ABSTRACT

Title of Thesis: CHARACTERIZATION OF UNBOUND PAVEMENT MATERIALS FOR MECHANISTIC-EMPIRICAL PERFORMANCE PREDICTION

Gervas Wambura, Master of Science, 2003

Thesis Directed by: Professor Charles W. Schwartz
Department of Civil Engineering

Unbound materials provide a significant portion of the structural capacity of layered flexible pavement systems. Recent advances in mechanistic-empirical modeling for pavements make it now possible to predict pavement performance in terms of fundamental engineering properties such as the resilient modulus and permanent deformation characteristics. The resilient modulus and permanent deformation characteristics of four coarse-grained unbound base materials and four fine-grained natural subgrade materials are evaluated via laboratory testing in this study. Specific details of the testing protocols including differences between large vs. small specimen response, sample conditioning effects, and the influence of stress level are investigated. The material property data measured in this study provide a valuable contribution to the small but growing database of typical

values as required in the forthcoming new national pavement design guide (2002 Design Guide, 2003).

CHARACTERIZATION OF UNBOUND PAVEMENT MATERIALS FOR MECHANISTIC-EMPIRICAL PERFORMANCE PREDICTION

by

Gervas Wambura

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Advisory Committee:

Professor Charles W. Schwartz, Chair
Professor Ali Haghani
Professor Dimitrios G. Goulias

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CHAPTER 1 INTRODUCTION

1.1 Background

Unbound materials provide a significant portion of the structural capacity of layered flexible pavement systems, and they have a major impact on the performance of the pavement over its design life. The stiffness (or lack thereof) of the unbound base, subbase, and subgrade layers will have a direct influence on the stresses and strains in the asphalt concrete surface layer, which in turn directly affects the permanent deformations (rutting) and fatigue cracking in the surface layer. Plastic deformations within the unbound layers themselves will also contribute to the rutting at the surface.

Recent advances in mechanistic-empirical modeling for pavements make it now possible to predict pavement performance in terms of fundamental engineering properties of the layer materials. The mechanistic-empirical modeling approach couples laboratory characterization of material properties and the theories of mechanics with empirical observations of distresses in field pavement sections. For unbound materials, the engineering properties of primary interest are the stiffness as quantified by the resilient modulus and the permanent deformation characteristics as measured in repeated load tests. In this thesis, the resilient modulus and permanent deformation characteristics of four coarse-grained unbound base materials and four fine-grained natural subgrade materials are evaluated via laboratory testing. Emphasis is on characterizing these materials in a manner consistent with the procedures required in the forthcoming new national pavement design guide ‘2002 DESIGN GUIDE (2003)’.

This study is part of a larger investigation into the behavior of unbound (base and subgrade) materials in geosynthetic-reinforced flexible pavements being performed under the overall direction of Montana State University with support from the U.S. Federal Highway Administration. The main objectives of the overall investigation are:

(1) To investigate and establish the benefits associated with the use of geosynthetics for base layer reinforcement in flexible pavements.

(2) To compare and evaluate results from this study with numerical models and design models from previous investigations of large-scale reinforced pavement test sections sponsored by the Montana Department of Transportation (MDT) under Perkins (1999, 2001a).

(3) To develop design procedures for geosynthetic reinforced flexible pavements that are consistent with the pavement design methods currently being developed under National Cooperative Highway Research Program (NCHRP) Project 1-37A for the 2002 Pavement Design Guide ‘2002 DESIGN GUIDE (2003)’.

The specific objective of the University of Maryland portion of this study was the determination of the resilient modulus and permanent deformation material response parameters consistent with the models being developed in the 2002 PDG. The University of Maryland tests conformed to those specified in the 2002 PDG for determining the material parameters required in the nonlinear elastic pavement response model and the permanent deformation (rutting) distress model.

All tests at the University of Maryland were performed on conventional 102mm or 152mm diameter triaxial laboratory specimens. The resilient modulus testing followed the recommendations given in the NCHRP 1-28A “harmonized” protocol (Andrei, 1999; Witczak, 2003), while the repeated load triaxial testing followed the protocols developed by Yau (1999).

Only unreinforced material conditions were evaluated in the University of Maryland laboratory tests. Reinforced material conditions were evaluated in a companion study performed at the Norwegian Foundation for Industrial and Technical Research (SINTEF) using a special large-scale triaxial apparatus capable of testing cylindrical specimens up to 300 mm diameter and 600 mm tall. SINTEF also performed some large unreinforced specimen tests for comparison with the small specimen results measured at the University of Maryland.

The specimen preparation and testing costs for the large geometry tests at SINTEF were too high to permit resilient modulus and repeated load permanent deformation testing on separate specimens. Consequently, each of the large specimen tests conducted in Norway consisted of a resilient modulus test followed by a repeated load permanent deformation test on the same specimen. This was a major deviation from the Andrei and Yau test protocols adopted in the 2002 PDG but was necessary as a matter of practicality. In order to confirm the consistency of the results between the Norwegian and Maryland testing programs, the Maryland testing program also included a limited number of unreinforced small specimen tests in which the full resilient modulus loading sequence was followed by the repeated load permanent deformation test on the same specimen.

1.2 Objective

The objectives of the University of Maryland portion of this study are as follows:

(1) Determine laboratory resilient modulus and permanent deformation characteristics for base and subgrade soils previously studied in large-scale laboratory and field pavement experiments.

(2) Determine for these materials the specific material properties required by the 2002 PDG for performance prediction using the 2002 PDG models.

(3) Evaluate some specific details of testing protocols:

- Large vs. small specimen response.
- Stress/test sequence (e.g., resilient modulus and permanent deformation testing on the same test specimen).
- Effect of stress level on permanent deformation behavior.

The data from this study provide valuable contributions to the small but growing database of typical material properties for use in the mechanistic-empirical design procedures in the 2002 Pavement Design Guide.

CHAPTER 2 TEST PROCEDURE

2.1 Study materials

Materials for testing were supplied from previous and ongoing investigations of large-scale laboratory and field test sections of reinforced flexible pavements. A total of 4 aggregate base materials and 4 subgrade materials were investigated. Aggregate base materials received from these supporting projects were designated GTX aggregate, CRREL aggregate, MSU-1 aggregate, and MSU-2 aggregate. Subgrade materials were designated CS subgrade, SSS subgrade, CRREL subgrade, and GTX subgrade. The CS subgrade and CRREL subgrade materials were received as Shelby tubes; all other materials were received in bulk form. Table 1 summarizes the materials investigated in this study.

Table 1. Study Materials

Experiment	Experiment Type	Designation		Reference
		Base	Subgrade	
MDT	Large Scale Laboratory Test	MSU-1	CS	Perkins (1999)
MDT	Large Scale Laboratory Test	MSU-1	SSS	Perkins (1999)
MSU	Large Scale Laboratory Test	MSU-2	CS	Perkins (2001a)
MSU	Large Scale Laboratory Test	MSU-1	CS	Perkins (2001a)
MSU	Large Scale Laboratory Test	GTX	GTX	Perkins (2001a)
CRREL	Field Section	CRREL	CRREL	Perkins (2001a)

Routine soil tests had been performed previously at Montana State University, the U.S. Army Cold Regions Research & Engineering Laboratory (CRREL), and Geotechnical Express (GTX) in Atlanta Georgia as part of the large-scale test section studies. These routine tests provided soil classification, grain size distribution, and compaction property information.

2.1.1 Soil Classification

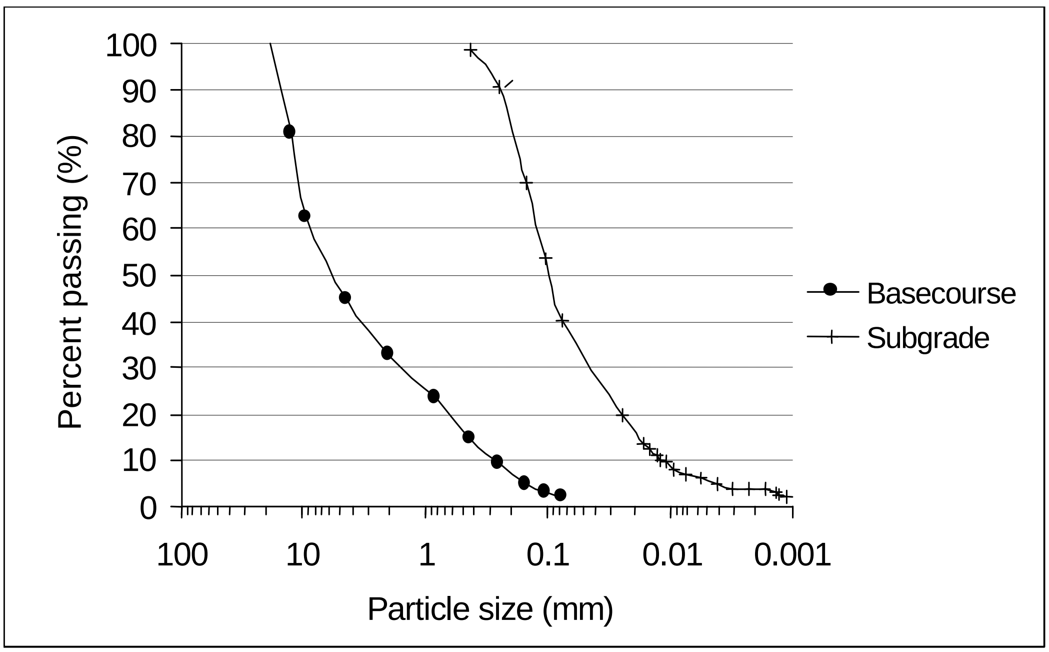
The AASHTO and Unified Soil Classifications for the four unbound granular materials and four unbound subgrade materials tested in this study are summarized in Table 2.

Table 2. Identification of Study Materials

Soil ID	Soil Description	Soil Classification	
		AASHTO	USC
GTX (Aggregate)	Crushed stone	A-1-a	GW
CRREL (Aggregate)	Gravel and sand	A-1-b	GM
MSU-1 (Aggregate)	Gravel and sand	A-1-b	GM
MSU-2 (Aggregate)	Gravel and sand	A-1-b	GM
CS (Subgrade)	Clay	A-7-6	CL
SSS (Subgrade)	Silty sand	A-4	SM
CRREL (Subgrade)	Clay	A-6	CL
GTX (Subgrade)	Clay	A-6	CL

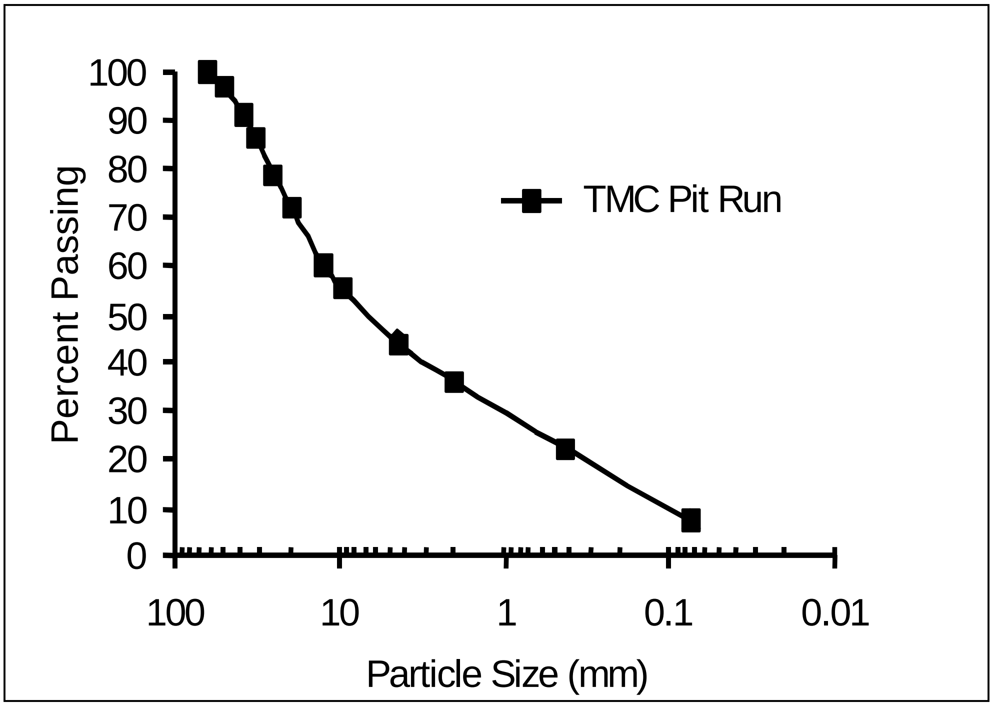
2.1.2 Gradation

Figure 1 shows the measured grain size distribution for the MSU-1 base aggregate and MSU SSS subgrade. Figure 2 shows grain size distribution for the MSU-2 base aggregate; for the MSU CS subgrade, 100% passed the No. 200 sieve. Figure 3 shows grain size distribution for CRREL base aggregate and CRREL subgrade. Figure 4 shows grain size distribution for GTX base aggregate. The GTX subgrade material is the same as the CRREL subgrade.



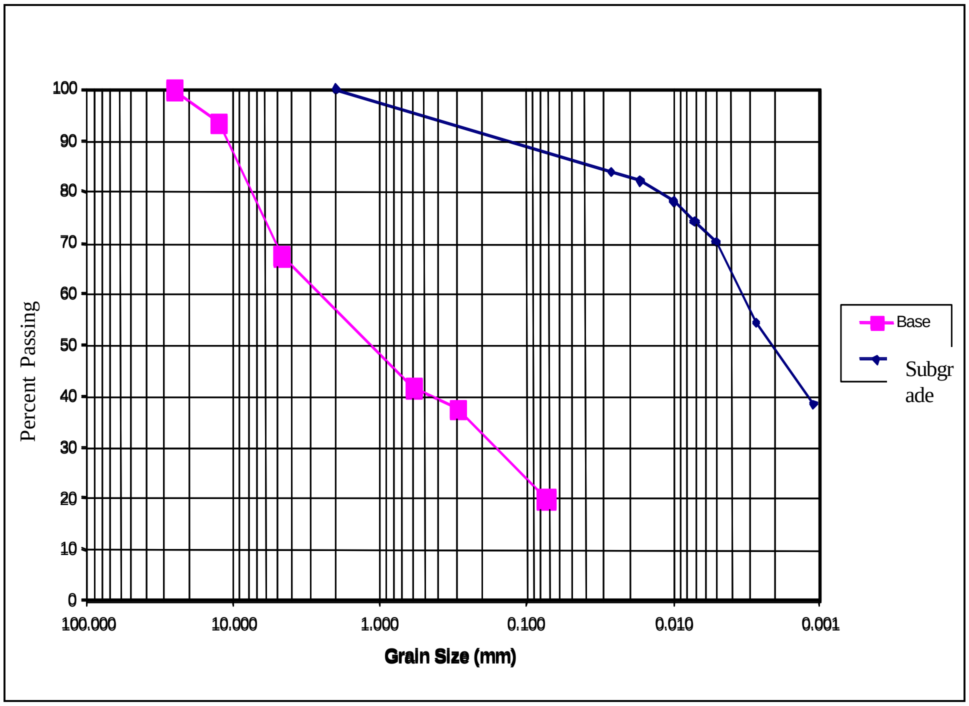
Note: Basecourse = MSU-1 Aggregate, Subgrade = MSU SSS

Figure 1. Grain Size Distribution for MSU-1 Aggregate and MSU SSS Subgrade (Montana State University)



Note: TMC Pit Run = MSU-2 Aggregate

Figure 2. Grain Size Distribution for MSU-2 Aggregate (Montana State University)



Note: Base = CRREL Base Aggregate, Subgrade = CRREL Subgrade

Figure 3. Grain Size Distribution for CRREL Base Aggregate and CRREL Subgrade (Cold Regions Research & Engineering Laboratory)

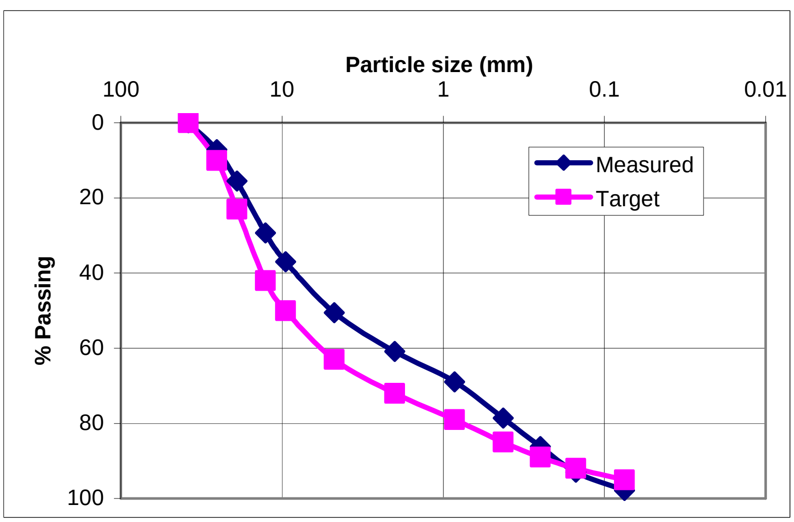


Figure 4. Grain Size Distribution for GTX Aggregate (Geotechnical Express)

2.1.3 Target Moisture Contents and Densities

The modified Proctor moisture–compacted density relationships for the study soils had been determined previously by researchers at Montana State University (MSU), the Cold Regions Research and Engineering Laboratory (CRREL), and Geotechnical Express (GTX) as part of the large-scale laboratory and field studies. These compaction curves were used to determine the target moisture and density values for the large-scale laboratory and field experiments. The same target moisture and density values were used for the small specimen laboratory testing conducted in the present study. Tables 3 and 4 summarize the target moisture contents and equivalent dry densities for each soil as determined from the actual test conditions in the large-scale laboratory and field sections.

Table 3. Target Moisture Contents and Densities for Aggregate Base Materials

Material	Soil Classification	w%	δ_d (kN/m^3)
GTX	Crushed stone	7.5	22.2
CRREL	Gravel and sand	4.1	20.8
MSU-1	Gravel and sand	6.0	20.7
MSU-2	Gravel and sand	6.4	21.0

Table 4. Target Moisture Contents and Densities for Subgrade Material

Material	Soil Classification	w%	δ_d (kN/m^3)
CS	Clay	45.0	11.4
SSS	Silty sand	14.0	14.8
CRREL	Clay	28.5	15.0
GTX	Clay	28.5	15.0

2.2 Test Specimen Preparation

Test specimens for both the resilient modulus and repeated load permanent deformation tests were prepared following the recommendations of the harmonized resilient modulus protocol developed as part of NCHRP Project 1-28A (Andrei, 1999; Witczak, 2003).

Most of the materials tested in this study were received in bulk (loose) form and compacted in the laboratory to the target moisture and density conditions. The CS subgrade and CRREL subgrade materials were received as undisturbed Shelby tubes samples. However, these materials had been cored several years prior to their shipment to the University of Maryland and were no longer in good condition. The CS subgrade samples had variable circumferences due to poor coring and the moisture content was inconsistent due to inadequate packaging and sealing. The CRREL subgrade could not be jacked out of the tubes due to rust development over the years. As a consequence, these materials were scooped from their Shelby tubes and then remolded to the target moisture and density conditions.

2.2.1 Compaction and Molding Procedure

Gradation data for the eight study soils were used to classify the materials as Type 1, 2, 3, or 4 as recommended by the harmonized protocol. Table 5 summarizes the material types according to the harmonized NCHRP 1-28A protocol. Table 6 summarizes the classification of the study materials according to the harmonized protocol. The classification logic is illustrated in the flow chart in Figure 5.

Table 5. "Harmonized " NCHRP 1-28A Materials Types (Andrei, 1999; Witczak, 2003)

Types of Materials	Material Preparation
Material Type 1	Includes all unbound granular base and subbase materials and all untreated subgrade soils with maximum particle sizes greater than 9.5mm (0.375in). All material greater than 25.4 mm (1.0in) shall be scalped off prior to testing.
Material Type 2	Includes all unbound granular base and subbase materials and all untreated subgrade soils which have a maximum particle size less than 9.5mm (0.375in) and which meet the criteria of less than 10% passing the 0.075mm (No. 200) sieve.
Material Type 3	Includes all unbound granular base and subbase materials and all untreated subgrade soils which have a maximum particle size less than 9.5mm (0.375in) and which meet the criteria of more than 10% passing the 0.075mm (N0. 200) sieve.
Material Type 4	Includes thin-walled tube samples of untreated subgrade soils.

Table 6. Classification of Study Soils

Soil	Material Type
Base Materials	
MSU-1	Type 1
MSU-2	Type 1
CRREL	Type 1
GTX	Type 1
Subgrade Materials	
CS	Type 3
SSS	Type 3
CRREL	Type 3
GTX	Type 3

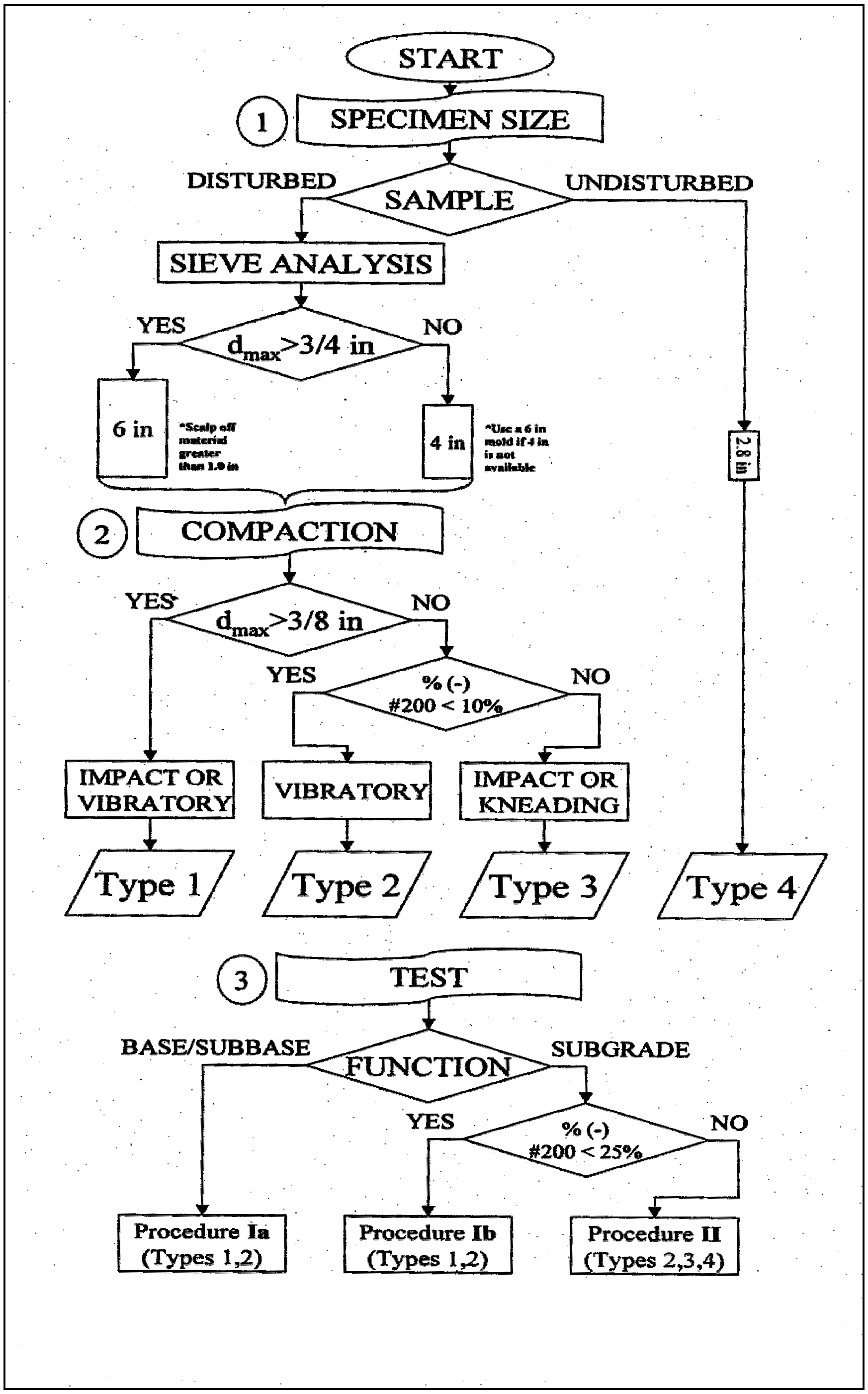


Figure 5. Harmonized Protocol Flowchart (Andrei, 1999; Witczak, 2003)

Test specimen sizes were determined following the procedures in the harmonized protocol. Materials with maximum particle sizes less than 19mm (3/4in) were compacted in a 102mm (4in) diameter mold. Materials with maximum particle sizes greater than 19mm (3/4in) were compacted in a 152mm (6in) diameter mold.

The harmonized protocol suggests scalping off all material greater than 25.4mm (1.0in) prior to compaction. However, this was not done for the GTX and MSU-2 base aggregate materials, the two materials that have aggregate greater than 25.4mm (1.0in), in order to maintain consistency with the large-scale cylinder tests performed in Norway.

All materials were mixed with water to the target moisture content and left overnight in a sealed plastic bag for the moisture content to equilibrate prior to compaction. The impact method of compaction was used to compact materials in layers on top of the lower load platen. The number of layers and the number of blows per layer required to achieve the target dry densities were established using trial-and-error. The target dry densities, moisture contents, and the actual values achieved for each replicate are shown in Tables 7 and 8.

Table 7. Moisture and Density Values for Resilient Modulus Test Specimens.

Soil	Replicate	δ_{dry} Target kN/m^3	δ_{dry} Achieved kN/m^3	w% Target	w% Achieved	Specimen Size (in X in)	Procedure
Base Materials							
MSU-1	1	20.7	20.7	6.0	5.9	4x8	Harmonized Ia
	2	20.7	20.7	6.0	5.6	4x8	Harmonized Ia
MSU-2	1	21.0	20.8	6.4	6.9	6x12	Harmonized Ia
	2	21.0	20.2	6.4	6.4	6x12	Harmonized Ia
CRREL	1	20.8	21.6	4.1	4.0	4x8	Harmonized Ia
	2	20.8	21.8	4.1	4.1	4x8	Harmonized Ia
GTX	1	22.2	22.3	4.2	4.1	6x12	Harmonized Ia
	2	22.2	22.3	4.2	4.0	6x12	Harmonized Ia
	3	22.2	22.3	4.2	4.1	6x12	Harmonized Ia
Subgrade Material							
CS	1	11.4	11.7	45.0	42.0	4x8	Harmonized II
	2	11.4	11.3	45.0	44.3	4x8	Harmonized II
	3	11.4	11.5	45.0	43.0	4x8	Harmonized II
SSS	1	14.8	14.7	14.0	14.4	4x8	Harmonized II
	2	14.8	14.7	14.0	14.5	4x8	Harmonized II
	3	14.8	15.1	14.0	14.1	4x8	Harmonized II
CRREL	1	15.0	15.3	28.5	27.7	4x8	Harmonized II
	2	15.0	15.2	28.5	27.9	4x8	Harmonized II
	3	15.0	15.2	28.5	28.2	4x8	Harmonized II
GTX	1	15.0	15.0	28.5	29.3	4x8	Harmonized II
	2	15.0	15.1	28.5	29.7	4x8	Harmonized II
	3	15.0	15.1	28.5	29.1	4x8	Harmonized II

Table 8. Moisture and Density Values for Repeated Load Test Specimens.

Soil	Replicate	δ_{dry} Target kN/m^3	δ_{dry} Achieved kN/m^3	w% Target	w% Achieved	Specimen Size (in X in)	Procedure
Base Materials							
MSU-1	1	20.7	20.8	6.0	5.6	4x8	Harmonized Ia
	2	20.7	20.6	6.0	6.3	4x8	Harmonized Ia
MSU-2	1	21.0	21.0	6.4	6.5	6x12	Harmonized Ia
	2	21.0	21.0	6.4	6.2	6x12	Harmonized Ia
CRREL	1	20.8	21.3	4.1	4.2	4x8	Harmonized Ia
	2	20.8	21.6	4.1	4.1	4x8	Harmonized Ia
GTX	1	22.2	22.3	4.2	4.1	6x12	Harmonized Ia
(Unconditioned)	2	22.2	24.2	4.2	4.2	6x12	Harmonized Ia
	3	22.2	24.2	4.2	4.2	6x12	Harmonized Ia
GTX	1	22.2	24.2	4.2	4.2	6x12	Harmonized Ia
(Conditioned)	2	22.2	24.2	4.2	4.2	6x12	Harmonized Ia
GTX (Conditioned/ High Stress)	1	22.2	24.2	4.2	4.1	6x12	Harmonized Ia
Subgrade Materials							
CS	1	11.4	11.2	45.0	47.8	4x8	Harmonized II
	2	11.4	11.2	45.0	48.1	4x8	Harmonized II
SSS	1	14.8	15.5	14.0	14.3	4x8	Harmonized II
	2	14.8	15.3	14.0	14.3	4x8	Harmonized II
CRREL	1	15.0	15.0	28.5	28.5	4x8	Harmonized II
	2	15.0	15.1	28.5	27.1	4x8	Harmonized II
GTX	1	15.0	14.8	28.5	30.4	4x8	Harmonized II
	2	15.0	14.9	28.5	29.8	4x8	Harmonized II

2.2.2 Rubber Membrane Placement

Rubber membranes 0.025in thick with internal diameters of 102mm (4in) or 152mm (6in) were used to seal the samples. Before placing the rubber membrane, the top load platen was centered on the specimen and lightly tapped to ensure a good smooth contact. A level was used on the top of the platen to check the alignment. The membranes were then carefully placed around the compacted sample using a membrane stretcher and secured to the top and bottom load platens using O-rings. High vacuum grease was used to prevent leaks at the contact between membrane and platens. The membrane was marked at the upper and lower quarter points where the top and bottom vertical clamps supporting the axial LVDTs were to be attached.

2.2.3 Instrumentation

The assembled test specimen was placed in the raised confining pressure cell of an MTS TestStar triaxial testing machine. The lower LVDT clamps were attached to the specimen at approximately the lower quarter points of the specimen using rubber bands. The lower LVDT clamps were used to hold the LVDT bodies. The upper LVDT clamps were attached in a similar manner, with care taken to align the clamps so that the LVDT cores held by upper clamps matched the LVDT bodies. A small amount of “5-minute” epoxy was placed on top of the four contact points to cement the clamps to the membrane. Figure 6 shows a schematic of the test set-up.

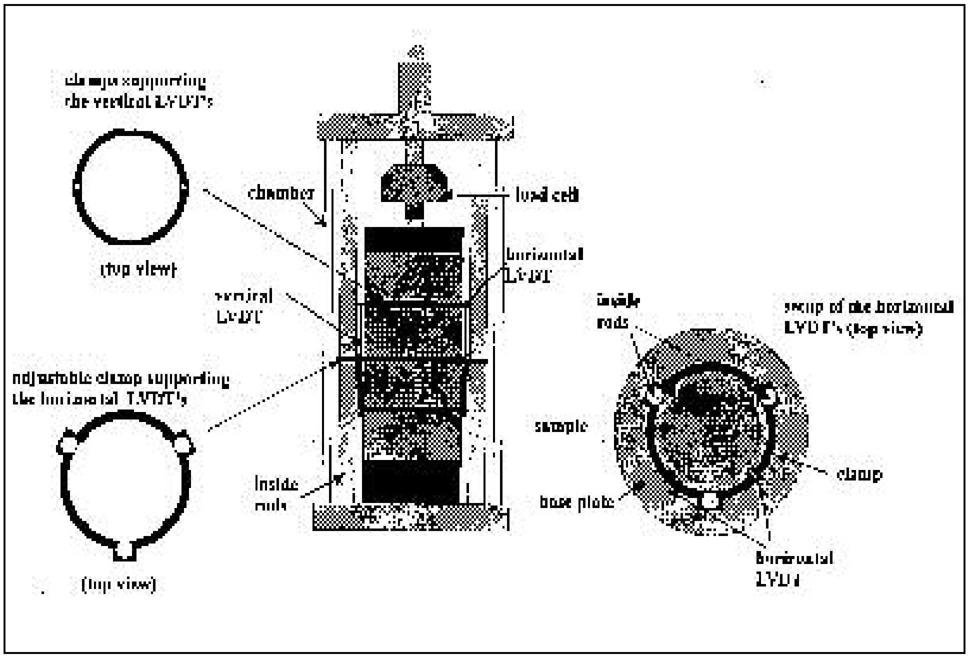


Figure 6. Schematic of Test Set-Up (Andrei, 1999; Witczak, 2003)

A gage length of 102mm (4in) was used for the 102mm (4in) x 201mm (8in) specimens while a gage length of 152mm (6in) was used for the 152mm (6in) x 304mm (12in) specimens. The LVDT range was ± 0.25 inches, and the LVDTs were regularly calibrated. Only two vertical LVDTs were installed at a 180^{o} spacing around the specimen; radial displacements were not measured. After LVDTs were installed, they were connected to the data acquisition and recording unit. The triaxial cell was then lowered and assembled. Figure 7 shows a typical specimen with attached LVDTs in the triaxial testing machine.

Figure 7. Actual Test Set-Up

2.3 Resilient Modulus Tests

Except as noted otherwise, all resilient modulus tests were performed using the harmonized protocols developed in NCHRP Project 1-28A (Andrei, 1999; Witczak, 2003).

2.3.1 Loading

An MTS closed loop, top-loading, electro-hydraulic system was used to perform all tests. Air was used as the confining fluid; the air pressure was maintained constant at the specified cell pressure for each step in the loading sequence. The cyclic loading consisted of repeated cycles of a haversine shaped load-pulse. These load pulses had a 0.1sec load duration and 0.9sec rest period for base/subbase materials and a 0.2sec load duration and 0.8sec rest period for subgrade materials. These loading and the rest times are intended to simulate field loading conditions. Three test sequences are provided in the general harmonized protocol based on the location of the material in the pavement structure (e.g., base layer vs. subgrade) and on the expected response of the material. Only two test sequences were required for the soils tested in this study:

- Granular base/subbase materials (Procedure Ia)
- Fine-grained subgrades (Procedure II)

The complete stress sequences for each of these loading procedures are given in Tables 9 and 10 respectively. These sequences are also indicated graphically in Figures 9 and 10. A key feature of the loading sequences in the harmonized protocols from NCHRP 1-28A is the attempt to keep the stress state away from the failure line for as long as possible during the testing in order to maximize data collection in the event of a premature specimen failure.

The NCHRP 1-28A harmonized protocol for resilient modulus testing also specifies an initial application of 1000 cycles at a confining pressure of 27.6 kPa (4.0psi), contact stress of 5.5 kPa (0.8psi), and deviatoric stress of 48.3 kPa (7.0psi) for conditioning of the subgrade test specimen prior to the main resilient modulus testing. For granular base materials, the protocol specifies an initial application of 1000 cycles at a confining pressure of 103.4 kPa (15.0 psi), contact stress of 20.7 kPa (3.0 psi), and deviatoric stess of 206.9 kPa (30.0 psi) for conditioning of the test specimen. All resilient modulus tests were performed undrained. The reasons for performing undrained tests are as follows:

- There is no significant difference between drained and undrained behavior of coarse materials due to low saturation levels at the target moisture contents.
- For fine-grained materials with high level of saturation, the loading time is too short during the dynamic loading to allow any significant dissipation of excess pore pressure inside the sample.
- The harmonized test protocols developed in NCHRP 1-28A (Andrei, 1999; Witczak, 2003) specify undrained loading.

Table 9. Harmonized Ia – Test Sequence for Base/Subbase Materials

Sequence	Confining Pressure (psi)	Contact Stress (psi)	Cyclic Stress (psi)	Principal Stresses Ratio	σ_1 (psi)	N_{rep}
Conditioning	15.0	3.0	30.0	3.0	48.0	1000
1	3.0	0.6	1.5	1.5	5.1	100
2	6.0	1.2	3.0	1.5	10.2	100
3	10.0	2.0	5.0	1.5	17.0	100
4	15.0	3.0	7.5	1.5	25.5	100
5	20.0	4.0	10.0	1.5	34.0	100
6	3.0	0.6	3.0	2.0	6.6	100
7	6.0	1.2	6.0	2.0	13.2	100
8	10.0	2.0	10.0	2.0	22.0	100
9	15.0	3.0	15.0	2.0	33.0	100
10	20.0	4.0	20.0	2.0	44.0	100
11	3.0	0.6	6.0	3.0	9.6	100
12	6.0	1.2	12.0	3.0	19.2	100
13	10.0	2.0	20.0	3.0	32.0	100
14	15.0	3.0	30.0	3.0	48.0	100
15	20.0	4.0	40.0	3.0	64.0	100
16	3.0	0.6	9.0	4.0	12.6	100
17	6.0	1.2	18.0	4.0	25.2	100
18	10.0	2.0	30.0	4.0	42.0	100
19	15.0	3.0	45.0	4.0	63.0	100
20	20.0	4.0	60.0	4.0	84.0	100
21	3.0	0.6	15.0	6.0	18.6	100
22	6.0	1.2	30.0	6.0	37.2	100
23	10.0	2.0	50.0	6.0	62.0	100
24	15.0	3.0	75.0	6.0	93.0	100
25	20.0	4.0	100.0	6.0	124.0	100
26	3.0	0.6	21.0	8.0	24.6	100
27	6.0	1.2	42.0	8.0	49.2	100
28	10.0	2.0	70.0	8.0	82.0	100
29	15.0	3.0	105.0	8.0	123.0	100
30	20.0	4.0	140.0	8.0	164.0	100

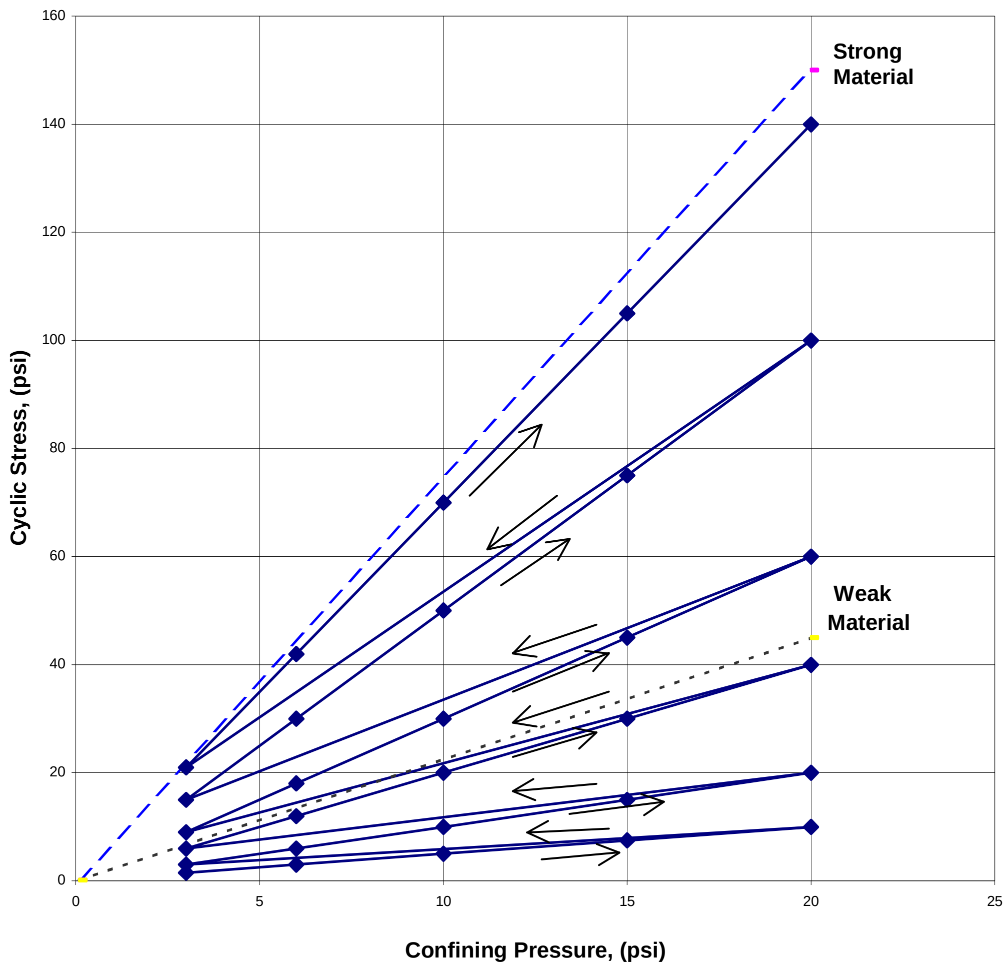


Figure 8. Stress Sequences for Base/Subbase Materials

Table 10. Harmonized II – Test Sequence for Fine – Grained Subgrade Materials

Sequence	Confining Pressure (psi)	Contact Stress (psi)	Cyclic Stress (psi)	Principal Stresses (psi)	σ_1 (psi)	N_{rep}
Conditioning	4.0	0.8	7.0	2.8	11.8	1000
1	8.0	1.6	4.0	1.5	13.6	100
2	6.0	1.2	4.0	1.7	11.2	100
3	4.0	0.8	4.0	2.0	8.8	100
4	2.0	0.4	4.0	3.0	6.4	100
5	8.0	1.6	7.0	1.9	16.6	100
6	6.0	1.2	7.0	2.2	14.2	100
7	4.0	0.8	7.0	2.8	11.8	100
8	2.0	0.4	7.0	4.5	9.4	100
9	8.0	1.6	10.0	2.3	19.6	100
10	6.0	1.2	10.0	2.7	17.2	100
11	4.0	0.8	10.0	3.5	14.8	100
12	2.0	0.4	10.0	6.0	12.4	100
13	8.0	1.6	14.0	2.8	23.6	100
14	6.0	1.2	14.0	3.3	21.2	100
15	4.0	0.8	14.0	4.5	18.8	100
16	2.0	0.4	14.0	8.0	16.4	100

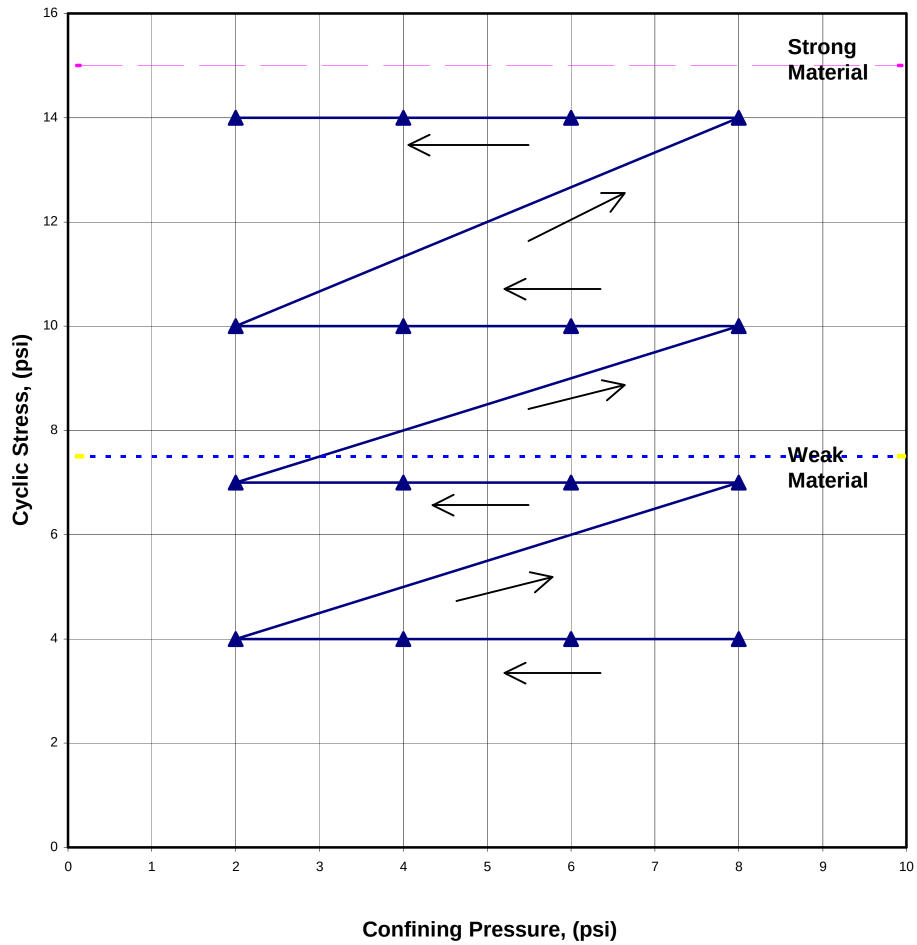


Figure 9. Stress Sequence for Fine-Grained Subgrades

2.3.2 Data Acquisition

MTS TestStar V4.0 was the software used for test control and data acquisition. A complete cycle consists of load, unload, and rest segments. The peak and rest load and displacement measurements were collected over the last five cycles of each stress sequence for analysis. Axial displacements were determined from the average of the two vertical LVDT measurements.

2.4 Repeated Load Permanent Deformation

Unless noted otherwise, all repeated load permanent deformation tests followed the protocols developed by Yau (1999).

2.4.1 Loading

The same MTS triaxial testing machine used for the resilient modulus tests was also used to conduct the repeated load permanent deformation tests. The repeated load permanent deformation tests were performed by applying a large number of loading cycles at a single level of stresses. For granular materials, the repeated loading consisted of a haversine stress pulse of 0.1 second duration followed by a 0.9 second rest period. For subgrade materials, the repeated loading consisted of a haversine stress pulse of 0.45 second duration followed by 1-second rest period. The tests were targeted at 100,000 load repetitions. Some tests were terminated prematurely, however, when the LVDTs reached their range limits. Air was used as the confining fluid, and all tests were performed undrained.

Two different stress states were initially selected to be used for loading specimens. The first consisted of a cyclic stress of 655 kPa (95 psi), a contact stress of 23.8 kPa (3.45 psi), and a confining stress of 103.4 kPa (15 psi). The second stress state consisted of a cyclic stress of 344.8 kPa (50.0 psi), a contact stress of 4.1 kPa (0.6 psi), and a confining stress of 20.7 kPa (3.0 psi). These two stress states were first applied to the base materials. However, the high stiffness due to the relatively high confining pressure in the first stress state often resulted in deflections that were below the LVDT resolution limit. Consequently, only the second stress state was applied to all base material test specimens.

The same two stress states were also applied to the subgrade materials. However, both stress states failed the relatively weak subgrade soils. As a result, the appropriate stress state for each subgrade material was determined using a constant strain rate test. A constant strain rate tests were performed for each subgrade soil at a 20.7 kPa (3.0 psi) confining pressure, and 65% of the stress at failure was selected as the cyclic stress for repeated load permanent deformation testing. The contact stress was set at 10% of the cyclic stress. The repeated load permanent deformation tests at SINTEF were done on the same specimens after completion of the M_R tests.

Table 11. Constant Strain Test Results for Subgrade Materials

Soil ID	Stress (kPa) at Failure	Strain at Failure	65% Stress (kPa)
SSS Subgrade	96.6	0.786	62.8
GTX Subgrade	27.6	0.3252	17.94
CRREL Subgrade	27.6	0.3252	17.94
CS Subgrade	56.6	0.6453	36.79

2.4.2 Data Acquisition

Axial displacement, confining stress, and axial load were recorded every 0.004 seconds using a logarithmic collection interval. Data were collected every cycle for the first 10 cycles, every 10^{th} cycle up to the 100^{th} cycle, every 100^{th} cycle up to the $1{,}000^{th}$ cycle, every $1{,}000^{th}$ cycle up to the $10{,}000^{th}$ cycle, and every $10{,}000^{th}$ cycle up to the $100{,}000^{th}$ cycle.

The recorded test data were used to compute the cyclic stress and strain amplitudes. The axial strains were calculated from the average of the readings from the two axial LVDTs.

CHAPTER 3 RESILIENT MODULUS RESULTS

3.1 Determination of Resilient Modulus

When unbound pavement materials are subjected to repeated loads which are small compared to the strength of the material, the resulting deformation observed for each load repetition is roughly proportional to the load and is nearly completely recoverable. This approximately linearly elastic behavior can be characterized by the unloading or resilient modulus. The resilient modulus is typically used in mechanistic pavement analyses for predicting the stresses and strains within the pavement. As compared to truly linearly elastic materials, the resilient modulus for unbound pavement materials is not a single value but depends on the state of stress. The resilient modulus test is designed to measure the material response under different stress combinations, from which a predictive equation can be calibrated using regression techniques to determine the value of the modulus for any stress state.

The resilient modulus (M_R) for unbound pavement materials is formally defined as the unloading modulus after several hundred cycles of repeated cyclic loading when the cyclic response of the material has stabilized. This is illustrated schematically in Figure 10. The resilient modulus is a secant modulus:

$$M_r = \frac{\sigma_{cyc}}{\varepsilon_r} \tag{1}$$

in which:

σ_{cyc} = peak axial cyclic stress

ε_r = peak axial resilient strain

Figures 11 and 12 show the typical load vs. time and strain vs. time resilient modulus test data for a single cycle of loading for the CS subgrade material. Tabular summaries of the resilient moduli measured at all stress states for each soil are included as Appendix A.

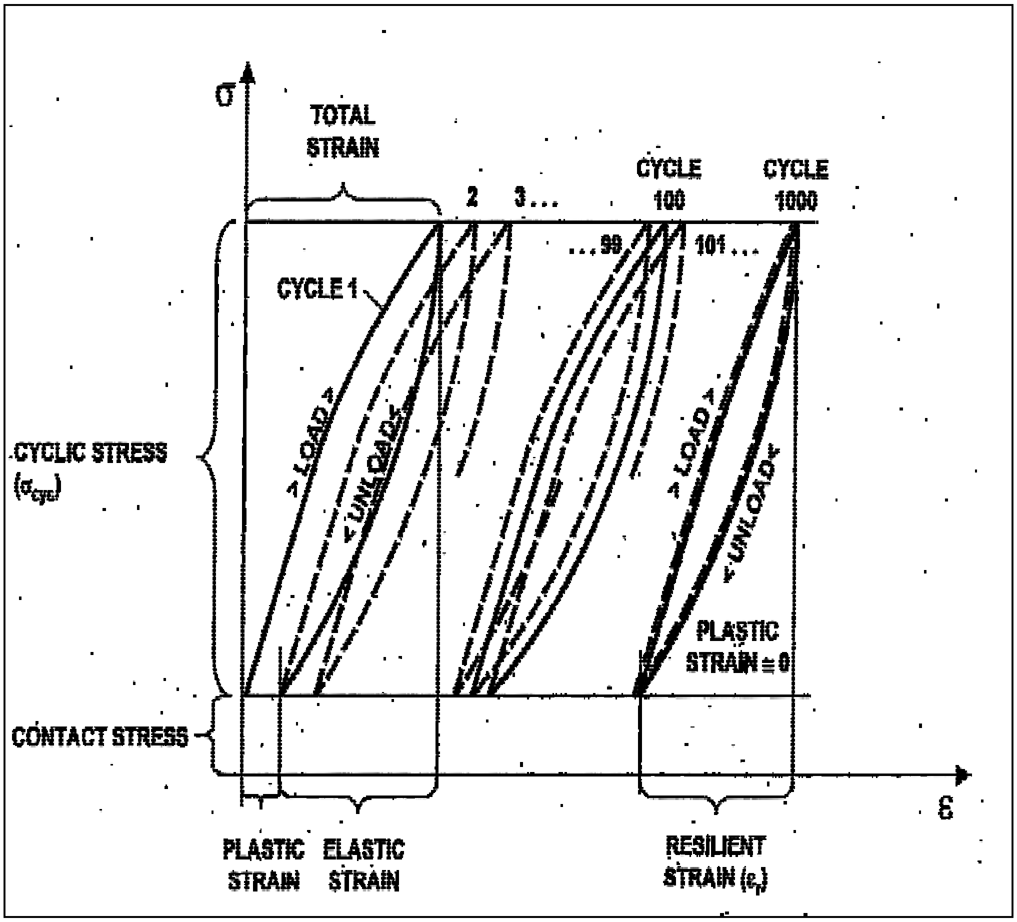


Figure 10. Resilient Behavior of Unbound Materials Under Repeated Loads

(Andrei, 1999; Witczak, 2003)

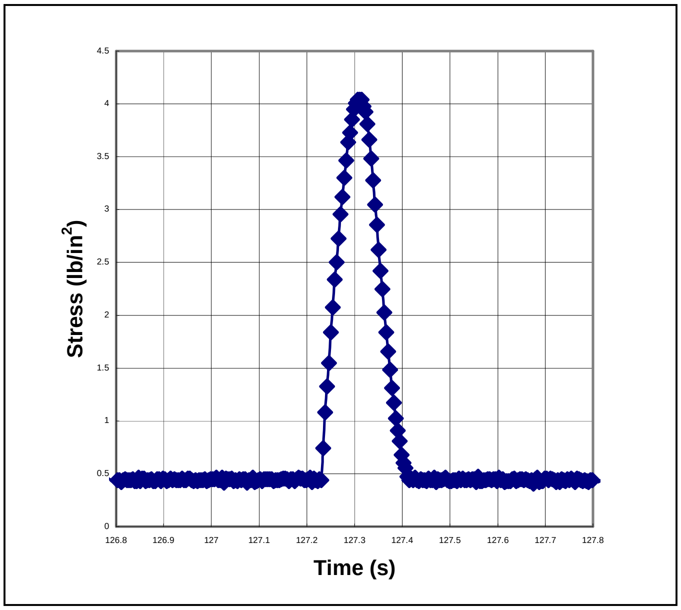


Figure 11. Load Vs. Time Response for CS Subgrade 1st Replicate 4th Sequence

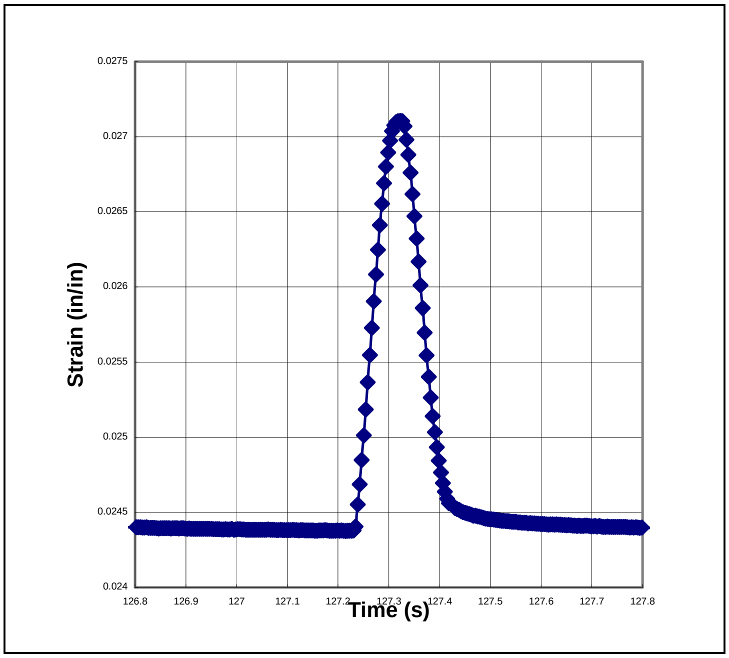


Figure 12. Strain Vs. Time Response for Cs Subgrade 1st Replicate 4th Sequence

3.2 Stress-Dependent Resilient Modulus Model

The resilient modulus for most unbound pavement materials is stress dependent. Many nonlinear models have been proposed over the years for incorporating the effects of stress level on the resilient modulus. A general form for these models can be expressed as (Andrei, 1999; Witczak, 2003):

$$M_R = k_1 p_a \left[\frac{\theta - 3k_6}{p_a}\right]^{k_2} \left[\frac{\tau_{oct}}{p_a} + k_7\right]^{k_3} \qquad (2)$$

in which:

$M_R =$ resilient modulus

$\theta = \sigma_1 + \sigma_2 + \sigma_3$ is the bulk stress

$\tau_{oct} = \left(\frac{1}{3}\right)\left[(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2\right]^{\frac{1}{2}}$ is the octahedral shear stress

$\sigma_1, \sigma_2, \sigma_3 =$ principal stress

$p_a =$ atmospheric pressure (to make equation 3 dimensionless)

k_1 through k_7 = material parameters, subject to the constraints $k_1 > 0$, $k_2 \geq 0$,

$k_3 \leq 0$, $k_6 \leq 0$, and $k_7 \geq 1$.

Equation 2 combines both the stiffening effect of the bulk stress (the term under the k_2 exponent) and the softening effect of shear stress (the term under the k_3 exponent). Through appropriate choices of the material parameters $k_1 – k_7$, one can recover the familiar two-parameter bulk stress model for granular materials and its companion two-parameter shear stress model for cohesive soils, the Uzan-Witczak "Universal" model (Witczak and Uzan, 1988), and the $k_1 – k_6$ model from the Strategic Highway Research Program's (SHRP) flexible pavement performance models (Lytton et al., 1993).

The model used here to incorporate the effect of stress level on the resilient modulus of unbound materials is based upon the recommendations from NCHRP Project 1-28A (Andrei, 1999; Witczak, 2003):

$$M_r = k_1 p_a \left(\frac{\theta}{p_a} \right)^{k_2} \left(\frac{\tau_{oct}}{p_a} + 1 \right)^{k_3} \tag{3}$$

in which:

M_r = resilient modulus

θ = bulk stress, $\theta = \sigma_1 + \sigma_2 + \sigma_3$

σ_1 = major principal stress (confining pressure plus deviator stress)

σ_2 = intermediate principal stress (confining pressure)

σ_3 = minor principal stress (confining pressure)

τ_{oct} = octahedral shear stress,

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

k_i = material parameters determined from regression analysis of the resilient modulus test results.

$k_1, k_2 \geq 0$

$k_3 \leq 0$

P_a = atmospheric pressure (14.7 psi/101.4 kPa)

The stress terms (θ, τ_{oct}) are normalized with respect to atmospheric pressure (p_a), so that all regression constants are dimensionless.

Equation 3, a simplified version of equation 2 with $k_6 = 0$ and $k_7 = 1$ has been adopted for the new proposed AASHTO Pavement Design Guide being developed in NCHRP Project 1-37A. In Equation 2, an increase in the volumetric stress (θ) produces stiffening of the material and a higher M_R ($k_2 \geq 0$) while an increase in the deviatoric stress (τ_{oct}) produces a softening of the material and a lower M_R value ($k3 \leq 0$). The stress stiffening effect typically predominates in granular materials (e.g., base materials) while the stress softening effect is more significant for fine-grained soils (e.g., subgrades).

3.3 Resilient Modulus Parameters for Study Soils

The nonlinear resilient modulus model in Equation 3 was calibrated to the test results for each soil in this study. Calibration was done using linear regression analysis in transformed log-log space. The k_1, k_2, and k_3 values determined from these regression analyses and the corresponding goodness-of-fit statistics are summarized in Table 12. The calibrated models provided good statistical fits in all cases, with high correlation coefficients (R^2) and low normalized standard error values (S_e/S_y) in log-log space. Plots of predicted vs. measured M_R values for all tested stress states for all soils are summarized in Figures 13 through 20.

Table 12. Resilient Modulus Test Results

Soil	Target γ_d (kN/m^3)	Target w (%)	Replicate	Actual γ_d (kN/m^3)	Actual w (%)	k_1	k_2	k_3	R^2	S_e/S_y
Base Materials										
CRREL	20.8	4.1	1	21.6	4.0	803	0.931	-0.612	0.952	0.222
			2	21.8	4.1	537	1.100	-0.561	0.997	0.054
			Combined			662	1.010	-0.585	0.954	0.209
GTX	22.2	4.2	1	22.3	4.1	685	1.124	-0.664	0.986	0.119
			2	22.3	4.0	866	1.034	-0.599	0.988	0.110
			3	22.3	4.1	672	1.128	-0.716	0.985	0.122
			Combined			741	1.091	-0.653	0.986	0.213
MSU-1	20.7	6.0	1	20.7	5.9	1043	0.813	-0.476	0.858	0.380
			2	20.7	5.6	871	1.008	-0.763	0.872	0.363
			Combined			957	0.906	-0.614	0.851	0.390
MSU-2	21.0	6.4	1	20.8	6.9	640	1.239	-0.651	0.976	0.158
			2	20.2	6.4	727	0.974	-0.481	0.933	0.259
			Combined			685	1.113	-0.581	0.971	0.290
Subgrade Materials										
CS	11.4	45.0	1	11.7	42.0	136	0.134	-3.033	0.973	0.164
			2	11.3	44.3	145	0.255	-3.986	0.979	0.144
			3	11.5	43.0	142	0.183	-3.138	0.960	0.201
			Combined			139	0.187	-3.281	0.948	0.423
SSS	14.8	14.0	1	14.7	14.4	301	0.928	-0.290	0.853	0.383
			2	14.7	14.5	569	1.146	-2.880	0.970	0.174
			3	15.1	14.1	477	0.966	-1.872	0.811	0.435
			Combined			449	1.030	-1.856	0.792	0.456
GTX	15.0	28.5	1	15.00	29.31	232	0.442	-19.818	0.935	0.256
			2	15.06	29.73	178	0.426	-18.303	0.892	0.330
			3	15.11	29.12	140	0.360	-13.993	0.906	0.306
			Combined			181	0.408	-17.391	0.637	0.603
CRREL	15.0	28.5	1	15.25	27.66	195	0.508	-19.416	0.901	0.315
			2	15.24	27.91	204	0.467	-17.655	0.984	0.128
			3	15.16	28.18	158	0.462	-18.048	0.976	0.157
			Combined			170	0.450	-16.388	0.635	0.604

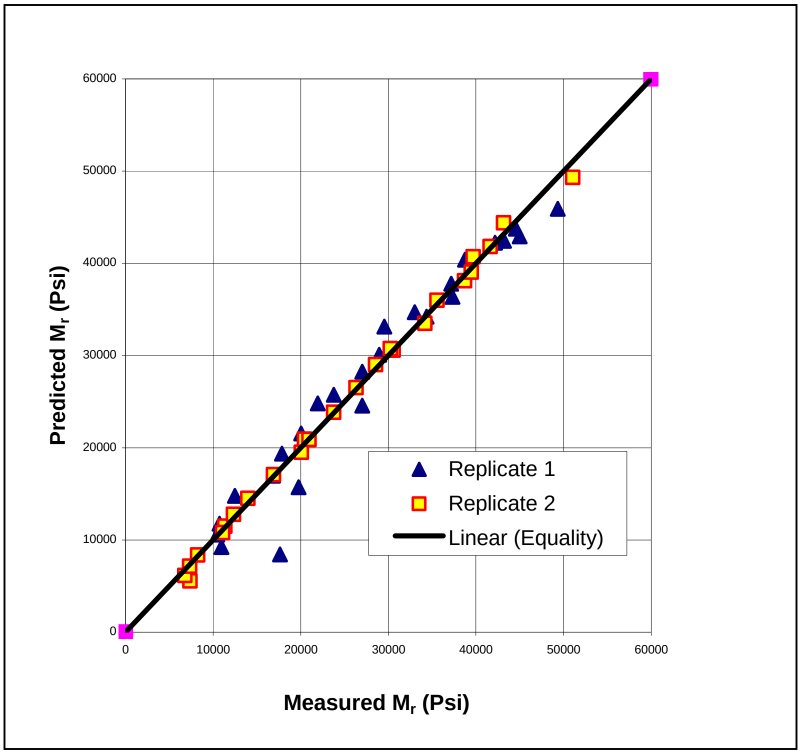


Figure 13. Measured Vs. Predicted M_R for CRREL Base

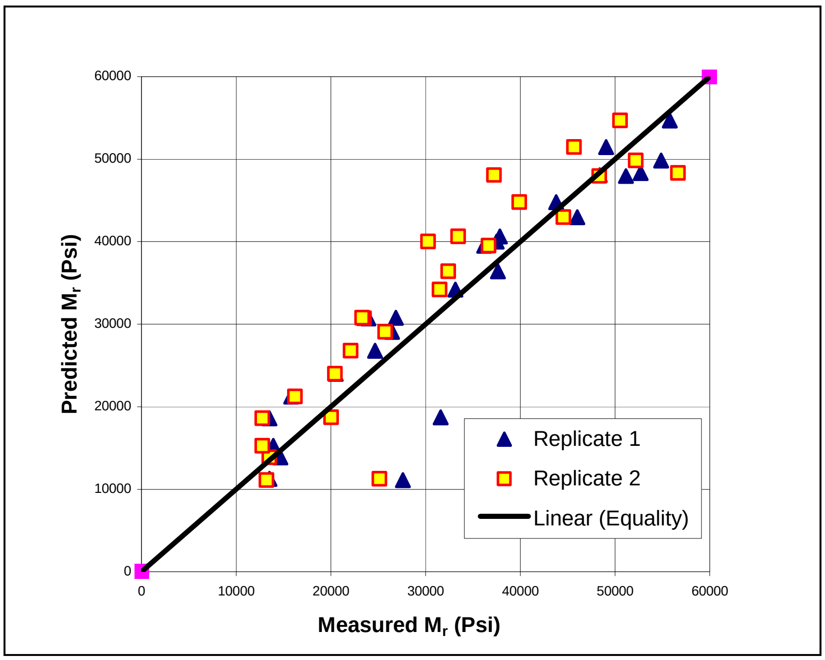


Figure 14. Measured Vs. Predicted M_R for MSU-1 Base

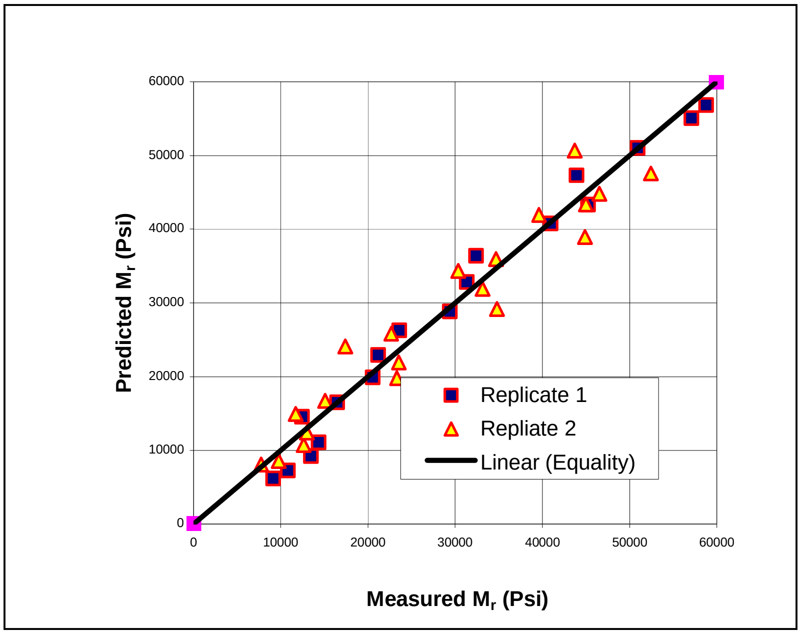


Figure 15. Measured Vs. Predicted M_R for MSU-2 Base

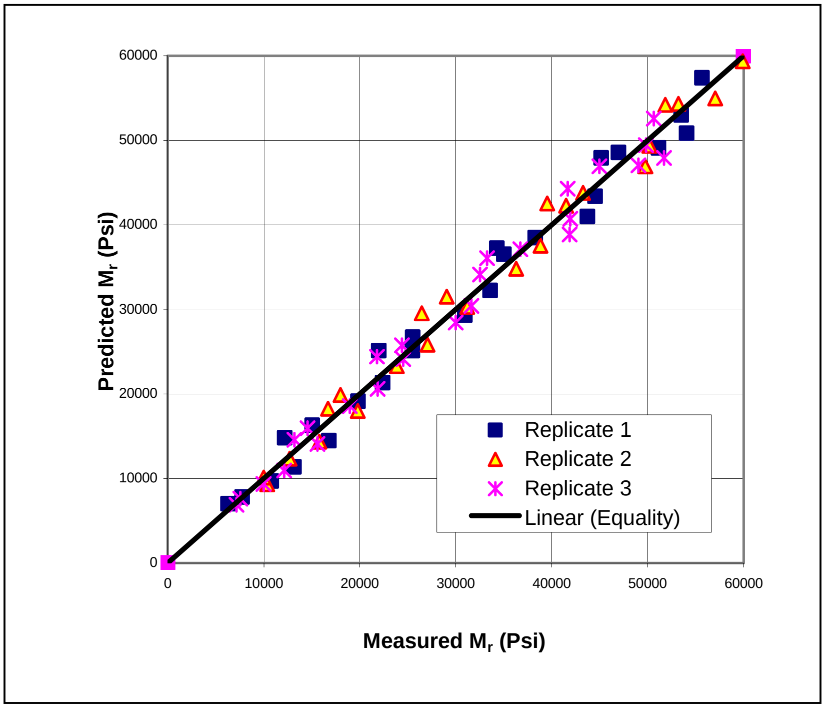


Figure 16. Measured Vs. Predicted M_R for GTX Base

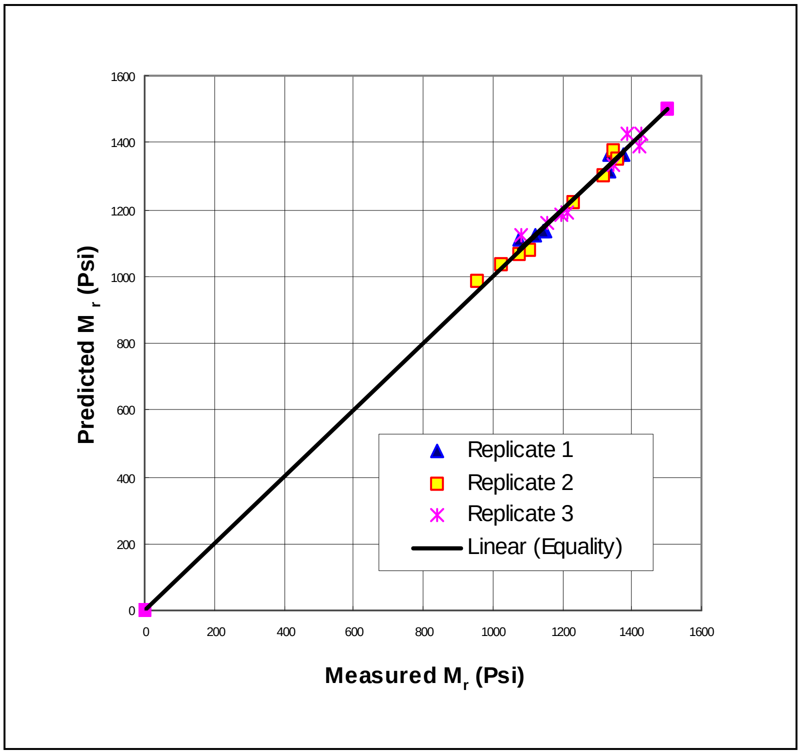


Figure 17. Measured Vs. Predicted M_R for CS Subgrade

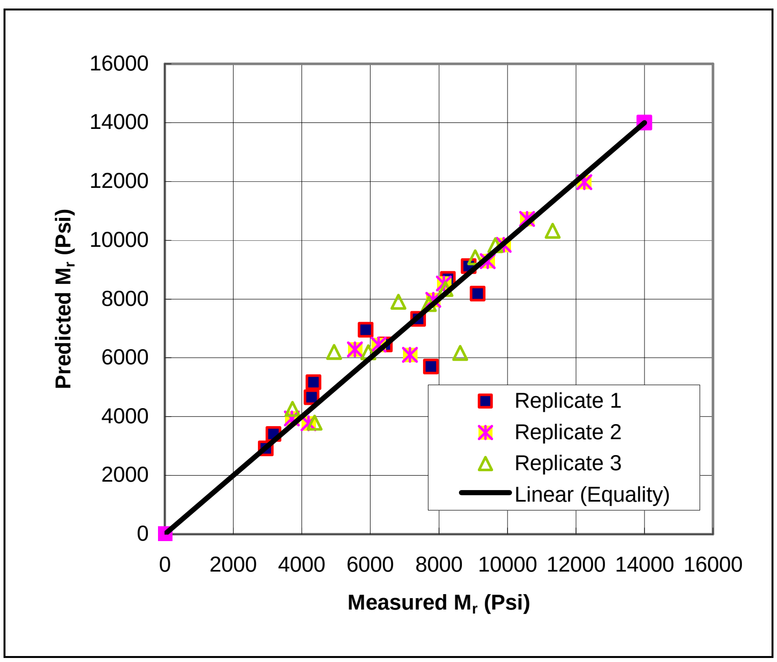


Figure 18. Measured Vs. Predicted M_R for SSS Subgrade

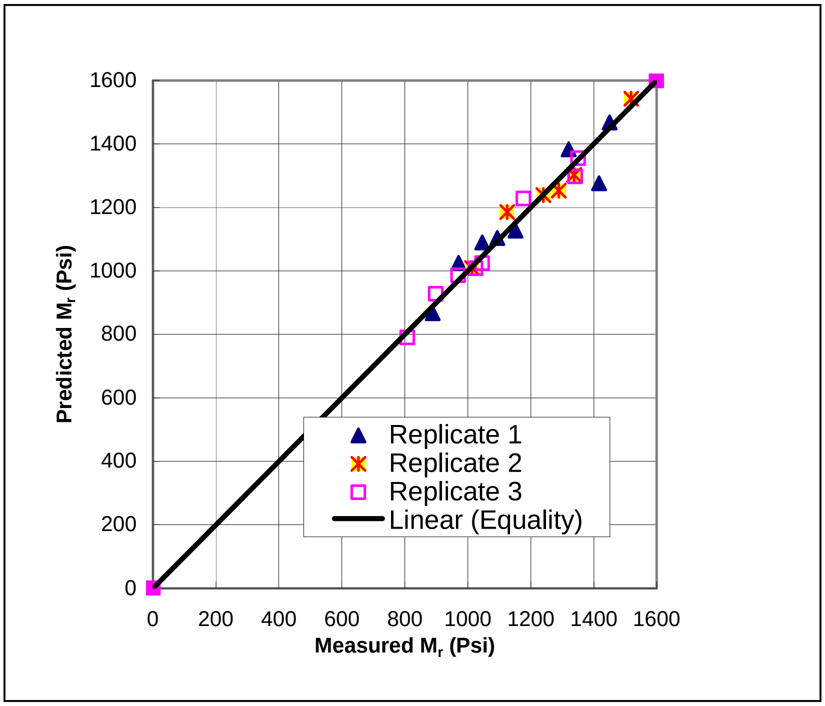


Figure 19. Measured Vs. Predicted M_R for CRREL Subgrade

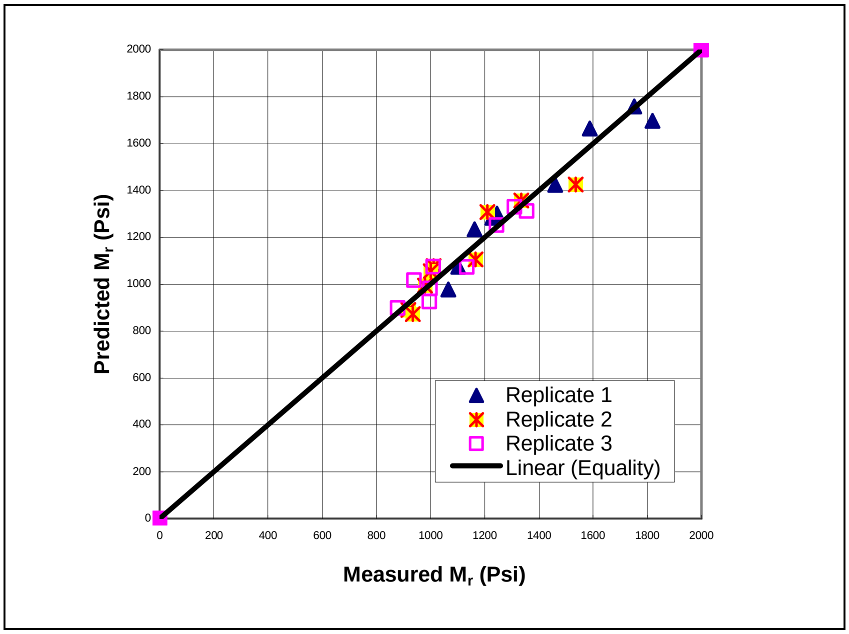


Figure 20. Measured Vs. Predicted MR for GTX Subgrade

Noteworthy observations regarding the resilient moduli results for the coarse-grained base materials (Figures 13-16) are as follows:

- All base materials tested had high resilient modulus results. Granular base materials having average particle sizes greater than 4.75mm had the highest resilient moduli. These materials were the MSU-2 and GTX base soils. Two of the other granular materials tested, the CRREL and MSU-1 bases, which have significant amounts of fines but are well graded, also exhibited high resilient moduli. Moduli values for the base materials ranged up to 60,000psi under the highest confinement pressures.
- Overall, the resilient moduli for each granular material increased as the volumetric stress (θ) increased, as expected.
- k_2 values for the granular base materials ranged from 0.813 to 1.239 and the k_3 values ranged from -0.476 to –0.763.
- Replicate-to-replicate repeatability for the coarse-grained base materials was very good.

Noteworthy observations regarding the resilient moduli results for the fine-grained subgrade materials (Figures 17 – 20) are as follows:

- The fine-grained subgrade materials had lower resilient modulus values than did the coarse-grained base materials, as expected. Maximum resilient moduli values were on the order of 14,000psi (SSS subgrade, Figure 18). Most of the subgrade soils exhibited maximum resilient modulus values less than 2000psi.

- The k_2 values for all fine-grained subgrade materials ranged from 0.134 to 1.146 and were generally lower than the values obtained for the granular base materials. The k_3 values for the subgrade materials, which ranged from–0.290 to –19.818, were also lower (i.e., more negative) than the values obtained for the granular materials. This is consistent with stress softening dominating over stress stiffening for the fine-grained subgrade soils as compared to the granular base materials.
- Replicate-to-replicate repeatability for the fine-grained subgrade materials was quite good.

CHAPTER 4 REPEATED LOAD PERMANENT DEFORMATION

4.1 Determination of Permanent Deformation Behavior

When unbound pavement materials are subjected to cyclic loading they exhibit elastoplastic behavior, characterized by increases in permanent deformations with increasing load repetitions. One of the main objectives of research into the long-term behavior of unbound pavement materials is to establish a constitutive relationship which permits accurate prediction of permanent strain. In such a relationship, it is essential to take into account the gradual accumulation of plastic strain as a function of the number of load applications and the important role played by stress state.

Permanent deformation behavior of unbound pavement materials has been studied than the resilient response for a number of reasons:

- The difficulty in making the transition from the laboratory test results to prediction of field behavior. This is due to the fact that the material in the pavement is subject to a very complex loading history (initial phase of pavement construction, highly varied traffic loading, variations in climatic conditions), which cannot be reproduced correctly in the laboratory.
- The difficulty of the testing due to the strong influence of the stress history. The repeated load permanent deformation test is a destructive test, and only one stress level can be applied to a single specimen. A large number of tests is therefore necessary to investigate how stress levels affect permanent deformation.

The repeated load triaxial test is most typically used to study the permanent deformation behavior of unbound pavement materials. In the most general case, tests are performed at different stress states (confining plus cyclic, one stress state per test specimen) in order to develop models that relate the permanent deformation response to the number of load cycles and the stress state. Figures 21 and 22 show the typical load vs. time and strain vs. time repeated load permanent deformation test data for a single cycle of loading for the CRREL base material. Tabular summaries of the repeated load tests data for each soil are included as Appendix B.

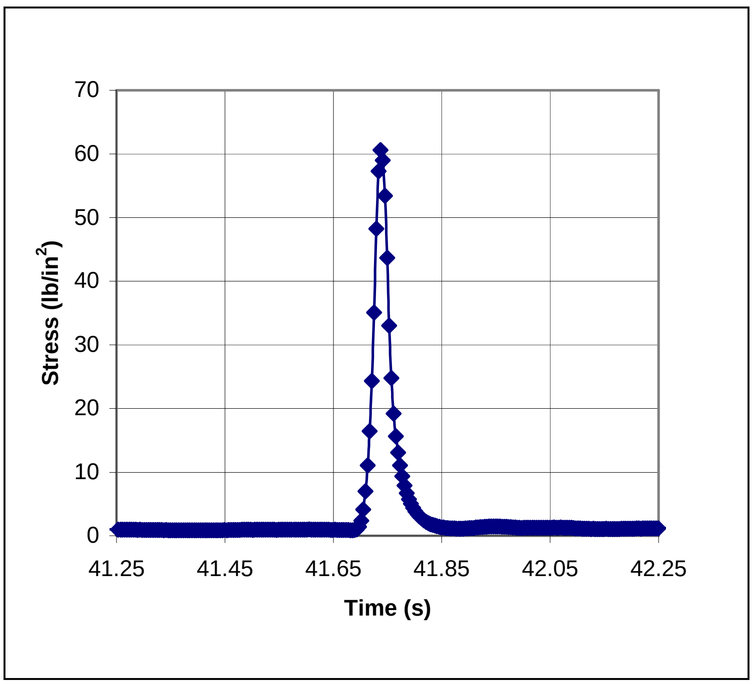


Figure 21. Load Vs. Time Response for CRREL Base 1st Replicate

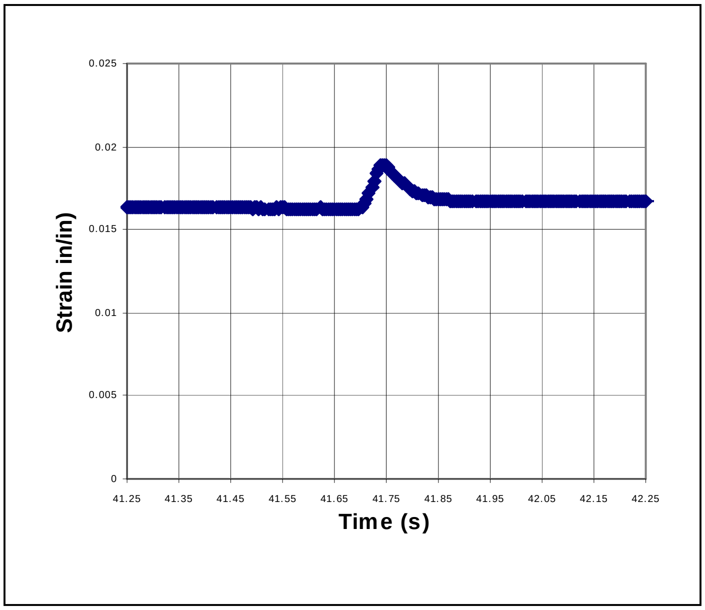


Figure 22. Strain Vs. Time Response for CRREL Base 1st Replicate

4.2 Repeated Load Permanent Deformation Models

Two empirical models for describing the repeated load permanent deformation behavior were considered. The first model is a straightforward power law relationship:

$$\varepsilon_p = aN^b \tag{4}$$

Where:

ε_p = accumulated plastic axial strain

N = number of load cycles

a and b = material parameters determined from regression analysis

The material parameters a and b will, in general, be functions of stress level.

The second empirical model is the strain ratio model:

$$\frac{\varepsilon_p}{\varepsilon_r} = \alpha N^{\beta} \tag{5}$$

Where:

ε_p = accumulated plastic axial strain

ε_r = resilient axial strain

N = number of load cycles

α and β = material parameters determined from regression analysis

The strain ratio is an attempt to "normalize" out stress level effects. This means that two tests on the same material run at different stress levels should give similar intercept and slope values for the $\log\left(\frac{\varepsilon_p}{\varepsilon_r}\right)$ vs. log N relationship.

4.3 Permanent Deformation Parameters for Study Soils

Both models were fit to the central linear portion (in log-log space) of the test results for the accumulated plastic strain or strain ratio. The material parameters a and b or α and β were determined using linear regression analysis in the transformed log-log space. The material parameters determined for each model for all soils and the corresponding goodness-of-fit statistics are summarized in Table 13. The calibrated models provided good statistical fits in all cases with high correlation coefficients (R^2). Plots of number of load cycles vs. accumulated plastic strain, number of load cycles vs. $\varepsilon_p/\varepsilon_r$, and number of load cycles vs. resilient strain for all soils are summarized in Figures 23 through 50. Plots of number of load cycles vs. resilient strain for all soils have been included as the measure of test quality. The resilient strain should remain approximately constant throughout a good quality test.

4.4 Conditioned and Unconditioned Tests for the GTX Aggregate

Sample conditioning, the application of repeated loads to the sample before the actual testing aiming at minimizing the bedding effects (i.e. irregularities between the specimen and the top and bottom platens), was performed on two GTX base material specimens. Full resilient modulus test was used as the sample conditioning step. This was performed to investigate the effects of sample conditioning to the permanent deformation test results. The rest of the tests were done unconditioned. The repeated load permanent deformation tests at SINTEF were done on the same specimens after completion of the M_R tests. This will be discussed further in section 5.3.

Table 13. Repeated Load Permanent Deformation Results

Material	Replicate	Required		Actual		$\varepsilon_p = aN^b$			$\varepsilon_p/\varepsilon_r = \alpha N^\beta$		
		w%	ρ_d	w%	ρ_d	a	b	R^2	α	β	R^2
CRREL Base	1	4.1	20.8	4.2	21.0	5.47E-03	0.333	0.97	1.71E+00	0.513	0.99
	2	4.1	20.8	4.2	21.0	6.21E-03	0.464	0.99	2.57E+00	0.602	0.97
	Combined					6.91E-03	0.323	0.84	2.48E+00	0.482	0.89
GTX Base (Unconditioned)	1	4.2	22.2	4.1	21.0	3.89E-04	0.196	0.96	8.16E-01	0.179	0.98
	2	4.2	22.2	4.2	21.0	3.84E-04	0.245	0.86	8.23E-01	0.218	0.99
	3	4.2	22.2	4.2	21.0	4.73E-04	0.247	0.91	1.02E+00	0.219	0.98
	Combined					4.13E-04	0.229	0.87	8.80E-01	0.205	0.91
GTX Base (Conditioned)	1	4.2	22.2	4.2	21.0	6.04E-05	0.360	0.98	6.81E-02	0.384	0.98
	2	4.2	22.2	4.2	21.0	6.13E-05	0.374	0.97	6.85E-02	0.400	0.98
	Combined					6.08E-05	0.367	0.97	6.83E-02	0.392	0.98
GTX Base (Conditioned/ High Stress)	1	4.2	22.2	4.1	21.0	2.36E-07	0.637	0.53	4.79E-04	0.612	0.51
MSU-1 Base	1	6.0	20.7	5.6	20.8	5.30E-03	0.226	0.96	3.55E+00	0.284	0.86
	2	6.0	20.7	6.3	20.6	9.94E-05	0.640	0.93	3.55E-01	0.794	0.99
	Combined					4.13E-03	0.289	0.72	2.31E+00	0.368	0.74
MSU-2 Base	1	6.4	21.0	6.5	21.0	6.43E-03	0.530	0.98	2.52E-01	0.456	0.99
	2	6.4	21.0	6.2	21.0	2.68E-04	0.239	0.98	5.54E-01	0.241	0.99
	Combined					1.41E-04	0.357	0.81	4.06E-01	0.316	0.90
CRREL Subgrade	1	28.5	15.0	28.5	15.0	3.83E-03	0.283	0.74	3.64E+00	0.245	0.94
	2	28.5	15.0	27.1	15.1	5.75E-04	0.524	0.75	1.21E+00	0.379	0.92
	Combined					1.50E-03	0.402	0.65	2.11E+00	0.311	0.84
CS Subgrade	1	45.0	11.4	47.8	11.2	3.95E-03	0.227	0.98	6.65E-01	0.237	0.83
	2	45.0	11.4	48.1	11.2	1.85E-05	0.358	0.98	2.99E-01	0.390	1.00
	Combined					2.73E-03	0.290	0.93	4.51E-01	0.310	0.89
GTX Subgrade	1	28.5	15.0	30.4	14.8	3.86E-03	0.230	0.95	3.15E+00	0.196	0.91
	2	28.5	15.0	29.8	14.9	1.42E-03	0.484	0.83	1.63E+00	0.455	0.95
	Combined					2.42E-03	0.346	0.74	2.37E+00	0.311	0.73
SSS Subgrade	1	14.0	14.8	14.3	15.5	3.07E-03	0.474	0.99	2.26E-00	0.435	0.99
	2	14.0	14.8	14.3	15.3	3.01E-03	0.481	0.99	3.47E-00	0.423	0.93
	Combined					3.04E-03	0.478	0.99	2.77E-00	0.433	0.90

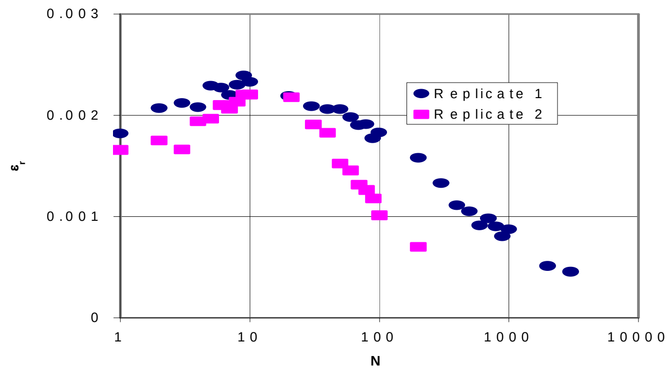


Figure 23. Resilient Strain vs. Number of Cycles for CRREL Base Material

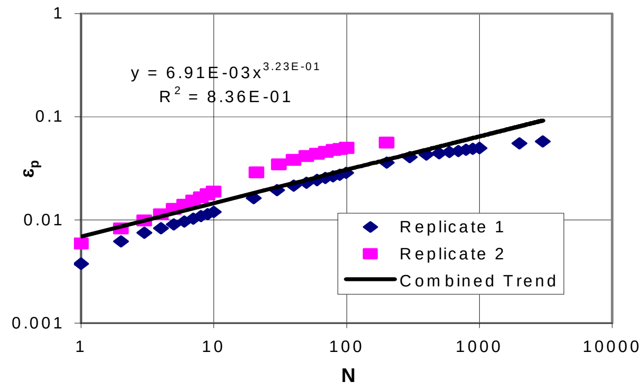


Figure 24. Plastic Strain vs. Number of Cycles for CRREL Base Material

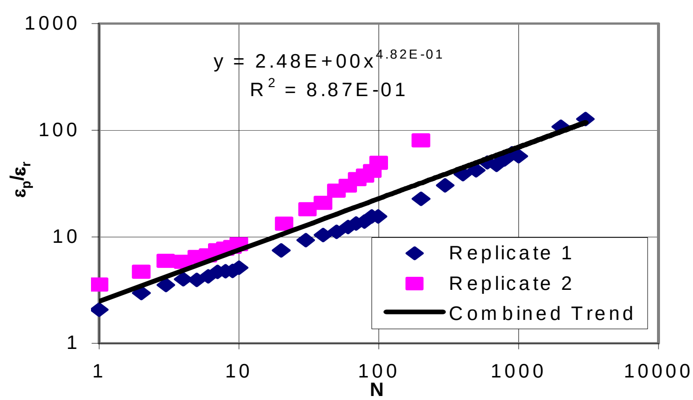


Figure 25. Plastic Strain to Resilient Strain Ratio vs. Number of Cycles for

CRREL Base Material

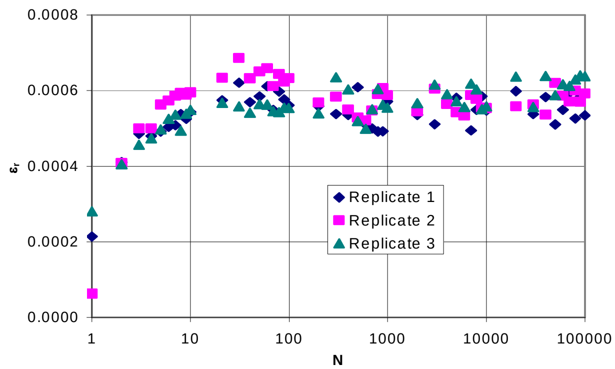


Figure 26. Resilient Strain vs. Number of Cycles for GTX Base Material (Unconditioned)

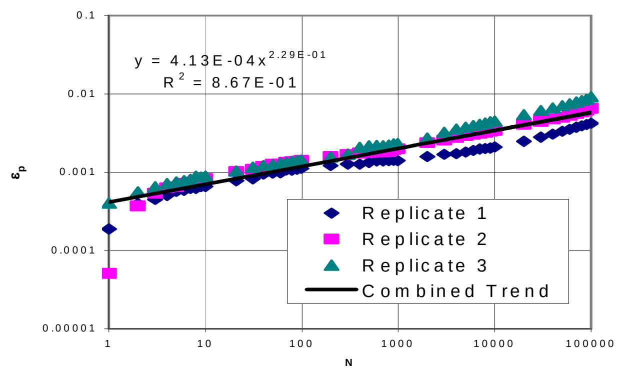


Figure 27. Plastic Strain vs. Number of Cycles for GTX Base Material (Unconditioned)

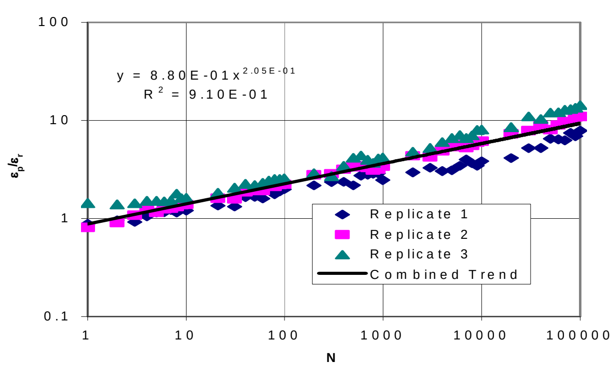


Figure 28. Plastic Strain to Resilient Strain Ratio vs. Number of Cycles for GTX Base material (Unconditioned)

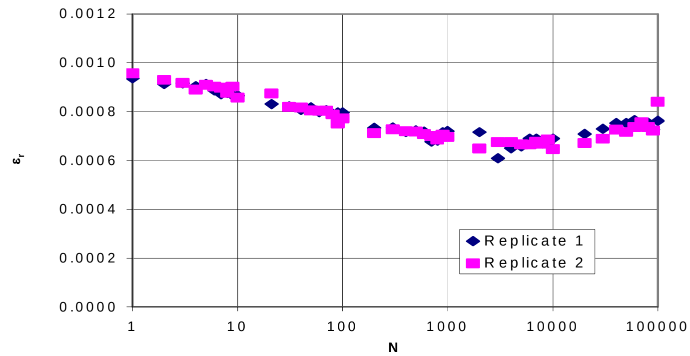


Figure 29. Resilient Strain vs. Number of Cycles for GTX Base Material

(Conditioned)

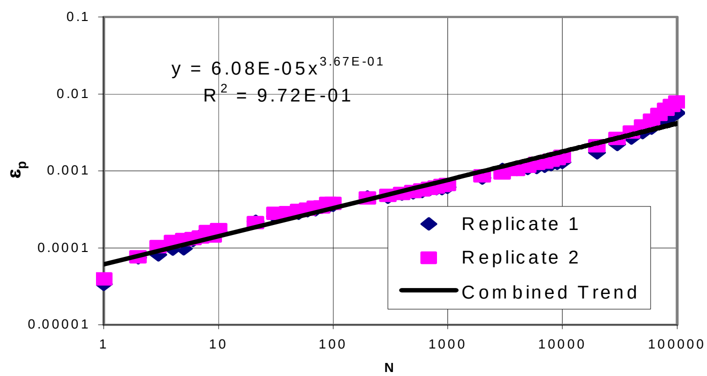


Figure 30. Plastic Strain vs. Number of Cycles for GTX Material

(Conditioned)

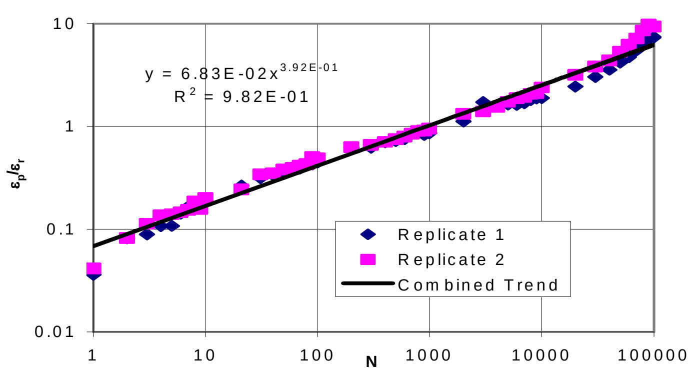


Figure 31. Plastic Strain to Resilient Strain Ratio vs. Number of Cycles for

GTX Material (Conditioned)

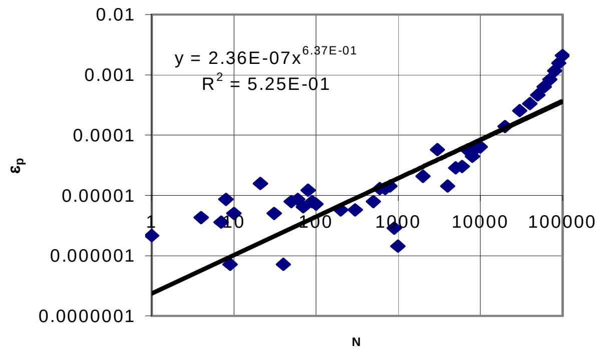


Figure 32. Plastic Strain vs. Number of Cycles for GTX Base Material

(Conditioned-High Confining Stress)

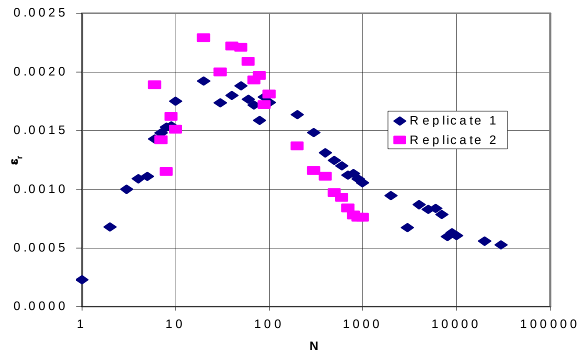


Figure 33. Resilient Strain vs. Number of Cycles for MSU-1 Base Material

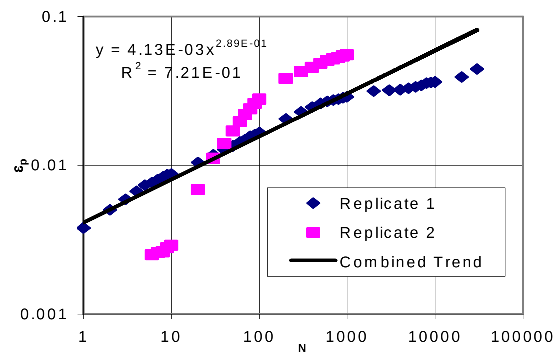


Figure 34. Plastic Strain vs. Number of Cycles for MSU-1 Base material

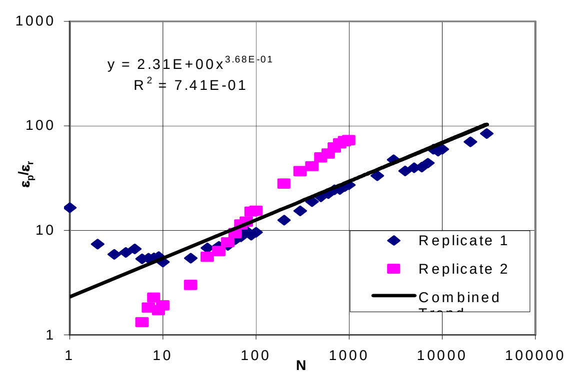


Figure 35. Plastic Strain to Resilient Strain Ratio vs. Number of Cycles for

MSU-1 Base Material

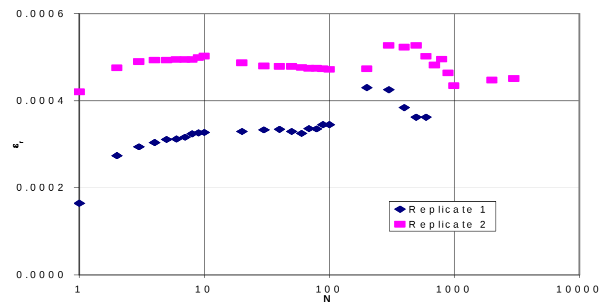


Figure 36. Resilient Strain vs. Number of Cycles for MSU-2 Base Material

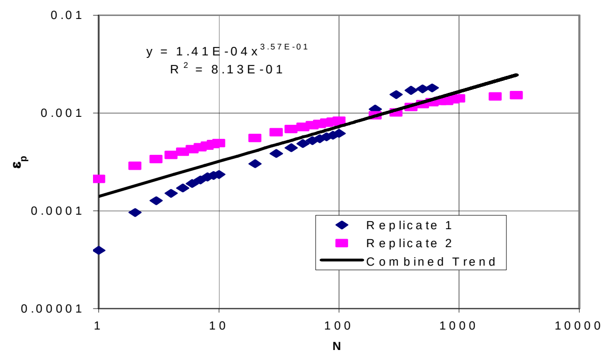


Figure 37. Plastic Strain vs. Number of Cycles for MSU-2 Base Material

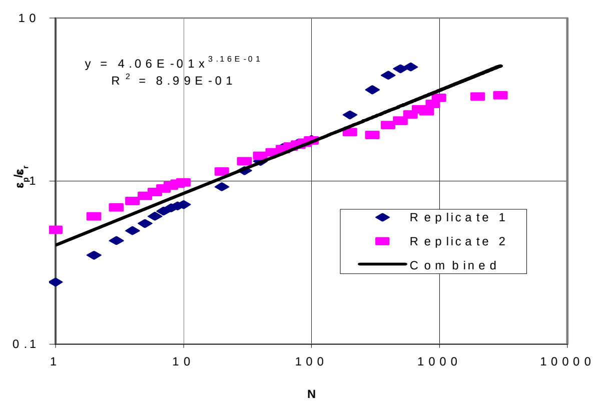


Figure 38. Plastic Strain to Resilient Strain Ratio vs. Number of Cycles for MSU-2 Base Material

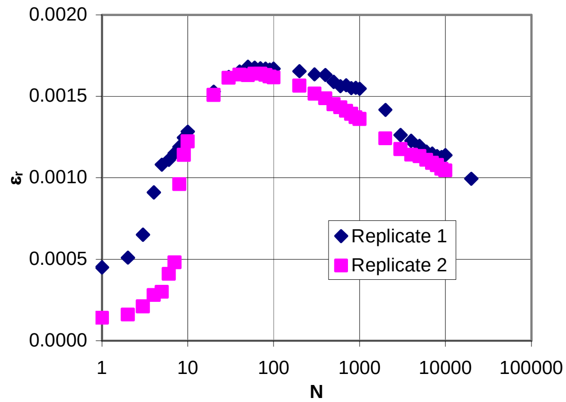


Figure 39. Resilient Strain vs. Number of Cycles for CRREL Subgrade Material

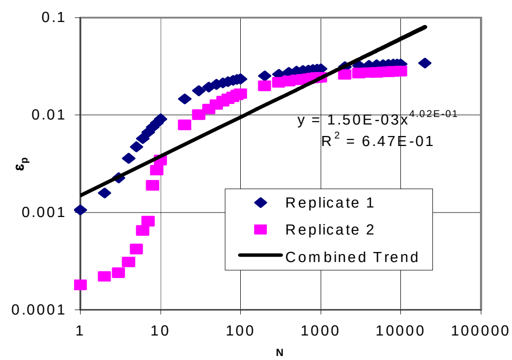


Figure 40. Plastic Strain vs. Number of Cycles for CRREL Subgrade Material

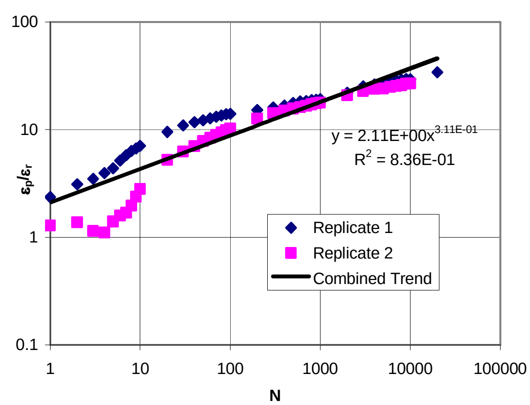


Figure 41. Plastic Strain to Resilient Strain Ratio vs. Number of Cycles for

CRREL Subgrade Material

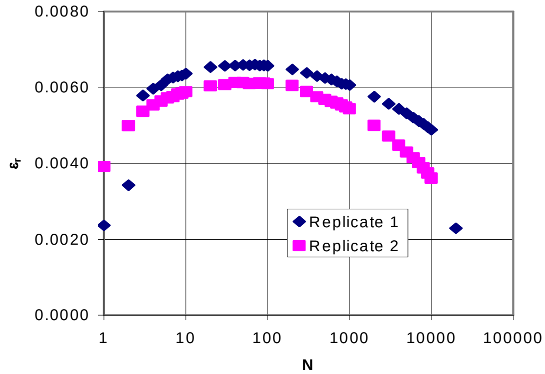


Figure 42. Resilient Strain vs. Number of Cycles for CS Subgrade Material

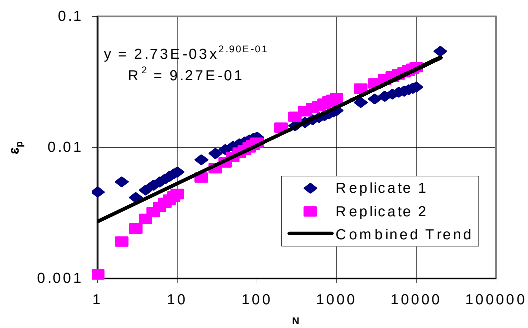


Figure 43. Plastic Strain vs. Number of Cycles for CS Subgrade Material

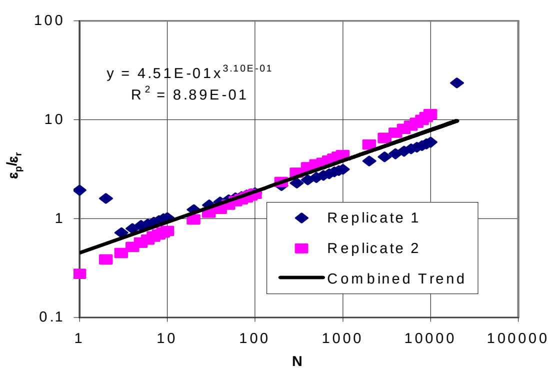


Figure 44. Plastic Strain to Resilient Strain Ratio vs. Number of Cycles for CS Subgrade Material

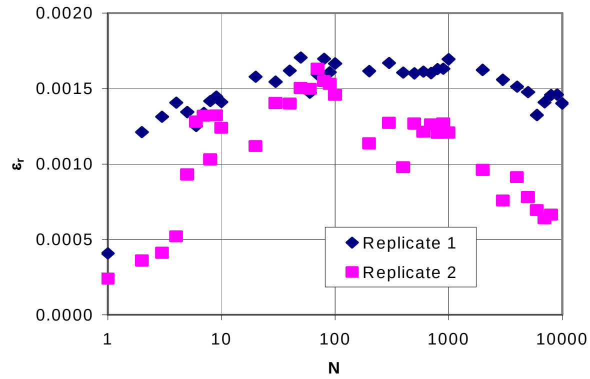


Figure 45. Resilient Strain vs. Number of Cycles for GTX Subgrade Material

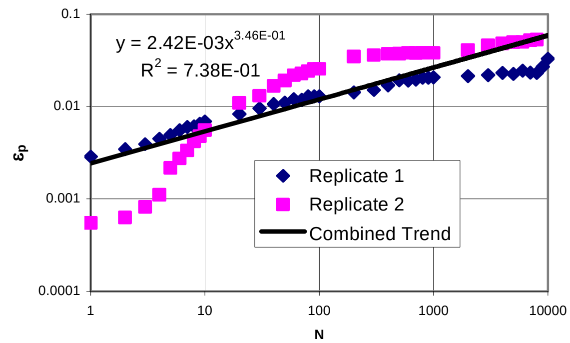


Figure 46. Plastic Strain vs. Number of Cycles for GTX Subgrade material

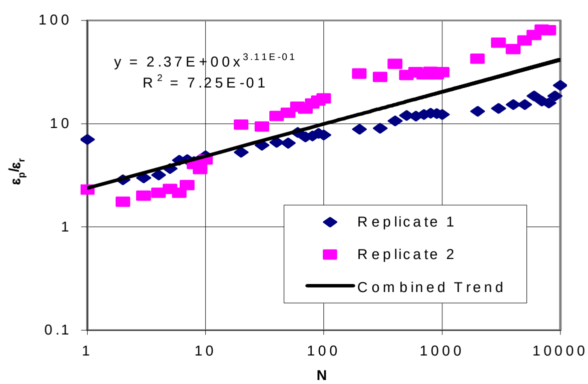


Figure 47. Plastic Strain to Resilient Strain Ratio vs. Number of Cycles for GTX Subgrade Material

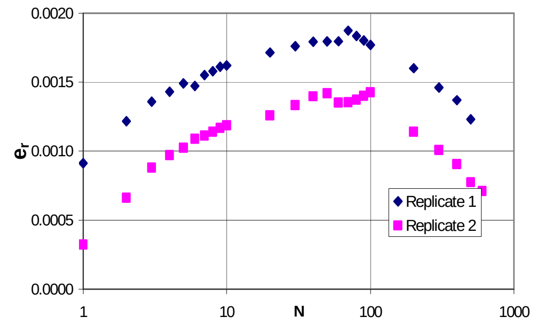


Figure 48. Resilient Strain vs. Number of Cycles for SSS Subgrade Material

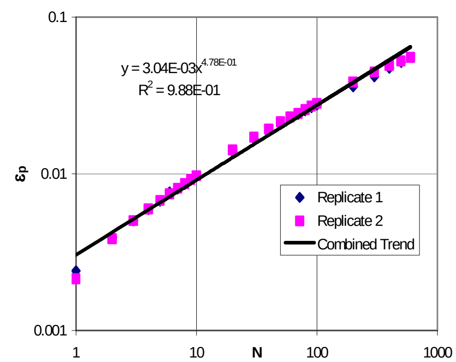


Figure 49. Plastic Strain vs. Number of Cycles for SSS Subgrade material

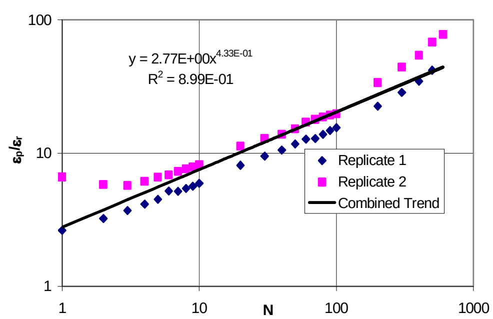


Figure 50. Plastic Strain to Resilient Strain Ratio vs. Number of Cycles for SSS Subgrade Material

Noteworthy observations regarding the repeated load permanent deformation results for the coarse-grained base materials (Figures 23-38) are as follows:

- The GTX granular base material having average particle sizes greater than 4.75mm had enough strength to reach 100,000 load cycles. Three other granular materials tested, CRREL, MSU-1, and MSU-2 failed before reaching 30,000 load cycles.
- The a values for the granular base materials tested unconditioned and at low stress ranged from 9.94E-05 to 5.30E-03 and b values ranged from 0.196 to 0.640. The α values for the granular base materials tested unconditioned and at low stress ranged from 8.16E-01 to 3.55E+00 and β values ranged from 0.179 to 0.794.
- The a and b values for the GTX granular base material tested conditioned and at high confining stress were 2.36E-07 and 0.637, respectively. The α and β values for the GTX granular base material tested conditioned and at high confining stress were 4.79E-04 and 0.612, respectively. The a value, the intercept, for conditioned GTX base material tests is low compared to the a value for unconditioned GTX base material tests. This illustrates that strains are induced during the conditioning step. The b value, the slope, is not very much affected by conditioning step.
- Replicate-to-replicate repeatability for the GTX and CRREL granular base materials was very good. The two other granular base materials tested, MSU-1 and MSU-2, had poorer replicate-to-replicate repeatability. This might have

been the consequence of exceeding the linear range of the LVDTs due to excessive deformation of specimens.

Noteworthy observations regarding the repeated load permanent deformation results for the fine-grained subgrade materials (Figures 39-50) are as follows:

- The a values for the fine-grained subgrade materials ranged from –2.490 to 3.95E-03 and b values ranged from 0.227 to 0.524. The α values for the fine-grained subgrade materials ranged from 6.65E-01 to 3.64E+00 and β values ranged from 0.196 to 0.457.
- Replicate-to-replicate repeatability for the fine-grained subgrade materials was not good. This might have been the consequence of exceeding the linear range of the LVDTs due to excessive deformation of specimens.
- The relative magnitudes of the permanent strains for coarse vs. fine soils could not be discussed because materials were tested at different stress states.

CHAPTER 5 DISCUSSION

5.1 Introduction

The primary objectives of this study are as follows:

(1) Determine laboratory resilient modulus and permanent deformation characteristics for base and subgrade soils previously studied in large-scale laboratory and field pavement experiments of geosynthetic reinforced flexible pavements.

(2) Determine for these materials the specific material properties required by the 2002 PDG for performance prediction using the 2002 PDG models.

(3) Evaluate some specific details of testing protocols:

- Large vs. small specimen response.
- Stress/test sequence (e.g., resilient modulus and permanent deformation testing on the same test specimen).
- Effect of stress level on permanent deformation behavior.

(4) To increase the database of typical values for the resilient modulus and repeated permanent deformation parameters for unbound pavement materials.

Objectives 1 and 2 have been addressed in the detailed tabulations presented previously in Tables 12 and 13. Objectives 3 and 4 will be addressed in the following sections.

5.2 Large Vs. Small Specimen Responses

Three large specimen resilient modulus tests on the GTX base material (unreinforced) were performed at SINTEF in Trondheim, Norway. These results can be compared with the small specimen resilient modulus tests performed on the same material at University of Maryland. Tables 14 and 15 summarize parameters from resilient modulus model fit at SINTEF and University of Maryland, respectively.

Table 14. Parameters from Resilient Modulus Model Fit (SINTEF Tests)

Sample ID	Density (kN/m^3)	k_1	k_2	k_3
Unreinforced 1	21.7	1100	0.874	-0.445
Unreinforced 2	21.9	1294	0.827	-0.602
Unreinforced 3	21.8	1837	1.206	-1.194
Combined 1 - 3		1587	0.559	-0.181

Table 15. Parameters from Resilient Modulus Model Fit (University of Maryland Tests)

Sample ID	Density (kN/m^3)	k_1	k_2	k_3
Unreinforced 1	22.3	665	1.124	-0.664
Unreinforced 2	22.3	866	1.034	-0.599
Unreinforced 3	22.3	672	1.128	-0.716
Unreinforced 1 - 3		741	1.091	-0.653

Comparison of results between SINTEF and University of Maryland tests are shown in Figures 51 and 52. Resilient modulus values were calculated using equation 2 for each of the stress conditions used in the resilient modulus test. For the University of Maryland tests, all figures use material values from the combined replicate values listed in Table 15. For the SINTEF tests, Figure 51 uses combined values reported in Table 14. Figure 52 eliminates test 3 from the SINTEF results, which has k_1, k_2, and k_3 values that are inconsistent with tests 1 and 2 and which may be an outlier.

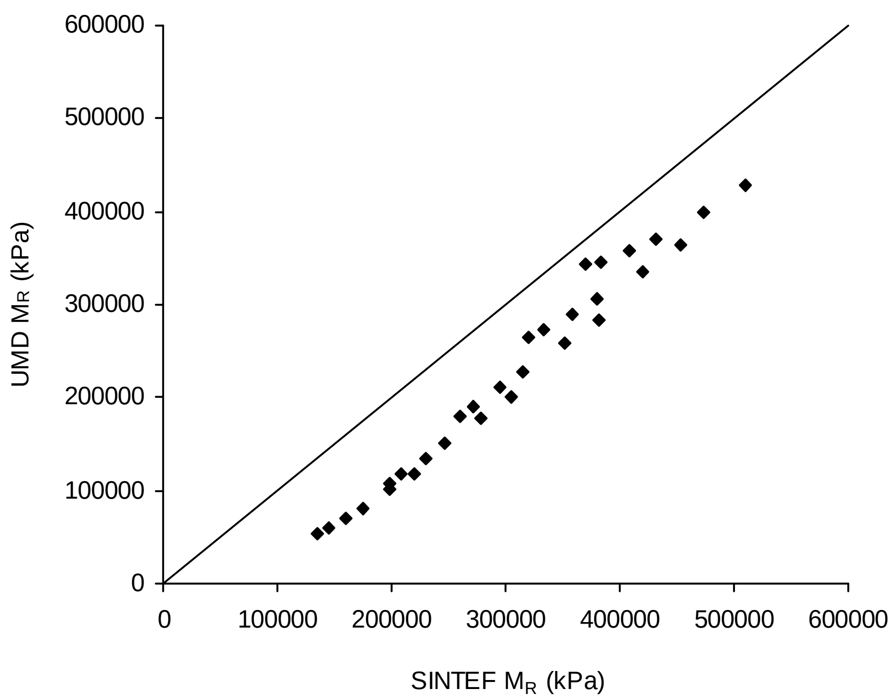


Figure 51. University of Maryland Combined Results Vs. SINTEF Combined Results

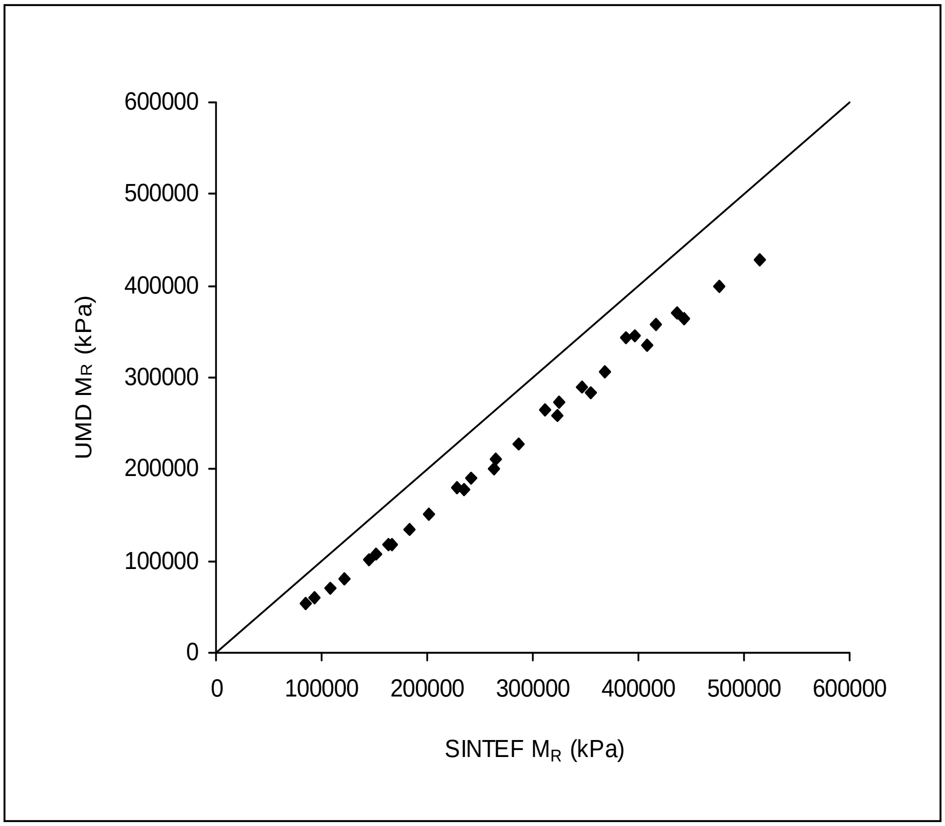


Figure 52. University of Maryland Combined Results Vs. SINTEF Test 1

SINTEF results give higher resilient modulus values as shown in Figure 51. The discrepancies between the two sets of results is greater for lower values of resilient modulus, with a ratio between SINTEF and University of Maryland M_R values ranging from 2.6 to 1.2. This might be contributed by the self-weight of the large sample which increases the stiffness of the sample resulting to higher resilient modulus. Elimination of test 3 from the SINTEF results, which was inconsistent with tests 1 and 2, also has results showing a higher shift between the results for lower values of resilient modulus but not to the extent as seen in Figure 51. A constant shift of 1.2 can be used to represent the average shift seen.

5.3 Conditioning Vs. Unconditioning

University of Maryland has traditionally run repeated load permanent deformation (RLPD) tests on unbound materials without any specimen conditioning. However, because of the sample preparation costs for the large cylinder tests performed at SINTEF, they were first performing a full M_R test sequence (NCHRP 1-28A protocol) and then a RLPD test on the same specimen. The initial M_R test sequence can be considered a specimen conditioning step for the RLPD. The question then arised as to what effect this initial M_R testing had on the measured RLPD response.

To address this question, we performed small cylinder (150mm diameter by 300mm tall) RLPD tests on unconditioned and M_R-conditioned specimens of the GTX Base material (2 replicates per case). The results are shown in Figure 53. Log-log regression fits to the data produce the following results:

Unconditioned: $$\log \frac{\varepsilon_p}{\varepsilon_r} = -1.1399 + 0.3846 \log N \qquad R^2 = 0.98 \qquad (6)$$

Conditioned: $$\log \frac{\varepsilon_p}{\varepsilon_r} = -0.0460 + 0.2205 \log N \qquad R^2 = 0.97 \qquad (7)$$

No attempt was made in these regressions to isolate the central linear (in log-log space) part of the RLPD response from the initial (primary) response or tertiary response; the regression lines are simply fit to the entire data record. The results in Figure 53 show that this is not an issue for the unconditioned data, which is linear (in log-log space) over the entire response record. However, the conditioned data show an initial nonlinear "stiffening" of the material and a later accelerating rate of permanent strain accumulation. A possible explanation for the more pronounced deviation in the initial response in the conditioned data is that the initial cycles of the RLPD test represent a relative unloading of the material, which had just previously been subjected to the highest (i.e., closest to failure) stress conditions during the M_R load sequence. A similar explanation for the later accelerating permanent strain accumulation is that the material is approaching tertiary failure; this is more pronounced in the conditioned vs. the unconditioned response because the conditioned material has previously been subjected to very high stresses during the M_R load sequence.

It is clear from Figure 53 that the M_R conditioning has a non-negligible effect on the overall magnitude of the RLPD response. Both the slope and intercept terms in Eqs. (6) and (7) differ significantly between the unconditioned and conditioned specimen cases. Thus, the question now becomes whether this difference can be accounted for in some rational way to make the conditioned results equivalent to the unconditioned response.

5.3.1 Theory

The M_R conditioning can be interpreted as applying some initial number of load cycles ΔN that induces some initial permanent strain $\Delta\varepsilon_p$ prior to the start of the actual RLPD loading. In other words, the N and ε_p measured in the conditioned tests are not the same N and ε_p measured in the unconditioned tests, but instead can be expressed as follows:

$N_{equiv} = N + \Delta N$ (8)

$(\varepsilon_p)_{equiv} = \varepsilon_p + \Delta\varepsilon_p$ (9)

in which N_{equiv} and $(\varepsilon_p)_{equiv}$ are the equivalent total number of load cycles and permanent strain including the loading cycles during the initial M_R sequence and where ΔN and $\Delta\varepsilon_p$ can be viewed as horizontal and vertical shift factors for the conditioned RLPD test results.

Note that the loading cycles during the initial M_R sequence are at various stress conditions, all of which are different from the stress conditions in the RLPD loading. However, the model form of Eq. (6) and (7) is designed to account for different stress conditions (at least as a first approximation) through normalization by the resilient strain term in the denominator.

The unknown ΔN and $\Delta\varepsilon_p$ values in Eq. (8) and (9) can be determined via nonlinear optimization by requiring that both the unconditioned and conditioned RLPD results conform to the same linear trend in log-log space, i.e.:

Unconditioned: $$\log \frac{\varepsilon_p}{\varepsilon_r} = a + b \log N \tag{10}$$

Conditioned: $$\log \frac{\varepsilon_p + \Delta\varepsilon_p}{\varepsilon_r} = a + b \log (N + \Delta N) \tag{11}$$

in which the regression coefficients *a* and *b* are required to be the same for both equations.

In actuality, the ΔN and $\Delta\varepsilon_p$ values in Eq. (10) and (11) are not completely unknown. The M_R test sequence for granular base materials consists of 4000 load cycles (1000 low stress preconditioning cycles followed by 100 cycles at each of 30 stress states). The permanent strain at end of the M_R test sequence is also measured during the conditioned tests. The permanent strains at the end of the M_R test sequence for the GTX Base material were 0.0033 and 0.0043 for two replicates.

5.3.2 Analysis Results

The nonlinear optimization of Eqs. (10) and (11) was performed for two cases: (a) no constraint on the horizontal shift ΔN; and (b) ΔN constrained to a value of 4000 (i.e., the number of load cycles in the M_R sequence). The vertical shift $\Delta\varepsilon_p$ was unconstrained in both cases.

Results from the unconstrained nonlinear optimization case are shown in Figure 54. The best-fit line through the unconditioned and shifted conditioned data occurred for values of the shift factors ΔN=615 and $\Delta\varepsilon_p$=2.87E-3:

$$\log\frac{\varepsilon_p}{\varepsilon_r} = -0.04095 + 0.2183\log N \qquad \frac{S_e}{S_y} = 0.189 \tag{12}$$

The low standard error ratio for Eq. (12) indicates a good statistical fit. However, close examination of the shifted conditioned data in Figure 54 suggests that there may be some bias; the shifted conditioned data are slightly overpredicted, then slightly underpredicted, and then slightly overpredicted again as N increases, suggesting that the shifted conditioned data are not as well represented by a power law model as are the unconditioned data. This behavior was also evident in the unshifted conditioned data in Figure 53; it is simply amplified by the shifting procedure.

Individual best-fit lines through the unconditioned and shifted conditioned data are also shown on Figure 54:

Unconditioned: $$\log\frac{\varepsilon_p}{\varepsilon_r} = -0.0483 + 0.2211\log N \qquad R^2 = 0.97 \tag{13}$$

Shifted Conditioned: $$\log\frac{\varepsilon_p}{\varepsilon_r} = -0.0061 + 0.2081\log N \qquad R^2 = 0.92 \tag{14}$$

The slope coefficients for both of these equations are comparable and similar to the value for the combined results (Eq. 12). The intercept coefficients in Eqs. (13) and (14) differ by approximately one order of magnitude, however.

Results from the nonlinear optimization case with ΔN constrained to a value of 4000 are shown in Figure 55. The best-fit line through the unconditioned and shifted conditioned data occurred at a vertical shift factor value $\Delta\varepsilon_p$=3.93E-3:

$$\log\frac{\varepsilon_p}{\varepsilon_r} = -0.06233 + 0.2484\log N \qquad \frac{S_e}{S_y} = 0.195 \tag{15}$$

The standard error ratio for Eq. (15) is again quite low, but the bias in the shifted conditioned data is more pronounced (Figure 55). Note that the vertical shift factor $\Delta\varepsilon_p$=4.18E-3 for the best-fit condition lies within the measured range of 3.3E-3 to 4.3E-3 for the two replicates.

Individual best-fit lines through the unconditioned and shifted conditioned data are also shown on Figure 55:

Unconditioned: $$\log\frac{\varepsilon_p}{\varepsilon_r} = -0.0483 + 0.2211\log N \qquad R^2 = 0.97 \qquad (16)$$

Shifted Conditioned: $$\log\frac{\varepsilon_p}{\varepsilon_r} = -0.2185 + 0.2697\log N \qquad R^2 = 0.85 \qquad (17)$$

The slope coefficients for both of these equations are comparable and similar to the value for the combined results (Eq. 15). The intercept coefficients in Eqs. (13) and (14) now differ only by about a factor of 4 and bracket the intercept coefficient for the combined regression in Eq. (15).

5.3.3 Conclusions

Treating the effects of the M_R conditioning as initial horizontal (N) and vertical (ε_p) offsets of the subsequent RLPD test results is arguably appropriate in concept and appears acceptable in practice. The ΔN shift can be taken as the total number of cycles during specimen conditioning (4000 for M_R conditioning using the NCHRP 1-28A protocols) and $\Delta\varepsilon_p$ can be set equal to the measured accumulated permanent strain at the end of the specimen conditioning. The shifted M_R-conditioned RLPD data follow the same overall trend (i.e., similar slope and intercept coefficients in log-log space) as the unshifted unconditioned RLPD data. There is a systematic bias in the measured vs. predicted unconditioned data that is magnified by the shifting procedure, suggesting that a linear fit (in log-log space, or power law in arithmetic space) is perhaps not the most appropriate model form for the shifted conditioned data. Nonetheless, the linear fit is judged sufficiently accurate for comparative analysis and prediction purposes.

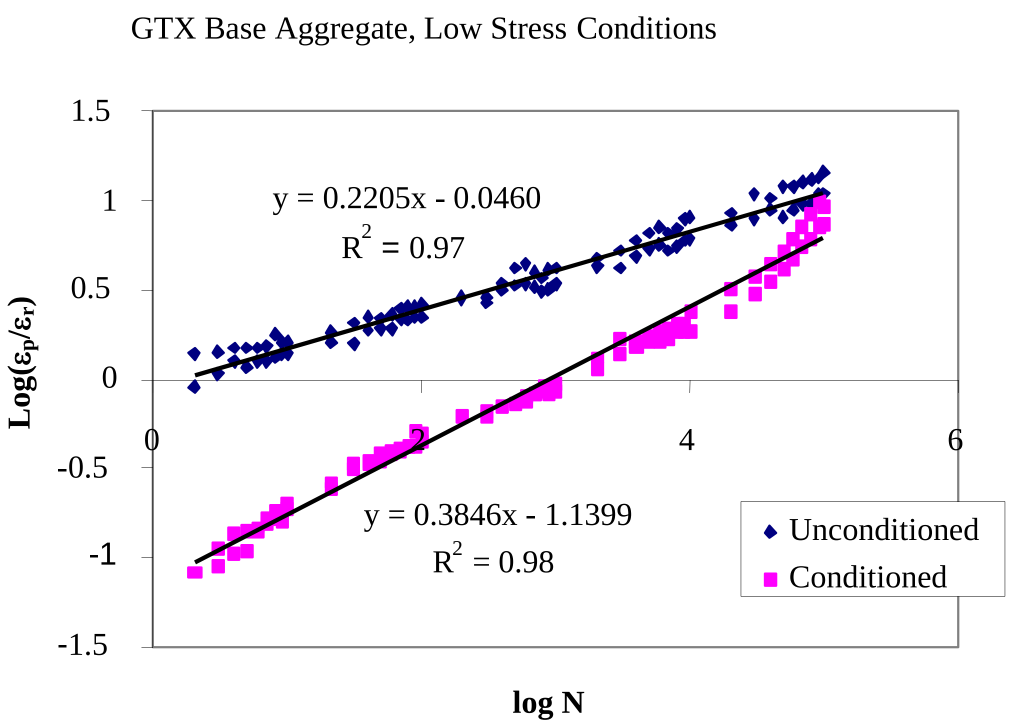


Figure 53. Repeated Load Permanent Deformation Test Results for

Unconditioned and M_R – Conditioned Specimens of GTX Base Material.

Confining Stress = 20.7 kPa, Contact Stress = 4.1 kPa, Cyclic Stress = 345kPa

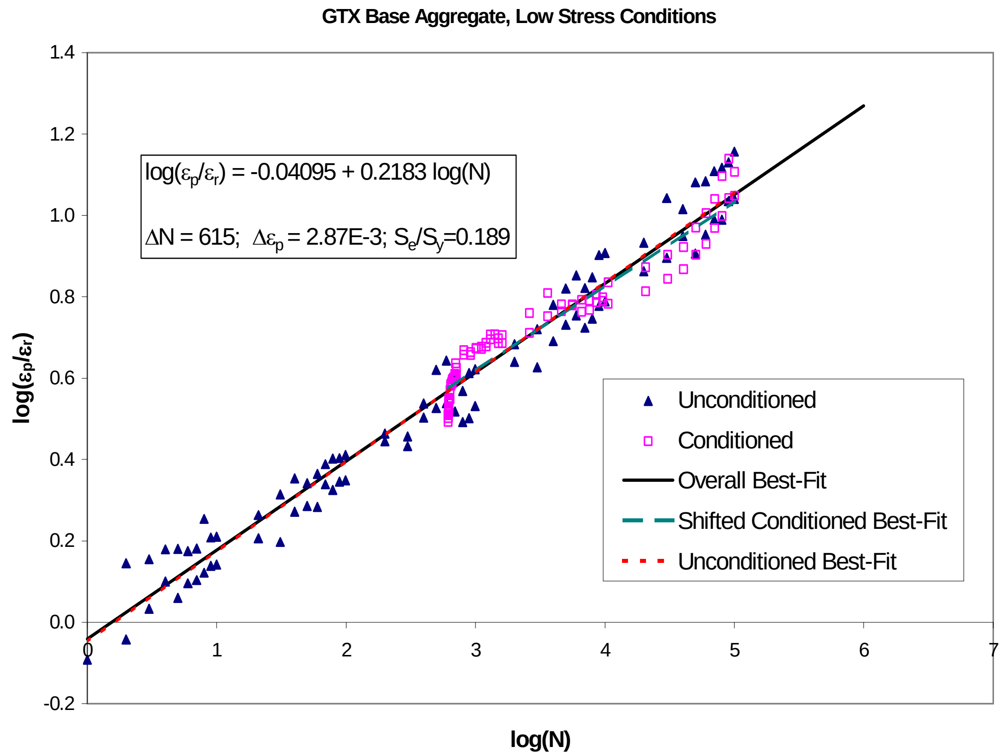


Figure 54. Unconstrained Nonlinear Optimization Results.

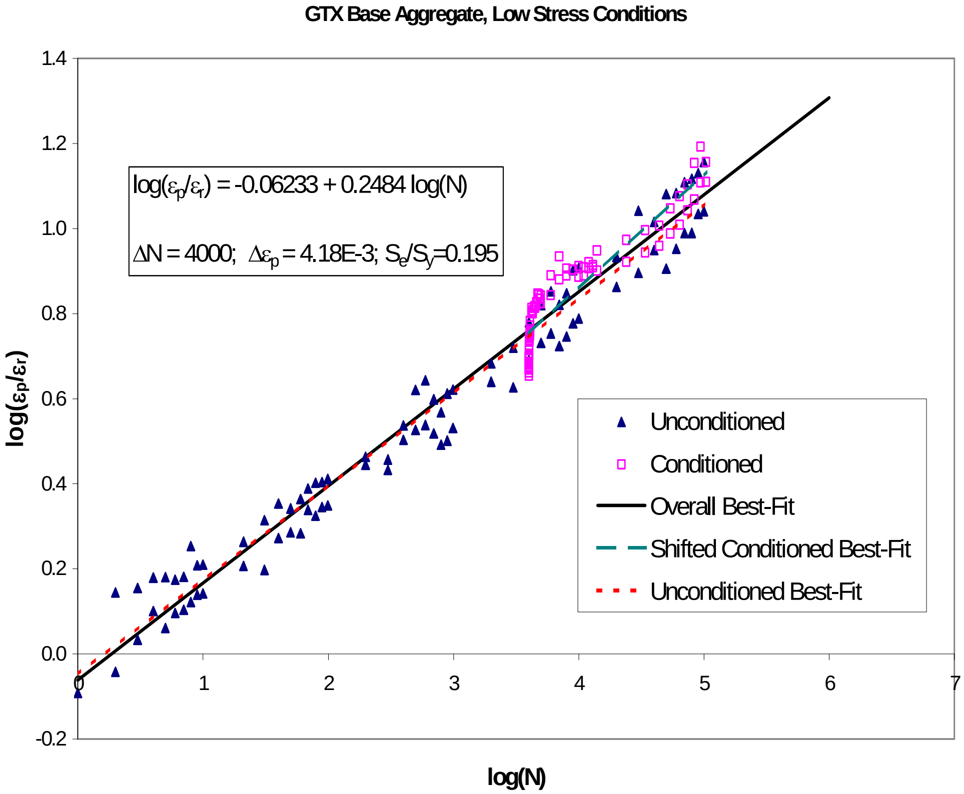


Figure 55. Nonlinear Optimization Results when ΔN Constrained to 4000.

5.4 Stress Level

Previous research has shown that stress level is one of the most important factors controlling the development of permanent strain in unbound pavement materials. Yau (1999) found that measured permanent axial strain is related to the ratio of (σ/σ_f), where σ and σ_f are the deviator stress and deviator stress at failure respectively.

In an attempt to evaluate stress level effects, the repeated load permanent deformation tests on the GTX base material were performed for the following conditions:

1. Specimens first conditioned by running a complete resilient modulus loading sequence followed by the repeated load permanent deformation test under low confining stress conditions (20.7 kPa confining stress, 4.1 kPa contact stress, 345 kPa cyclic deviator stress, $\sigma1/\sigma3 = 16.7$).
2. Specimens first conditioned by running a complete resilient modulus loading sequence followed by the repeated load permanent deformation test under high confining stress conditions (103.5 kPa confining stress, 23.8 kPa contact stress, 655 kPa cyclic deviator stress, $\sigma1/\sigma3 = 6.3$).

In this study, σ_f was not measured and therefore could not do the same as Yau did. Instead, only two combinations, $\Delta\sigma$-σ_3, were looked at. The stress states used at the University of Maryland were supposed to be the same as those ones used at SINTEF for the purpose of comparison. Therefore, constant strain test was done only for subgrade materials to obtain stress at failure because these materials could not withstand the stresses used in the study.

Observations drawn from these results are as follows:

- Behavior under low confining stress conditions (Figure 56) are much as expected, with the accumulated plastic strain vs. number of load cycles following a power law relationship (straight line on log-log plot) over much of the response, with some indication of tertiary flow failure (increase rate of plastic accumulation) after about 10,000 or 100,000 cycles.
- For the first 5000 cycles under high confining stress conditions (Figure 57), the plastic strains are less than 10^{-5} and below the resolution of the LVDTs and data acquisition system. Overall, the accumulated plastic strains for the high confining stress loading are approximately one order of magnitude smaller than those for the low confining stress loading. The increase in deviator stress for this stress state has not been proportional to the increase in confining stress.

Test results for the replicates conditioned and tested at low confining stress conditions showed better consistency compared to the replicates which were unconditioned and tested at low confining stress conditions (Figures 56 and 58, respectively).

The evaluation of strain ratio ($\varepsilon_p/\varepsilon_r$) approach to see if this normalized stress effects (as postulated earlier) could not be done because of the poor results from the high confining stress tests.

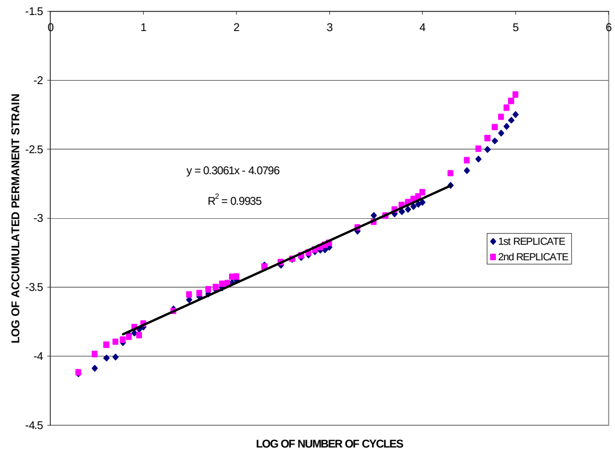


Figure 56. Repeated Load Permanent Deformation Test Results for MR-Conditioned GTX Base Material Specimens Under Low Confining Stress Condition

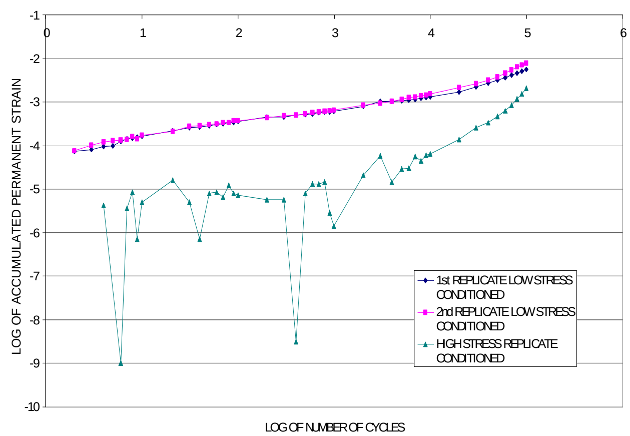


Figure 57. Repeated Load Permanent Deformation Test Results for MR-Conditioned GTX Base Material Specimens Under High Confining Stress Conditions

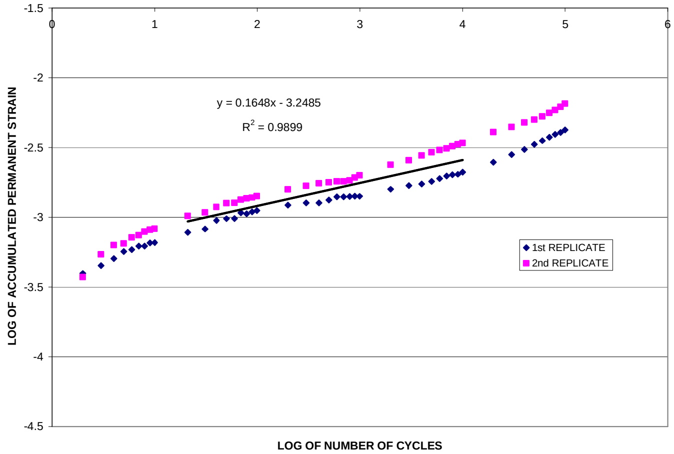


Figure 58. Repeated Load Permanent Deformation Test Results for

Unconditioned GTX Base Material Specimens Under Low Stress Conditions

5.5 Database of Typical Values

An expanded database for the typical values for resilient modulus and repeated load permanent deformation parameters has been developed using data from this study and prior work. Tables 16 and 17 show the k_i values for all unbound pavement materials tested during this research and Amber Yau (Yau, 1999). Tables 18 and 19 show the a, b, α, and β values for all unbound pavement materials tested during this research and Dragos Andrei (Andrei, 1999; Witczak, 2003).

Table 16. Resilient Modulus Parameters for the Current Study

Soil ID	Soil Description	Soil Classification		γ_d (kN/m^3)	w%	k_1	k_2	k_3
		AASHTO	USC					
GTX (Aggregate)	Crushed Stone	A-1-a	GW	22.2	4.2	741	1.091	-0.653
CRREL (Aggregate)	Gravel and Sand	A-1-b	GM	20.8	4.1	662	1.010	-0.585
MSU-1 (Aggregate)	Gravel and Sand	A-1-b	GM	20.7	6.0	957	0.906	-0.614
MSU-2 (Aggregate)	Gravel and Sand	A-1-b	GM	21.0	6.4	685	1.113	-0.581
CS (Subgrade)	Clay	A-7-6	CL	11.4	45.0	139	0.187	-3.281
SSS (Subgrade)	Silty Sand	A-4	SM	14.8	14.0	449	1.030	-1.856
GTX (Subgrade)	Clay	A-6	CL	15.0	28.5	181	0.408	-17.391
CRREL (Subgrade)	Clay	A-6	CL	15.0	28.5	170	0.450	-16.388

Table 17. Resilient Modulus Parameters from Andrei (1999)

Soil ID	Soil Description	Soil Classification		γ_d (pcf)	w%	k_1	k_2	k_3
		AASHTO	USC					
S12	Class 6 Base	A-1-a	SW-SM	142.31	4.33	781.396	1.049	-0.251
S1	Silty Sand from Moulton Pit	A-4(1)	SM	130.80	8.23	358.542	1.391	-0.900
S2	Clay from St. Albans	A-6(9)	CL	106.47	16.87	1772080	0.085	-0.253
S11	Class 6 Subbase	A-1-b	SM	135.51	7.85	306.126	1.415	-0.467
S7	ALF Subgrade	A-4(3)	SM	118.74	12.18	724.233	0.116	-0.815
S13	Silty Sand Subgrade	A-6(7)	CL	110.88	13.14	2464.486	-0.010	-0.278

Table 18. Repeated Load Permanent Deformation Parameters for the Current Study

Soil ID	Soil Description	Soil Classification		σ_f (psi)	σ (psi)	σ/σ_f	w%	γ_d (kN/m^3)	$\varepsilon_p = aN^b$		$\varepsilon_p/\varepsilon_r = \alpha N^\beta$	
		AASHTO	USC						a	b	α	β
GTX (Aggregate)	Crushed Stone	A-1-a	GW	15.5	10.1	0.65	7.5	22.2	6.91E-03	0.323	2.48E+00	0.482
CRREL (Aggregate)	Gravel and Sand	A-1-b	GM	11.3	7.3	0.65	4.1	20.8	4.13E-04	0.229	8.80E-01	0.205
MSU-1 (Aggregate)	Gravel and Sand	A-1-b	GM	13.7	8.9	0.65	6.0	20.7	4.13E-03	0.289	2.31E+00	0.368
MSU-2 (Aggregate)	Gravel and Sand	A-1-b	GM	11.9	7.7	0.65	6.4	21.0	1.41E-04	0.357	4.06E-01	0.316
CS (Subgrade)	Clay	A-7-6	CL	8.2	5.3	0.65	45.0	11.4	1.50E-03	0.402	2.11E+00	0.311
SSS (Subgrade)	Silty Sand	A-4	SM	14.0	9.1	0.65	14.0	14.8	2.73E-03	0.290	4.51E-01	0.310
CRREL (Subgrade)	Clay	A-6	CL	4.0	2.6	0.65	28.5	15.0	2.42E-03	0.346	2.37E+00	0.311
GTX (Subgrade)	Clay	A-6	CL	4.0	2.6	0.65	28.5	15.0	-2.49	0.46	4.77E-01	0.457

Note: Assumed Values for Base Materials Friction Angle

Table 19. Repeated Load Permanent Deformation Parameters from Yau (1999)

Soil ID	Soil Description	Soil Classification		σ_f	σ	σ/σ_f	γ_d (pcf)	w%	$\varepsilon_p = aN^b$		$\varepsilon_p/\varepsilon_r = \alpha N^\beta$	
		AASHTO	USC						a	b	α	β
S1	Silty sand from Moulton Pit	A-4(1)	SM	11.3	5.8	0.51	121.4	9.9	0.0004	0.1037	1.6270	0.0750
				11.3	6.2	0.55	120.9	10.2	0.0003	0.1086	1.0279	0.0796
				11.3	8.1	0.71	121.4	9.8	0.0010	0.1309	2.3747	0.1133
				11.3	11.0	0.97	120.6	10.3	0.0018	0.1921	2.6748	0.1765
				19.6	15.3	0.78	120.9	10.4	0.0022	0.1074	4.1851	0.1148
S2	Silty clay from Lyme/ Jenks	A-4(8)	CL	15.7	6.0	0.38	110.7	16.3	0.0002	0.0728	0.5179	0.0624
				15.7	6.0	0.38	111.1	15.6	6.0E-05	0.1515	1.34E-01	0.1504
				15.7	9.9	0.63	111.0	16.1	0.0016	0.208	0.9323	0.1560
				15.7	14.1	0.90	111.1	15.9	0.0032	0.2515	1.4113	0.1815
S3	Clay from St. Albans	A-6(9)	CL	18.7	6.5	0.35	106.9	19.9	0.0012	0.2012	0.4353	0.2324
				18.7	8.6	0.46	106.4	19.9	0.0044	0.1837	1.1496	0.1840
				18.7	10.9	0.58	106.8	19.9	0.0038	0.2495	0.8477	0.2245
S4	Stiff Clay	A-7-5(11)	ML	13.4	5.4	0.40	98.8	22.2	0.0002	0.2301	0.1583	0.2781
				13.4	5.5	0.41	95.8	23.5	0.0002	0.1863	0.1693	0.2417
				13.4	8.9	0.67	96.0	23.5	0.0010	0.2183	0.3480	0.2376
				13.4	9.1	0.68	97.5	24.0	9.0E-05	0.3987	8.52E-02	0.3133
				13.4	10.1	0.75	96.1	23.3	0.0039	0.2328	0.8893	0.2186
				13.4	10.3	0.77	95.6	23.4	0.0008	0.2648	0.2535	0.2531
				13.4	12.4	0.92	95.8	23.4	0.0012	0.5789	0.2756	0.5584
				13.4	13.7	1.02	96.4	22.8	0.0030	0.4767	0.5031	0.4537

CHAPTER 6 SUMMARY, CONCLUSIONS AND RECOMMENGATIONS

6.1 Summary

The primary objectives of this research were:

1. To determine the resilient modulus and permanent deformation characteristics for base and subgrade soils that had been studied previously in field- and large-scale laboratory pavement tests.
2. To determine for these materials the specific material properties required by the 2002 PDG to enable performance prediction using the 2002 PDG models.
3. To explore some details of the testing protocols:

- The differences between large vs. small specimen response
- The influence of sample conditioning and test sequence (e.g., performing resilient modulus followed by permanent deformation test on the same specimen).
- The effect of stress level on permanent deformation behavior.

4. To add to the database of typical values for the resilient modulus and repeated load permanent deformation parameters for unbound pavement materials.

This study is part of a larger investigation into the behavior of unbound base and subgrade materials in geosynthetic-reinforced flexible pavements.

Resilient modulus tests were performed using the harmonized protocols developed in NCHRP Project 1-28A (Andrei, 1999; Witczak, 2003). The stress-dependent resilient modulus model employed in the 2002 Pavement Design Guide was used for analyzing all resilient modulus test results. The resilient modulus material parameters for all soils in the study are summarized in Table 12 presented previously. Detailed resilient modulus test results are included in Appendix A.

Repeated load permanent deformation tests were performed using the protocols developed by Yau (1999). Two empirical models, a straightforward power law relations and a strain ratio model, were used for interpreting the repeated load permanent deformation test results. The permanent deformation material parameters for all soils in the study are summarized in Table 13 presented previously. Detailed permanent deformation test results are included in Appendix B.

6.2 Conclusions

6.2.1 Resilient Modulus

The following are the key findings from this study with regard to resilient modulus:

• The data measured in this study confirm that the resilient modulus of unbound materials is stress dependent. The resilient modulus for the coarse-grained materials increased with increasing volumetric stress and was relatively less sensitive to deviatoric stress, as expected. Conversely, the resilient modulus for the fine-grained subgrade soils was less sensitive to volumetric stress and more sensitive to deviatoric stress. This is consistent with the commonly observed stress-stiffening for coarse-grained soils and stress-softening for fine-grained materials.

• The stress-dependent resilient modulus model incorporated in the 2002 PDG provided a good representation for the data measured in this study. Most of the regressions for the resilient modulus model parameters had R^2 values greater than 0.9 and S_e/S_y values less than 0.4 (all in log-log space), suggesting that the regressions provide good fits to the measured data.

• The large specimens tested in Norway showed consistently larger resilient modulus values as compared to the conventionally-sized specimens tested in this study. These differences may be due in part to differences in sample preparation and in part to more significant nonuniformities in the stresses within the large specimens due to self-weight effects within the soil specimen itself and to gradients in the confining pressure due to the self-weight effects within the water confining fluid.

• The resilient modulus parameters measured in this study are broadly comparable to those measured by Andrei (1999) in NCHRP Project 1-28A, particularly when pairs of similar soil classifications are compared directly. The results from the present study provide a valuable addition to the database of resilient modulus properties of unbound pavement materials suitable for use in the 2002 PDG.

6.2.2 Repeated Load Permanent Deformation

The following are the key findings and recommendations from this study with regard to permanent deformation behavior:

• Both the straightforward power law model and the strain ratio model provided good representations of the test data. Most of the regressions for the permanent deformation material parameters had R^2 values greater than 0.9 and S_e/S_y values less than 0.2 (in log-log space).

- The resilient strain measured in some of the tests varied considerably during some of the tests, suggesting degraded quality of the test results. The most likely cause of this is loosening of the LVDT attachment clamps due to the vibrations during the repeated load tests and, in some cases, perhaps reaching the end of the linear calibration range for the LVDTs.
- Comparison of conditioned vs. unconditioned repeated load test results for the GTX base material indicated that excessive sample conditioning loading may significantly alter the repeated load response measured subsequently in the test. The conditioned tests exhibited significantly smaller permanent strains than in the corresponding unconditioned tests. This difference is the result of the permanent deformations accumulated during the sample conditioning prior to the repeated load test. An approximate correction procedure for the effects of sample conditioning is developed.
- The attempt to evaluate the ability of the strain ratio model to normalize for stress levels was unsuccessful because of the very poor test data from the high confining stress tests. Further work is suggested for the evaluation of the strain ratio model.
- For reasons of practicality, all repeated load tests conducted in this study were limited to about 10^5 load cycles. A transition from secondary (decreasing plastic strain rate) to tertiary (increasing plastic strain rate) permanent deformation is often observed at load repetitions beyond 10^5 cycles. This secondary-tertiary

transition is of interest for modeling the long-term performance of pavements. Laboratory evaluation of permanent deformation characteristics at very large numbers of cycle (10^6 and beyond) is an area that still needs further study.

The repeated load material behavior measured in this study is broadly comparable to that measured by Yau (1999). Yau examined a larger range of stress levels over a smaller set of soils than in the present study. The results from the present study provide a valuable addition to the database of permanent deformation properties of unbound pavement materials.

APPENDIX A

APPENDIX A RESILIENT MODULUS TEST DATA

Table A-1. Resilient Modulus Test Data for CRREL Base Material

Test ID	Sequence	Vertical Strain	Contact Stress (psi)	Confining Pressure (psi)	Cyclic Stress (psi)	θ (psi)	τ_{oct} (psi)	σ_1 (psi)	M_R (psi)
CRREL BASE 1st Replicate	1	4.09E-05	0.60	3.07	0.72	10.55	0.62	4.40	17623
	2	1.27E-04	1.17	5.96	2.51	21.55	1.74	9.64	19768
	3	1.81E-04	2.04	9.98	4.89	36.87	3.27	16.91	27007
	4	2.35E-04	3.07	15.08	8.07	56.36	5.25	26.21	34378
	5	2.63E-04	4.02	20.08	11.35	75.60	7.25	35.45	43204
	6	1.98E-04	0.60	3.06	2.17	11.96	1.31	5.83	10960
	7	3.29E-04	1.16	6.00	5.54	24.69	3.16	12.70	16819
	8	4.44E-04	2.04	9.97	10.54	42.48	5.93	22.54	23760
	9	5.30E-04	3.00	14.91	17.48	65.21	9.66	35.39	33003
	10	5.68E-04	4.01	20.02	23.99	88.07	13.20	48.02	42197
	11	4.61E-04	0.61	3.03	4.84	14.55	2.57	8.48	10496
	12	6.89E-04	1.20	6.07	12.30	31.71	6.36	19.57	17847
	13	8.68E-04	2.04	10.03	23.44	55.58	12.01	35.52	27008
	14	9.56E-04	3.03	14.98	35.69	83.66	18.25	53.70	37326
	15	1.04E-03	4.05	20.10	46.70	111.03	23.92	70.84	44990
	16	7.04E-04	0.63	2.97	7.56	17.09	3.86	11.15	10734
	17	1.01E-03	1.19	6.06	20.15	39.52	10.06	27.40	20036
	18	1.22E-03	2.06	10.00	35.35	67.41	17.64	47.41	28956
	19	1.40E-03	3.02	15.04	51.98	100.11	25.93	70.04	37193
	20	1.52E-03	4.01	19.99	67.65	131.64	33.78	91.65	44559
	21	1.18E-03	0.61	2.99	14.79	24.37	7.26	18.39	12506
	22	1.61E-03	1.22	5.95	35.32	54.39	17.23	42.49	21959
	23	1.97E-03	2.08	10.03	58.14	90.30	28.38	70.24	29538
	24	2.18E-03	3.00	15.04	84.55	132.69	41.27	102.60	38762
	25	2.20E-03	4.05	20.03	108.67	172.83	53.14	132.76	49332
CRREL Base 2nd Replicate	1	1.74E-04	0.61	3.02	1.29	10.97	0.90	4.92	7386
	2	2.31E-04	1.23	6.03	2.63	21.96	1.82	9.90	11375
	3	2.44E-04	2.03	10.04	4.91	37.06	3.27	16.98	20089
	4	2.71E-04	3.00	15.02	7.74	55.82	5.07	25.77	28547
	5	2.80E-04	4.03	20.06	10.84	75.04	7.01	34.93	38724
	6	3.81E-04	0.50	3.06	2.59	12.26	1.46	6.15	6802
	7	4.77E-04	1.21	6.06	5.89	25.28	3.35	13.16	12349
	8	4.95E-04	2.08	10.01	10.13	42.23	5.75	22.21	20448
	9	5.24E-04	3.06	15.04	16.02	64.20	9.00	34.12	30563
	10	5.39E-04	4.08	19.93	21.30	85.17	11.96	45.31	39487
	11	6.66E-04	0.59	3.03	4.90	14.57	2.59	8.52	7355
	12	8.39E-04	1.21	5.85	11.73	30.48	6.10	18.79	13987
	13	8.98E-04	2.00	10.00	21.36	53.37	11.01	33.36	23784
	14	9.44E-04	3.04	15.05	32.28	80.49	16.65	50.38	34193
	15	1.02E-03	4.02	20.06	42.26	106.47	21.82	66.34	41623
	16	9.46E-04	0.60	3.02	7.81	17.46	3.97	11.43	8253
	17	1.11E-03	1.20	6.06	18.79	38.16	9.42	26.05	16909
	18	1.24E-03	2.01	10.02	32.66	64.72	16.34	44.69	26331
	19	1.35E-03	3.03	14.93	47.85	95.66	23.98	65.81	35554
	20	1.45E-03	4.06	20.01	62.46	126.55	31.36	86.53	43168
	21	1.29E-03	0.61	2.97	14.35	23.88	7.05	17.93	11096
	22	1.55E-03	1.21	6.05	32.38	51.73	15.84	39.64	20945
	23	1.76E-03	2.02	9.93	53.30	85.12	26.08	65.25	30242
	24	1.93E-03	3.02	15.02	76.57	124.65	37.52	94.61	39709
	25	1.98E-03	4.09	19.97	101.06	165.06	49.57	125.12	51042

Table A-2. Resilient Modulus Test Data for MSU-1 Base Material

Test ID	Sequence	Vertical Strain	Contact Stress (psi)	Confining Pressure (psi)	Cyclic Stress (psi)	θ (psi)	τ_{oct} (psi)	σ_1 (psi)	M_R (psi)
MSU-1 1st Replicate	1	4.74E-05	0.60	3.02	0.64	10.30	0.59	4.26	13510
	2	1.08E-05	1.29	5.92	0.34	19.39	0.77	7.55	31602
	3	1.53E-04	2.03	9.93	4.04	35.87	2.86	16.00	26441
	4	2.17E-04	3.09	15.07	7.87	56.17	5.16	26.03	36169
	5	2.28E-04	4.00	20.09	11.67	75.94	7.39	35.77	51145
	6	6.46E-06	0.71	3.06	0.18	10.06	0.42	3.94	27590
	7	3.23E-04	1.19	6.06	5.10	24.48	2.97	12.36	15801
	8	4.07E-04	2.21	9.94	9.75	41.78	5.63	21.90	23947
	9	4.59E-04	2.97	15.02	17.35	65.39	9.58	35.34	37834
	10	4.63E-04	4.05	19.93	24.42	88.26	13.42	48.40	52714
	11	2.82E-04	0.58	3.14	4.14	14.14	2.22	7.86	14676
	12	5.92E-04	1.27	6.01	12.14	31.46	6.32	19.43	20509
	13	7.20E-04	1.96	10.12	23.86	56.17	12.17	35.94	33126
	14	7.71E-04	3.07	15.06	35.46	83.70	18.16	53.58	46001
	15	8.38E-04	4.05	19.96	45.95	109.88	23.57	69.96	54861
	16	4.80E-04	0.64	3.08	6.68	16.56	3.45	10.40	13919
	17	8.23E-04	1.36	6.04	20.28	39.77	10.20	27.69	24653
	18	9.48E-04	1.88	10.05	35.69	67.73	17.71	47.62	37625
	19	1.18E-03	3.05	14.96	51.53	99.44	25.73	69.53	43787
	20	1.33E-03	4.04	20.04	65.49	129.65	32.78	89.57	49059
	21	9.94E-04	0.69	3.04	13.42	23.25	6.65	17.16	13509
	22	1.30E-03	1.34	6.08	34.81	54.40	17.04	42.23	26854
	23	1.51E-03	2.01	10.09	56.70	88.98	27.68	68.80	37510
	24	1.69E-03	3.09	14.88	82.00	129.72	40.11	99.97	48388
	25	1.90E-03	4.02	20.08	106.09	170.35	51.91	130.19	55767
MSU-1 2nd Replicate	1	4.74E-05	0.48	3.01	1.19	10.69	0.79	4.68	25138
	2	1.46E-04	1.20	6.06	2.93	22.32	1.94	10.20	20028
	3	1.74E-04	2.04	10.03	4.49	36.60	3.08	16.55	25732
	4	2.24E-04	2.87	15.07	8.21	56.28	5.22	26.15	36645
	5	2.50E-04	4.07	19.96	12.08	76.04	7.61	36.11	48357
	6	1.68E-04	0.49	3.05	2.22	11.87	1.28	5.76	13216
	7	3.45E-04	1.20	6.04	5.59	24.90	3.20	12.83	16225
	8	4.44E-04	1.91	10.09	10.43	42.60	5.82	22.43	23523
	9	5.06E-04	3.16	15.02	16.92	65.15	9.47	35.11	33444
	10	4.16E-04	4.05	20.03	23.54	87.70	13.01	47.63	56651
	11	3.18E-04	0.61	3.07	4.29	14.10	2.31	7.97	13519
	12	5.61E-04	1.23	6.07	11.47	30.90	5.99	18.77	20451
	13	7.47E-04	2.03	9.98	23.52	55.47	12.04	35.52	31477
	14	7.92E-04	2.77	15.09	35.30	83.33	17.95	53.16	44546
	15	8.85E-04	4.05	20.00	46.20	110.25	23.69	70.26	52208
	16	5.76E-04	0.52	3.05	7.35	17.02	3.71	10.92	12757
	17	8.90E-04	1.19	6.06	19.67	39.03	9.84	26.92	22092
	18	1.06E-03	2.04	9.92	34.28	66.06	17.12	46.23	32389
	19	1.28E-03	3.08	15.01	51.23	99.33	25.60	69.31	39883
	20	1.46E-03	4.05	20.11	66.67	131.06	33.34	90.84	45672
	21	1.11E-03	0.64	3.07	14.10	23.94	6.95	17.81	127572
	22	1.47E-03	1.20	6.06	34.18	53.55	16.68	41.44	3310
	23	1.88E-03	2.04	10.02	56.84	88.94	27.76	68.90	30270
	24	2.19E-03	3.02	15.05	81.7	129.75	39.88	9964	37245
	25	2.11E-03	4.06	19.94	106.78	170.67	52.25	130.79	50550

Table A-3. Resilient Modulus Test Data for MSU-2 Base Material

Test ID	Sequence	Vertical Strain	Contact Stress (psi)	Confining Pressure (psi)	Cyclic Stress (psi)	θ (psi)	τ_{oct} (psi)	σ_1 (psi)	M_R (psi)
MSU-2 1st Replicate	1	1.22E-04	0.60	3.03	1.12	10.81	0.81	4.75	9165
	2	2.44E-04	1.25	6.03	3.04	22.38	2.02	10.31	12445
	3	2.41E-04	2.01	10.04	5.69	37.81	3.63	17.74	23595
	4	2.31E-04	3.01	14.94	9.47	57.28	5.88	27.41	40956
	5	2.08E-04	4.02	20.04	11.89	76.02	7.50	35.94	57099
	6	2.73E-04	0.60	3.05	2.95	12.69	1.68	6.60	10827
	7	4.05E-04	1.21	6.06	6.66	26.05	3.71	13.93	16458
	8	4.13E-04	2.01	10.02	12.15	44.23	6.67	24.18	29384
	9	3.93E-04	3.02	15.06	17.79	65.98	9.81	35.86	45232
	10	3.82E-04	4.00	20.09	22.46	86.73	12.47	46.55	58805
	11	4.81E-04	0.60	3.02	6.48	16.15	3.34	10.10	13474
	12	6.68E-04	1.20	6.06	13.71	33.09	7.03	20.97	20537
	13	7.29E-04	2.01	10.01	22.86	54.89	11.72	34.87	31343
	14	7.35E-04	3.00	15.10	32.28	80.57	16.63	50.38	43922
	15	7.54E-04	4.02	20.04	41.33	105.45	21.38	65.38	54837
	16	6.89E-04	0.62	3.02	9.89	19.57	4.95	13.53	14353
	17	9.72E-04	1.20	6.03	20.58	39.87	10.27	27.81	21176
	18	1.01E-03	2.02	10.05	32.76	64.92	16.39	44.83	32413
	19	9.22E-04	3.01	15.06	46.95	95.14	23.55	65.02	50938
	20	8.67E-04	4.00	20.01	60.22	124.26	30.28	84.24	69456
MSU-2 2nd Replicate	1	1.69E-04	0.60	3.16	1.32	11.39	0.90	5.08	7767
	2	2.51E-04	1.20	5.97	2.94	22.05	1.95	10.11	11697
	3	3.23E-04	2.00	10.03	5.61	37.71	3.59	17.65	17380
	4	2.80E-04	3.01	15.11	8.49	56.83	5.42	26.61	30342
	5	2.53E-04	4.00	20.01	11.37	75.41	7.25	35.38	44987
	6	2.86E-04	0.60	2.97	2.80	12.32	1.60	6.38	9787
	7	4.28E-04	1.20	6.09	6.45	25.92	3.61	13.74	15079
	8	5.04E-04	2.00	9.99	11.42	43.40	6.33	23.41	22659
	9	4.91E-04	3.01	15.05	17.03	65.18	9.44	35.08	34682
	10	4.81E-04	4.01	20.07	22.37	86.59	12.43	46.45	46518
	11	4.97E-04	0.60	3.15	6.28	16.34	3.24	10.03	12634
	12	5.91E-04	1.20	6.22	13.78	33.64	7.06	21.20	23303
	13	6.50E-04	2.01	10.10	22.62	54.95	11.61	34.74	34783
	14	7.35E-04	3.00	14.97	33.00	80.91	16.97	50.97	44892
	15	8.18E-04	4.01	20.03	42.89	107.00	22.11	66.93	52410
	16	7.72E-04	0.60	3.07	10.03	19.84	5.01	13.70	12990
	17	8.82E-04	1.20	6.01	20.78	40.02	10.36	27.99	23538
	18	1.01E-03	2.00	10.08	33.53	65.76	16.75	45.60	33126
	19	1.23E-03	3.01	15.06	48.58	96.78	24.32	66.66	39626
	20	1.45E-03	4.00	20.23	63.52	128.21	31.83	87.75	43723

Table A-4. Resilient Modulus Test Data for GTX Base Material

Test ID	Sequence	Vertical Strain	Contact Stress (psi)	Confining Pressure (psi)	Cyclic Stress (psi)	θ (psi)	τ_{oct} (psi)	σ_1 (psi)	M_R (psi)
GTX Base 1st Replicate	1	2.05E-04	0.60	3.03	1.30	11.00	0.90	4.94	6321
	2	2.42E-04	1.2	6.05	2.94	22.28	1.95	10.19	12164
	3	2.43E-04	2.00	10.07	5.35	37.55	3.47	17.42	21976
	4	2.33E-04	3.00	15.07	7.97	56.20	5.17	26.05	34294
	5	2.22E-04	4.01	20.06	10.46	74.64	6.82	34.52	46996
	6	3.63E-04	0.60	3.01	2.82	12.44	1.61	6.42	7759
	7	4.22E-04	1.20	6.02	6.36	25.62	3.56	13.58	15060
	8	4.22E-04	2.00	10.05	10.77	42.91	6.02	22.82	25513
	9	4.14E-04	3.00	15.07	15.86	64.06	8.89	33.93	38302
	10	4.07E-04	4.00	20.07	20.80	85.00	11.69	44.87	51119
	11	5.72E-04	0.60	3.06	6.17	15.94	3.19	9.83	10785
	12	6.57E-04	1.20	6.07	13.03	32.42	6.71	20.29	19813
	13	6.76E-04	2.00	9.91	20.93	52.66	10.81	32.84	30959
	14	7.05E-04	3.00	15.08	30.84	79.08	15.95	48.92	43761
	15	7.59E-04	4.01	20.05	41.05	105.20	21.24	65.11	54065
	16	7.26E-04	0.60	3.04	9.56	19.30	4.79	13.21	13158
	17	8.63E-04	1.20	6.02	19.32	38.57	9.67	26.54	22394
	18	9.25E-04	2.00	10.12	31.08	63.44	15.59	43.20	33595
	19	1.04E-03	3.01	15.02	46.17	94.25	23.18	64.20	44549
	20	1.15E-03	4.00	20.04	61.47	125.60	30.86	85.51	53492
	21	9.79E-04	0.60	3.07	16.42	26.24	8.02	20.10	16774
	22	1.23E-03	1.21	6.02	31.33	50.59	15.33	38.55	25494
	23	1.45E-03	2.00	10.06	50.94	83.13	24.96	63.00	35049
	24	1.68E-03	3.02	15.03	75.90	124.02	37.21	93.96	45194
	25	1.18E-03	4.01	20.02	100.92	164.99	49.47	124.95	55663
GTX Base 2nd Replicate	1	1.31E-04	0.60	3.09	1.36	11.24	0.92	5.05	10351
	2	1.87E-04	1.21	6.04	3.11	22.44	2.04	10.36	16687
	3	2.07E-04	2.01	10.05	5.47	37.62	3.53	17.53	26469
	4	2.06E-04	3.01	15.07	8.15	56.38	5.26	26.23	39549
	5	2.03E-04	4.01	20.04	10.80	74.95	6.99	34.86	53189
	6	2.76E-04	0.60	3.03	2.76	12.45	1.58	6.39	9973
	7	3.50E-04	1.20	6.04	6.30	25.61	3.53	13.54	17979
	8	3.85E-04	2.00	10.05	11.18	43.33	6.22	23.23	29071
	9	3.75E-04	3.02	14.98	16.25	64.20	9.08	34.25	43298
	10	3.74E-04	4.00	20.03	21.32	85.41	11.94	45.35	57021
	11	4.90E-04	0.60	3.06	6.22	15.99	3.22	9.88	12689
	12	5.66E-04	1.21	6.08	13.52	32.95	6.94	20.80	23867
	13	6.03E-04	2.00	10.07	21.89	54.10	11.26	33.96	36300
	14	6.35E-04	3.02	15.14	31.61	80.05	16.33	49.77	49771
	15	6.85E-04	4.01	20.03	41.56	105.65	21.48	65.60	60701
	16	6.24E-04	0.60	3.02	9.84	19.50	4.92	13.46	15775
	17	7.41E-04	1.20	6.05	20.04	39.39	10.01	27.29	27050
	18	8.25E-04	2.03	10.04	32.05	64.22	16.07	44.13	38834
	19	9.24E-04	3.02	15.04	46.37	94.53	23.28	64.44	50202
	20	1.02E-03	4.01	20.04	61.36	125.49	30.82	85.41	59911
	21	8.79E-04	0.60	2.91	17.39	26.73	8.48	20.91	19799
	22	1.05E-03	1.20	6.06	32.73	52.12	15.99	39.99	31191
	23	1.24E-03	2.00	10.06	51.61	83.80	25.27	63.67	41517
	24	1.47E-03	3.01	15.01	75.94	123.99	37.22	93.97	51817
	25	1.63E-03	4.03	20.03	100.33	164.44	49.19	124.39	61609

Table A-5. Resilient Modulus Test Data for GTX Base and CS Subgrade Material

Test ID	Sequence	Vertical Strain	Contact Stress (psi)	Confining Pressure (psi)	Cyclic Stress (psi)	θ (psi)	τ_{oct} (psi)	σ_1 (psi)	MR (psi)
GTX Base 3rd Replicate	1	1.84E-04	0.60	3.05	1.32	11.07	0.90	4.97	7161
	2	2.20E-04	1.20	6.11	2.90	22.44	1.93	10.21	13196
	3	2.47E-04	2.00	10.05	5.38	37.52	3.48	17.42	21775
	4	2.40E-04	3.01	15.04	7.98	56.12	5.18	26.03	33282
	5	2.38E-04	4.01	20.02	10.72	74.79	6.94	34.75	44971
	6	3.62E-04	0.62	3.03	2.75	12.47	1.59	6.40	7583
	7	4.34E-04	1.20	6.08	6.32	25.76	3.54	13.60	14544
	8	4.46E-04	2.00	9.99	10.90	42.87	6.08	22.89	24405
	9	4.42E-04	3.01	15.08	16.24	64.50	9.08	34.33	36728
	10	4.30E-04	4.00	20.07	21.09	85.30	11.83	45.16	49060
	11	6.08E-04	0.60	3.07	6.06	15.86	3.14	9.73	9974
	12	7.08E-04	1.20	6.06	13.43	32.80	6.90	20.69	18960
	13	7.22E-04	2.00	10.03	21.66	53.75	11.15	33.69	29996
	14	7.38E-04	3.01	15.03	30.90	79.00	15.98	48.94	41882
	15	7.97E-04	4.00	20.01	41.17	105.21	21.29	65.18	51675
	16	7.86E-04	0.60	3.03	9.53	19.23	4.77	13.16	12124
	17	9.14E-04	1.20	6.01	19.96	39.18	9.97	27.16	21841
	18	9.85E-04	2.02	10.00	31.14	63.15	15.63	43.16	31626
	19	1.09E-03	3.00	15.01	45.89	93.91	23.05	63.90	41951
	20	1.23E-03	4.01	20.07	61.17	125.39	30.73	85.25	49812
	21	1.08E-03	0.61	3.07	16.89	26.71	8.25	20.57	15577
	22	1.30E-03	1.20	6.06	31.98	51.35	15.64	39.24	24512
	23	1.54E-03	2.00	10.04	50.27	82.39	24.64	62.31	32546
	24	1.81E-03	3.01	15.01	75.28	123.33	36.90	93.30	41669
	25	1.99E-03	4.00	20.00	100.58	164.57	49.30	124.58	50608
CS Subgrade 1st Replicate	1	2.82E-03	1.61	8.08	3.72	29.57	2.51	13.40	1336
	2	2.73E-03	1.21	6.07	3.71	23.12	2.32	10.99	1375
	3	2.67E-03	0.83	4.03	3.63	16.54	2.10	8.49	1357
	4	2.54E-03	0.41	2.02	3.65	10.14	1.92	6.09	1334
	5	5.45E-03	1.61	8.05	6.16	31.94	3.66	15.83	1151
	6	5.48E-03	1.21	6.03	6.18	25.48	3.48	13.42	1145
	7	5.62E-03	0.81	4.08	6.21	19.27	3.31	11.10	1122
	8	5.47E-03	0.42	2.05	6.06	12.63	3.06	8.53	1074
CS Subgrade 2nd Replicate	1	2.59E-03	1.61	8.14	3.63	29.67	2.47	13.38	1344
	2	2.52E-03	1.20	6.07	3.63	23.03	2.28	10.90	1357
	3	2.62E-03	0.80	4.04	3.61	16.54	2.08	8.45	1316
	4	2.64E-03	0.42	2.07	3.44	10.07	1.82	5.93	1234
	5	5.49E-03	1.61	8.07	6.10	31.91	3.63	15.78	1107
	6	5.60E-03	1.22	6.06	6.06	25.46	3.43	13.34	1078
	7	5.84E-03	0.81	4.03	6.00	18.89	3.21	10.84	1025
	8	6.00E-03	0.41	2.02	5.87	12.35	2.96	8.31	953
CS Subgrade 3rd Replicate	1	2.98E-03	1.61	8.10	3.91	29.81	2.60	13.61	1388
	2	2.83E-03	1.22	6.06	3.78	23.19	2.36	11.06	1425
	3	2.92E-03	0.80	4.05	3.79	16.75	2.16	8.64	1419
	4	2.81E-03	0.42	2.07	3.63	10.26	1.91	6.12	1346
	5	5.50E-03	1.63	8.04	6.26	32.01	3.72	15.93	1216
	6	5.61E-03	1.20	6.05	6.22	25.56	3.50	13.47	1198
	7	5.77E-03	0.80	4.06	6.22	19.20	3.31	11.08	1158
	8	5.99E-03	0.44	2.04	6.10	12.67	3.08	8.58	1081

Table A-6. Resilient Modulus Test Data for SSS Subgrade Material

Test ID	Sequence	Vertical Strain	Contact Stress (psi)	Confining Pressure (psi)	Cyclic Stress (psi)	θ (psi)	τ_{oct} (psi)	σ_1 (psi)	M_R (psi)
SSS Subgrade 1st Replicate	1	3.96E-04	1.61	8.22	3.62	29.89	2.46	13.45	9133
	2	5.57E-04	1.17	6.10	3.58	23.04	2.24	10.85	6427
	3	7.75E-04	0.75	4.02	3.32	16.12	1.92	8.09	4286
	4	9.50E-04	0.44	2.14	2.80	9.68	1.53	5.39	2953
	5	7.91E-04	1.55	8.18	6.54	32.62	3.81	16.26	8262
	6	1.06E-03	1.14	6.07	6.21	25.55	3.46	13.41	5867
	7	1.28E-03	0.84	3.99	5.58	18.40	3.03	10.42	4347
	8	1.51E-03	0.42	2.14	4.80	11.64	2.46	7.36	3172
	9	1.02E-03	1.61	8.15	9.02	35.07	5.01	18.77	8876
	10	1.12E-03	1.2	5.99	8.31	27.48	4.49	15.51	7397
	11	9.88E-04	0.86	4.09	7.68	20.82	4.03	12.63	7771
SSS Subgrade 2nd Replicate	1	2.87E-04	1.61	8.12	3.52	29.49	2.42	13.25	12244
	2	3.64E-04	1.20	6.07	3.43	22.83	2.18	10.70	9424
	3	5.06E-04	0.80	3.96	3.16	15.83	1.87	7.92	6241
	4	6.51E-04	0.41	2.07	2.73	9.35	1.48	5.21	4192
	5	5.80E-04	1.61	8.05	6.13	31.89	3.65	15.79	10572
	6	7.31E-04	1.21	6.00	5.95	25.15	3.38	13.16	8144
	7	9.92E-04	0.80	3.97	5.50	18.20	2.97	10.27	5548
	8	1.30E-03	0.46	2.00	4.81	11.27	2.48	7.27	3711
	9	8.80E-04	1.61	8.14	8.70	34.74	4.86	18.45	9891
	10	1.06E-03	1.23	6.01	8.29	27.54	4.49	15.52	7840
	11	1.06E-03	0.85	3.99	7.58	20.39	3.97	12.42	7157
SSS Subgrade 3rd Replicate	1	3.06E-04	1.61	8.11	3.46	29.40	2.39	13.18	11323
	2	3.98E-04	1.21	6.12	3.26	22.84	2.11	10.60	8196
	3	4.94E-04	0.80	4.12	2.94	16.10	1.76	7.86	5941
	4	5.77E-04	0.46	2.11	2.52	9.30	1.40	5.09	4375
	5	6.27E-04	1.61	8.09	6.04	31.93	3.61	15.74	9646
	6	8.33E-04	1.22	5.88	5.68	24.53	3.25	12.78	6819
	7	1.04E-03	0.84	4.07	5.16	18.20	2.83	10.07	4945
	8	1.26E-03	0.50	2.22	4.69	11.85	2.45	7.41	3724
	9	9.84E-04	1.41	8.14	8.91	34.74	4.87	18.46	9059
	10	1.08E-03	1.20	6.04	8.33	27.66	4.49	15.58	7707
	11	8.87E-04	0.88	4.01	7.65	20.56	4.02	12.54	8621

Table A-7. Resilient Modulus Test Data for GTX Subgrade Material

Test ID	Sequence	Vertical Strain	Contact Stress (psi)	Confining Pressure (psi)	Cyclic Stress (psi)	θ (psi)	τ_{oct} (psi)	σ_1 (psi)	M_R (psi)
GTX Subgrade 1st Replicate	1	4.83E-04	0.6114	8.0260	0.8470	25.5364	0.6875	9.4844	1752
	2	4.75E-04	0.4552	6.0439	0.8635	19.4504	0.6216	7.3626	1819
	3	4.87E-04	0.3072	4.1012	0.7730	13.3838	0.5092	5.1814	1588
	4	4.90E-04	0.1509	2.0371	0.7154	6.9778	0.4084	2.9035	1460
	5	1.08E-03	0.6279	7.9790	1.3404	25.9054	0.9279	9.9473	1245
	6	1.08E-03	0.4716	6.0133	1.3240	19.8354	0.8465	7.8089	1227
	7	1.08E-03	0.3401	4.1000	1.2582	13.8981	0.7534	5.6982	1162
	8	1.07E-03	0.2003	2.0616	1.1842	7.5693	0.6526	3.4461	1102
	9	1.70E-03	0.6690	8.1349	1.8092	26.8829	1.1682	10.6131	1066
GTX Subgrade 2nd Replicate	1	5.57E-04	0.6279	8.1304	0.8552	25.8744	0.6991	9.6135	1536
	2	6.72E-04	0.4634	6.0817	0.8964	19.6049	0.6410	7.4415	1334
	3	7.14E-04	0.2907	4.1753	0.8635	13.6800	0.5441	5.3294	1210
	4	6.91E-04	0.1509	2.0480	0.8059	7.1008	0.4510	3.0048	1166
	5	1.37E-03	0.6114	8.1106	1.3898	26.3331	0.9434	10.1118	1011
	6	1.36E-03	0.4552	6.0193	1.3651	19.8782	0.8581	7.8396	1001
	7	1.36E-03	0.3072	3.9917	1.3322	13.6145	0.7728	5.6311	979
	8	1.35E-03	0.1674	2.1175	1.2417	7.7615	0.6643	3.5266	918
	9	1.86E-03	0.6525	8.1178	1.7434	26.7494	1.1294	10.5138	935
GTX Subgrade 3rd Replicate	1	5.96E-04	0.6690	8.0467	0.7812	25.5903	0.6836	9.4969	1310
	2	5.95E-04	0.4470	6.0657	0.8059	19.4500	0.5906	7.3186	1354
	3	6.08E-04	0.3072	4.1839	0.7566	13.6154	0.5014	5.2476	1244
	4	6.31E-04	0.1509	2.0423	0.7154	6.9933	0.4084	2.9087	1134
	5	1.10E-03	1.0966	8.0341	1.0937	26.2926	1.0325	10.2244	998
	6	1.24E-03	0.4799	6.0058	1.2500	19.7474	0.8154	7.7357	1010
	7	1.26E-03	0.3483	3.9629	1.1842	13.4211	0.7224	5.4953	939
	8	1.28E-03	0.2003	2.0320	1.1266	7.4229	0.6255	3.3589	879
	9	1.67E-03	0.6854	8.1486	1.6611	26.7924	1.1062	10.4952	996

Table A-8. Resilient Modulus Test Data for CRREL Subgrade Material

Test ID	Sequence	Vertical Strain	Contact Stress (psi)	Confining Pressure (psi)	Cyclic Stress (psi)	θ (psi)	τ_{oct} (psi)	σ_1 (psi)	M_R (psi)
CRREL Subgrade 1st Replicate	1	6.52E-04	0.6197	8.0315	0.9457	25.6598	0.7379	9.5968	1450
	2	5.92E-04	0.7430	6.0994	0.8388	19.8799	0.7457	7.6811	1417
	3	6.19E-04	0.3072	4.1066	0.8059	13.4328	0.5247	5.2196	1320
	4	6.57E-04	0.1509	2.0433	0.7566	7.0372	0.4278	2.9507	1152
	5	1.31E-03	0.6361	8.0325	1.4309	26.1645	0.9744	10.0995	1094
	6	1.33E-03	0.4552	5.9690	1.3898	19.7519	0.8697	7.8139	1046
	7	1.35E-03	0.3072	3.9715	1.3157	13.5374	0.7650	5.5944	971
	8	1.35E-03	0.1838	2.0193	1.2088	7.4505	0.6565	3.4119	888
CRREL Subgrade 2nd Replicate	1	5.17E-04	0.6032	8.0451	0.8799	25.6183	0.6991	9.5282	1703
	2	5.25E-04	0.4470	6.1862	0.8799	19.8855	0.6255	7.5131	1675
	3	5.47E-04	0.2989	4.1390	0.8306	13.5466	0.5325	5.2685	1519
	4	5.78E-04	0.1674	2.2066	0.7730	7.5601	0.4433	3.1469	1337
	5	1.14E-03	0.6197	8.0011	1.4638	26.0867	0.9821	10.0845	1289
	6	1.15E-03	0.4470	6.0822	1.4309	20.1244	0.8852	7.9600	1240
	7	1.18E-03	0.3072	4.0588	1.3240	13.8075	0.7689	5.6899	1125
	8	1.21E-03	0.1674	2.0100	1.2253	7.4227	0.6565	3.4027	1013
CRREL Subgrade 3rd Replicate	1	5.96E-04	0.6032	8.0881	0.8059	25.6735	0.6643	9.4972	1351
	2	5.89E-04	0.4634	6.0296	0.7894	19.3417	0.5906	7.2825	1341
	3	6.15E-04	0.3072	4.0364	0.7237	13.1399	0.4859	5.0672	1177
	4	6.45E-04	0.1509	2.0280	0.6743	6.9093	0.3890	2.8533	1046
	5	1.32E-03	0.6032	8.0252	1.3569	26.0358	0.9240	9.9853	1025
	6	1.36E-03	0.4634	6.0827	1.3157	20.0272	0.8387	7.8618	970
	7	1.39E-03	0.3318	4.0971	1.2500	13.8731	0.7457	5.6789	898
	8	1.41E-03	0.2003	2.0125	1.1431	7.3809	0.6332	3.3558	808

APPENDIX B

APPENDIX B REPEATED LOAD PERMANENT DEFORMATION TEST DATA

Table B-1. Repeated Load Permanent Deformation Test Data for GTX Base Low-Stress (Conditioned)

Replicate	Cycle N	ε_1	ε_1^p	ε_1^r
1st Replicate	1	9.70E-04	3.37E-05	9.36E-04
	2	9.88E-04	7.46E-05	9.13E-04
	3	9.98E-04	8.18E-05	9.16E-04
	4	1.00E-03	9.69E-05	9.04E-04
	5	1.01E-03	9.83E-05	9.14E-04
	6	1.01E-03	1.26E-04	8.86E-04
	7	1.02E-03	1.44E-04	8.71E-04
	8	1.02E-03	1.47E-04	8.77E-04
	9	1.02E-03	1.57E-04	8.66E-04
	10	1.03E-03	1.63E-04	8.66E-04
	21	1.05E-03	2.20E-04	8.30E-04
	31	1.08E-03	2.57E-04	8.21E-04
	40	1.08E-03	2.71E-04	8.07E-04
	50	1.10E-03	2.82E-04	8.18E-04
	60	1.10E-03	3.04E-04	7.98E-04
	70	1.12E-03	3.14E-04	8.07E-04
	80	1.13E-03	3.39E-04	7.92E-04
	90	1.14E-03	3.41E-04	7.97E-04
	100	1.15E-03	3.57E-04	7.96E-04
	200	1.19E-03	4.58E-04	7.34E-04
	300	1.19E-03	4.58E-04	7.35E-04
	399	1.22E-03	5.02E-04	7.16E-04
	498	1.24E-03	5.21E-04	7.23E-04
	597	1.26E-03	5.43E-04	7.18E-04
	696	1.25E-03	5.73E-04	6.77E-04
	795	1.27E-03	5.89E-04	6.80E-04
	894	1.31E-03	5.90E-04	7.15E-04
	993	1.34E-03	6.17E-04	7.20E-04
	2000	1.52E-03	8.05E-04	7.16E-04
	3000	1.66E-03	1.05E-03	6.09E-04
	3999	1.70E-03	1.05E-03	6.50E-04
	4998	1.73E-03	1.07E-03	6.57E-04
	5997	1.81E-03	1.12E-03	6.89E-04
	6996	1.85E-03	1.16E-03	6.89E-04
	7995	1.89E-03	1.22E-03	6.69E-04
	8994	1.93E-03	1.26E-03	6.72E-04
	9993	1.99E-03	1.30E-03	6.89E-04
	20000	2.44E-03	1.73E-03	7.08E-04
	30000	2.95E-03	2.22E-03	7.29E-04
	39999	3.43E-03	2.68E-03	7.53E-04
	49998	3.90E-03	3.15E-03	7.53E-04
	59997	4.40E-03	3.63E-03	7.65E-04
	69996	4.88E-03	4.13E-03	7.53E-04
	79995	5.39E-03	4.64E-03	7.54E-04
	89994	5.87E-03	5.14E-03	7.27E-04
	99993	6.40E-03	5.64E-03	7.62E-04

Replicate	Cycle N	ε_1	ε_1^p	ε_1^r
2nd Replicate	1	9.96E-04	3.95E-05	9.56E-04
	2	1.01E-03	7.61E-05	9.29E-04
	3	1.01E-03	1.03E-04	9.17E-04
	4	1.01E-03	1.21E-04	8.89E-04
	5	1.04E-03	1.27E-04	9.09E-04
	6	1.03E-03	1.31E-04	9.01E-04
	7	1.03E-03	1.38E-04	8.96E-04
	8	1.04E-03	1.62E-04	8.76E-04
	9	1.04E-03	1.42E-04	9.02E-04
	10	1.03E-03	1.72E-04	8.57E-04
	21	1.09E-03	2.12E-04	8.73E-04
	31	1.10E-03	2.79E-04	8.19E-04
	40	1.10E-03	2.86E-04	8.17E-04
	50	1.11E-03	3.05E-04	8.05E-04
	60	1.12E-03	3.16E-04	8.03E-04
	70	1.14E-03	3.34E-04	8.03E-04
	80	1.13E-03	3.37E-04	7.88E-04
	90	1.13E-03	3.76E-04	7.51E-04
	100	1.15E-03	3.78E-04	7.71E-04
	200	1.16E-03	4.45E-04	7.12E-04
	300	1.21E-03	4.79E-04	7.27E-04
	399	1.23E-03	5.07E-04	7.19E-04
	498	1.26E-03	5.37E-04	7.18E-04
	597	1.27E-03	5.63E-04	7.08E-04
	696	1.29E-03	5.92E-04	6.99E-04
	795	1.30E-03	6.15E-04	6.85E-04
	894	1.35E-03	6.40E-04	7.05E-04
	993	1.36E-03	6.62E-04	6.96E-04
	2000	1.51E-03	8.57E-04	6.49E-04
	3000	1.61E-03	9.39E-04	6.75E-04
	3999	1.72E-03	1.04E-03	6.75E-04
	4998	1.82E-03	1.15E-03	6.66E-04
	5997	1.92E-03	1.25E-03	6.65E-04
	6996	1.98E-03	1.30E-03	6.77E-04
	7995	2.05E-03	1.38E-03	6.68E-04
	8994	2.13E-03	1.44E-03	6.85E-04
	9993	2.19E-03	1.54E-03	6.45E-04
	20000	2.79E-03	2.12E-03	6.70E-04
	30000	3.32E-03	2.63E-03	6.88E-04
	39999	3.92E-03	3.19E-03	7.26E-04
	49998	4.53E-03	3.81E-03	7.16E-04
	59997	5.31E-03	4.57E-03	7.36E-04
	69996	6.18E-03	5.42E-03	7.56E-04
	79995	7.04E-03	6.30E-03	7.36E-04
	89994	7.80E-03	7.08E-03	7.22E-04
	99993	8.71E-03	7.87E-03	8.40E-04

Table B-2. Repeated Load Permanent Deformation Test Data for GTX Base Low-Stress (Unconditioned)

Replicate	Cycle N	ε_1	ε_1^p	ε_1^r
1st Replicate	1	4.03E-04	1.89E-04	2.14E-04
	2	8.06E-04	3.95E-04	4.11E-04
	3	9.35E-04	4.49E-04	4.86E-04
	4	9.85E-04	5.05E-04	4.80E-04
	5	1.06E-03	5.68E-04	4.92E-04
	6	1.09E-03	5.86E-04	5.04E-04
	7	1.13E-03	6.22E-04	5.08E-04
	8	1.16E-03	6.22E-04	5.38E-04
	9	1.18E-03	6.55E-04	5.25E-04
	10	1.20E-03	6.57E-04	5.43E-04
	21	1.35E-03	7.79E-04	5.74E-04
	31	1.44E-03	8.23E-04	6.21E-04
	40	1.51E-03	9.45E-04	5.69E-04
	50	1.56E-03	9.75E-04	5.85E-04
	60	1.59E-03	9.78E-04	6.12E-04
	69	1.62E-03	1.07E-03	5.49E-04
	79	1.66E-03	1.06E-03	5.97E-04
	89	1.67E-03	1.09E-03	5.76E-04
	99	1.68E-03	1.12E-03	5.61E-04
	199	1.78E-03	1.22E-03	5.58E-04
	299	1.81E-03	1.27E-03	5.38E-04
	398	1.81E-03	1.27E-03	5.35E-04
	497	1.94E-03	1.33E-03	6.09E-04
	596	1.91E-03	1.40E-03	5.10E-04
	695	1.90E-03	1.40E-03	5.00E-04
	794	1.90E-03	1.41E-03	4.92E-04
	893	1.91E-03	1.42E-03	4.92E-04
	992	1.98E-03	1.41E-03	5.71E-04
	2000	2.12E-03	1.58E-03	5.35E-04
	2999	2.20E-03	1.69E-03	5.11E-04
	3998	2.30E-03	1.73E-03	5.66E-04
	4997	2.38E-03	1.80E-03	5.81E-04
	5996	2.44E-03	1.89E-03	5.45E-04
	6995	2.47E-03	1.98E-03	4.94E-04
	7994	2.56E-03	2.01E-03	5.49E-04
	8993	2.62E-03	2.03E-03	5.85E-04
	10000	2.65E-03	2.10E-03	5.47E-04
	20000	3.08E-03	2.48E-03	5.99E-04
	29999	3.35E-03	2.81E-03	5.38E-04
	39998	3.64E-03	3.06E-03	5.83E-04
	49997	3.84E-03	3.33E-03	5.10E-04
	59996	4.09E-03	3.54E-03	5.49E-04
	69995	4.33E-03	3.73E-03	5.95E-04
	79994	4.45E-03	3.92E-03	5.26E-04
	89993	4.63E-03	4.05E-03	5.83E-04
	99992	4.76E-03	4.22E-03	5.35E-04

Replicate	Cycle N	ε_1	ε_1^p	ε_1^r
2nd Replicate	1	1.14E-04	5.10E-05	6.30E-05
	2	7.80E-04	3.71E-04	4.09E-04
	3	1.04E-03	5.40E-04	5.00E-04
	4	1.13E-03	6.30E-04	5.00E-04
	5	1.21E-03	6.47E-04	5.63E-04
	6	1.29E-03	7.16E-04	5.74E-04
	7	1.33E-03	7.44E-04	5.86E-04
	8	1.38E-03	7.86E-04	5.94E-04
	9	1.40E-03	8.11E-04	5.89E-04
	10	1.42E-03	8.25E-04	5.95E-04
	21	1.65E-03	1.02E-03	6.34E-04
	31	1.77E-03	1.08E-03	6.86E-04
	40	1.81E-03	1.18E-03	6.32E-04
	50	1.91E-03	1.26E-03	6.50E-04
	60	1.93E-03	1.27E-03	6.59E-04
	69	1.94E-03	1.33E-03	6.12E-04
	79	2.00E-03	1.36E-03	6.44E-04
	89	2.00E-03	1.38E-03	6.24E-04
	99	2.04E-03	1.41E-03	6.33E-04
	199	2.15E-03	1.58E-03	5.68E-04
	299	2.25E-03	1.67E-03	5.84E-04
	398	2.30E-03	1.75E-03	5.50E-04
	497	2.31E-03	1.78E-03	5.28E-04
	596	2.32E-03	1.80E-03	5.21E-04
	695	2.36E-03	1.81E-03	5.48E-04
	794	2.42E-03	1.83E-03	5.90E-04
	893	2.54E-03	1.93E-03	6.07E-04
	992	2.59E-03	2.00E-03	5.88E-04
	2000	2.93E-03	2.38E-03	5.45E-04
	2999	3.17E-03	2.56E-03	6.05E-04
	3998	3.33E-03	2.77E-03	5.64E-04
	4997	3.46E-03	2.92E-03	5.43E-04
	5996	3.56E-03	3.03E-03	5.34E-04
	6995	3.70E-03	3.11E-03	5.88E-04
	7994	3.80E-03	3.22E-03	5.78E-04
	8993	3.88E-03	3.32E-03	5.55E-04
	10000	3.95E-03	3.40E-03	5.53E-04
	20000	4.63E-03	4.07E-03	5.58E-04
	29999	5.00E-03	4.44E-03	5.63E-04
	39998	5.31E-03	4.77E-03	5.36E-04
	49997	5.61E-03	4.99E-03	6.20E-04
	59996	5.85E-03	5.26E-03	5.86E-04
	69995	6.15E-03	5.58E-03	5.71E-04
	79994	6.46E-03	5.86E-03	6.00E-04
	89993	6.76E-03	6.19E-03	5.71E-04
	99992	7.09E-03	6.50E-03	5.92E-04

Replicate	Cycle N	ε_1	ε_1^p	ε_1^r
3rd Replicate	1	6.84E-04	4.03E-04	2.81E-04
	2	9.70E-04	5.65E-04	4.05E-04
	3	1.11E-03	6.53E-04	4.57E-04
	4	1.19E-03	7.16E-04	4.74E-04
	5	1.25E-03	7.53E-04	4.97E-04
	6	1.31E-03	7.85E-04	5.25E-04
	7	1.35E-03	8.14E-04	5.36E-04
	8	1.38E-03	8.86E-04	4.94E-04
	9	1.41E-03	8.71E-04	5.39E-04
	10	1.44E-03	8.91E-04	5.49E-04
	21	1.61E-03	1.04E-03	5.67E-04
	31	1.71E-03	1.15E-03	5.58E-04
	40	1.76E-03	1.22E-03	5.41E-04
	50	1.80E-03	1.24E-03	5.64E-04
	60	1.86E-03	1.30E-03	5.63E-04
	69	1.89E-03	1.34E-03	5.45E-04
	79	1.91E-03	1.37E-03	5.43E-04
	89	1.97E-03	1.41E-03	5.55E-04
	99	1.98E-03	1.43E-03	5.54E-04
	199	2.11E-03	1.57E-03	5.39E-04
	299	2.36E-03	1.72E-03	6.35E-04
	398	2.68E-03	2.08E-03	6.03E-04
	497	2.69E-03	2.17E-03	5.19E-04
	596	2.70E-03	2.20E-03	4.99E-04
	695	2.73E-03	2.18E-03	5.50E-04
	794	2.83E-03	2.23E-03	6.04E-04
	893	2.86E-03	2.30E-03	5.62E-04
	992	2.88E-03	2.32E-03	5.55E-04
	2000	3.30E-03	2.73E-03	5.67E-04
	2999	2.94E-03	3.23E-03	6.16E-04
	3998	4.15E-03	3.56E-03	5.90E-04
	4997	4.35E-03	3.78E-03	5.72E-04
	5996	4.52E-03	3.96E-03	5.56E-04
	6995	4.71E-03	4.09E-03	6.18E-04
	7994	4.85E-03	4.25E-03	6.03E-04
	8993	4.95E-03	4.40E-03	5.51E-04
	10000	5.07E-03	4.51E-03	5.58E-04
	20000	6.09E-03	5.45E-03	6.36E-04
	29999	6.70E-03	6.14E-03	5.57E-04
	39998	7.26E-03	6.62E-03	6.39E-04
	49997	7.68E-03	7.09E-03	5.88E-04
	59996	8.10E-03	7.48E-03	6.17E-04
	69995	8.48E-03	7.87E-03	6.12E-04
	79994	8.87E-03	8.24E-03	6.29E-04
	89993	9.29E-03	8.65E-03	6.41E-04
	99992	9.79E-03	9.15E-03	6.38E-04

Table B-3. Repeated Load Permanent Deformation Test Data for GTX Base High-Stress (Conditioned)

Replicate	Cycle N	ε_1	ε_1^p	ε_1^r
	1	5.91E-04	2.15E-06	5.89E-04
	2	5.56E-04	-4.31E-06	5.60E-04
	3	5.70E-04	-2.15E-06	5.72E-04
	4	5.69E-04	4.31E-06	5.65E-04
	5	5.67E-04	-5.74E-06	5.73E-04
	6	5.69E-04	1.00E-09	5.69E-04
	7	5.61E-04	3.59E-06	5.57E-04
	8	5.75E-04	8.61E-06	5.66E-04
	9	5.77E-04	7.19E-07	5.76E-04
	10	5.71E-04	5.03E-06	5.66E-04
	21	5.51E-04	1.58E-05	5.35E-04
	31	5.55E-04	5.03E-06	5.50E-04
	40	5.47E-04	7.19E-07	5.46E-04
	50	5.45E-04	7.90E-06	5.37E-04
	60	5.44E-04	8.61E-06	5.35E-04
	70	5.41E-04	6.46E-06	5.35E-04
	80	5.38E-04	1.22E-05	5.26E-04
	90	5.43E-04	7.90E-06	5.35E-04
	100	5.37E-04	7.18E-06	5.30E-04
	200	5.28E-04	5.74E-06	5.22E-04
	300	5.46E-04	5.74E-06	5.40E-04
	399	5.39E-04	3.10E-09	5.39E-04
	498	5.52E-04	7.90E-06	5.44E-04
	597	5.43E-04	1.29E-05	5.30E-04
	696	5.41E-04	1.29E-05	5.28E-04
	795	5.54E-04	1.44E-05	5.40E-04
	894	5.38E-04	2.87E-06	5.35E-04
	993	5.39E-04	1.44E-06	5.38E-04
	2000	5.46E-04	2.08E-05	5.25E-04
	3000	5.62E-04	5.74E-05	5.05E-04
	3999	5.67E-04	1.44E-05	5.53E-04
	4998	5.88E-04	2.87E-05	5.59E-04
	5997	5.86E-04	3.01E-05	5.56E-04
	6996	6.04E-04	5.67E-05	5.47E-04
	7995	6.12E-04	4.45E-05	5.67E-04
	8994	6.29E-04	6.10E-05	5.68E-04
	9993	6.40E-04	6.39E-05	5.76E-04
	20000	7.68E-04	1.39E-04	6.29E-04
	30000	8.93E-04	2.55E-04	6.38E-04
	39999	1.01E-03	3.33E-04	6.81E-04
	49998	1.16E-03	4.63E-04	6.92E-04
	59997	1.35E-03	6.36E-04	7.18E-04
	69996	1.61E-03	8.38E-04	7.73E-04
	79995	1.97E-03	1.17E-03	8.04E-04
	89994	2.42E-03	1.57E-03	8.45E-04
	99993	2.95E-03	2.09E-03	8.58E-04

Table B-4. Repeated Load Permanent Deformation Test Data for CRREL Base Low-Stress (Unconditioned)

Replicate	Cycle N	ε_1	ε_1^p	ε_1^r
1st Replicate	1	5.59E-03	3.77E-03	1.82E-03
	2	8.24E-03	6.17E-03	2.07E-03
	3	9.61E-03	7.49E-03	2.12E-03
	4	1.04E-02	8.32E-03	2.08E-03
	5	1.13E-02	9.01E-03	2.29E-03
	6	1.19E-02	9.63E-03	2.27E-03
	7	1.25E-02	1.03E-02	2.20E-03
	8	1.32E-02	1.09E-02	2.30E-03
	9	1.38E-02	1.14E-02	2.39E-03
	10	1.42E-02	1.19E-02	2.33E-03
	20	1.85E-02	1.63E-02	2.19E-03
	30	2.16E-02	1.95E-02	2.09E-03
	40	2.36E-02	2.15E-02	2.06E-03
	50	2.51E-02	2.30E-02	2.06E-03
	60	2.64E-02	2.44E-02	1.98E-03
	69	2.73E-02	2.54E-02	1.90E-03
	79	2.84E-02	2.65E-02	1.91E-03
	89	2.93E-02	2.75E-02	1.77E-03
	99	3.03E-02	2.85E-02	1.83E-03
	200	3.75E-02	3.59E-02	1.58E-03
	299	4.19E-02	4.06E-02	1.33E-03
	398	4.39E-02	4.28E-02	1.11E-03
	497	4.54E-02	4.43E-02	1.05E-03
	596	4.64E-02	4.55E-02	9.12E-04
	695	4.77E-02	4.67E-02	9.82E-04
	794	4.87E-02	4.78E-02	9.01E-04
	893	4.97E-02	4.89E-02	8.02E-04
	1000	5.08E-02	4.99E-02	8.73E-04
	2000	5.56E-02	5.51E-02	5.11E-04
	2999	5.82E-02	5.77E-02	4.55E-04

Replicate	Cycle N	ε_1	ε_1^p	ε_1^r
2nd Replicate	1	7.56E-03	5.90E-03	1.66E-03
	2	9.96E-03	8.21E-03	1.75E-03
	3	1.15E-02	9.85E-03	1.66E-03
	4	1.32E-02	1.13E-02	1.94E-03
	5	1.47E-02	1.27E-02	1.97E-03
	6	1.61E-02	1.40E-02	2.10E-03
	7	1.74E-02	1.53E-02	2.06E-03
	8	1.86E-02	1.65E-02	2.13E-03
	9	1.98E-02	1.76E-02	2.20E-03
	10	2.09E-02	1.87E-02	2.20E-03
	21	3.10E-02	2.88E-02	2.18E-03
	31	3.64E-02	3.45E-02	1.91E-03
	40	3.99E-02	3.81E-02	1.83E-03
	50	4.27E-02	4.12E-02	1.52E-03
	60	4.52E-02	4.37E-02	1.45E-03
	70	4.69E-02	4.56E-02	1.31E-03
	80	4.86E-02	4.73E-02	1.26E-03
	90	4.98E-02	4.86E-02	1.18E-03
	100	5.08E-02	4.98E-02	1.01E-03
	200	5.68E-02	5.61E-02	6.99E-04

Table B-5. Repeated Load Permanent Deformation Test Data for MSU-1 Base Low-Stress (Unconditioned)

Replicate	Cycle N	ε_1	ε_1^p	ε_1^r
1st Replicate	1	4.03E-03	3.80E-03	2.30E-04
	2	6.71E-03	5.03E-03	6.80E-04
	3	6.91E-03	5.91E-03	1.00E-03
	4	7.78E-03	6.69E-03	1.09E-03
	5	8.47E-03	7.36E-03	1.11E-03
	6	9.10E-03	7.67E-03	1.43E-03
	7	9.53E-03	8.05E-03	1.48E-03
	8	9.90E-03	8.37E-03	1.53E-03
	9	1.02E-02	8.66E-03	1.54E-03
	10	1.05E-02	8.75E-03	1.75E-03
	20	1.24E-02	1.05E-02	1.92E-03
	30	1.35E-02	1.18E-02	1.74E-03
	40	1.45E-02	1.27E-02	1.80E-03
	50	1.54E-02	1.35E-02	1.88E-03
	60	1.62E-02	1.44E-02	1.77E-03
	69	1.66E-02	1.49E-02	1.72E-03
	79	1.73E-02	1.57E-02	1.59E-03
	89	1.79E-02	1.61E-02	1.79E-03
	100	1.84E-02	1.67E-02	1.74E-03
	200	2.21E-02	2.05E-02	1.64E-03
	299	2.44E-02	2.29E-02	1.48E-03
	398	2.59E-02	2.46E-02	1.31E-03
	497	2.73E-02	2.60E-02	1.25E-03
	596	2.81E-02	2.69E-02	1.20E-03
	695	2.86E-02	2.75E-02	1.12E-03
	794	2.90E-02	2.79E-02	1.13E-03
	893	2.95E-02	2.84E-02	1.09E-03
	992	2.99E-02	2.88E-02	1.06E-03
	2000	3.24E-02	3.15E-02	9.47E-04
	2999	3.27E-02	3.20E-02	6.75E-04
	3998	3.32E-02	3.23E-02	8.69E-04
	4997	3.37E-02	3.29E-02	8.28E-04
	5996	3.44E-02	3.36E-02	8.37E-04
	6995	3.53E-02	3.45E-02	7.85E-04
	7994	3.63E-02	3.57E-02	5.98E-04
	8993	3.67E-02	3.61E-02	6.30E-04
	9992	3.70E-02	3.64E-02	6.07E-04
	20000	3.99E-02	3.93E-02	5.58E-04
	29999	4.50E-02	4.45E-02	5.28E-04

Replicate	Cycle N	ε_1	ε_1^p	ε_1^r
2nd Replicate	6	4.39E-03	2.50E-03	1.89E-03
	7	4.01E-03	2.59E-03	1.42E-03
	8	3.77E-03	2.62E-03	1.15E-03
	9	4.41E-03	2.79E-03	1.62E-03
	10	4.41E-03	2.90E-03	1.51E-03
	20	9.16E-03	6.87E-03	2.29E-03
	30	1.31E-02	1.11E-02	2.00E-03
	40	1.62E-02	1.40E-02	2.22E-03
	50	1.92E-02	1.70E-02	2.21E-03
	60	2.17E-02	1.96E-02	2.09E-03
	69	2.38E-02	2.19E-02	1.93E-03
	79	2.59E-02	2.39E-02	1.97E-03
	89	2.77E-02	2.60E-02	1.72E-03
	100	2.96E-02	2.78E-02	1.81E-03
	200	3.97E-02	3.83E-02	1.37E-03
	299	4.39E-02	4.27E-02	1.16E-03
	398	4.66E-02	4.55E-02	1.11E-03
	497	4.93E-02	4.83E-02	9.70E-04
	596	5.13E-02	5.04E-02	9.30E-04
	695	5.27E-02	5.19E-02	8.40E-04
	794	5.38E-02	5.30E-02	7.80E-04
	893	5.50E-02	5.42E-02	7.60E-04
	992	5.59E-02	5.51E-02	7.60E-04

Table B-6. Repeated Load Permanent Deformation Test Data for MSU-2 Base Low-Stress (Unconditioned)

Replicate	Cycle N	ε_1	ε_1^p	ε_1^r
1st Replicate	1	2.05E-04	3.95E-05	1.66E-04
	2	3.70E-04	9.62E-05	2.74E-04
	3	4.21E-04	1.27E-04	2.94E-04
	4	4.55E-04	1.51E-04	3.04E-04
	5	4.82E-04	1.71E-04	3.11E-04
	6	5.02E-04	1.90E-04	3.12E-04
	7	5.23E-04	2.07E-04	3.16E-04
	8	5.46E-04	2.22E-04	3.24E-04
	9	5.56E-04	2.30E-04	3.26E-04
	10	5.62E-04	2.35E-04	3.27E-04
	20	6.33E-04	3.04E-04	3.29E-04
	30	7.19E-04	3.86E-04	3.33E-04
	40	7.75E-04	4.41E-04	3.34E-04
	50	8.16E-04	4.87E-04	3.29E-04
	60	8.46E-04	5.21E-04	3.25E-04
	69	8.82E-04	5.46E-04	3.36E-04
	79	9.06E-04	5.71E-04	3.35E-04
	89	9.36E-04	5.91E-04	3.45E-04
	100	9.64E-04	6.19E-04	3.45E-04
	200	1.52E-03	1.09E-03	4.30E-04
	299	1.97E-03	1.54E-03	4.30E-04
	398	2.09E-03	1.71E-03	3.80E-04
	497	2.13E-03	1.77E-03	3.60E-04
	596	2.16E-03	1.81E-03	3.50E-04

Replicate	Cycle N	ε_1	ε_1^p	ε_1^r
2nd Replicate	1	6.31E-04	2.11E-04	4.20E-04
	2	7.64E-04	2.89E-04	4.75E-04
	3	8.27E-04	3.37E-04	4.90E-04
	4	8.64E-04	3.71E-04	4.93E-04
	5	8.93E-04	4.00E-04	4.93E-04
	6	9.19E-04	4.24E-04	4.95E-04
	7	9.39E-04	4.44E-04	4.95E-04
	8	9.57E-04	4.62E-04	4.95E-04
	9	9.78E-04	4.79E-04	4.99E-04
	10	9.94E-04	4.92E-04	5.02E-04
	20	1.04E-03	5.55E-04	4.85E-04
	30	1.11E-03	6.32E-04	4.78E-04
	40	1.16E-03	6.83E-04	4.77E-04
	50	1.20E-03	7.18E-04	4.82E-04
	60	1.22E-03	7.48E-04	4.72E-04
	69	1.25E-03	7.71E-04	4.79E-04
	79	1.27E-03	7.93E-04	4.77E-04
	89	1.29E-03	8.13E-04	4.77E-04
	100	1.31E-03	8.34E-04	4.76E-04
	200	1.42E-03	9.42E-04	4.78E-04
	299	1.54E-03	1.01E-03	5.30E-04
	398	1.67E-03	1.15E-03	5.20E-04
	497	1.76E-03	1.23E-03	5.30E-04
	596	1.79E-03	1.29E-03	5.00E-04
	695	1.80E-03	1.32E-03	4.80E-04
	794	1.82E-03	1.32E-03	5.00E-04
	893	1.83E-03	1.37E-03	4.60E-04
	992	1.83E-03	1.40E-03	4.30E-04
	2000	1.92E-03	1.47E-03	4.50E-04
	2999	1.96E-03	1.51E-03	4.50E-04

Table B-7. Repeated Load Permanent Deformation Test Data for CS-Subgrade Low-Stress (Unconditioned)

Replicate	Cycle N	ε_1	ε_1^p	ε_1^r
1st Replicate	1	6.95E-03	4.58E-03	2.37E-03
	2	8.89E-03	5.47E-03	3.42E-03
	3	9.95E-03	4.16E-03	5.79E-03
	4	1.07E-02	4.72E-03	5.98E-03
	5	1.12E-02	5.16E-03	6.04E-03
	6	1.17E-02	5.45E-03	6.25E-03
	7	1.20E-02	5.76E-03	6.24E-03
	8	1.23E-02	6.03E-03	6.27E-03
	9	1.26E-02	6.28E-03	6.32E-03
	10	1.29E-02	6.49E-03	6.41E-03
	20	1.46E-02	8.05E-03	6.55E-03
	30	1.56E-02	9.01E-03	6.59E-03
	40	1.62E-02	9.64E-03	6.56E-03
	50	1.68E-02	1.02E-02	6.60E-03
	60	1.73E-02	1.07E-02	6.60E-03
	70	1.76E-02	1.10E-02	6.60E-03
	80	1.80E-02	1.14E-02	6.60E-03
	90	1.83E-02	1.17E-02	6.60E-03
	100	1.86E-02	1.20E-02	6.60E-03
	200	2.05E-02	1.40E-02	6.50E-03
	300	2.10E-02	1.46E-02	6.40E-03
	400	2.18E-02	1.55E-02	6.30E-03
	500	2.26E-02	1.63E-02	6.30E-03
	600	2.32E-02	1.70E-02	6.20E-03
	700	2.37E-02	1.75E-02	6.20E-03
	800	2.42E-02	1.81E-02	6.10E-03
	900	2.47E-02	1.86E-02	6.10E-03
	1000	2.53E-02	1.92E-02	6.10E-03
	2000	2.78E-02	2.20E-02	5.80E-03
	3000	2.91E-02	2.35E-02	5.60E-03
	4000	3.33E-02	2.46E-02	8.70E-03
	5000	3.08E-02	2.55E-02	5.30E-03
	6000	3.16E-02	2.64E-02	5.20E-03
	7000	3.20E-02	2.69E-02	5.10E-03
	8000	3.26E-02	2.76E-02	5.00E-03
	9000	3.33E-02	2.83E-02	5.00E-03
	10000	3.38E-02	2.89E-02	4.90E-03
	20000	5.66E-02	5.43E-02	2.30E-03

Replicate	Cycle N	ε_1	ε_1^p	ε_1^r
2nd Replicate	1	5.00E-03	1.08E-03	3.92E-03
	2	6.91E-03	1.92E-03	4.99E-03
	3	7.77E-03	2.40E-03	5.37E-03
	4	8.39E-03	2.85E-03	5.54E-03
	5	8.85E-03	3.21E-03	5.64E-03
	6	9.22E-03	3.50E-03	5.72E-03
	7	9.53E-03	3.77E-03	5.76E-03
	8	9.22E-03	3.40E-03	5.82E-03
	9	1.01E-02	4.21E-03	5.89E-03
	10	1.03E-02	4.41E-03	5.89E-03
	20	1.19E-02	5.89E-03	6.01E-03
	30	1.30E-02	6.94E-03	6.06E-03
	40	1.38E-02	7.68E-03	6.12E-03
	50	1.45E-02	8.42E-03	6.08E-03
	60	1.52E-02	9.10E-03	6.10E-03
	70	1.57E-02	9.54E-03	6.16E-03
	80	1.61E-02	9.98E-03	6.12E-03
	90	1.65E-02	1.04E-02	6.10E-03
	100	1.69E-02	1.08E-02	6.10E-03
	200	2.02E-02	1.41E-02	6.10E-03
	300	2.30E-02	1.71E-02	5.90E-03
	400	2.47E-02	1.89E-02	5.80E-03
	500	2.56E-02	1.99E-02	5.70E-03
	600	2.62E-02	2.06E-02	5.60E-03
	700	2.71E-02	2.15E-02	5.60E-03
	800	2.78E-02	2.23E-02	5.50E-03
	900	2.86E-02	2.31E-02	5.50E-03
	1000	2.92E-02	2.38E-02	5.40E-03
	2000	3.30E-02	2.80E-02	5.00E-03
	3000	3.54E-02	3.07E-02	4.70E-03
	4000	3.74E-02	3.29E-02	4.50E-03
	5000	3.90E-02	3.47E-02	4.30E-03
	6000	4.01E-02	3.60E-02	4.10E-03
	7000	4.13E-02	3.73E-02	4.00E-03
	8000	4.25E-02	3.86E-02	3.90E-03
	9000	4.36E-02	3.98E-02	3.80E-03
	10000	4.45E-02	4.09E-02	3.60E-03

Table B-8. Repeated Load Permanent Deformation Test Data for MSU-SSS-Subgrade Low-Stress (Unconditioned)

Replicate	Cycle N	ε_1	ε_1^p	ε_1^r
2nd Replicate	1	3.31E-03	2.40E-03	9.10E-04
	2	5.14E-03	3.92E-03	1.22E-03
	3	6.38E-03	5.02E-03	1.36E-03
	4	7.36E-03	5.93E-03	1.43E-03
	5	8.19E-03	6.70E-03	1.49E-03
	6	9.11E-03	7.64E-03	1.47E-03
	7	9.56E-03	8.01E-03	1.55E-03
	8	1.02E-02	8.58E-03	1.62E-03
	9	1.07E-02	9.11E-03	1.59E-03
	10	1.12E-02	9.62E-03	1.58E-03
	20	1.56E-02	1.39E-02	1.70E-03
	30	1.85E-02	1.67E-02	1.80E-03
	40	2.07E-02	1.89E-02	1.80E-03
	50	2.28E-02	2.10E-02	1.80E-03
	60	2.46E-02	2.28E-02	1.80E-03
	70	2.59E-02	2.40E-02	1.90E-03
	80	2.71E-02	2.53E-02	1.80E-03
	90	2.83E-02	2.65E-02	1.80E-03
	100	2.93E-02	2.75E-02	1.80E-03
	200	3.76E-02	3.60E-02	1.60E-03
	300	4.32E-02	4.17E-02	1.50E-03
	400	4.87E-02	4.73E-02	1.40E-03
	500	5.28E-02	5.16E-02	1.20E-03

Replicate	Cycle N	ε_1	ε_1^p	ε_1^r
2nd Replicate	1	2.45E-03	2.13E-03	3.20E-04
	2	4.50E-03	3.84E-03	6.60E-04
	3	5.90E-03	5.02E-03	8.80E-04
	4	6.92E-03	5.95E-03	9.70E-04
	5	7.77E-03	6.75E-03	1.02E-03
	6	8.53E-03	7.44E-03	1.09E-03
	7	9.19E-03	8.08E-03	1.11E-03
	8	1.01E-02	8.66E-03	1.44E-03
	9	1.04E-02	9.20E-03	1.20E-03
	10	1.09E-02	9.71E-03	1.19E-03
	20	1.55E-02	1.42E-02	1.30E-03
	30	1.84E-02	1.71E-02	1.30E-03
	40	2.07E-02	1.93E-02	1.40E-03
	50	2.29E-02	2.15E-02	1.40E-03
	60	2.44E-02	2.30E-02	1.40E-03
	70	2.56E-02	2.42E-02	1.40E-03
	80	2.70E-02	2.56E-02	1.40E-03
	90	2.84E-02	2.70E-02	1.40E-03
	100	2.95E-02	2.81E-02	1.40E-03
	200	3.96E-02	3.85E-02	1.10E-03
	300	4.56E-02	4.46E-02	1.00E-03
	400	5.00E-02	4.91E-02	9.00E-04
	500	5.34E-02	5.26E-02	8.00E-04
	600	5.60E-02	5.53E-02	7.00E-04

Table B-9. Repeated Load Permanent Deformation Test Data for GTX-Subgrade Low-Stress (Unconditioned)

Replicate	Cycle N	ε_1	ε_1^p	ε_1^r
1st Replicate	1	3.28E-03	2.87E-03	4.10E-04
	2	4.67E-03	3.46E-03	1.21E-03
	3	5.24E-03	3.93E-03	1.31E-03
	4	5.89E-03	4.48E-03	1.41E-03
	5	6.28E-03	4.94E-03	1.34E-03
	6	6.80E-03	5.55E-03	1.25E-03
	7	7.35E-03	6.01E-03	1.34E-03
	8	7.51E-03	6.09E-03	1.42E-03
	9	7.99E-03	6.54E-03	1.45E-03
	10	8.31E-03	6.90E-03	1.41E-03
	20	9.90E-03	8.32E-03	1.58E-03
	30	1.11E-02	9.56E-03	1.54E-03
	40	1.23E-02	1.07E-02	1.60E-03
	50	1.27E-02	1.10E-02	1.70E-03
	60	1.36E-02	1.21E-02	1.50E-03
	70	1.35E-02	1.19E-02	1.60E-03
	80	1.46E-02	1.29E-02	1.70E-03
	90	1.45E-02	1.29E-02	1.60E-03
	100	1.46E-02	1.29E-02	1.70E-03
	200	1.58E-02	1.42E-02	1.60E-03
	300	1.68E-02	1.51E-02	1.70E-03
	400	1.86E-02	1.70E-02	1.60E-03
	500	2.08E-02	1.92E-02	1.60E-03
	600	2.08E-02	1.92E-02	1.60E-03
	700	2.12E-02	1.96E-02	1.60E-03
	800	2.21E-02	2.05E-02	1.60E-03
	900	2.21E-02	2.05E-02	1.60E-03
	1000	2.24E-02	2.07E-02	1.70E-03
	2000	2.30E-02	2.14E-02	1.60E-03
	3000	2.35E-02	2.19E-02	1.60E-03
	4000	2.47E-02	2.32E-02	1.50E-03
	5000	2.41E-02	2.26E-02	1.50E-03
	6000	2.58E-02	2.45E-02	1.30E-03
	7000	2.47E-02	2.33E-02	1.40E-03
	8000	2.46E-02	2.31E-02	1.50E-03
	9000	2.86E-02	2.71E-02	1.50E-03
	10000	3.44E-02	3.30E-02	1.40E-03

Replicate	Cycle N	ε_1	ε_1^p	ε_1^r
2nd Replicate	1	7.90E-04	5.50E-04	2.40E-04
	2	9.90E-04	6.30E-04	3.60E-04
	3	1.23E-03	8.20E-04	4.10E-04
	4	1.63E-03	1.11E-03	5.20E-04
	5	3.10E-03	2.17E-03	9.30E-04
	6	4.02E-03	2.74E-03	1.28E-03
	7	4.66E-03	3.34E-03	1.32E-03
	8	5.21E-03	4.18E-03	1.03E-03
	9	6.10E-03	4.78E-03	1.32E-03
	10	6.81E-03	5.57E-03	1.24E-03
	20	1.20E-02	1.09E-02	1.10E-03
	30	1.45E-02	1.31E-02	1.40E-03
	40	1.80E-02	1.66E-02	1.40E-03
	50	2.06E-02	1.91E-02	1.50E-03
	60	2.32E-02	2.17E-02	1.50E-03
	70	2.43E-02	2.27E-02	1.60E-03
	80	2.58E-02	2.42E-02	1.60E-03
	90	2.71E-02	2.56E-02	1.50E-03
	100	2.71E-02	2.56E-02	1.50E-03
	200	3.57E-02	3.46E-02	1.10E-03
	300	3.72E-02	3.59E-02	1.30E-03
	400	3.81E-02	3.71E-02	1.00E-03
	500	3.87E-02	3.74E-02	1.30E-03
	600	3.92E-02	3.80E-02	1.20E-03
	700	3.92E-02	3.79E-02	1.30E-03
	800	3.92E-02	3.80E-02	1.20E-03
	900	3.94E-02	3.81E-02	1.30E-03
	1000	3.93E-02	3.81E-02	1.20E-03
	2000	4.16E-02	4.06E-02	1.00E-03
	3000	4.67E-02	4.59E-02	8.00E-04
	4000	4.90E-02	4.81E-02	9.00E-04
	5000	5.06E-02	4.98E-02	8.00E-04
	6000	5.07E-02	5.00E-02	7.00E-04
	7000	5.26E-02	5.20E-02	6.00E-04
	8000	5.38E-02	5.31E-02	7.00E-04

Table B-10. Repeated Load Permanent Deformation Test Data for CRREL-Subgrade Low-Stress (Unconditioned)

Replicate	Cycle N	ε_1	ε_1^p	ε_1^r
1st Replicate	1	1.51E-03	1.06E-03	4.50E-04
	2	2.09E-03	1.58E-03	5.10E-04
	3	2.92E-03	2.27E-03	6.50E-04
	4	4.51E-03	3.60E-03	9.10E-04
	5	5.80E-03	4.72E-03	1.08E-03
	6	6.84E-03	5.73E-03	1.11E-03
	7	7.80E-03	6.65E-03	1.15E-03
	8	8.72E-03	7.53E-03	1.19E-03
	9	9.56E-03	8.31E-03	1.25E-03
	10	1.04E-02	9.08E-03	1.32E-03
	20	1.61E-02	1.46E-02	1.50E-03
	30	1.93E-02	1.77E-02	1.60E-03
	40	2.11E-02	1.94E-02	1.70E-03
	50	2.23E-02	2.06E-02	1.70E-03
	60	2.30E-02	2.13E-02	1.70E-03
	70	2.37E-02	2.20E-02	1.70E-03
	80	2.44E-02	2.27E-02	1.70E-03
	90	2.48E-02	2.31E-02	1.70E-03
	100	2.50E-02	2.33E-02	1.70E-03
	200	2.68E-02	2.51E-02	1.70E-03
	300	2.79E-02	2.63E-02	1.60E-03
	400	2.89E-02	2.73E-02	1.60E-03
	500	2.97E-02	2.81E-02	1.60E-03
	600	3.02E-02	2.86E-02	1.60E-03
	700	3.05E-02	2.89E-02	1.60E-03
	800	3.09E-02	2.93E-02	1.60E-03
	900	3.11E-02	2.95E-02	1.60E-03
	1000	3.13E-02	2.97E-02	1.60E-03
	2000	3.26E-02	3.12E-02	1.40E-03
	3000	3.32E-02	3.19E-02	1.30E-03
	4000	3.35E-02	3.23E-02	1.20E-03
	5000	3.38E-02	3.26E-02	1.20E-03
	6000	3.40E-02	3.28E-02	1.20E-03
	7000	3.42E-02	3.30E-02	1.20E-03
	8000	3.43E-02	3.32E-02	1.10E-03
	9000	3.44E-02	3.33E-02	1.10E-03
	10000	3.45E-02	3.34E-02	1.10E-03
	20000	3.50E-02	3.40E-02	1.00E-03

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