	
					TTI	UTEP	*TxDOT Recom.*	Sample Prep	Testing	Asphalt-Binder	Plant-Mix
1	Specific gravity (SG)	T 228	As per spec	Specific gravity	3		*1*[a]	2	2	40	2000
2	Viscosity	T 316	315 °C	Viscosity	3		*1*[a]	1	1	40	2000
3	DSR[f]	T 315	As per spec	True grade, G*, & G*/Sin(δ)	3		*1*[a]	2	3	30	1500
4	DSR – RTFO	T 240	As per spec	True grade, G*, & G*/Sin(δ)	3		*0*[b]	4	3	30	1500
5	DSR – PAV	R 28	As per spec	G*, G*.Sin(δ), & true grade	3		*0*[b]	24	3	30	1500
6	MSCR	TP 70	As per spec; min 3 test temperatures per binder	R100, R3200, R_{diff}, $J_{nr}100$, $J_{nr}3200$, & $J_{nr-diff}$	9		*9 (3 x 3 temps)*	4	6	60	3000
7	BBR[f]	T 313 R28	As per spec; min 2 temps	Stiffness, m-value	6 (3 x 2 temps)		*2*[a] (1 x 2 temps)	26	4	120	7000
8	Elastic recovery (ductility)	(D 6084-A)	As per TxDOT spec @ 50 °F	Elastic recovery	3		*3*	8	2	100	6000
9	Binder PG grading	M 320, Item 300, MP 19	As per spec	PG grade	-	-	-	-	-	-	-
Total material to sample from the field					33	0	*17*	71	24	450	24500 **(≥ 65 lbs)**

Note: *a*- results for first test sections were very repeatable with CV less than 5%, so no need for 3 or more replicates; *b* – tests will be done on extracted binders only and treated as RTFO residue, so no need for RTFO or PAV; *f* – also run the intermediate temperature DSR and BBR on the extracted binders as it is (with no PAV) for mixes with RAP or RAS

Table A-2. Texas PG Binder Grading Specification (Item 300).

Property and Test Method	Performance Grade																	
	PG 58			PG 64				PG 70				PG 76				PG 82		
	-22	-28	-34	-16	-22	-28	-34	-16	-22	-28	-34	-16	-22	-28	-34	-16	-22	-28
Average 7-day max pavement design temperature, °C[1]	< 58			< 64				< 70				< 76				< 82		
Min pavement design temperature, °C[1]	>-22	>-28	>-34	>-16	>-22	>-28	>-34	>-16	>-22	>-28	>-34	>-16	>-22	>-28	>-34	>-16	>-22	>-28
ORIGINAL BINDER																		
Flash point, T 48, Min, °C	230																	
Viscosity, T 316:[2,3] Max, 3.0 Pa·s, test temperature, °C	135																	
Dynamic shear, T 315:[4] G*/sin(δ), Min, 1.00 kPa Test temperature @ 10 rad/sec., °C	58			64				70				76				82		
Elastic recovery, D 6084, 50°F, % Min	–	–	30	–	–	30	50	–	30	50	60	30	50	60	70	50	60	70
ROLLING THIN-FILM OVEN (Tex-541-C)																		
Mass loss, Tex-541-C, Max, %	1.0																	
Dynamic shear, T 315: G*/sin(δ), Min, 2.20 kPa Test temperature @ 10 rad/sec., °C	58			64				70				76				82		
PRESSURE AGING VESSEL (PAV) RESIDUE (R 28)																		
PAV aging temperature, °C	100																	
Dynamic shear, T 315: G*/sin(δ), Max, 5000 kPa Test temperature @ 10 rad/sec., °C	25	22	19	28	25	22	19	28	25	22	19	28	25	22	19	28	25	22

Table A-2 (Continued). Texas PG Binder Grading Specification (Item 300).

Property and Test Method	Performance Grade																	
	PG 58			PG 64				PG 70				PG 76				PG 82		
	-22	-28	-34	-16	-22	-28	-34	-16	-22	-28	-34	-16	-22	-28	-34	-16	-22	-28
Average 7-day max pavement design temperature, °C[1]	< 58			< 64				< 70				< 76				< 82		
Min pavement design temperature, °C[1]	>-22	>-28	>-34	>-16	>-22	>-28	>-34	>-16	>-22	>-28	>-34	>-16	>-22	>-28	>-34	>-16	>-22	>-28
Creep stiffness, T 313:[5, 6] *S*, max, 300 MPa, *m*-value, min, 0.300 Test temperature @ 60 sec., °C	-12	-18	-24	-6	-12	-18	-24	-6	-12	-18	-24	-6	-12	-18	-24	-6	-12	-18
Direct tension, T 314:[6] Failure strain, min, 1.0% Test temperature @ 1.0 mm/min., °C	-12	-18	-24	-6	-12	-18	-24	-6	-12	-18	-24	-6	-12	-18	-24	-6	-12	-18

1. Pavement temperatures are estimated from air temperatures using an algorithm contained in a Department-supplied computer program, may be provided by the Department, or by following the procedures outlined in AASHTO MP 2 and PP 28.
2. This requirement may be waived at the Department's discretion if the supplier warrants that the asphalt binder can be adequately pumped, mixed, and compacted at temperatures that meet all applicable safety, environmental, and constructability requirements. At test temperatures where the binder is a Newtonian fluid, any suitable standard means of viscosity measurement may be used, including capillary (T 201 or T 202) or rotational viscometry (T 316).
3. Viscosity at 135°C is an indicator of mixing and compaction temperatures that can be expected in the lab and field. High values may indicate high mixing and compaction temperatures. Additionally, significant variation can occur from batch to batch. Contractors should be aware that variation could significantly impact their mixing and compaction operations. Contractors are therefore responsible for addressing any constructability issues that may arise.
4. For quality control of unmodified asphalt binder production, measurement of the viscosity of the original asphalt binder may be substituted for dynamic shear measurements of $G^*/\sin(\delta)$ at test temperatures where the asphalt is a Newtonian fluid. Any suitable standard means of viscosity measurement may be used, including capillary (T 201 or T 202) or rotational viscometry (T 316).
5. Silicone beam molds, as described in AASHTO TP 1-93, are acceptable for use.
6. If creep stiffness is below 300 MPa, direct tension test is not required. If creep stiffness is between 300 and 600 MPa, the direct tension failure strain requirement can be used instead of the creep stiffness requirement. The *m*-value requirement must be satisfied in both cases.

Table A-3. AASHTO MP 19 PG Grading Specification for Asphalt-Binders.

Table 1—Performance-Graded Asphalt Binder Specification[a]

Performance Grade	PG 46			PG 52							PG 58				
	34	40	46	10	16	22	28	34	40	46	16	22	28	34	40
Average 7-day max pavement design temp, °C[b]	<46			<52							<58				
Min pavement design temp, °C[b]	>-34	>-40	>-6	>-10	>-6	>-22	>-28	>-34	>-40	>-46	>-16	>-22	>-28	>-34	>-40
Original Binder															
Flash point temp, T 48, min °C	230														
Viscosity, T 316:[d] max 3 Pa·s, test temp, °C	135														
Dynamic shear, T 315:[d] G*/sinδ, min 1.00 kPa[e] test temp @ 10 rad/s, °C	46			52							58				
Rolling Thin-Film Oven Residue (T 240)															
Mass change, max, percent[f]	1.00														
MSCR, TP 70: Standard Traffic "S" Grade $J_{nr3.2}$, max 4.0 kPa^{-1} J_{nrdiff}, max 75% test temp, °C	46			52							58				
MSCR, TP 70: Heavy Traffic "H" Grade $J_{nr3.2}$, max 2.0 kPa^{-1} J_{nrdiff}, max 75% test temp, °C	46			52							58				
MSCR, TP 70: Very Heavy Traffic "V" Grade $J_{nr3.2}$, max 1.0 kPa^{-1} J_{nrdiff}, max 75% test temp, °C	46			52							58				
MSCR, TP 70: Extremely Heavy Traffic "E" Grade $J_{nr3.2}$, max 0.5 kPa^{-1} J_{nrdiff}, max 75% test temp, °C	46			52							58				
Pressurized Aging Vessel Residue (R 28)															
PAV aging temp, °C[g]	90			90							100				
Dynamic shear, T 315: "S" Grade G* sinδ, max 5000 kPa[e] test temp @ 10 rad/s, °C	10	7	4	25	22	19	16	13	10	7	25	22	19	16	13
Dynamic shear, T 315: "H", "V", "E" Grades G* sinδ, max 6000 kPa[e] test temp @ 10 rad/s, °C	10	7	4	25	22	19	16	13	10	7	25	22	19	16	13
Creep stiffness, T 313:[h] *S*, max 300 MPa *m*-value, min 0.300 test temp @ 60 s, °C	–24	–30	–36	0	–6	–12	–18	–24	–30	–36	–6	–12	–18	–24	–30
Direct tension, T 314:[h] Failure strain, min 1.0% test temp @ 1.0 mm/min, °C	–24	–30	–36	0	–6	–12	–18	–24	–30	–36	–6	–12	–18	–24	–30

[a] MSCR testing on RTFO residue should be performed at the PG grade based on the environmental high pavement temperature. Grade bumping is accomplished by requiring a lower J_{nr} value while testing at the environmental temperature.

[b] Pavement temperatures are estimated from air temperatures using an algorithm contained in the LTPP Bind program, may be provided by the specifying agency, or by following the procedures as outlined in M 323 and R 35, excluding the provisions for "grade bumping".

[c] This requirement may be waived at the discretion of the specifying agency if the supplier warrants that the asphalt binder can be adequately pumped and mixed at temperatures that meet all applicable safety standards.

[d] For quality control of unmodified asphalt binder production, measurement of the viscosity of the original asphalt binder may be used to supplement dynamic shear measurements of G*/sinδ at test temperatures where the asphalt is a Newtonian fluid.

[e] G*/sinδ = high temperature stiffness and G* sinδ = intermediate temperature stiffness.

[f] The mass change shall be less than 1.00 percent for either a positive (mass gain) or a negative (mass loss) change.

[g] The PAV aging temperature is based on simulated climatic conditions and is one of three temperatures, 90°C, 100°C, or 110°C. Normally the PAV aging temperature is 100°C for PG 58-xx and above. However, in desert climates, the PAV aging temperature for PG 70-xx and above may be specified as 110°C.

[h] If the creep stiffness is below 300 MPa, the direct tension test is not required. If the creep stiffness is between 300 and 600 MPa, the direct tension failure strain requirement can be used in lieu of the creep stiffness requirement. The *m*-value requirement must be satisfied in both cases.

Table A-3. AASHTO MP 19 PG Grading Specification for Asphalt-Binders (Continued).

Table 1—Performance-Graded Asphalt Binder Specification[a] *(continued)*

Performance Grade	PG 64						PG 70					
	10	16	22	28	34	40	10	16	22	28	34	40
Average 7-day max pavement design temp, °C[b]							<70					
Min pavement design temp, °C[b]	>–10	>–16	>–22	>–28	>–34	>–40	>–10	>–16	>–22	>–28	>–34	>–40
	Original Binder											
Flash point temp, T 48, min °C	230											
Viscosity, T 316:[c] max 3 Pa·s, test temp, °C	135											
Dynamic shear, T 315:[d] G*/sinδ, min 1.00 kPa[e] test temp @ 10 rad/s, °C	64						70					
	Rolling Thin-Film Oven Residue (T 240)											
Mass change, max, percent[f]	1.00											
MSCR, TP 70: Standard Traffic "S" Grade $J_{nr3.2}$, max 4.0 kPa^{-1} $J_{nr diff}$, max 75% test temp, °C	64						70					
MSCR, TP 70: Heavy Traffic "H" Grade $J_{nr3.2}$, max 2.0 kPa^{-1} $J_{nr diff}$, max 75% test temp, °C	64						70					
MSCR, TP 70: Very Heavy Traffic "V" Grade $J_{nr3.2}$, max 1.0 kPa^{-1} $J_{nr diff}$, max 75% test temp, °C	64						70					
MSCR, TP 70: Extremely Heavy Traffic "E" Grade $J_{nr3.2}$, max 0.5 kPa^{-1} $J_{nr diff}$, max 75% test temp, °C	64						70					
	Pressurized Aging Vessel Residue (R 28)											
PAV aging temp, °C[g]	100						100 (110)					
Dynamic shear, T 315: "S" Grade G* sinδ, max 5000 kPa[e] test temp @ 10 rad/s, °C	31	28	25	22	19	16	34	31	28	25	22	19
Dynamic shear, T 315: "H, "V", "E" Grades G* sinδ, max 6000 kPa[e] test temp @ 10 rad/s, °C	31	28	25	22	19	16	34	31	28	25	22	19
Creep stiffness, T 313:[h] S, max 300 MPa m-value, min 0.300 test temp @ 60 s, °C	0	–6	–12	–18	–24	–30	0	–6	–12	–18	–24	–30
Direct tension, T 314:[h] Failure strain, min 1.0% test temp @ 1.0 mm/min, °C	0	–6	–12	–18	–24	–30	0	–6	–12	–18	–24	–30

[a] MSCR test on RTFO residue should be performed at the PG grade based on the environmental high pavement temperature. Grade bumping is accomplished by requiring a lower J_{nr} value while testing at the environmental temperature.

[b] Pavement temperatures are estimated from air temperatures using an algorithm contained in the LTPP Bind program, may be provided by the specifying agency, or by following the procedures as outlined in M 323 and R 35, excluding the provisions for "grade bumping".

[c] This requirement may be waived at the discretion of the specifying agency if the supplier warrants that the asphalt binder can be adequately pumped and mixed at temperatures that meet all applicable safety standards.

[d] For quality control of unmodified asphalt binder production, measurement of the viscosity of the original asphalt binder may be used to supplement dynamic shear measurements of G*/sinδ at test temperatures where the asphalt is a Newtonian fluid.

[e] G*/sinδ = high temperature stiffness and G* sinδ = intermediate temperature stiffness.

[f] The mass change shall be less than 1.00 percent for either a positive (mass gain) or a negative (mass loss) change.

[g] The PAV aging temperature is based on simulated climatic conditions and is one of three temperatures, 90°C, 100°C, or 110°C. Normally the PAV aging temperature is 100°C for PG 58-xx and above. However, in desert climates, the PAV aging temperature for PG 70-xx and above may be specified as 110°C.

[h] If the creep stiffness is below 300 MPa, the direct tension test is not required. If the creep stiffness is between 300 and 600 MPa, the direct tension failure strain requirement can be used in lieu of the creep stiffness requirement. The m-value requirement must be satisfied in both cases.

Table A-2. AASHTO MP 19 PG Grading Specification for Asphalt-Binders (Continued).

Table 1—Performance-Graded Asphalt Binder Specification[a] *(continued)*

Performance Grade	PG 76					PG 82				
	10	16	22	28	34	10	16	22	28	34
Average 7-day max pavement design temp, °C[b]	<76					<82				
Min pavement design temp, °C[b]	>–10	>–16	>–22	>–28	>–34	>–10	>–16	>–22	>–28	>–34
Original Binder										
Flash point temp, T 48, min°C	230									
Viscosity, T 316:[c] max 3 Pa·s, test temp, °C	135									
Dynamic shear, T 315:[d] G*/sin δ, min 1.00 kPa[e] test temp @ 10 rad/s, °C	76					82				
Rolling Thin-Film Oven Residue (T 240)										
Mass change, max, percent[f]	1.00									
MSCR, TP 70: Standard Traffic "S" Grade $J_{nr3.2}$, max 4.0 kPa^{-1} J_{nrdiff}, max 75% test temp, °C	76					82				
MSCR, TP 70: Heavy Traffic "H" Grade $J_{nr3.2}$, max 2.0 kPa^{-1} J_{nrdiff}, max 75% test temp, °C	76					82				
MSCR, TP 70: Very Heavy Traffic "V" Grade $J_{nr3.2}$, max 1.0 kPa^{-1} J_{nrdiff}, max 75% test temp, °C	76					82				
MSCR, TP 70: Extremely Heavy Traffic "E" Grade $J_{nr3.2}$, max 0.5 kPa^{-1} J_{nrdiff}, max 75% test temp, °C	76					82				
Pressurized Aging Vessel Residue (R 28)										
PAV aging temp, °C[g]	100 (110)					100 (110)				
Dynamic shear, T 315: "S" Grade G* sinδ, max 5000 kPa[e] test temp @ 10 rad/s, °C	37	34	31	28	25	40	37	34	31	28
Dynamic shear, T 315: "H", "V", "E" Grades G* sinδ, max 6000 kPa[e] test temp @ 10 rad/s, °C	37	34	31	28	25	40	37	34	31	28
Creep stiffness, T 313:[h] *S*, max 300 MPa *m*-value, min 0.300 test temp @ 60 s, °C	0	–6	–12	–18	–24	0	–6	–12	–18	–24
Direct tension, T 314:[h] Failure strain, min 1.0% test temp @ 1.0 mm/min, °C	0	–6	–12	–18	–24	0	–6	–12	–18	–24

[a] MSCR test on RTFO residue should be performed at the PG grade based on the environmental high pavement temperature. Grade bumping is accomplished by requiring a lower J_{nr} value while testing at the environmental temperature.

[b] Pavement temperatures are estimated from air temperatures using an algorithm contained in the LTPP Bind program, may be provided by the specifying agency, or by following the procedures as outlined in M 323 and R 35, excluding the provisions for "grade bumping".

[c] This requirement may be waived at the discretion of the specifying agency if the supplier warrants that the asphalt binder can be adequately pumped and mixed at temperatures that meet all applicable safety standards.

[d] For quality control of unmodified asphalt binder production, measurement of the viscosity of the original asphalt binder may be used to supplement dynamic shear measurements of G*/sinδ at test temperatures where the asphalt is a Newtonian fluid.

[e] G*/sinδ = high temperature stiffness and G* sinδ = intermediate temperature stiffness.

[f] The mass change shall be less than 1.00 percent for either a positive (mass gain) or a negative (mass loss) change.

[g] The PAV aging temperature is based on simulated climatic conditions and is one of three temperatures, 90°C, 100°C, or 110°C. Normally the PAV aging temperature is 100°C for PG 58-xx and above. However, in desert climates, the PAV aging temperature for PG 70-xx and above may be specified as 110°C.

[h] If the creep stiffness is below 300 MPa, the direct tension test is not required. If the creep stiffness is between 300 and 600 MPa, the direct tension failure strain requirement can be used in lieu of the creep stiffness requirement. The *m*-value requirement must be satisfied in both cases.

APPENDIX B: LAB TEST DATA ANALYSIS (HMA MIXES)

Table B-1. Test Plans for HMA Mixes (Plant-Mix/Cores Only).

#	Test	Spec	Test Parameters	Output Data	Sample Replicates			Time (hrs)		Material Requirement (grams)
					TTI	UTEP	*TxDOT Recom.*	Sample Prep	Testing	
1	AC extraction	Tex-210-F [a]	As per spec	AC % (by weight)	3		***3***	2	16	5000
		Tex-236-F	As per spec	AC%	3		***0***[b]	2	5	5000
2	Aggregate gradation	Tex-200-F	As per spec	Particle size distribution	3		***3***	14	1	(Aggregates from Tex-210-F)
3	Hamburg	Tex-242-F	As per spec	Rut depth and number of wheel passes	3 (3 sets of 2)		***1***[c] *(1 set of 2)*	24	14	20000
4	Overlay	Tex-248-F	0.025 inch, 93% load drop, 77 °F	Max load & number of cycles to failure	5		***5***	72	36	25000
5	OT fracture properties	Report 0-5798-2, PP 97 (DM + OT)		*A & n*	5		***5***	80	14	25000
6	Dynamic modulus (DM)	AASHTO TP 62-03	As per spec; 5 temps; 6 frequencies	Dynamic modulus	3		***3***	72	120	22000
7	Permanent deformation (RLPD)	Report 0-5798 (New)	(a)104 °F, 20 psi, & 10 000 cycles, & (b) 122°F, 20 psi, & 10 000 cycles,	α, μ , & microstrains	6 (3 x 2 temps)		***6*** (3 x 2 temps)	72	27	45000
8	Indirect tension (IDT)	Tex-226-F	As per spec	IDT strength	3	-	***3***	72	2	15000
9	Thermal coefficient	TTI improvised	14 – 104 °F	Thermal coefficient (α)	3		***3***	72	36	22000
		Tex-428-A								
Total material to sample from the field					37		***32***	482	271	184000 **(≥ 405 lbs)**

Note: *a*- test to be performed only if data cannot be obtained from QC/QA records; *b* - no need to do Tex-236-F if Tex-210-F is being conducted, though time consuming and costly, TxDOT prefers Tex-210 because it is more accurate; *c* – results for first test sections were very repeatable with CV less than 5%, so no need for 3 replicate sets.

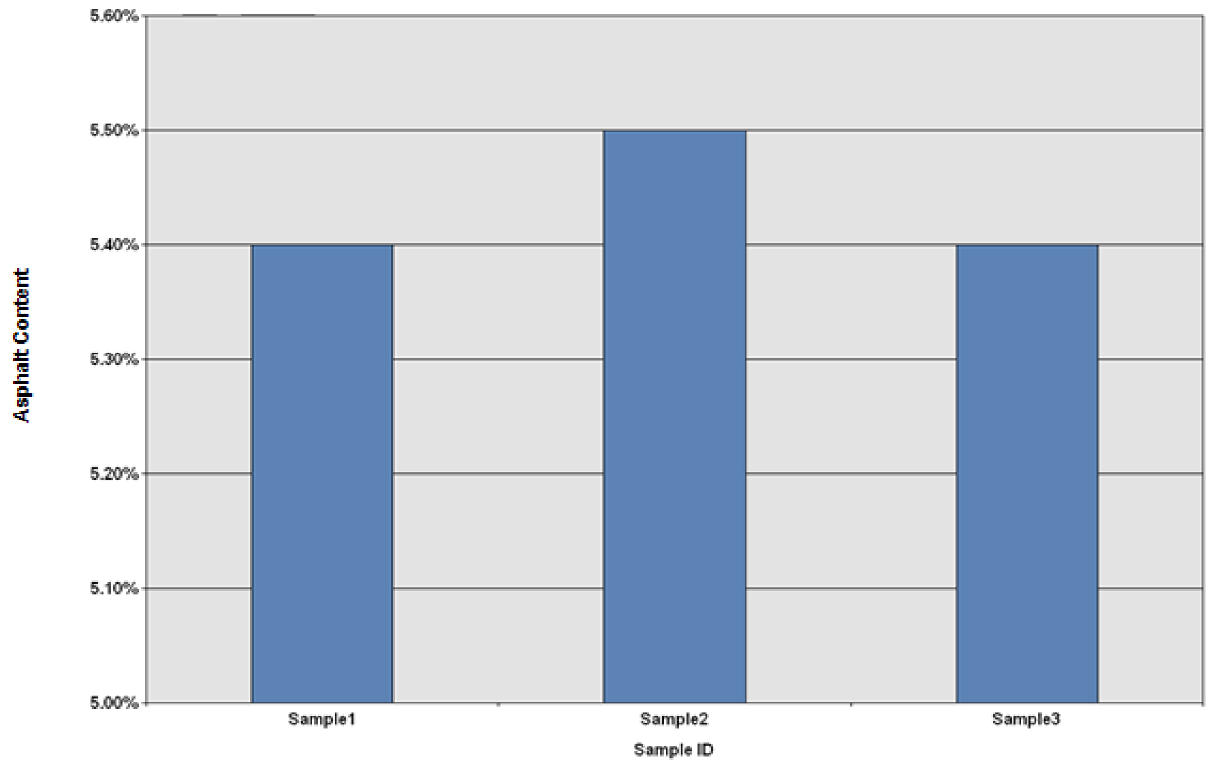


Figure B-1. Asphalt Extraction Results (Tex-210-F).

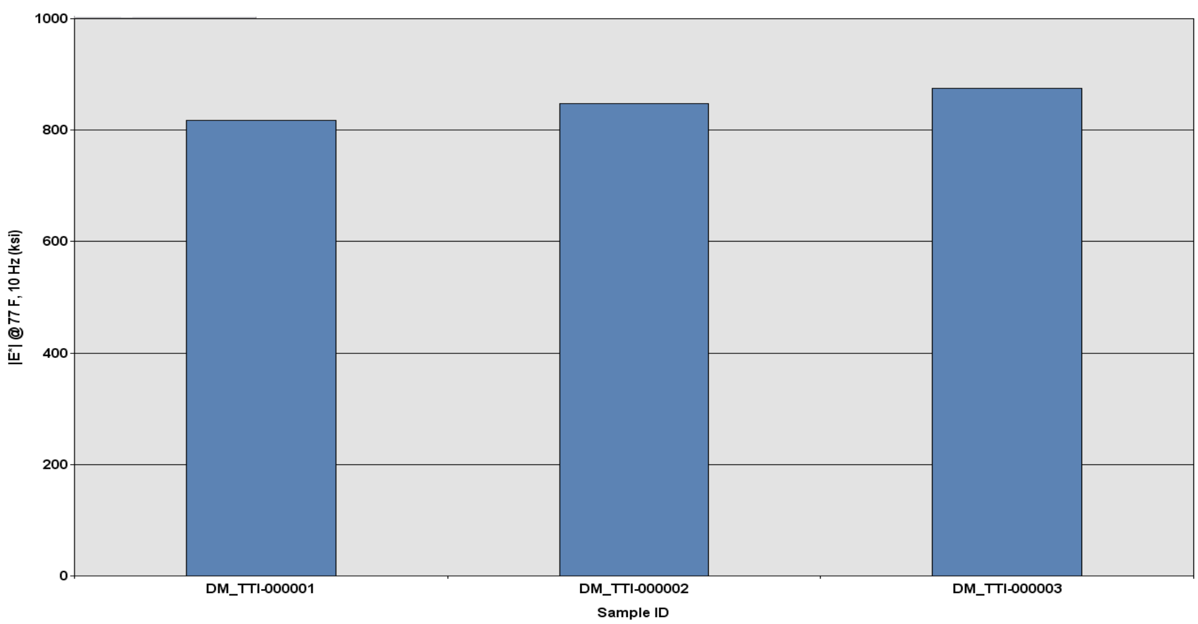


Figure B-2. Dynamic Modulus Test Results (|E*| @ 77°F, 10 Hz (ksi)).

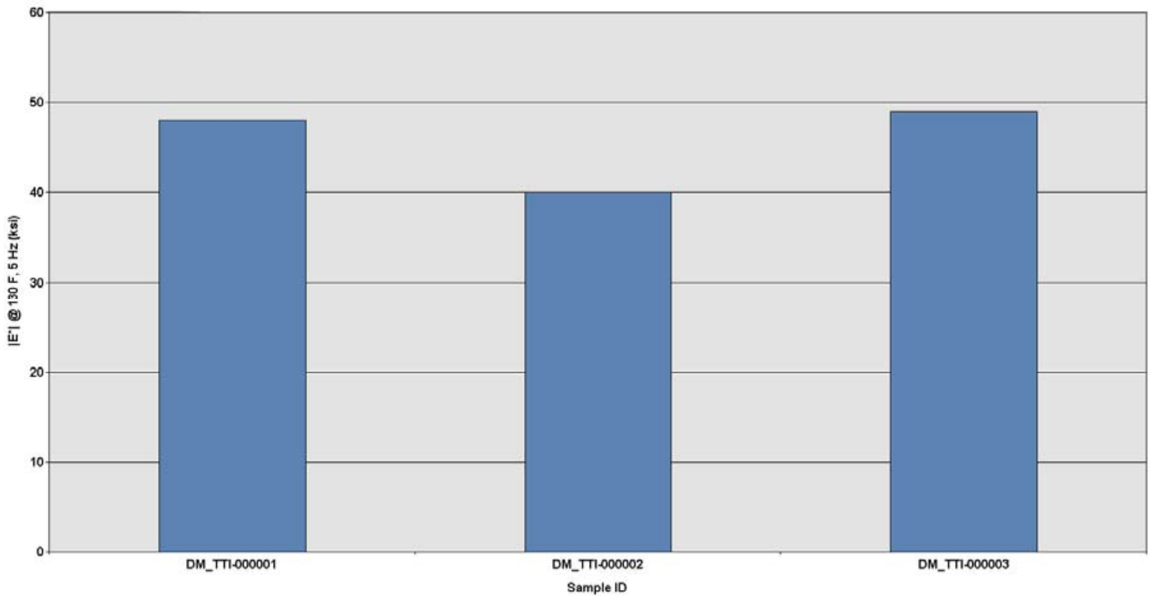


Figure B-3. Dynamic Modulus Test Results (|E*| @ 130°F, 5 Hz (ksi)).

TEMP. & LOADING FREQ.			|E*| ksi			Avg	COV
Temperature		Freq. (Hz)	Sample# 1	Sample# 2	Sample# 3		
(C)	(F)						
-10	14	25	4,657	5,366	4,930	4,984	7.17%
-10	14	10	4,527	5,095	4,763	4,795	5.95%
-10	14	5	4,271	4,867	4,549	4,562	6.53%
-10	14	1	3,847	4,354	4,034	4,078	6.29%
-10	14	0.5	3,626	4,053	3,785	3,821	5.65%
-10	14	0.1	3,071	3,352	3,095	3,173	4.91%
4.4	40	25	2,947	3,449	3,517	3,304	9.43%
4.4	40	10	2,770	3,183	3,177	3,044	7.77%
4.4	40	5	2,575	2,891	2,906	2,791	6.71%
4.4	40	1	2,081	2,340	2,383	2,268	7.22%
4.4	40	0.5	1,864	2,121	2,159	2,048	7.85%
4.4	40	0.1	1,426	1,572	1,601	1,533	6.10%
21.1	70	25	1,227	1,384	1,346	1,319	6.18%
21.1	70	10	985	1,042	1,076	1,034	4.46%
21.1	70	5	821	873	898	864	4.53%
21.1	70	1	485	505	537	509	5.16%
21.1	70	0.5	355	375	396	375	5.41%
21.1	70	0.1	177	188	199	188	5.95%
37.8	100	25	417	351	357	375	9.87%
37.8	100	10	265	212	215	231	12.93%
37.8	100	5	177	140	142	153	13.74%
37.8	100	1	75	59	59	65	14.52%
37.8	100	0.5	54	44	44	47	12.06%
37.8	100	0.1	29	25	24	26	9.65%
54.4	130	25	140	107	139	129	14.31%
54.4	130	10	74	60	75	70	12.35%
54.4	130	5	48	40	49	46	11.04%
54.4	130	1	21	17	23	20	13.98%
54.4	130	0.5	18	16	20	18	12.18%
54.4	130	0.1	12	11	15	13	15.23%

Figure B-4. Dynamic Modulus Test Results.

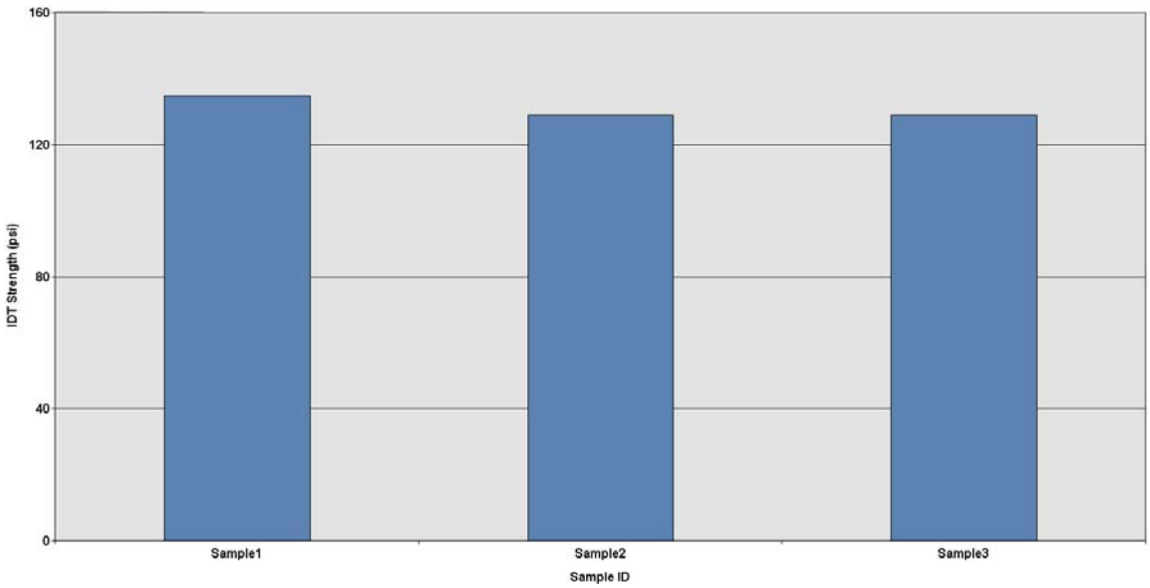


Figure B-4. Indirect Tensile Test Results (Atlanta District).

Overlay Tester for HMA Fracture Properties: *A* and *n*

Figure B-5 shows the key parts of the OT; it consists of two steel plates, one fixed, and the other that moves horizontally to simulate the opening and closing of joints or cracks in the old pavements beneath HMA overlays. The OT specimen is glued to the two steel plates, with half of its length resting on each plate. Generally, the OT is run in an opening displacement-controlled cyclic mode at a predefined loading rate. The key components and features of this procedure are described below.

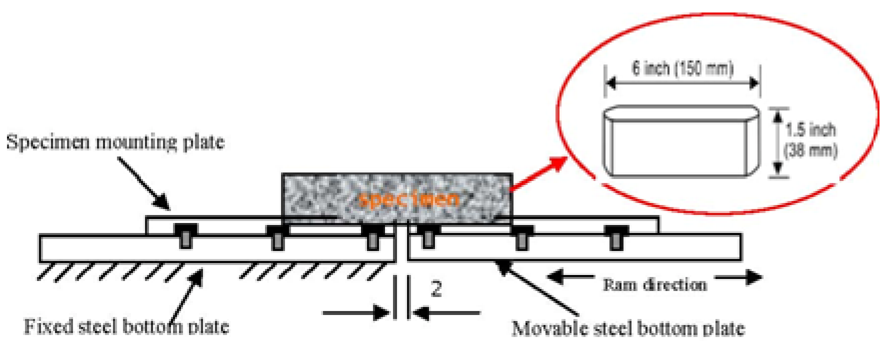
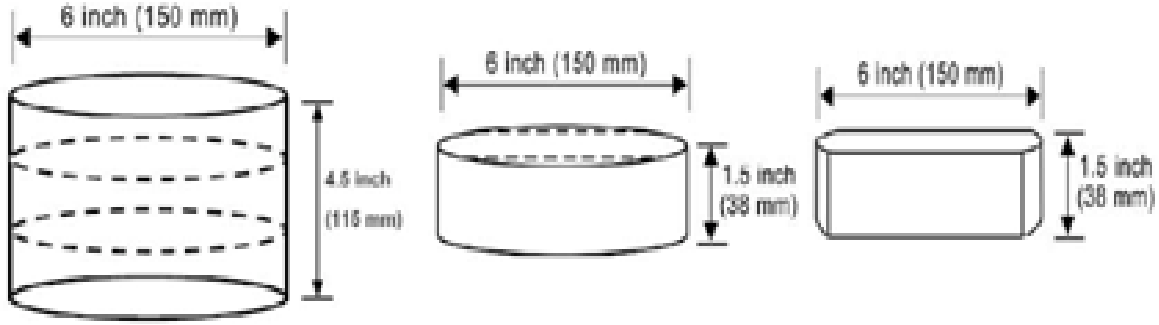


Figure B-5. The OT Concept.

OT Specimen

One important feature of the OT for fracture properties (*A* and *n*) is the specimen size: 6-inch (150 mm) long by 3-inch (75 mm) wide by 1.5-inch (38 mm) high. This size of specimen can be easily cut from a sample that the SGC prepared or from a field core. Figure B-6 shows the OT specimen preparation sequence for an SGC molded specimen.



(a) Original specimen (b) Specimen after cutting (c) Final test specimen

Figure B-6. OT Specimen Preparation from SGC Molded Sample.

Enhanced OT Test Procedure for Fracture Properties (A and n)

Over the past several years, the regular OT test (Tex-248-F) was used for determining HMA fracture properties. Two problems have been identified with the regular OT test for HMA fracture properties. One is the unknown specimen modulus that is critical to determine the fracture parameter *A* value; the other is that the opening displacement of 0.025 inch (0.64 mm) under regular OT test is too big for many Texas limestone mixes, resulting in a very low number of cycles to failure for the regular OT test that are not enough for fracture properties determination. After recognizing these two problems, an enhanced, two-step OT test procedure was proposed and is presented next. It is worth noting that the previously published 0-5798-P1: Laboratory and Field Procedures Used to Characterize Materials does not contain the latest development on determining fracture properties (*A* and *n*). The following steps should be followed instead of the previous ones documented in the 0-5798-P1.

- Step 1, OT-E test:

First, to perform the OT-E test using the OT machine, the regular OT machine needs to be enhanced with three additional apparatus: 1) sample end plates and glue gig, 2) connecting plates, and 3) external LVDTs. Figure B-7 shows the sample end plates, glue gig, and glued specimen within the glue gig. Figure B-8 illustrates the connecting plates and associated assembling steps. Figure B-9 displays the external LVDTs and overview of the specimen with mounted LVDTs. Note that the gauge length of the LVDTs is 3.5 inches (88 mm).

Figure B-7. Sample End Plates and Glue Jig.

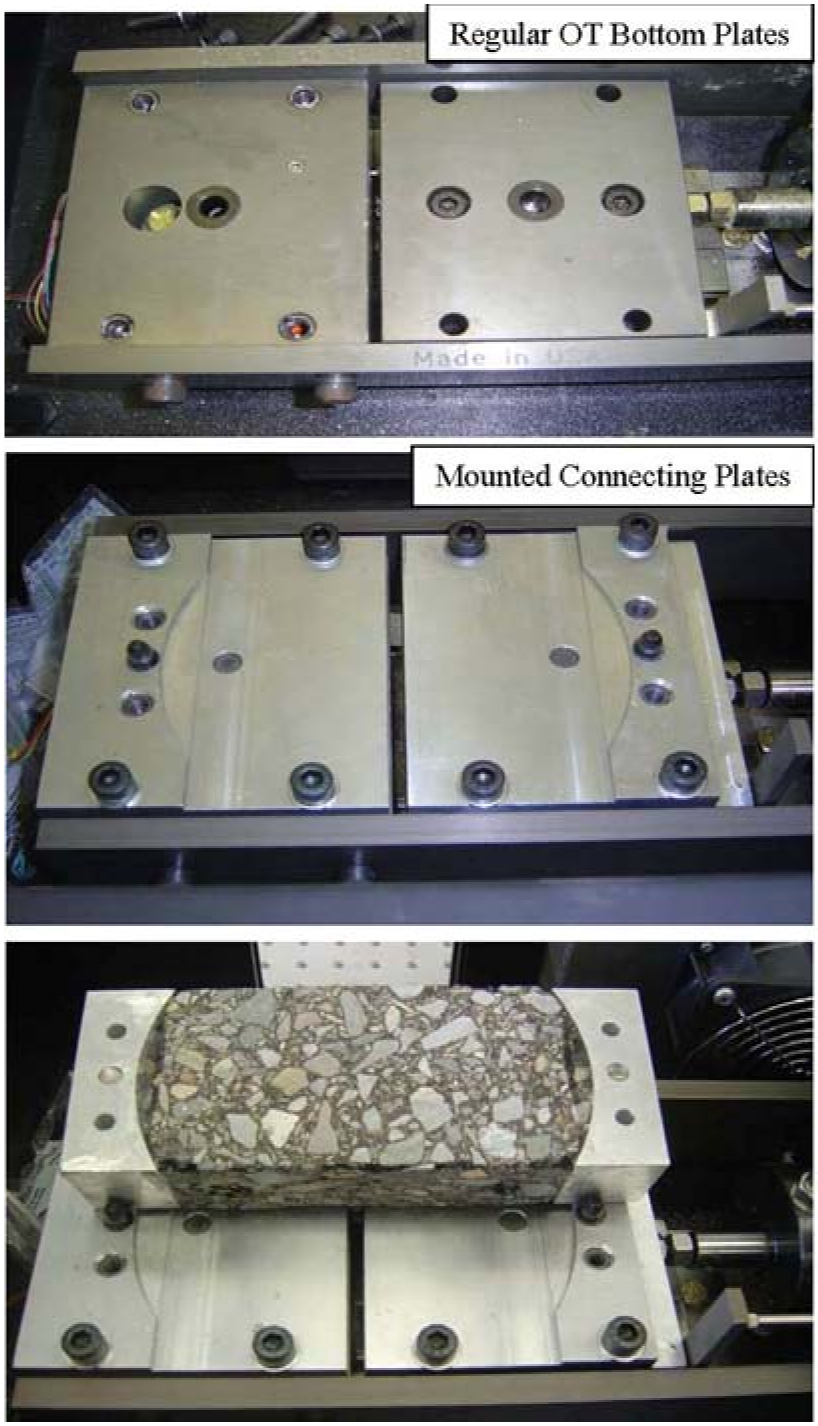


Figure B-8. OT Connecting Plates.

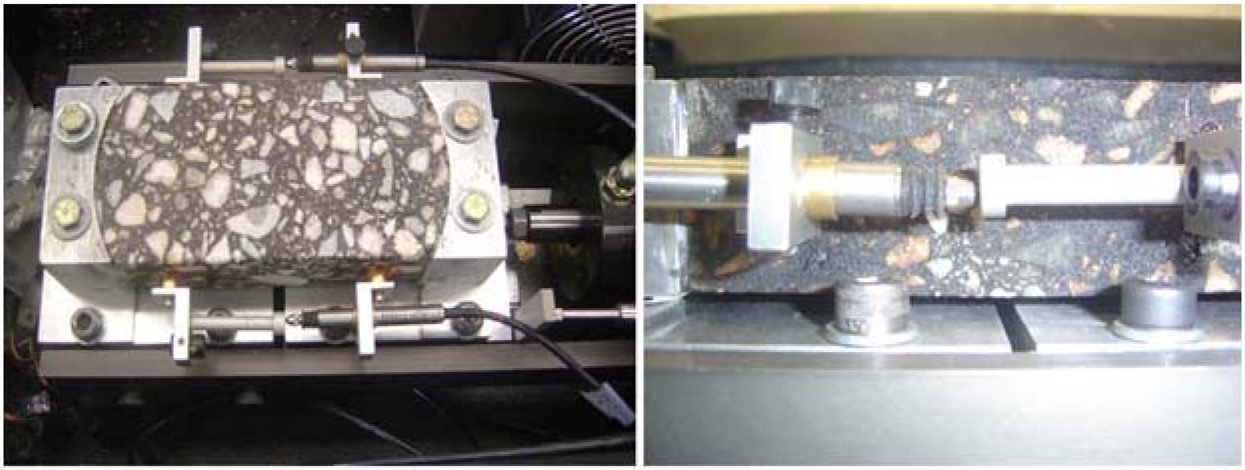


Figure B-9. External LVDTs and Overview of the LVDT Mounted Specimen.

Second, the main purpose of the OT-E test here is not to develop the *E* master curve, but rather to determine the *E* value for later SIF calculation. Thus, the proposed OT-E test is to be conducted at the same test temperature and frequency in a displacement controlled tension mode as those used for the standard OT test. For example, if the OT is run at 77°F (25°C) and 0.1 Hz (10 sec per cycle), then the corresponding OT-E test should be performed at 77°F (25°C) and 0.1 Hz as well, but its opening displacement should be much smaller so that no damage will occur to the specimen. The recommended opening displacement is 0.0009 inch (0.023 mm) and the corresponding strain level within the specimen is about 75 microstrain, which is consistent with the MEPDG dynamic modulus test (AASHTO TP62-03).

Third, the proposed loading waveform for OT-E test is haversine-shaped. There are two reasons to choose the haversine loading waveform. One is that most modulus test procedures, including the MEPDG dynamic modulus test, use this type of loading waveform. The other reason is that it is easy to analyze and model the stress-strain curves and then determine the modulus value using the equations given below.

stress: $$\sigma = \sigma_0 \sin(\omega t)$$

strain: $$\varepsilon = \varepsilon_0 \sin(\omega t - \theta)$$

dynamic modulus: $$E = \frac{\sigma_0}{\varepsilon_0}$$

where σ_0 is peak stress; ε_0 is peak strain; E is dynamic modulus; θ is phase angle; ω is angular velocity; and t is time.

• Step 2, OT test:

A modified version of TxDOT test method Tex-248-F should be followed when running the OT for fracture properties (*A* and *n*). As noted previously, the minor required changes are:

- Reduce the opening displacement to 0.017 inch (0.43 mm) from the regular 0.025 inch (0.63 mm).
- Run the OT until it reaches 100 cycles. If the OT stopped within less than 50 cycles, reduce the opening displacement to 0.015 inch or less, run it again until it reaches a minimum of 50 cycles.

After performing these two OT tests, fracture properties, *A* and *n* can be determined based on the collected test data. Detailed information is given in next section.

Determination of Fracture Properties: A and n

HMA mixtures are complex materials. However, for simplicity and practical applications, HMA mixtures are often assumed to be quasi-elastic materials represented by dynamic modulus and Poisson's ratio. With this assumption, the well-known Paris' Law (Paris and Erdogan 1963) shown below can be used to describe crack propagation of HMA mixtures.

$$\frac{dc}{dN} = A(\Delta K)^n$$

where *c* is crack length; *N* is number of load repetitions; *dc/dN* is crack speed or rate of crack growth; ΔK is change of stress intensity factor (SIF); and *A* and *n* are fracture properties of material.

In view of the Paris' Law Model, it can be seen that the information required for determining fracture properties (*A* and *n*) includes 1) crack length (*c*) corresponding to a specific number of load repetitions (*N*), and 2) the SIF corresponding to any specific crack length (*c*). The proposed approach for determining the SIF and crack length (*c*) is discussed as follows.

Crack Length Estimation

To monitor crack length growth, researchers have used several different techniques such as crack foil (Jacobs 1995) or the Digital Image Correlation (DIC) techniques (Seo et al. 2004). Recently, TTI purchased a DIC system with *two cameras* to monitor crack growth on both sides of the specimen. It was found that crack propagation is a very complicated phenomenon. Even for such a small OT specimen, a crack grows in a 3-D field rather than a 2-D cross-sectional field. Furthermore, the crack growth rate on one side of the specimen, in most cases, is different from that on the other side. HMA mix heterogeneity, non-uniform air void distribution, and residual stresses are considered some of the contributing factors for the observed differences in the crack growth rate on either side of the OT specimen during testing. Recognizing the complexity of crack growth, researchers made some simplification and the following assumptions in this project in order to practically estimate crack length:

- An equivalent (or ideal) crack starts from the bottom at the center of the OT specimen and propagates vertically (in a 2-D field) to the top surface of the specimen.
- The reduction of the maximum load from the first cycle is attributed to crack development/growth.
- As assumed previously, HMA mixtures are quasi-elastic and represented by dynamic modulus and Poisson's ratio (μ=0.35). Note that the visco-elastic properties of HMA mixtures are indirectly considered through using dynamic modulus, which is time-temperature dependent.

With these assumptions, a back calculation approach can be used for crack length estimation. Actually, Jacobs (1995) and later Roque et al. (1999) have successfully used this approach to estimate the crack length from the recorded load and/or strain. In particular for the OT, the maximum load required to reach a specific maximum opening displacement (MOD) gap opening between the plates) is proportional to the dynamic modulus of the OT specimen, and decreases with crack length growth, provided that the MOD is constant. To exclude the influence of the dynamic modulus and the MOD, the maximum load corresponding to any crack length was normalized to the maximum load corresponding to zero crack length, which is determined through extrapolation. Figure B-10 shows the relationship between the normalized maximum load (*y*) and crack length (*x*) developed through FE calculations. A corresponding regression equation is also presented in Figure B-10.

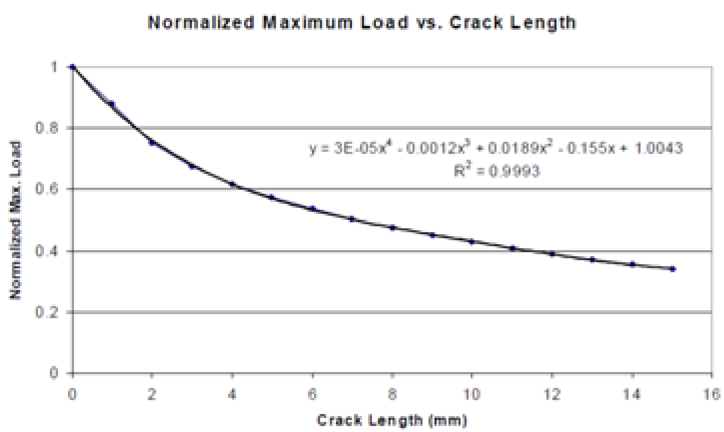


Figure B-10. Normalized Maximum Load vs. Crack Length.

Since the maximum load at each cycle is automatically recorded during the OT testing, it is easy to estimate the equivalent crack length (*c*) for each specific cycle (*N*) from Figure B-10, and then develop the relationship between the *c* and *N*, and accordingly d*c*/d*N* vs. *N*.

SIF Determination

Based on the previous assumptions discussed above, the SIF was specifically analyzed for OT specimens using a *2-D CrackPro* FE program (a modified *SA-CrackPro* program). The SIF is linearly proportional to the dynamic modulus (*E*) of the OT specimen and the MOD. Therefore, the SIFs corresponding to variable crack lengths (*c*) were calculated only for *E* =1 MPa (0.145 ksi) and MOD =1 mm. Figure 4-19 presents these results.

To facilitate implementation, a regression equation (shown in Figure B-11) was developed for the SIF vs. crack length at the condition of *E*=1 MPa (0.145 ksi) and MOD = 1 mm. For any other *E* and *MOD* combinations, Equation 4-52 can determine the corresponding SIF:

$$SIF = 0.2911 * E * MOD * c^{0.4590} \qquad \text{(Equation 4-52)}$$

where *E* is the dynamic modulus; *MOD* is the maximum opening displacement; and *c* is the crack length.

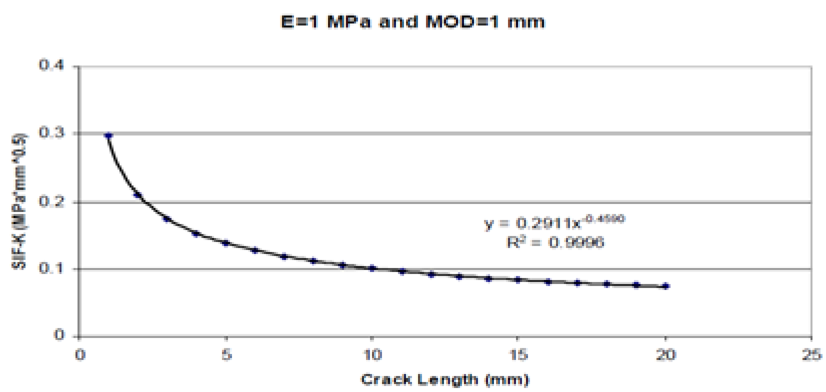


Figure B-11. Calculated SIF vs. Crack length.

Figure B-11 shows that the SIF decreases rapidly at the beginning and its decreasing rate becomes smaller and smaller with crack length growth. This observation indicates that the initial crack propagation stage is very important to determine reasonable fracture properties of HMA mixtures for the OT, which means that the required fracture properties should be determined from the initial stage of the OT testing (perhaps within 20 minutes). This feature separates the displacement-controlled OT from all other load-controlled fracture tests, such as direct tension test (Majidzadeh et al. 1970; Salam 1971; Molenaar 1983; Jacobs 1995) and indirect tension test (Roque et al. 1999), because these load-controlled tests are often focused on the late crack propagation stage where the SIF increases rapidly so that these tests generally take a very long time (i.e., hours.)

Determination of Fracture Properties: *A and n*

With known SIF (*K*) and crack growth rate (*dc/dN*), the fracture properties (*A* and *n*) can be readily determined. Figure 4-20 shows the five steps of determining the HMA fracture properties (*A* and *n*). Currently, a Microsoft© Excel macro named *TTI-OT* has been developed to automatically analyze the OT test results and determine the HMA fracture properties (*A* and *n*).

THE REPEATED LOAD PERMANENT DEFORMATION (RLPD) TEST

Laboratory Determination of HMA Rutting Properties: *μ* and *α*

The most often used laboratory test for determining the permanent deformation properties of HMA materials is the repeated load test. Generally, the repeated load test is run without confining pressure with 0.1 second loading and 0.9 second rest period. After reviewing historical references about the repeated load test in the literature (Kenis 1978; Witczak et al. 2000), Zhou et al. have standardized a repeated load test protocol for HMA mixes and documented it in Report 0-5798-P1: Laboratory and Field Procedures Used to Characterize Materials. But, it was found later that it is ideal to conduct the repeated load test at three temperatures for the Texas climate: 77°F/25°C, 104°F/40°C, and 122°F/50°C. Table B-3 lists the applied load for each temperature. In case of preferring only one test temperature, the recommended test temperature is 104°F/40°C. The specimen size is 4-inch (100 mm) diameter by 6-inch (150 mm) high and its preparation is the same as that for the dynamic modulus test, to be discussed later. The detailed test protocol can be found in Report 0-5798-P1 (Zhou et al. 2009a).

Table B-3. Repeated Load Test Temperatures and Load Levels.

Test temperature (ºF)	77	104	122
Applied deviator stress (psi)	30	20	10

To determine the rutting parameters from the repeated load test, the accumulative permanent deformation (or strain) versus the number of load repetitions (*N*), as shown in Figure B-12, is generally plotted on a log-log scale and is often expressed by the classical power law model:

$$\varepsilon_p = aN^b$$

where parameters *a* and *b* are regression constants depending on the mix itself, test temperature, and load level. The intercept *a* represents the permanent strain at *N*=1, whereas the slope *b* represents the rate of change in permanent strain as a function of the change in load repetitions (log*N*). Note that the parameters *a* and *b*, are determined from the linear portion of the permanent strain curve only.

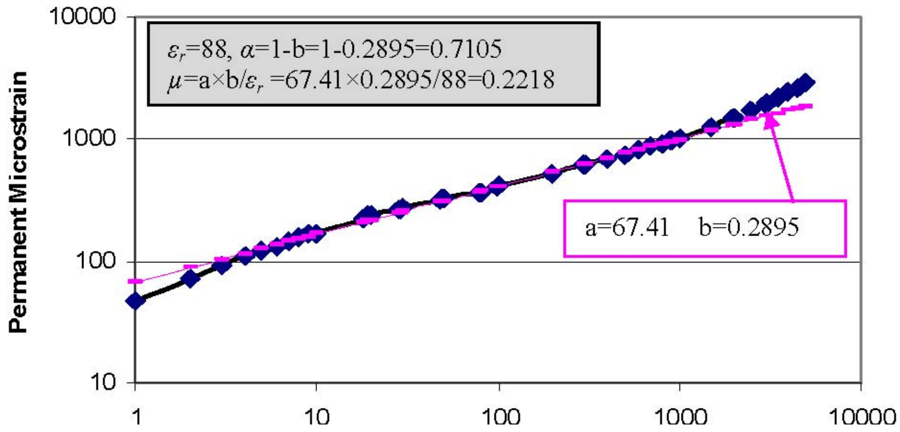


Figure B-12. Plot of Regression Constants "a" and "b" from Log Permanent Strain— Log Number of Loading Cycles.

From the previous equation, the permanent strain per load repetition $\Delta\varepsilon p(N)$ can be deduced and expressed by the following model:

$$\Delta\varepsilon_p(N) = abN^{b-1}$$

Meanwhile, the resilient strain (εr) is generally assumed to be independent of the load repetitions (N) and is calculated based on the measurement on the 200th repetition. As a consequence, the ratio of permanent strain to resilient strain of the HMA mix can be expressed by the following model:

$$\frac{\Delta\varepsilon p(N)}{\varepsilon r} = \left(\frac{ab}{\varepsilon r}\right)N^{b-1}$$

Rutting parameters μ and α, are defined as follows:

$$\mu = \frac{ab}{\varepsilon r}$$

$$\alpha = 1-b$$

For the HMA mix shown in Figure B-12, known resilient microstrain εr = 88, intercept a =67.41, and slope b=0.2895, the rutting parameters μ and α can be determined as follows:

$$\mu = \frac{ab}{\varepsilon r} = (67.41 \times 0.2895) \div 88 = 0.2218$$

$$\alpha = 1- b = 1- 0.2895 = 0.7105$$

APPENDIX C: BASE AND SUBGRADE SOIL TESTS

RECOMMENDED PERMANENT DEFORMATION AND RESILIENT MODULUS LABORATORY TEST PROTOCOLS FOR UNBOUND GRANULAR BASE/SUBBASE MATERIALS AND SUBGRADE SOILS

1. SCOPE

1.1 This test method describes the laboratory preparation and testing procedures for the determination of permanent deformation and resilient modulus (Mr) of unbound granular base/subbase materials and subgrade soils for pavement performance prediction. This test procedure has been adapted primarily from the standard test methods recommended by the National Cooperative Highway Research Program (NCHRP) Project 1-28A.

1.2 The methods described herein are applicable to laboratory-molded samples of unbound granular base/subbase materials and subgrade soils.

1.3 In this test procedure, stress states used for permanent deformation and resilient modulus testing are based upon whether the specimen is located in the base/subbase or the subgrade. Specimen size for testing depends upon the maximum particle size of the material.

1.4 The values of permanent deformation and resilient modulus determined from these procedures are the measures of permanent deformation properties and the modulus of unbound granular base/subbase materials and subgrade soils with the consideration of their stress-dependency.

1.5 Resilient modulus values can be used with structural response analysis models to calculate the pavement structural response to wheel loads, and with the combination of permanent deformation properties and pavement design procedures to predict rutting performance.

2. REFERENCED DOCUMENTS

2.1 TxDOT Procedures:

- Tex-110-E Particle Size Analysis of Soils.
- Tex-104-E Determining Liquid Limits of Soils.
- Tex-105-E Determining Plastic Limit of Soils.
- Tex-106-E Calculating the Plasticity Index of Soils.
- Tex-108-E Determining Specific Gravity of Soils.
- Tex-113-E Laboratory Compaction Characteristics and Moisture-Density Relationship of Base Materials.
- Tex-114-E Laboratory Compaction Characteristics and Moisture-Density Relationship of Subgrade, Embankment Soils, and Backfill Material.
- Tex-103-E Determining Moisture Content in Soil Materials.
- Tex-117-E Triaxial Compression for Disturbed Soils and Base Materials.

3. TERMINOLOGY

3.1 *Unbound Granular Base and Subbase Materials*—These include soil-aggregate mixtures and naturally occurring materials. No binding or stabilizing agent is used to prepare unbound granular base or subbase layers. These materials are classified as Type 1 and Type 2, as subsequently defined in 3.3 and 3.4.

3.2 *Subgrade*—Subgrade soils may be naturally occurring or prepared and compacted before the placement of subbase and/or base layers. These materials are classified as Type 1, Type 2, and Type 3, as subsequently defined in 3.3, 3.4, and 3.5.

3.3 *Material Type 1*—These include all unbound granular base and subbase materials and all untreated subgrade soils with maximum particle sizes greater than 3/8 in. (9.5 mm). All material greater than 1.0 in. (25 mm) shall be scalped off prior to testing. Materials classified as Type 1 shall be molded in either a 6 in. (150 mm) diameter mold. Materials classified as Type 1 shall be compacted as per Tex-113-E.

3.4 *Material Type 2*—These include all unbound granular base and subbase materials and all untreated subgrade soils that have a maximum particle size less than 3/8 in (9.5 mm) and that meet the criteria of less than 10 percent passing the No. 200 (75 µm) sieve. Materials classified as Type 2 shall be molded in a 4 in (100 mm) diameter mold and compacted as per Tex-114-E

3.5 *Material Type 3*—These include all untreated subgrade soils that have a maximum particle size less than 3/8 in (9.5 mm) and that meet the criteria of more than 10 percent passing the No. 200 (75 mm) sieve. Materials classified as Type 3 shall be molded in a 4 in (100 mm) diameter mold and compacted as per Tex-114-E.

3.6 *Permanent Deformation*—Permanent deformation is determined by repeated load compression tests on specimens of the unbound materials. Permanent deformation is the unrecovered deformation during the testing.

3.7 *Resilient Modulus*—The resilient modulus is determined by repeated load compression tests on test specimens of the unbound materials. Resilient modulus (Mr) is the ratio of the peak axial repeated deviator stress to the peak recoverable axial strain of the specimen.

3.8 *Loading Wave Form*—Test specimens are loaded using a haversine load pulse with 0.1 to 0.2 second loading and 0.8 to 0.9 second rest period.

3.9 *Maximum Applied Axial Load* (P_{max})—The load applied to the sample consisting of the contact load and cyclic load (confining pressure is not included):

$$P_{max} = P_{contact} + P_{cyclic}$$

3.10 Contact Load ($P_{contact}$)—Vertical load placed on the specimen to maintain a positive contact between the loading ram and the specimen top cap. The contact load includes the weight of the top cap and the static load applied by the ram of the loading system.

3.11 Cyclic Axial Load—Repetitive load applied to a test specimen:

$$P_{cyclic} = P_{max} - P_{contact}$$

3.12 *Maximum Applied Axial Stress* (σ_{max})—The axial stress applied to the sample consisting of the contact stress and the cyclic stress (the confining stress is not included):

$$\sigma_{max} = P_{max}/A$$

where A is the cross sectional area of the sample.

3.13 *Cyclic Axial Stress* (σ_{cyclic})—Cyclic applied axial stress:

$$\sigma_{cyclic} = P_{cyclic}/A$$

3.14 *Contact Stress* ($\sigma_{contact}$)—Axial stress applied to a test specimen to maintain a positive contact between the specimen cap and the specimen:

$$\sigma_{contact} = P_{contact}/A$$

The contact stress shall be maintained so as to apply a constant anisotropic confining stress ratio:

$$(\sigma_{contact} + \sigma_3)/\sigma_3 = 1.2$$

where σ_3 is the applied confining pressure in the triaxial chamber (i.e., the minor principal stress).

3.15 e_r is the resilient (recoverable) axial deformation due to σ_{cyclic}.

3.16 ε_r is the resilient (recoverable) axial strain due to σ_{cyclic}:

$$\varepsilon_r = e_r/L$$

where L is the distance between measurement points for resilient axial deformation

3.17 e_p is the permanent (unrecoverable) axial deformation due to ε_{cyclic}.

3.18 ε_p is the permanent (unrecoverable) axial strain due to ε_{cyclic}:

$$\varepsilon_p = e_p / L$$

3.19 *Resilient Modulus* (M_r) is defined as:

$$M_r = \varepsilon_{cyclic} / \varepsilon_r$$

3.20 Load duration is the time interval the specimen is subjected to a cyclic stress pulse.

3.21 Cycle duration is the time interval between the successive applications of a cyclic stress.

4. SUMMARY OF METHOD

4.1 A repeated axial stress of fixed magnitude, load duration, and cycle duration is applied to a cylindrical test specimen. The test is performed in a triaxial cell, and the specimen is subjected to a repeated (cyclic) stress and a constant confining stress provided by means of cell air pressure. Both total resilient (recoverable) and permanent axial deformation responses of the specimen are recorded and used to calculate the permanent deformation properties and the resilient modulus.

5. SIGNIFICANCE AND USE

5.1 The resilient modulus test results provide a basic constitutive relationship between stiffness and stress state of pavement materials for use in the structural analysis of layered pavement systems.

5.2 The permanent deformation properties of pavement materials can be determined from the first 10,000 cycles of the repeated load test. The information is critical for pavement rutting performance prediction.

6. PERMANENT DEFORMATION AND RESILIENT MODULUS TEST APPARATUS

6.1 *Triaxial Pressure Chamber*—The pressure chamber contains the test specimen and the confining fluid during the test. Figure C-1 shows a typical triaxial chamber suitable for use in resilient modulus testing of soils. The axial deformation is measured internally, directly on the specimen, using normal gauges with rubber bands (see Figure C-2), non-contact sensors, or clamps. For soft and very soft subgrade specimens (where the undrained shear strength, s_u, is less than 36 kPa or 750 psf), rubber bands or clamps should not be used since these may damage the specimen. In this case, the top to bottom platen measurements can be used to measure axial deformation of these weak soils.

6.1.1 Air shall be used in the triaxial chamber as the confining fluid for all testing.

6.1.2 The chamber shall be made of suitable transparent material (such as polycarbonate).

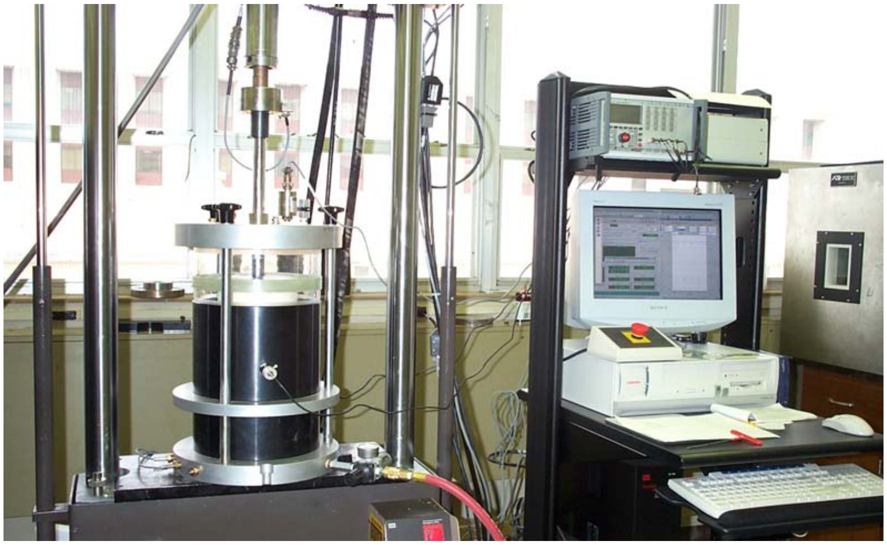


Figure C-1. Triaxial Cell and Test System.

Figure C-2. Sample with Instruments.

6.2 *Loading Device*—The loading device shall be a top-loading, closed-loop electro-hydraulic testing machine with a function generator that is capable of applying repeated cycles of a haversine-shaped load pulse. Each pulse shall have a 0.1 sec duration followed by a rest period of 0.9 sec duration for base/subbase materials and 0.2 sec duration followed by a rest period of 0.8 sec duration for subgrade materials. For non-plastic granular material, it is permissible, if desired, to reduce the rest period to 0.4 sec to shorten testing time; the loading time may be increased to 0.15 sec if required.

6.2.1 The electro-hydraulic system-generated haversine waveform and the response waveform shall be displayed to allow the operator to adjust the gains to ensure they coincide during conditioning and testing.

6.3 Load and Specimen Response Measuring Equipment

6.3.1 The axial load measuring device should be an electronic load cell, which is preferred to be located inside the triaxial cell. The load cell should have the capacities presented in Table C-1.

Table C-1. Load Cell Capacity.

Sample Diameter in (mm) Max.	Load Capacity lb (kN)	Required Accuracy lb (N)
4.0 (100)	2000 (9)	±4 (±18)
6.0 (150)	5000 (22)	±5 (±22)

6.3.2 The chamber pressures shall be monitored with conventional pressure gauges, manometers, or pressure transducers accurate to 0.1 psi (0.7 kPa).

6.3.3 Axial deformation is to be measured with displacement transducers. Deformation shall be measured over approximately the middle half of the specimen. Axial deformations shall be measured at a minimum of two locations 180 degrees apart (in a plan view). Table C-2 summarizes the specifications for displacement transducers.

Table C-2. Specifications for Measurement of Displacements.

<table>
<tr><th colspan="2">Material/Specimen Diameter (in)</th><th>Min. Range (in)</th><th>Approximate Resilient Specimen Displacement (in)</th></tr>
<tr><td rowspan="2">Aggregate Base</td><td>6</td><td>±0.25</td><td>0.001</td></tr>
<tr><td>4</td><td>±0.10</td><td>0.00065</td></tr>
<tr><td>Subgrade Soil (sand and cohesive)</td><td>4</td><td>±0.25</td><td>0.0014</td></tr>
</table>

Note: For soft subgrade soil, permanent and resilient displacement shall be measured over entire specimen height.

Note 1—Misalignment or dirt on the shaft of the transducer can cause the shafts of the LVDTs to stick. The laboratory technician shall depress and release each LVDT back and forth a number of times prior to each test to assure that they move freely and are not sticking. A cleaner/lubricant specified by the manufacturer shall be applied to the transducer shafts on a regular basis.

6.3.4 Data Acquisition: An analog-to-digital (A/D) data acquisition system is required. Suitable signal excitation, conditioning, and recording equipment are required for simultaneous recording of axial load and deformations. The system should meet or exceed the following additional requirements: (1) 25 μs A/D conversion time; (2) 12-bit resolution; (3) single- or multiple-channel throughput (gain = 1) of 30 kHz; (4) software selectable gains; (5) measurement accuracy of full scale (gain = 1) of ±0.02 percent; and

(6) non-linearity of ±0.5 percent. The signal shall be clean and free of noise. Filtering the output signal during or after data acquisition is discouraged.

If a filter is used, it should have a frequency higher than 10 to 20 Hz. A supplemental study should be made to ensure correct peak readings are obtained from filtered data compared to unfiltered data. A minimum of 200 data points from each displacement transducer shall be recorded per load cycle.

6.4 *Specimen Preparation Equipment*—A variety of equipment is required to prepare compacted specimens that are representative of field conditions. Use of different materials and different methods of compaction in the field requires the use of varying compaction energies in the laboratory.

6.5 *Miscellaneous Apparatus*—This includes calipers, micrometer gauge, steel rule (calibrated to 0.02 in., 0.5 mm), rubber membranes 0.02 to 0.03 in. (0.25 to 0.8 mm) thickness, rubber O-rings, vacuum source with bubble chamber and regulator, membrane expander, porous stones (subgrade), 0.25 in. (6.4 mm) thick porous stones or bronze discs (base/subbase), scales, moisture content cans, and data sheets.

6.6 *Periodic System Calibration*—The entire system (transducers, signal conditioning, and recording devices) shall be calibrated every two weeks or after every 50 tests. Daily and other periodic checks of the system may also be performed as necessary. No permanent deformation and resilient modulus testing will be conducted unless the entire system meets the established calibration requirements.

7. PREPARATION OF TEST SPECIMENS

7.1 The following guidelines, based on the sieve analysis test results, shall be used to determine the test specimen size:

7.1.1 Use 6 in. (150 mm) diameter and 12 in. (300 mm) high specimens for all Type 1 material.

7.1.2 Use 4 in (100 mm) diameter and 8 in. (200 mm) high specimens for all Type 2 and Type 3 materials.

7.2 *Laboratory Compacted Specimens*—Reconstituted test specimens of all types shall be prepared to the specified or in situ dry unit weight (γ_d) and moisture content (ω). Laboratory compacted specimens shall be prepared for all unbound granular base and subbase material and for all subgrade soils.

7.2.1 *Moisture Content*—For in situ materials, the moisture content of the laboratory compacted specimen shall be the in situ moisture content for that layer obtained in the field using Tex-103-E. If data are not available on in situ moisture content, refer to Section 7.2.3.

7.2.1.1 The moisture content of the laboratory compacted specimen should not vary from the nominal value by more than ±0.5 percent for all materials.

7.2.2 *Compacted Density*—The unit weight of a compacted specimen shall be the in-place dry unit weight obtained in the field for that layer using Tex-115-E or other suitable methods. If these data are not available on in situ density, then refer to Section 7.2.3.

7.2.2.1 The dry unit weight of a laboratory compacted specimen should not vary more than ±1.0 percent from the target dry unit weight for that layer.

7.2.3 If either the in situ moisture content or the in-place dry unit weight is not available, use the optimum moisture content and 100 percent of the maximum dry unit weight by using Tex-113-E for the base/subbase and 95 percent of Tex-114-E for the subgrade.

7.2.3.1 The moisture content of the laboratory compacted specimen should not vary from the required value by more than ±0.5 percent for all materials. The dry unit weight of a laboratory compacted specimen should not vary more than ±1.0 percent from the target dry unit weight for that layer.

7.2.4 *Sample Reconstitution*—Reconstitute the specimen for all materials. The target moisture content and unit weight to be used in determining needed material qualities are given in Section 7.2. After this step is completed, specimen compaction can begin.

7.3 Compaction Methods and Equipment for Reconstituting Specimens

7.3.1 Specimens of Type 1 materials shall be compacted by Tex-113-E.

7.3.2 Specimens of Type 2 materials shall be compacted by Tex-114-E.

7.3.3 Specimens of Type 3 materials shall be compacted by Tex-114-E.

8. TEST PROCEDURE

Following this test procedure, a permanent deformation and resilient modulus test is performed on all materials using a triaxial cell (confined).

8.1 Apparatus and Sample Preparation

8.1.1 Assembly of the triaxial cell: If the specimen is not yet in place, place it with end platens into position on the pedestal of the triaxial cell. Proper positioning of the specimen is extremely critical in applying a concentric load to the specimen. Couple the loading device to the specimen using a smooth steel ball. To center the specimen, slowly rotate the ball as the clearance between the load piston ball decreases and a small amount of load is applied to the specimen. Be sure the ball is concentric with the piston that applies the load (watch the gap around the ball). Shift the specimen laterally to achieve a concentric loading.

8.1.2 Check and adjust the axial displacement measurement system, load cell, and data acquisition system, and make sure these are working properly.

8.1.3 If the confining air pressure supply line is not already connected, connect the supply line to the triaxial chamber.

8.1.4 Open all valves on drainage lines leading to the inside of the specimen. This is necessary to develop confining pressure on the specimen.

8.1.5 Apply the specified preconditioning conditioning confining pressure (as shown in Table 3 based on material type) to the test specimen. A contact stress equal to 20 percent of the confining pressure shall be applied to the specimen so that the load piston stays in contact with the top platen at all times.

8.1.6 *Preconditioning*—Apply 100 repetitions of preconditioning at a maximum axial stress and a corresponding cyclic stress as shown in Table C-3 using a haversine-shaped load pulse followed by a rest period(also shown in Table C-3).

8.2 Permanent Deformation Test

8.2.1 Apply a 10,000 cycles of haversine loading (P_{cyclic}) equivalent to a maximum axial stress and a corresponding cyclic stress using a haversine-shaped, load pulse followed by a rest period (as shown in Table C-3). Stop the test if the vertical permanent strain reaches 5 percent before 10,000 cycles are completed.

Table C-3. Preconditioning and Permanent Deformation Data Based on Material Type.

Material Type	Sequence	Confining Pressure		Cyclic Stress		Maximum Stress		Load Pulse Duration	Rest Period
		KPa	psi	KPa	psi	KPa	psi	sec	sec
1	Preconditioning	103.5	15	20.7	3	41.4	6	0.1	0.9
	Permanent Deformation	103.5	15	207	30	227.7	33		
2	Preconditioning	27.6	4	6.9	1	12.4	1.8	0.2	0.8
	Permanent Deformation	27.6	4	55.2	8	60.7	8.8		
3	Preconditioning	27.6	4	6.9	1	12.4	1.8	0.2	0.8
	Permanent Deformation	27.6	4	48..3	7	53.8	7.8		

8.2.2 During the load applications, record the load applied and the axial deformation measured from two displacement transducers through the data acquisition system. Signal-to-noise ratio should be at least 10. All data should be collected in real time and collected/ processed so as to minimize phase errors due to sequential channel sampling. In order to save storage space during data acquisition for 10,000 cycles, researchers recommend using the data acquisition of the cycles shown in Table C-4.

Table C-4. Suggested Data Collection for Triaxial Repeated Load Permanent Deformation Test for All Materials.

Data Collection During Cycles	Data Collection During Cycles	Data Collection During Cycles	Data Collection During Cycles
1--15	450	1300	4000
20	500	1400	4500
30	550	1500	5000
40	600	1600	5500
60	650	1700	6000
80	700	1800	6500
100	750	1900	7000
130	800	2000	7500
160	850	2200	8000
200	900	2400	8500
250	950	2600	9000
300	1000	2800	9500
350	1100	3000	10000
400	1200	3500	

8.3 Resilient Modulus Test

8.3.1 Specimen Testing—If the vertical permanent strain has neither reached 5 percent nor the specimen failed during permanent deformation test, the same specimen may be used to perform the resilient modulus test even though a new specimen is preferred.

8.3.2 If the vertical permanent strain exceeds 5 percent during permanent deformation testing, mold a new specimen, and then go back to section 8.1.1. In addition, reduce the load repetitions from 10,000 to 1,000 during the repeated load permanent deformation test. If the sample again reaches 5 percent total vertical permanent strain during the repeated load test, then the test shall be terminated. No further testing of this material is necessary.

8.3.3 Perform the resilient modulus test following the load sequence shown in Tables C-5, C-6, or C-7 based on the soil type. Begin with Sequence No. 1.

8.3.4 Apply 100 repetitions of the corresponding cyclic axial stress using a haversine-shaped load pulse followed by a rest period described in Table C-3. Record the average recovered deformations from each displacement transducer separately for the last five cycles.

8.3.5 At the completion of this test, reduce the confining pressure to zero, and remove the sample from the triaxial chamber.

8.3.6 Remove the membrane from the specimen, and use the entire specimen to determine moisture content in accordance with Tex-103-E.

Table C-5. Permanent Deformation and Resilient Modulus Test Sequence for Type 1 Material.

Sequence	Confining Pressure		Contact Stress		Cyclic Stress		Maximum Stress		Nrep.
	KPa	psi	KPa	psi	KPa	psi	KPa	psi	
Preconditioning	103.5	15.0	20.7	3.0	20.7	3.0	41.4	6.0	100
Permanent Deformation	103.5	15.0	20.7	3.0	207.0	30.0	227.7	33.0	10000
1	20.7	3.0	4.1	0.6	10.4	1.5	14.5	2.1	100
2	41.4	6.0	8.3	1.2	20.7	3.0	29.0	4.2	100
3	69.0	10.0	13.8	2.0	34.5	5.0	48.3	7.0	100
4	103.5	15.0	20.7	3.0	51.8	7.5	72.5	10.5	100
5	138.0	20.0	27.6	4.0	69.0	10.0	96.6	14.0	100
6	20.7	3.0	4.1	0.6	20.7	3.0	24.8	3.6	100
7	41.4	6.0	8.3	1.2	41.4	6.0	49.7	7.2	100
8	69.0	10.0	13.8	2.0	69.0	10.0	82.8	12.0	100
9	103.5	15.0	20.7	3.0	103.5	15.0	124.2	18.0	100
10	138.0	20.0	27.6	4.0	138.0	20.0	165.6	24.0	100
11	20.7	3.0	4.1	0.6	41.4	6.0	45.5	6.6	100
12	41.4	6.0	8.3	1.2	82.8	12.0	91.1	13.2	100
13	69.0	10.0	13.8	2.0	138.0	20.0	151.8	22.0	100
14	103.5	15.0	20.7	3.0	207.0	30.0	227.7	33.0	100
15	138.0	20.0	27.6	4.0	276.0	40.0	303.6	44.0	100
16	20.7	3.0	4.1	0.6	62.1	9.0	66.2	9.6	100
17	41.4	6.0	8.3	1.2	124.2	18.0	132.5	19.2	100
18	69.0	10.0	13.8	2.0	207.0	30.0	220.8	32.0	100
19	103.5	15.0	20.7	3.0	310.5	45.0	331.2	48.0	100
20	138.0	20.0	27.6	4.0	414.0	60.0	441.6	64.0	100
21	20.7	3.0	4.1	0.6	103.5	15.0	107.6	15.6	100
22	41.4	6.0	8.3	1.2	207.0	30.0	215.3	31.2	100
23	69.0	10.0	13.8	2.0	345.0	50.0	358.8	52.0	100
24	103.5	15.0	20.7	3.0	517.5	75.0	538.2	78.0	100
25	138.0	20.0	27.6	4.0	690.0	100.0	717.6	104.0	100
26	20.7	3.0	4.1	0.6	144.9	21.0	149.0	21.6	100
27	41.4	6.0	8.3	1.2	289.8	42.0	298.1	43.2	100
28	69.0	10.0	13.8	2.0	483.0	70.0	496.8	72.0	100
29	103.5	15.0	20.7	3.0	724.5	105.0	745.2	108.0	100
30	138.0	20.0	27.6	4.0	966.0	140.0	993.6	144.0	100

Table C-6. Permanent Deformation and Resilient Modulus Test Sequence for Type 2 Material.

Sequence	Confining Pressure		Contact Stress		Cyclic Stress		Maximum Stress		Nrep.
	KPa	psi	KPa	psi	KPa	psi	KPa	psi	
Preconditioning	27.6	4.0	5.5	0.8	6.9	1.0	12.4	1.8	100
Permanent Deformation	27.6	4.0	5.5	0.8	55.2	8.0	60.7	8.8	10000
1	13.8	2.0	2.8	0.4	6.9	1.0	9.7	1.4	100
2	27.0	4.0	5.5	0.8	55.2	8.0	60.7	8.8	100
3	41.4	6.0	8.3	1.2	20.7	3.0	29.0	4.2	100
4	55.2	8.0	11.0	1.6	27.6	4.0	38.6	5.6	100
5	82.2	12.0	16.6	2.4	41.4	6.0	58.0	8.4	100
6	13.8	2.0	2.8	0.4	13.8	2.0	16.6	2.4	100
7	27.6	4.0	5.5	0.8	27.6	4.0	33.1	4.8	100
8	41.4	6.0	8.3	1.2	41.4	6.0	49.7	7.2	100
9	55.2	8.0	11.0	1.6	55.2	8.0	66.2	9.6	100
10	82.8	12.0	16.6	2.4	82.8	12.0	99.4	14.4	100
11	13.8	2.0	2.8	0.4	27.6	4.0	30.4	4.4	100
12	27.6	4.0	5.5	0.8	55.2	8.0	60.7	8.8	100
13	41.4	6.0	8.3	1.2	82.8	12.0	91.1	13.2	100
14	55.2	8.0	11.0	1.6	110.4	16.0	121.4	17.6	100
15	82.8	12.0	16.6	2.4	165.6	24.0	182.2	26.4	100
16	13.8	2.0	2.8	0.4	41.4	6.0	44.2	6.4	100
17	27.6	4.0	5.5	0.8	82.8	12.0	88.3	12.8	100
18	41.4	6.0	8.3	1.2	124.2	18.0	132.5	19.2	100
19	55.2	8.0	11.0	1.6	165.6	24.0	176.6	25.6	100
20	82.8	12.0	16.6	2.4	248.4	36.0	265.0	38.4	100

Table C-7. Permanent Deformation and Resilient Modulus Test Sequence for Type 3 Material.

Sequence	Confining Pressure		Contact Stress		Cyclic Stress		Maximum Stress		Nrep.
	KPa	psi	KPa	psi	KPa	psi	KPa	psi	
Preconditioning	27.6	4.0	5.5	0.8	6.9	1.0	12.4	1.8	100
Permanent Deformation	27.6	4.0	5.5	0.8	48..3	7.0	53.8	7.8	10000
1	55.2	8.0	11.0	1.6	27.6	4.0	38.6	5.6	100
2	41.4	6.0	8.3	1.2	27.6	4.0	35.9	5.2	100
3	27.6	4.0	5.5	0.8	27.6	4.0	33.1	4.8	100
4	13.8	2.0	2.8	0.4	27.6	4.0	30.4	4.4	100
5	55.2	8.0	11.0	1.6	48.3	7.0	59.3	8.6	100
6	41.4	6.0	8.3	1.2	48.3	7.0	56.6	8.2	100
7	27.6	4.0	5.5	0.8	48.3	7.0	53.8	7.8	100
8	13.8	2.0	2.8	0.4	48.3	7.0	51.1	7.4	100
9	55.2	8.0	11.0	1.6	69.0	10.0	80.0	11.6	100
10	41.4	6.0	8.3	1.2	69.0	10.0	77.3	11.2	100
11	27.6	4.0	5.5	0.8	69.0	10.0	74.5	10.8	100
12	13.8	2.0	2.8	0.4	69.0	10.0	71.8	10.4	100
13	55.2	8.0	11.0	1.6	96.0	14.0	107.6	15.6	100
14	41.4	6.0	8.3	1.2	96.0	14.0	104.9	15.2	100
15	27.6	4.0	5.5	0.8	96.0	14.0	102.1	14.8	100
16	13.8	2.0	2.8	0.4	96.0	14.0	99.4	14.4	100

9. CALCULATIONS

Calculation of Permanent Strain

9.1 Calculate the average axial deformation for each specimen by averaging the readings from the two displacement transducers. Convert the average deformation values to total axial strain by dividing by the gauge length, L. Figure C-3 shows the typical total axial strain versus time.

9.2 Compute the cumulative axial permanent strain (ε_p) and resilient strain (ε_r) at 200th load repetition.

9.3 Plot the cumulative axial permanent strain versus the number of loading cycles in a log space (shown in Figure C-4). Determine the permanent deformation parameters, intercept (a) and slope (b), from the linear portion of the permanent strain curve (log-log scale), which is also demonstrated in Figure C-4.

9.4 Compute the rutting parameters α, μ from:

$$\mu = \frac{ab}{\varepsilon_r}$$

$$\alpha = 1 - b$$

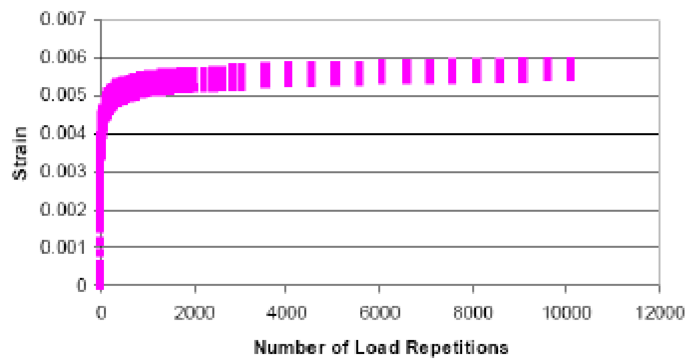


Figure C-3. Triaxial Repeated Load Test Results: Strain vs. Number of Load Repetitions.

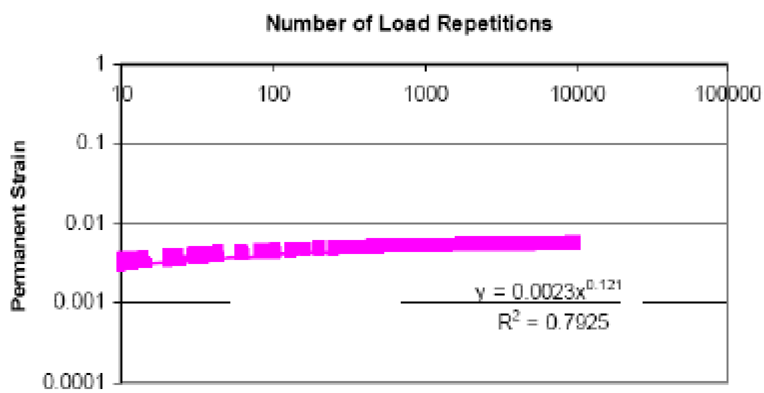


Figure C-4. Permanent Strain vs. Number of Load Repetitions.

Calculation of Resilient Modulus

9.5 The resilient modulus is calculated from each of the last five cycles of each load sequence and then averaged. The data reduction processes preferred to be fully automated to minimize the chance for human error.

9.6 Using nonlinear regression techniques fit the following resilient modulus model to the data obtained from the applied procedure. The equation for the nonlinear models is:

$$M_R = k_1 p_a \left(\frac{\theta}{p_a}\right)^{k_2} \left(\frac{\tau_{oct}}{p_a} + 1\right)^{k_3} \quad (k1, k2 \geq 0, k3 \leq 0)$$

Where:

MR = resilient modulus.

Θ = bulk stress, $\theta = \sigma 1 + \sigma 2 + \sigma 3$.

τ_{oct} = octahedral shear stress.

$$\tau_{oct} = \frac{1}{3}\sqrt{(\sigma_1 - \sigma_2)^2 + (\sigma_1 - \sigma_3)^2 + (\sigma_2 - \sigma_3)^2}.$$

σ_1 = major principal stress $= \sigma_{max} + \sigma_c$.

$\sigma_2 = \sigma_3$ = minor principal stresses $= \sigma_c$.

k_1, k_2, k_3 = regression constants.

p_a = atmospheric pressure (14.7 psi).

To facilitate the analysis, an Excel© Macro has been developed to directly read the output file from the resilient modulus test and automatically determine parameters k_1, k_2, and k_3.

10. REPORT

10.1 Permanent Deformation Test:

10.1.1 Report all specimen basic information including specimen identification, dates of manufacturing and testing, specimen diameter and length, confining pressure, stress levels used, and axial permanent deformation parameters: α, μ (or ε_r, a, and b).

10.2 Resilient Modulus Test

10.2.1 Report all specimen basic information including specimen identification, dates of manufacturing and testing, specimen diameter, and length.

10.2.2 Report the average peak stress (σ_o) and strain (ε_o) for each confining pressure–cyclic stress combination tested.

10.2.3 For each confining pressure–cyclic stress combination tested, report the resilient modulus for each replicate test specimen.

10.2.4 Report nonlinear resilient modulus model and the model parameters: k_1, k_2, and k_3.

Table C-8. Test Plans for the Base Materials (Flex).

#	Test	Spec	Test Parameters	Output Data	Sample Replicates			Time (hrs)		Material Requirement
					TTI	UTEP	***TxDOT Recom.***	Sample Prep	Testing	
1	Sieve analysis [a,b]	Tex-110-E		Gradation	3	Stock	***Stock (Tex-110-E for +#40 & Tex-111-E for -#40)***	1 hrs (24 hrs)	8 hrs	700 lbs [c]
2	Atterberg limits [a]	Tex-104-E, 105-E, 106-E		PI, LL, & PL	3	2 [d]	***1+***	1 hrs (12 hrs)	2 hrs	3 lbs
3	Specific gravity	ASTM C-127, 128		SG value	3	2 [d]	***2 [d]***	1 hrs (19 hrs)	1 hrs (12 hrs)	12 lbs
4	Wet Ball Mill [a,e]	Tex-116-E		Wet Ball Mill value	3	2 [d]	***0***	1 hrs (2hrs)	3hrs (24 hrs)	22 lbs
5	MD Curve [a]	Tex-113-E	6″ x 8″	MDD, OMC	3	2 [d]	***1+***	1 hrs (4-12hrs)	2 hrs	160 lbs
6	Texas Triaxial	Tex-117-E	6″ x 8″	Classification, C, & ϕ	3 (@ each pressure)	2 [d] (@ each pressure)	***1 [f]***	5 hrs (10 days)	4 hrs	240 lbs
7	Resilient modulus	Tech Memo (1-28A)	6″ x 12″ OMC	k- parameters	3	2 [d]	***2 [d]***	1 hrs (24 hrs)	10 hrs	70 lbs
8	Permanent deformation	Tech Memo (1-28A)	6″ x 18″ OMC	α & μ	3	2 [d]	***2 [d]***	1 hrs (24 hrs)	10 hrs	70 lbs
9	Shear strength	Tex-143	6″ x 8″	C and ϕ	3	2 [d]	***2 [d]***	1 hrs (24 hrs)	4 hrs	120 lbs
10	Soil suction	Filter paper		Suction coefficient	3					
Total material to sample from the field										**≥ 700 lbs**

Note: * - Time in parenthesis refers to wait (cure) time, a - Perform sieve analysis and compare gradation to TXDOT. If gradation matches then use TXDOT QC data, otherwise run test, b - Include sieves #100 and #200, which will be washed, c - This represents the minimum total amount of material sampled from the field and used in Steps 2-9, d - A third test is performed if the duplicate results vary with a wide margin, e - If available use from TXDOT QC 1+ - Researchers to run one test, if the results match the districts they can use district results, if not the researchers will run two samples; *f* – 1 sample at each confining pressure.

Table C-9. Test Plans for the Base Materials (Treated – CTB).

#	Test	Spec	Test Parameters	Output Data	Sample Replicates			Time (hrs)		Material Requirement
					TTI	UTEP	*TxDOT Recom.*	Sample Prep	Testing	
1	Sieve analysis[a,b]	Tex-110-E		Gradation	3	Stock	***Stock***	1 hr (24hrs)	8 hrs	550 lbs[c]
2	Atterberg Limit[d, e]	Tex-104-E, 105-E,106-E		PI, LL, & PL	3	2[f]	***1+***	1 hrs (12 hrs)	2 hrs	6 lbs
3	Sulfate content[d]	Tex-145-E		Sulfate content	3	2[f]	***0***	1 hrs (12 hrs)	2 hrs	1 lbs
4	Wet Ball Mill[d]	Tex-116-E		Wet Ball Mill value	3	2[f]	***0***	1 hrs (2hrs)	3hrs (24 hrs)	22 lbs
5	MD Curve[e]	Tex-113-E		MDD & OMC	3	2[f]	***1+***	1 hrs (4-12hrs)	2 hrs	160 lbs
6	Unconfined compressive strength[e]	Tex-120-E etc		UCS	3	2[f]	***1***[i]	1 hrs (7 days)	1 hrs	40 lbs
7	Resilient modulus[e, i]	Zero confinement		k- parameters	3	2[f]	***2***[f]	1 hrs (7 days)	2 hrs	70 lbs
8	Modulus of rupture[e,h]	Tex-448-A		Modulus of Rupture	3	2[f]	***2***[f]	6 hrs (7 days)	1 hrs	140 lbs
Total material to sample from the field										**≥ 550 lbs**

Note: * - Time in parenthesis refers to wait (cure) time, a - Perform sieve analysis and compare gradation to TXDOT. If gradation matches then use TXDOT QC data, otherwise run test, b - Include sieves #100 and #200, c - This represents the minimum total amount of material sampled from the field and used in Tests 2-9, d - Test is performed before treatment , e - Test is performed after treatment, f - A third test is performed if the duplicate results vary with a wide margin, g - Test only for asphalt treated & low stabilizer content (<2%), h - Test only for cement treated (>4%), i -Run FFRC instead of RM at zero confinement, i – includes running 3 samples at the cement content.

Table C-10. Test Plans for the Base Materials (Treated – Asphalt/Low Stabilizers).

#	Test	Spec	Test Parameters	Output Data	Sample Replicates			Time (hrs)		Material Requirement
					TTI	UTEP	*TxDOT Recom.*	Sample Prep	Testing	
1	Sieve analysis[a,b]	Tex-110-E		Gradation	3	Stock	***Stock***	1 hr (24hrs)	8 hrs	550 lbs[c]
2	Atterberg Limit[d, e]	Tex-104-E, 105-E,106-E		PI, LL, & PL	3	2[f]	***1***+	1 hrs (12 hrs)	2 hrs	6 lbs
3	Sulfate content[d]	Tex-145-E		Sulfate content	3	2[f]	***0***	1 hrs (12 hrs)	2 hrs	1 lbs
4	Wet Ball Mill[d]	Tex-116-E		Wet Ball Mill value	3	2[f]	***0***	1 hrs (2hrs)	3hrs (24 hrs)	22 lbs
5	MD Curve[e]	Tex-113-E		MDD & OMC	3	2[f]	***1***+	1 hrs (4-12hrs)	2 hrs	160 lbs
6	Unconfined compressive strength[e]	Tex-120-E etc		UCS	3	2[f]	***i***[g]	1 hrs (7 days)	1 hrs	40 lbs
7	Resilient modulus[e, i]	Zero confinement		k- parameters	3	2[f]	***2***[f]	1 hrs (7 days)	2 hrs	70 lbs
8	Permanent deformation[e,g]	Zero confinement		α & μ	3	2[f]	***2***[f]	1 hrs (7 days)	10 hrs	70 lbs
Total material to sample from the field										**≥ 550 lbs**

Note: * - Time in parenthesis refers to wait (cure) time, a - Perform sieve analysis and compare gradation to TXDOT. If gradation matches then use TXDOT QC data, otherwise run test, b - Include sieves #100 and #200, c - This represents the minimum total amount of material sampled from the field and used in Tests 2-9, d - Test is performed before treatment , e - Test is performed after treatment, f - A third test is performed if the duplicate results vary with a wide margin, g - Test only for asphalt treated & low stabilizer content (< 2%), h - Test only for cement treated (>4%), i -Run FFRC instead of RM at zero confinement, i – includes running 3 samples at the cement content.

Table C-11. Test Plans for the Subgrade Soil Materials (Raw).

#	Test	Spec	Test Parameters	Output Data	Sample Replicates			Time (hrs)		Material Requirement
					TTI	UTEP	*TxDOT Recom.*	Sample Prep	Testing	
1	Sieve Analysis[a,b]			Gradation	3	Stock	***Stock (Tex-110-E, Part I for +#40 and Part II for -#40 [hydrometer])***	1 hr (24 hrs)	8 hrs	310 lbs[c]
2	Atterberg limits	Tex-104-E,105-E,106-E		PI, LL, & PL	3	2[d]	***1+***[e]	1 hrs (12 hrs)	2 hrs	3 lbs
3	Specific gravity	Tex-108-E		SG value	3	2[d]	***2***[d]	1 hrs (19 hrs)	1 hrs (12 hrs)	1 lbs
4	Sulfate content	Tex-145-E		Sulfate content	3	2[d]	***0***	1 hrs (12 hrs)	2 hrs	1 lbs
5	Organic content	Tex-408-A		Organic content	3	2[d]	***0***	1 hrs (24 hrs)	2 hrs	1 lbs
6	MD curve	Tex-114-E		MDD & OMC	3	2[d]	***1+***[e]	1 hrs (4-12hrs)	2 hrs	80 lbs
7	Texas Triaxial	Tex-117-E		Classification, C, & ϕ	3 (@ each stress level)	2[d] (@ each stress level)	***1***[f](@ each stress level)	1 hrs (10 days)	6 hrs	120 lbs
8	Resilient modulus	Tech Memo (1-28A)	4″ x 8″	k- parameters	3	2[d]	***2***[d]	1 hrs (24 hrs)	10 hrs	20 lbs
9	Permanent deformation	Tech Memo (1-28A)	4″ x 8″	α & μ	3	2[d]	***2***[d]	1 hrs (24 hrs)	10 hrs	20 lbs
10	Shear strength	Tex-143		C & ϕ	3	2[d]	***2***[d]	1 hrs (24 hrs)	8 hrs	60 lbs
11	Soil suction	Filter paper or pressure plate		Suction coefficient	3					
Total material to sample from the field										**≥ 310 lbs**

Note: * - Time in parenthesis refers to wait(cure) time, a - Perform sieve analysis and compare gradation to TXDOT. If gradation matches then use TXDOT QC data, otherwise run test, *b* - Include sieves #100 and #200, c - This represents the minimum total amount of material sampled from the field and used in Tests 2-10, *d* - A third test is performed if the duplicate results vary with a wide margin, e – plus 1 sample for every change in material, *f* – 1 sample at each confining pressure.

Table C-12. Test Plans for the Subgrade Soil Materials (Treated).

#	Test	Spec	Test Parameters	Output Data	Sample Replicates			Time (hrs)		Material Requirement
					TTI	UTEP	*TxDOT Recom.*	Sample Prep	Testing	
1	Gradation[a,b]	Tex-110-E		Gradation	3	Stock	***Stock (Tex-110-E, Part I for +#40 and Part II for -#40 [hydrometer])***	1 hr (24 hrs)	8 hrs	150 lbs[c]
2	Atterberg limits[d,e]	Tex-104-E, 105-E,106-E		PI, LL, & PL	3	2[f]	***1+***[e]	1 hrs (12 hrs)	2 hrs	6 lbs
3	Sulfate content[e]	Tex-145-E		Sulfate content	3	2[f]	***2***[d]	1 hrs (12 hrs)	2 hrs	1 lbs
4	Organic content[e]	Tex-408-A		Organic content	3	2[f]	***0***	1 hrs (24 hrs)	2 hrs	1 lbs
5	MD Curve[e]	Tex-114-E		MDD & OMC	3	2[f]	***0***	1 hrs (4-12hrs)	2 hrs	80 lbs
6	Unconfined compressive strength[e]	Tex-121-E etc		UCS	3	2[f]	***1+***[e]	1 hrs (7 days)	1 hrs	20 lbs
7	Resilient modulus[e,g]	Zero confinement		k- parameters	3	2[f]	***2***[d]	1 hrs (7 days)	2 hrs	20 lbs
8	Permanent deformation[e]	Zero confinement		α & μ	3	2[f]	***2***[d]	1 hrs (7 days)	10 hrs	20 lbs
Total material to sample from the field										**≥ 150 lbs**

Note: * - Time in parenthesis refers to wait(cure) time, a - Perform sieve analysis and compare gradation to TXDOT. If gradation matches then use TXDOT QC data, otherwise run test, b - Include sieves #100 and #200, c - This represents the minimum total amount of material sampled from the field and used in Tests 2-8, d - Test is performed before treatment , e - Test is performed after treatment, f - A third test is performed if the duplicate results vary with a wide margin, g - Run FFRC instead of RM at zero confinement, e – plus 1 sample for every change in material.

APPENDIX D: FIELD TEST DATA ANALYSIS

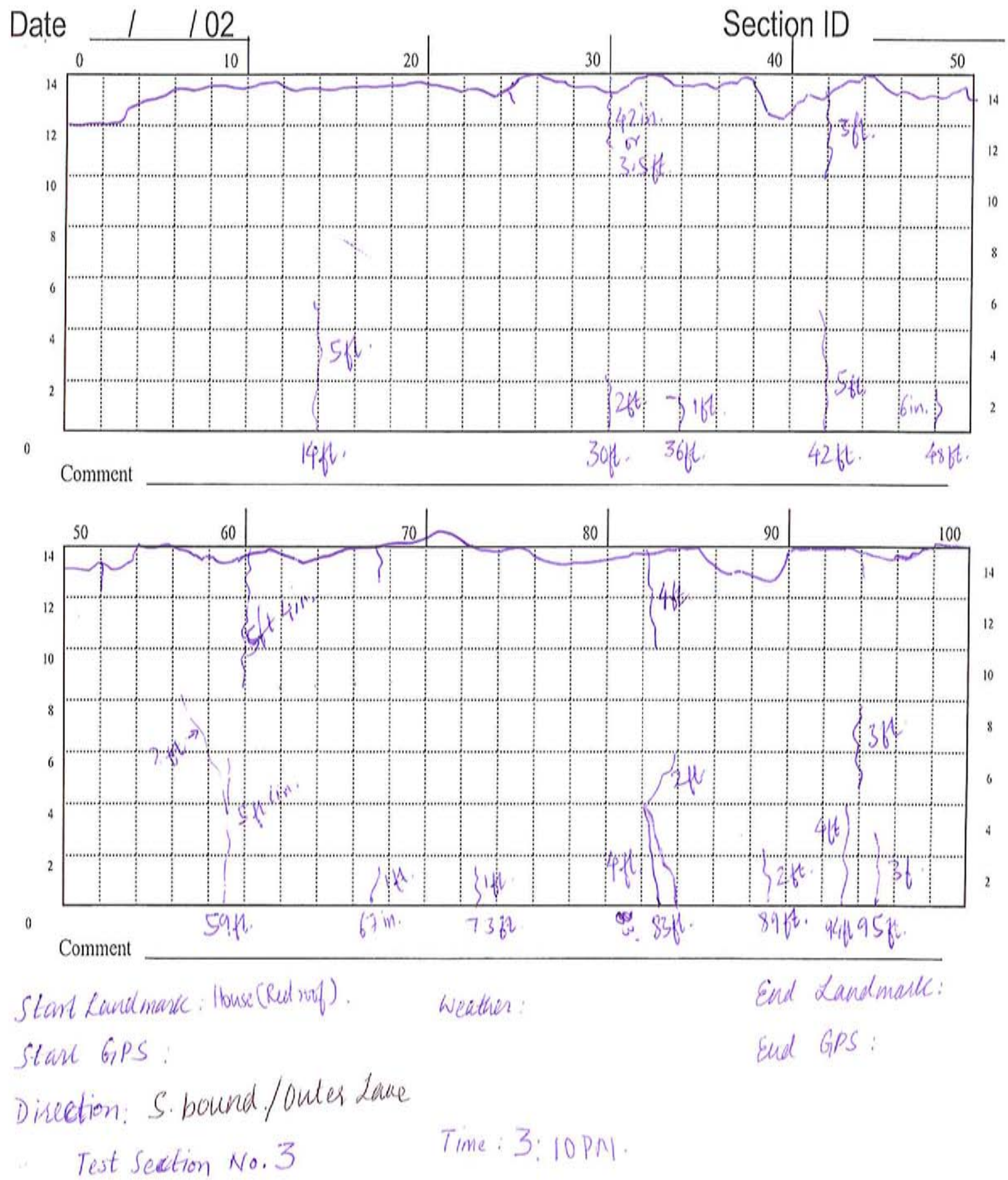


Figure D-1. Crack Survey Map for US 59 (Atlanta, TX) (Page 1).

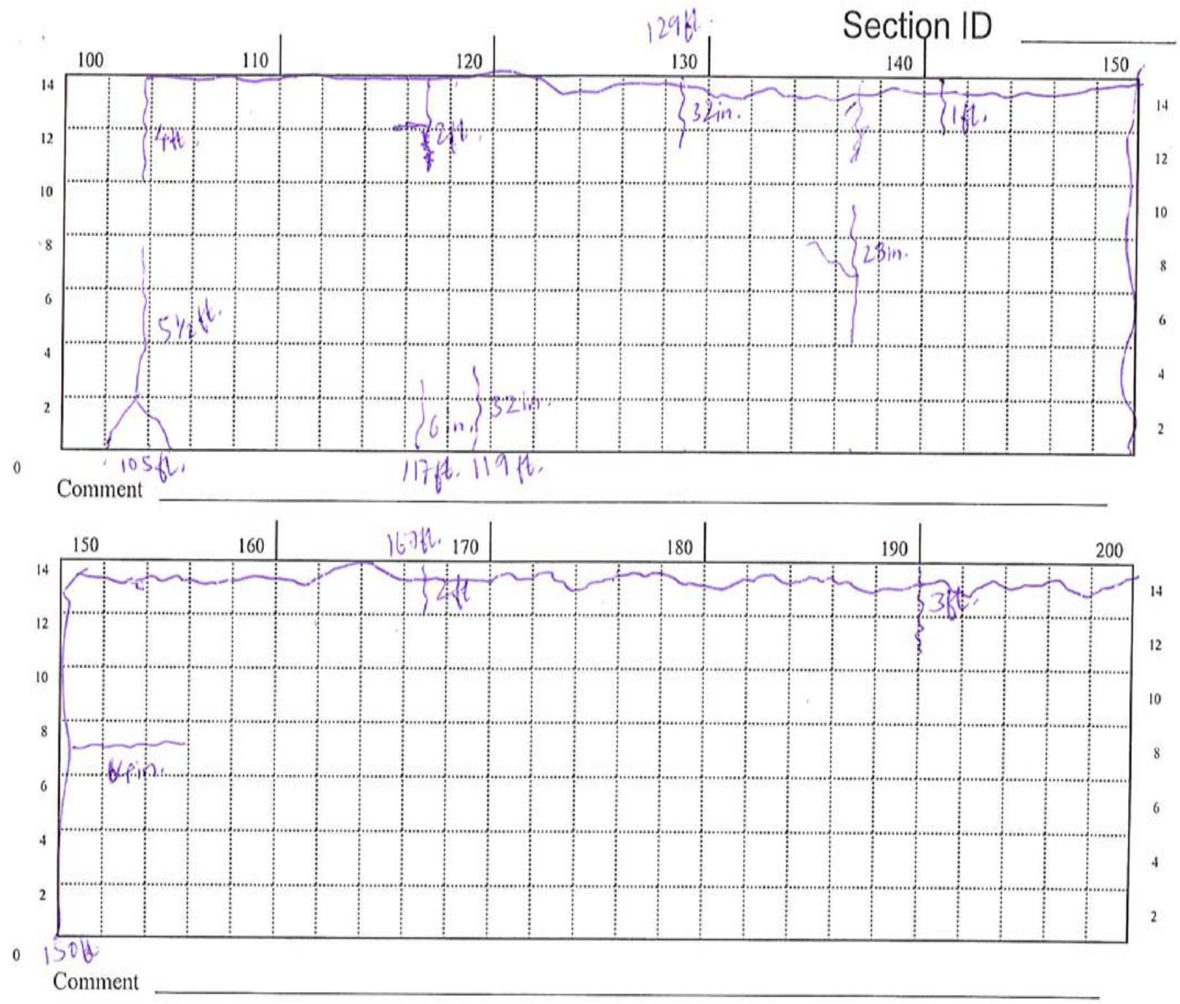


Figure D-2. Crack Survey Map for US 59 (Atlanta, TX) (Page 2).

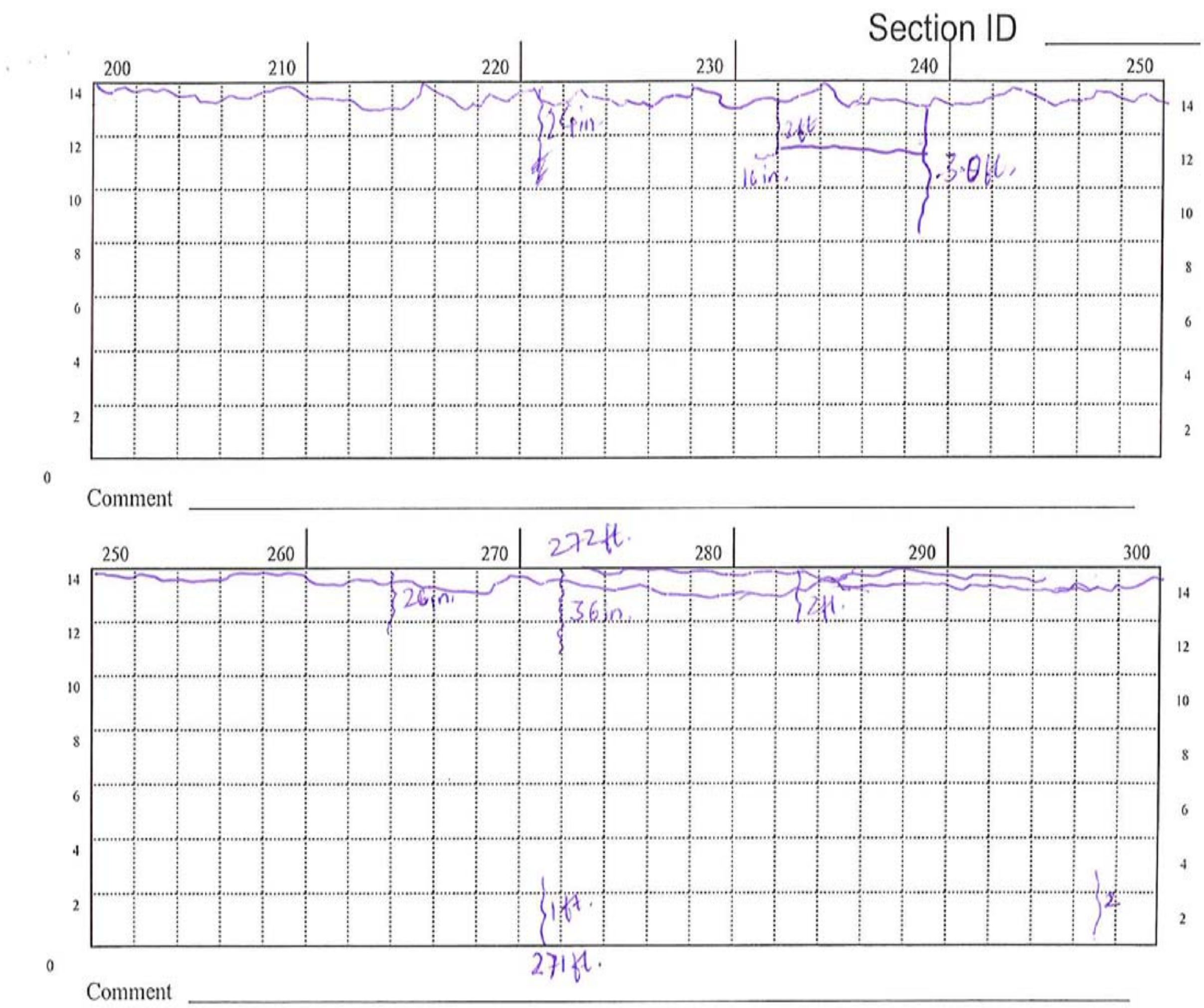


Figure D-3. Crack Survey Map for US 59 (Atlanta, TX) (Page 3).

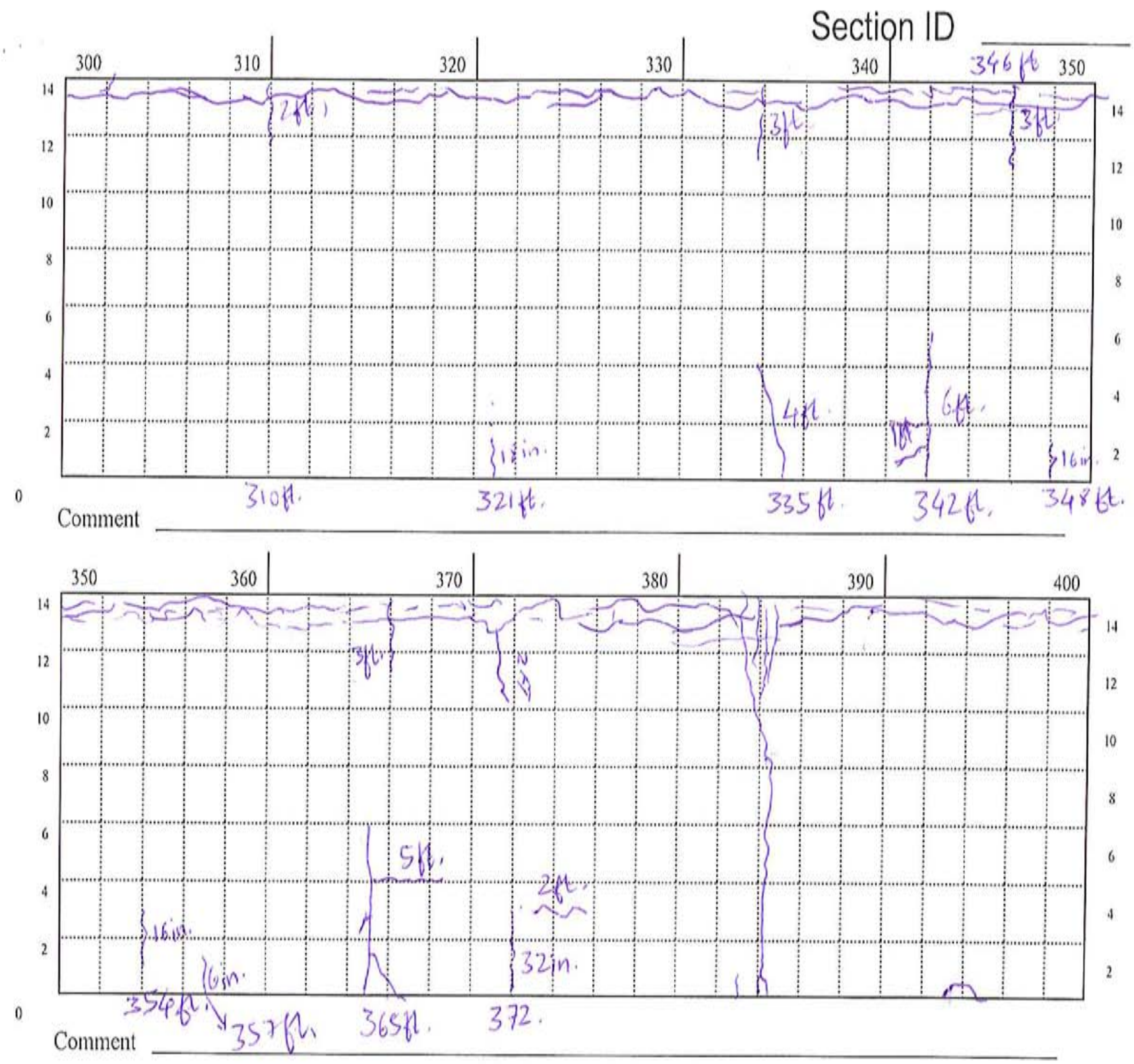


Figure D-4. Crack Survey Map for US 59 (Atlanta, TX) (Page 4).

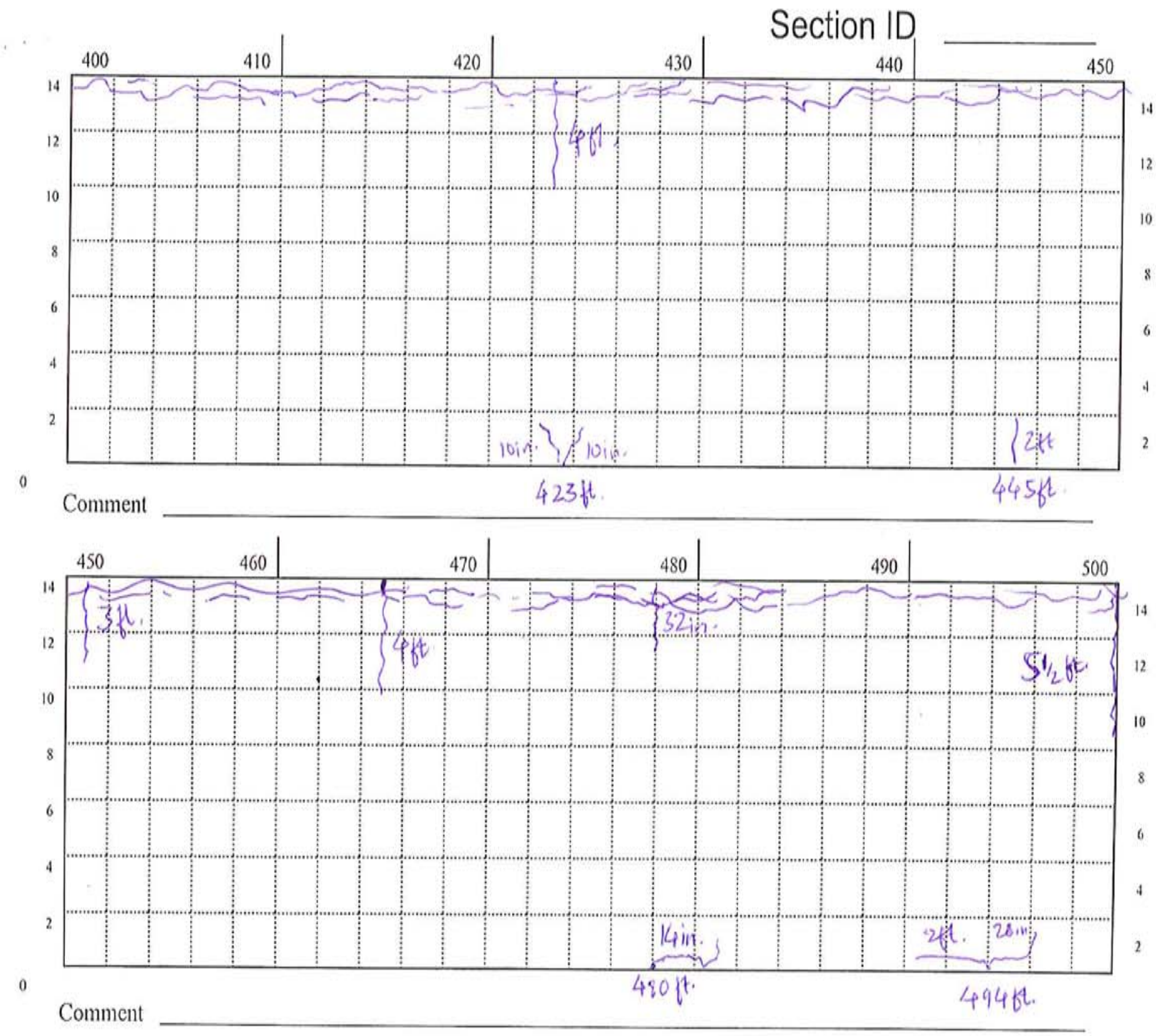


Figure D-5. Crack Survey Map for US 59 (Atlanta, TX) (Page 5).