# ASSESSMENT OF THE DATABASE FROM THE PAVEMENT SUBGRADE PERFORMANCE STUDY

## FINAL REPORT

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## ABSTRACT

A national pooled fund study supported by 19 states, the FHWA and the U.S. Army Corps of Engineers was conducted at the Cold Region Research Laboratory (CRREL) of the U.S. Army Corps of Engineers in Hanover, New Hampshire. The study entitled Pavement Subgrade Performance Study (PSPS) aimed to develop failure criteria and prediction models for permanent deformation in the subgrade soil that incorporate the effect of soil type and moisture content. Full-scale pavement structures were built with the same crushed stone base and asphalt concrete surface layers on top of four types of subgrade soils. Each of the four soils was placed at three in-situ moisture contents: the optimum and two other contents above the optimum. The pavements were subjected to full scale accelerated pavement testing (APT); the MARK IV HVS machine was used as the loading device. Even though an extensive volume of response and performance data was collected in this study, limited analysis of the results has been performed.

This document presents an in-depth assessment of the data obtained in the PSPS study. It describes in detail the data submitted by CRREL for the PSPS project and the new data assembled as well as the in-depth assessment and validation of data. The process used to identify incomplete, missing and erroneous data is highlighted. In addition, this report summarizes the results of laboratory resilient modulus testing on the three subgrade soils included in the PSPS project, describes the data assembled in the PSPS project database and provides an outline for a work plan for further analysis of the data.

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# CHAPTER 1. INTRODUCTION

The project entitled Pavement Subgrade Performance Study (PSPS) funded through a state pool fund by the Federal Highway Administration (FHWA) was conducted at the Cold Region Research Laboratory (CRREL) of the U.S. Army Corps of Engineers in Hanover, New Hampshire, between 1999 and 2007. The project aimed to develop prediction models for permanent deformation in the subgrade soil that incorporate the effect of soil type and moisture content. In this project, flexible pavements with the same granular base layer and asphalt concrete surface layer were built inside the Frost Effects Research Facility and were subjected to accelerated pavement testing (APT).

The pavements were built with a combination of four soil types and three moisture levels, which resulted in a total of 12 sets of pavement sections, named cells. Each of the four soil types were placed in the pits of the facility at three moisture contents. For each cell, between four and six pavement sections, named windows, were subjected to accelerated pavement testing. The MARK HVS IV was used as the loading device. Up to four wheel load magnitudes were used for the windows in the same cell.

The test sections were instrumented with stress, strain, moisture and temperature sensors. Surface rutting was monitored with a laser profilometer. Falling Weight Deflectometer (FWD) tests were performed on each pavement section before the application of accelerated traffic. The project was finalized and the final report was submitted in January 2007 (Cortez et al., 2007). The detailed results and data obtained in this experiment are available; a data report was submitted for each cell of pavement sections, along with a compiled database of raw data. The final report contains a description of the work conducted, as well as some limited analysis of the data.

The PSPS study is unique. It is the only research study that has recorded permanent deformation data in the subgrade soil under APT, for such a large factorial of soil types and moisture contents. The bonanza of data this study has recorded can lead to development of advanced models for permanent deformation in subgrade soil layer, which will likely improve significantly the current design methods for asphalt pavements. Thus, it is imperative to conduct an in-depth assessment of the data obtained in the PSPS study.

## 1.1 Objectives

The objectives of this research project are:

- To review in detail the data collected in the PSPS study and to check for completeness, quality, and consistency with pavement engineering principles and with other similar field and laboratory studies conducted in the United States and overseas;
- To assemble additional available data, including laboratory test results, and enhance the initial database;

- To obtain construction quality assurance testing and forensic testing from all test cells
- To convert the Excel database in a new format which will allow easy import in statistical or other analytical software packages;
- To develop the catalog and dictionary for the data assembled in the enhanced database;
- To prepare a detailed work plan for future data analysis and modeling, and;
- To facilitate the development of Second Generation Design Models for subgrade materials for pavements from the data and results of the PSP study.

## 1.2. Summary of the results from the Pavement Subgrade Performance Study

A national pooled fund study [SPR2(208)] supported by 19 states, the FHWA and the U.S. Army Corps of Engineers was conducted at the CRREL of the U.S. Army Corps of Engineers in Hanover, New Hampshire (Cortez, 2007). The study aimed to develop failure criteria and prediction models for permanent deformation in the subgrade soil that incorporates the effect of soil type and moisture content. In this project, flexible pavements with the same 229 mm (9 in.) granular base layer and a 76 mm (3 in.) asphalt concrete surface layer were built inside the Frost Effects Research Facility of CRREL and were subjected to (APT). All pavement sections were 23 meters (75 ft) long and 6.4 m (21 ft.) wide and 3.3m (11 ft.) deep. Thus, the subgrade soil layer placed on top of a concrete floor was 3.05 m (10 ft.) thick.

The pavements were built with a combination of four subgrade soil types and three moisture levels, which resulted in a total of 12 sets of pavement sections, named cells. Each of the four subgrade soils were placed in the pits of the facility, at three moisture contents (Table 1.1), one of the three being the optimum moisture content. The moisture content was controlled during construction and it was assumed to remain constant throughout the accelerated pavement testing. The top 1.5 m (5 ft.) of the soil was placed in 150 mm (6 in.) lifts. The density and uniformity of the compacted soil was determined with nuclear density gages, the Clegg hammer and the FWD.

The properties and the classifications of the four soils are given in Table 1.2. For each cell, between four and six replicate pavement sections, named windows, were subjected to APT. Up to four wheel load magnitudes were used for the windows in the same cell. The windows were approximately 1.3 m (4.3 ft.) apart. As a result of a finite element analysis, it was assumed that loading of one window did not affect the performance of the adjacent windows.

The MARK HVS IV was used as the loading device; the HVS wheel traveled at a constant speed of 12 km/h (7.5 mph) over a length of 6 meters (20ft.) Traffic was uni-directional with uniform lateral wander so that a width of 0.91 m (3 ft.) would be contacted by the tires. A dual truck tire wheel assembly, with a wheel load between 20.0 and 103.5kN ( 4.5 to 23.2 kips) and tire inflation pressure of 689 kPa (100 psi) was used to apply the accelerated traffic.

The test sections were instrumented with stress, strain, moisture and temperature sensors. Surface rutting was monitored with a laser profilometer. FWD tests were performed on each pavement section before and during the application of accelerated traffic.

Permanent and resilient deformations at various locations in the pavement structures were measured by stacks of εmu coils. Stresses in the subgrade and base courses were measured using stress cells. Stress and strain measurements were performed for vertical, transverse and longitudinal directions. The stresses and strains measured in the transverse and longitudinal directions were much smaller than those recorded in the vertical direction. Figure 1.1 is a schematic diagram showing the location of the εmu coils (Cortez, 2007).

**TABLE 1.1 Experimental test matrix**

| Subgrade Moisture Content | AASHTO Soil Type | | | |
|---|---|---|---|---|
| | A-2-4 | A-4 | A-6 | A-7-5 |
| M1 | Optimum<br>10 %<br>TS 701 | Optimum<br>17 %<br>TS 702 | Optimum<br>16 %<br>TS 709 | Optimum<br>20.4 %<br>TS 712 |
| M2 | 12 %<br>TS 707 | 19 %<br>TS 704 | 19 %<br>TS 708 | 21 % (soil borderline to A-6)<br>TS 710 |
| M3 | 15 %<br>TS 703 | 23 %<br>TS 705 | 22%<br>TS 706 | 25 %<br>TS 711 |

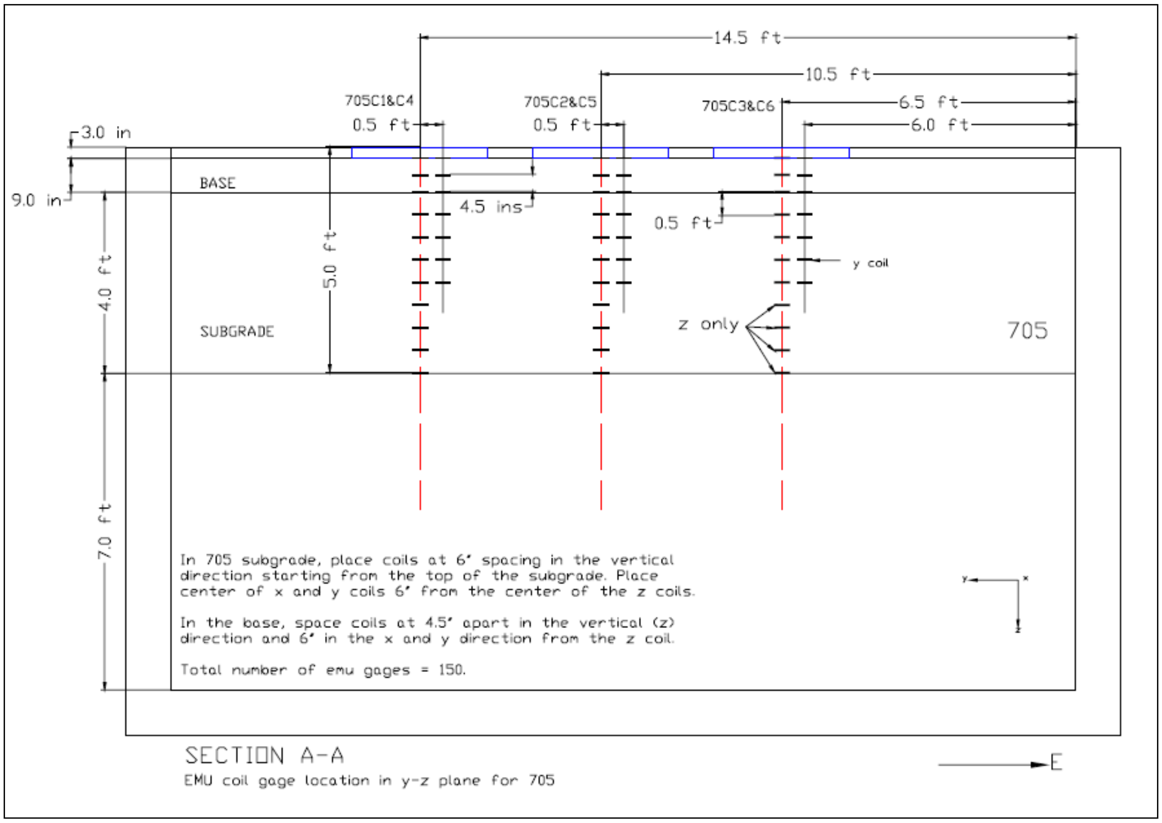
*TS – test section*

**TABLE 1.2 Soil classification and properties**

| AASHTO Soil Classification | Maximum Dry Density (kg/m3) | Liquid Limit | Plasticity Index | Percent Passing #10 sieve | Percent Passing #200 sieve | Percent < 0.002 mm | Specific Gravity |
|---|---|---|---|---|---|---|---|
| A-2-4 | 1934 | 30 | 2.1 | 71.8 | 31.2 | 3 | 2.72 |
| A-4 | 1780 | 28 | 18 | 97.8 | 84.7 | 20 | 2.72 |
| A-6 | 1800 | 29 | 13 | 99.9 | 98.9 | 52.2 | 2.70 |
| A-7-5 | 1700 | 55 | 21 | 100 | 88 | 75.2 | 2.71 |

The project was finalized and the final report was submitted in January 2007 (Cortez, 2007). The detailed results and data obtained in this experiment are available; a data report was submitted for each cell of pavement sections, along with a compiled database of raw data. The final report contains a description of the work conducted, as well as some limited analysis of the data.

**Figure 1.1** Cross section of test section showing the location of εmu sensors (Cortez, 2007)



In 705 subgrade, place coils at 6" spacing in the vertical direction starting from the top of the subgrade. Place center of x and y coils 6" from the center of the z coils.

In the base, space coils at 4.5" apart in the vertical (z) direction and 6" in the x and y direction from the z coil.

Total number of emu gages = 150.

The major conclusions obtained so far in the study are:

1. The contribution of the subgrade soil to the permanent deformation at the pavement surface varied greatly from one soil to another and was dependent on moisture content (Table 1.3). This clearly reveals that there is no unique contribution of the pavement layers to the permanent deformation at the pavement surface, as it was assumed in the national calibration of the NCHRP Mechanistic-Empirical Pavement Design Guide (M-E PDG).

2. The second major consequence of this finding is that it is not useful to develop failure criteria for permanent deformation in the subgrade layer since the other layers contribute as well to the permanent deformation or rutting at the pavement surface. Surprisingly, the clayey subgrade (AASHTO soil 7-5) had the lowest contribution to the permanent deformation at the pavement surface. This suggests that the properties of the asphalt concrete and the crushed stone layers might not have been the same on all cells.

**TABLE 1.3 Percent permanent deformations in pavement layers after loading**

| Soil Type | Cell | Moisture Content | Asphalt | Base | Subgrade |
|---|---|---|---|---|---|
| A-2-4 | 701 | Optimum | 20.0 | 43.0 | 37.0 |
| | 707 | Optimum+2% | 26.0 | 34.7 | 39.3 |
| | 703 | Optimum+5% | 15.8 | 37.1 | 47.1 |
| A-4 | 702 | Optimum | 21.0 | 53.0 | 26.0 |
| | 704 | Optimum+2% | 17.0 | 49.4 | 33.6 |
| | 705 | Optimum+6% | 13.2 | 24.2 | 62.6 |
| A-6 | 709 | Optimum | 12.9 | 56.7 | 30.4 |
| | 708 | Optimum+2% | 25.6 | 49.8 | 24.6 |
| | 706 | Optimum+6% | 13.3 | 37.5 | 49.2 |
| A6/A7-6 | 710 | Optimum +0.5% | 50 | 30 | 20 |
| A-7-5 | 712 | Optimum | 51.6 | 31.2 | 17.2 |
| | 711 | Optimum+5% | 53.0 | 25.0 | 22.0 |

3. For some soils, the lowest permanent deformation in the subgrade soil was not always recorded for the optimum moisture content. It was concluded that the optimum moisture content makes the soil achieve the maximum dry density for a given compaction effort, but it does not lead to the highest shear strength.

4. The effect of wheel load magnitude on the development of permanent deformation in the subgrade was in most cases as expected: higher wheel loads led to higher permanent deformations. An analysis of the data led to the estimation of the damage induced to the subgrade by overloaded truck axles. However, in some instances, for the same soil type and moisture content, the highest permanent deformation was not recorded for the highest wheel load. This suggests that a more thorough look must be taken at the variability in the properties of pavements constructed in the same cell and at how this may have influenced the performance of each window.

5. Permanent deformation prediction models were developed for each of the four soil types included in the study. A summary of the models is given in Table 1.4. The models related the plastic strain to the wheel load magnitude, moisture condition and the number of load cycles. However, the models are applicable only to the geometry of the pavement structures tested in this study. As stated by Cortez (2007), “some adaptation is needed to consider the effect of asphalt and base thickness values that differ from those used in the test sections”. Moreover, no assessment of the reliability of the proposed models was provided.

**TABLE 1.4 Permanent strain prediction models (Cortez, 2007)**

Subgrade Soil Type A-2-4, for moisture content from optimum to 6% wet of optimum.
$\varepsilon_{p,\,z=0} = (0.3554*N^{0.2884}) * (0.98 + 0.00000004668*L^{3.5}) * (0.37+0.00750973*\Delta w^{1.6148})*6562$

Subgrade Soil Type A-4, for moisture content from optimum to 4% wet of optimum.
$\varepsilon_{p,\,z=0} = (-1.6+0.835N^{0.2094})*(0.11 + 0.000055L^{2.374})*(1+ 1.2\ \Delta w)*(0.26+0.028*\Delta w^{1.428})*6562$

Subgrade Soil Type A-6, for moisture content from optimum to 4% wet of optimum
$\varepsilon_{p,\,z=0} = (1.5+0.425N^{0.427}) * (-9.45+6.56L^{0.123}) * (0.304+0.004*\Delta w^{2.162}) * 6562$

Subgrade Soil Type A-7-5, for moisture content from optimum to 6 percent wet of optimum.
$\varepsilon_{p,\,z=0} = (0.749N^{0.115})*(0.936 + 0.00000001256L^{4.2165})*(0.172+0.004*\Delta w^{1.513})*6562$

where:
$\varepsilon_{p,\,z=0}$ = Vertical permanent strain on top of the subgrade
$\varepsilon_{p,\,z=6}$ = Vertical permanent strain at depth of 152.4 mm (6 in) below the top of the subgrade = $0.65*\varepsilon_{p,\,z=0}$
N = Number of traffic repetitions
L = Half axle load intensity in kN (1 kN = 0.2248 kips)
$\Delta w$ = Percent gravimetric moisture content differential from optimum

Despite of these findings, the analysis of the data conducted so far has not answered many important questions:

- What is the reliability of the data collected in the PSPS study? Is the collected data consistent with the current concepts related to development of stresses and strains in a flexible pavement structure under a passing wheel? What data should be retained for the development of sound permanent deformation models? What additional data is needed?
- How do the results of this study relate to similar field and laboratory studies conducted in the United States and overseas to study permanent deformation in subgrade layers?
- Using data from this study alone, what is the most reliable model for predicting permanent strain in the subgrade soil? Is it better to employ the same permanent strain model for all soils, or each soil would require a different model?
- Can sound models for predicting permanent strains in the subgrade soil from resilient strain and vertical stresses be developed from the data collected in the project? Is it better to include statistical reliability concepts in the development of such models to enhance their effectiveness?
- Is the model employed in the NCHRP M-E PDG an effective and reliable model for all soils? If yes, what are the model's parameters for the four soil tested in the study?

It is thus clear that only limited analysis and quality checks have been conducted on the data collected in the PSPS study.

As mentioned previously, this study is unique in that it is the only research study that has provided permanent deformation data in the subgrade soil recorded under accelerated pavement testing, for such a large factorial combination of soil type and moisture contents. However, because of the complexity of data collected, in terms of the number of variables involved and the sheer volume of the data and some incomplete/missing data, an in-depth detailed assessment of the data obtained in the PSPS study was needed in order to facilitate further analysis and model development. Since the interagency agreement between FHWA and CRREL has expired and the funds have exhausted, it was imperative to conduct the in-depth data assessment in a new research project.

The in-depth analysis of the data and the development of sound permanent deformation models require:

- The evaluation and validation of the data collected in the PSPS study. The assessment and validation of the data has not been done due to the very large volume and the complexity of the data collected. Incomplete, missing and erroneous data also needs to be identified.
- Conversion of the initial database in a new format facilitating the use of the data (e.g. Microsoft Access database). In the initial form, the data is reported in tabular form in Microsoft Excel spreadsheet format. In this format the data can be easily visualized but it cannot be imported into statistical software packages (e.g. SAS, SPSS, Statistica) for model development. A catalog and a dictionary of the data currently available are also needed.
- A work plan for the data analysis and the development of advanced permanent deformation models. Such a work plan can be prepared only after an in-depth knowledge of the collected data and the comprehensive review of the current models and concepts related to permanent deformation of subgrade soils.

# CHAPTER 2. DATA AVAILABILITY

The data collected by CRREL for the PSPS study was provided in:

- One summary report for the entire project;
- Twelve reports (one per experimental cell);
- Excel database (one file for each cell);
- FWD deflection data files in original format (one file per experimental cell);
- Four DVDs with response signal data, in text (*.txt) and Excel (*.xls) files.

An evaluation of the data availability was performed in the first three months of this project and was reported to the Technical Advisory Committee (TAC) at the January 13, 2009 meeting. After the meeting, a request for the missing data was submitted to CRREL, but no response was received.

A second request was submitted at the end of May 2009. This time the data used to build the charts in the reports was requested; if it was not already provided. The request indicated, for each cell, the specific charts for which data was needed. Dr. Edel Cortez responded and submitted additional data, but only for the following experimental cells: 701, 707,702, 706 and 708 (partially).

After the new data was received, a second evaluation of data availability was conducted. Tables 2.2 to 2.5 provide a summary of data availability resulting from the second evaluation; the colored codes used to indicate the data availability are given in Table 2.1.

The availability of the response data (stresses, strains and deformations) is discussed in Chapter 7.

**TABLE 2.1** Codes used to indicate data availability

| Code | Meaning of the codes |
|---|---|
| D | Data is reported in the Excel database |
| E | Data is reported on DVDs. This was done for the FWD files. It is not included in the original Excel database |
| R | Data is given in the reports for each cell, or in the final report (body or appendix). It is not included in the original database |
| A | Data was provided by Dr. Edel Cortez on June 28, 2009 and was added to the database |
| S | The data was given in reports only as a statistic (average, CV, range, etc.) or only presented in a graph/chart. No values are given. Values are needed so that they can be included in the database. |
| N | It was reported that the values were measured. However, no values, not even a statistic, were included in the database or reports. Values are needed so that they can be included in the database or be used to estimate other variables. |
|  | A blank cell means that it was not mentioned in the report that the associated measurements were performed. Therefore, the data may not exist. |

TABLE 2.2 Data Availability – Material Characterization

| | | **A-2-4** | | | **A-4** | | | **A-6** | | | **A-6 / A-7-6** | **A-7-5** | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 701 | 707 | 703 | 702 | 704 | 705 | 709 | 708 | 706 | 710 | 712 | 711 |
| Subgrade Soil | Gradation | A | | | A | | | A | | | A | A | |
| | LL & PI | A | | | A | | | A | | | A | A | |
| | Proctor | A | | | A | | | A | | | A | A | |
| | Source | N | | | N | | | N | | | N | N | |
| | CBR | | | | A | | | A | | | A | A | |
| Base | Gradation | A | | | | | | | | | | | |
| | Proctor | A - contradictory | | | | | | | | | | | |
| | Source | N | | | | | | | | | | | |
| HMA - gradation | | | | | R | R | R | N | N | R | | | |
| Binder content | | | R | | R | R | R | R | R | R | R | R | R |
| Binder grade | | | R | | R | R | R | R | R | R | R | R | R |
| Mix Design | | | | | | | R | | | R | | | |

TABLE 2.3 Data Availability – Construction Information

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

**TABLE 2.4** Data Availability – APT Testing

| | | **A-2-4** | | | **A-4** | | | **A-6** | | | **A-6 / A-7-6** | **A-7-5** | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 701 | 707 | 703 | 702 | 704 | 705 | 709 | 708 | 706 | 710 | 712 | 711 |
| Loading | Dates | R | N | R | R | R | N | R | R | R | R | R | R |
| | Wheel Load | D | D | D | D | D | D | D | D | D | D | D | D |
| | Tire pressure | S | S | S | S | S | S | S | S | S | S | S | S |
| | Wander | R | R | R | S | S | S | S | S | S | S | S | S |
| MC | Subgrade | S | S | S | N | R | S | S | R | S | R | N | S |
| | Base | | | | N | N | S | S | N | N | | | |
| Temp. | Air | S | R | A | N | N | S | S | R | A | R | N | S |
| | HMA | S | R | A | N | N | S | S | R | A | R | N | S |

**TABLE 2.5** – Data Availability – Post-Mortem Investigation

| | | **A-2-4** | | | **A-4** | | | **A-6** | | | **A-6 / A-7-6** | **A-7-5** | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 701 | 707 | 703 | 702 | 704 | 705 | 709 | 708 | 706 | 710 | 712 | 711 |
| MC | Subgrade | | A | | | | R | S | S | | S | S | S |
| | Base | | A | | | | R | S | S | | S | S | S |
| Density | Subgrade | | A | | | | R | S | A | | S | S | S |
| | Base | | A | | | | R | S | A | | S | S | S |
| Thickness AC & Base | | | A | | | | R | S | R | | S | S | S |
| CBR / $M_R$ | Vane | | A | | | | R | S | S | | S | | |
| | DCP | | S | | | | R | S | S | | N | S | S |
| | L-FWD | | | | | | R | | S | | | | |

In addition to the data collected for the experiment, most APT facilities keep an activity log to record the construction dates of for each layer, the dates when the APT testing was performed, and when the post-mortem evaluation was done. The log is very helpful since it allows relating on the same time scale the material testing, the APT testing, and the response and performance measurements. This helps with the data check and calculation of some variables (e.g. average air or pavement temperature during the APT loading). Unfortunately, such a log was not kept for the PSPS project; difficulties were encountered in data assessment and verification because of this.

# CHAPTER 3. EVALUATION OF MATERIAL CHARACTERIZATION DATA

The availability of the material characterization data is indicated in Table 2.2. However, only the maximum dry density, optimum moisture content, liquid and plastic limits and soil classification are included in the PSPS Excel database.

Therefore, data given in the project reports or provided by Dr. Edel Cortez was added to the Excel database and was considered for inclusion in the enhanced database. The following is a discussion on the source and evaluation of the material characterization data.

## 3.1. Particle Size Distribution

Particle size distribution is one of the most important characteristics of soils; it is used for soil classification. The project reports delivered by CRREL included only the gradation curves; they did not provide the particle size data. After the data request, Dr. Edel Cortez provided a file with the particle size data; it is shown in the first four columns of Table 3.1. It seemed that the tests were conducted on the soils from the stockpiles in the late 1990’s, before the soils were actually placed into the pits.

After comparing with the gradation curves from the project reports, it was found that the particle size data provided for the A-7-6 soil was not correct. This data (marked in gray in Table 3.1) is for a much finer soil than for the soil that was placed in the pits for Cells 711 and 712. It is proposed that this data will not be included in the database. For the A-7-5 soil, the particle size data was extracted from the charts given in the reports for cells 711 and 712. This particle size data seems accurate and will be included in the database.

The particle size data for the borderline A-6/A-7-6 soil used in cell 710 was also provide by Dr. Cortez; it will be added to the database. The gradation data for the aggregate base was also found in several files provided by Dr. Cortez. However, the data was not consistent for all files. Therefore, only the data shown in the last column of Table 3.1 was retained for inclusion in the database; it matches the gradation curves given in project reports.

## 3.2. Moisture – Density Data

The relationship between dry density and the moisture content represents the most critical compaction characteristic of a soil. The determination of the maximum dry density (MDD) that can be achieved at standard compaction energy and the corresponding moisture content is essential for the soil compaction process. The maximum densification of the soil and thus, the minimum deformations under service loads, are achieved when the soil is compacted at this optimum moisture content (OMC).

**TABLE 3.1** Gradation data for subgrade soils and aggregate base

| **Sieve size (mm)** | **A-2-4** | **A-4** | **A-6** | **A-7-6** | **A-7-5** (report) | **A-6/A-7-6** | **Base** |
|---|---|---|---|---|---|---|---|
| | Provided by Dr. Cortez | | | | | | |
| 38.1 | 100 | 100 | 100 | 100 | 100 | 100 | 100 |
| 25.4 | 97.1 | 100 | 100 | 100 | 100 | 100 | 99.3 |
| 19.1 | | | | | | | 82.0 |
| 9.52 | 87.4 | 99.5 | 100 | 100 | 100 | 100 | 67.1 |
| 4.75 | 82.0 | 98.9 | 100 | 100 | 100 | 100 | 44.7 |
| 2 | 75.0 | 97.9 | 99.8 | 99.8 | 100 | 100 | 32.4 |
| 0.84 | 63.5 | 94.7 | 99.6 | 99.8 | 98 | 100 | 24.1 |
| 0.42 | 47.0 | 91.9 | 99.4 | 99.8 | 95 | 100 | 18.7 |
| 0.25 | 37.6 | 89.9 | 99.1 | 99.8 | 92 | 100 | 17.0 |
| 0.149 | 33.4 | 88.2 | 98.8 | 99.8 | 90 | 99.9 | 13.0 |
| 0.074 | 29.9 | 84.7 | 98.6 | 99.8 | 88 | 98.0 | 11.1 |
| 0.0289 | | 76.2 | 96.3 | 99.8 | 68 | 97.4 | 8.0 |
| 0.0257 | | 74.2 | 95.1 | 99.8 | | 96.6 | |
| 0.0214 | | 69.7 | 93.2 | 99.8 | 63 | 95.2 | |
| 0.0186 | | 66.6 | 92.4 | 99.6 | | 94.6 | |
| 0.0163 | | 63.2 | 91.3 | 99.5 | | 93.8 | |
| 0.0151 | | 61.4 | 90.5 | 99.4 | 57 | 93 | |
| 0.0111 | | 56.4 | 88.1 | 99.4 | | 86.2 | |
| 0.0097 | | 53.7 | 86.4 | 99.3 | | 84.8 | |
| 0.0088 | | 51 | 85.1 | 99.2 | 50 | 84 | |
| 0.008 | | 48.2 | 83.8 | 98 | | 83.6 | |
| 0.007 | | 45.1 | 82.5 | 96.8 | | 83.4 | |
| 0.0063 | | 42.3 | 80.2 | 95.5 | | 83.2 | |
| 0.0059 | | 40 | 77.9 | 94.6 | 46 | 83.1 | |
| 0.0051 | | 35.5 | 75.6 | 92.9 | | 82.2 | |
| 0.0043 | | 31.8 | 70.7 | 91.6 | | 77.8 | |
| 0.003 | | 25.8 | 63.2 | 85.8 | 38 | 71.2 | |
| 0.0027 | | 24.5 | 60.9 | 84 | | 68.2 | |
| 0.0023 | | 21.8 | 57.2 | 80.1 | 33 | 62.1 | |
| 0.0013 | | 15.4 | 48.7 | 68.4 | | 55 | |
| 0.0012 | | | 46.7 | 66.7 | | 50.2 | |
| 0.0011 | | | | 63.1 | | 46.2 | |

The MDD and the OMC were given in project reports for the subgrade soils and the aggregate base. However, the dry density vs. moisture content data, the data used to determine the MDD and OMC, were given only in charts.

Table 3.2 gives the moisture-density data obtained in the Standard Proctor Test (AASHTO T 99-90). The data for A-2-4, A-4 and A-6 soils was provided by Dr. Cortez. He also provided the data for the A-7-6 soil, but this soil was not used. Therefore, the data was extracted from the charts given in reports for the A6/A-7-6 soil used in test section 710 and the A-7-5 soil used in sections 711 and 712.

**TABLE 3.2** Dry Density and Moisture Content Data for Subgrade Soils

| A-2-4<br>Cells:<br>701; 707 and 703 | | A-4<br>Cells:<br>702; 704 and 705 | | A-6<br>Cells:<br>709; 708 and 706 | | A-7-6<br>Cells:<br>NOT USED | |
|---|---|---|---|---|---|---|---|
| Date: | 11/97 | Date: | 10/95 | Date: | 2/98 | Date: | 2/98 |
| Moisture Content (%) | Dry Unit Weight (pcf) | Moisture Content (%) | Dry Unit Weight (pcf) | Moisture Content (%) | Dry Unit Weight (pcf) | Moisture Content (%) | Dry Unit Weight (pcf) |
| 6.9 | 118.5 | 7.9 | 104.7 | 20.7 | 107.9 | 22.0 | 92.3 |
| 8.8 | 119.0 | 13.4 | 109.5 | 22.6 | 103.7 | 22.9 | 94.6 |
| 12.2 | 118.5 | 15.9 | 113.7 | 24.8 | 99.3 | 25.3 | 94.6 |
| 15.5 | 115.9 | 19.2 | 108.5 | 27.1 | 95.4 | 34.0 | 87.3 |
| 16.9 | 113.6 | | | 15.5 | 112.4 | | |
| | | | | 9.0 | 103.4 | | |
| MDD= 120.7pcf<br>(1,935 kg/$m^3$)<br>OMC = 10.0% | | MDD = 111.1pcf<br>(1,780 kg/$m^3$)<br>OMC = 17.0% | | MDD = 111.8pcf<br>(1,791 kg/$m^3$)<br>OMC = 16.1% | | | |

| A6/A-7-6<br>Cells: 710 | | | A-7-5<br>Cells: 711 and 712 | | |
|---|---|---|---|---|---|
| Report 710 | | | Report 712 | | |
| Moisture Content (%) | Dry Unit Weight (kg/$m^3$) (pcf) | | Moisture Content (%) | Dry Unit Weight (kg/$m^3$) (pcf) | |
| 13.4 | 1,715 | 107.0 | 17.8 | 1,645 | 102.6 |
| 15.4 | 1,782 | 111.2 | 19.6 | 1,695 | 105.8 |
| 17.2 | 1,800 | 112.3 | 21.6 | 1,692 | 103.3 |
| 19.0 | 1,750 | 109.2 | 23.3 | 1,655 | 101.8 |
| 21.2 | 1,677 | 104.6 | 23.9 | 1,632 | 98.0 |
| | | | 25.6 | 1,570 | 95.2 |
| | | | 27.3 | 1,525 | |
| Maximum Dry Density<br>1,800 kg/m3 112.3pcf<br>Optimum Moisture Content<br>17.0% | | | Maximum Dry Density<br>1,700 kg/$m^3$ 106.1pcf<br>Optimum Moisture Content<br>20.5% | | |

The base course material was crushed gravel and it was classified as an A-1-a or GP-GM in the AASHTO and ASTM classification systems, respectively. Table 3.3 contains the dry density vs. moisture data for the unbound aggregate base determined in the Standard and Modified Proctor test (AASHTO T 99 and T 180). This test was repeated several times during the project and showed that the base material used was not the same for all test sections. However, no test was done on the base material used in the sections 701, 703 and 707, when the A-2-4 subgrade soil was tested.

**TABLE 3.3** Dry Density and Moisture Content Data for the Aggregate Base

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Base – Standard Proctor<br>Cells: 702, 704 and 705 | | | Base – Standard Proctor<br>Cells: 706 | | | | | |
| Report 702 – Figure 2b | | | Report 706 – June-02<br>708 - same as for 706 | | | | | |
| Moisture Content (%) | Dry Unit Weight (kg/m$^3$) (pcf) | | Moisture Content (%) | Dry Unit Weight (kg/m$^3$) (pcf) | | | | |
| 5.3 | 2,043 | 127.5 | 3.6 | 2,202 | 137.4 | | | |
| 7.8 | 2,093 | 130.6 | 5.9 | 2,281 | 142.2 | | | |
| 9.5 | 2,122 | 132.4 | 7.24 | 2,403 | 150 | | | |
| 10.3 | 2,115 | 132.0 | 9.0 | 2,318 | 144.6 | | | |
| 11.1 | 2,086 | 130.2 | | | | | | |
| 13.0 | 1,996 | 124.6 | | | | | | |
| Maximum Dry Density<br>2,120 kg/m$^3$<br>Optimum Moisture Content<br>9.5% | | | Maximum Dry Density<br>2,403 kg/m$^3$<br>Optimum Moisture Content<br>7.5% | | | | | |
| Base – Modified Proctor<br>Cells: 702, 704 and 705 | | | Base – Modified Proctor<br>Cells: 708 | | | Base – Modified Proctor<br>Cells: 709, 710, 711 and 712 | | |
| Report 702 – From Cortez<br>Same as Rep 702 – Figure 2b | | | Report 708 – Figure 4 | | | Report 710 | | |
| Moisture Content (%) | Dry Unit Weight (kg/m$^3$) (pcf) | | Moisture Content (%) | Dry Unit Weight (kg/m$^3$) (pcf) | | Moisture Content (%) | Dry Unit Weight (kg/m$^3$) (pcf) | |
| 4.8 | 2,180 | 136.1 | 1.8 | 2,332 | 145.5 | 2.1 | 1,950 | 121.7 |
| 6.0 | 2,243 | 140.0 | 3.0 | 2,353 | 146.8 | 4.7 | 2,180 | 136.0 |
| 6.8 | 2,201 | 137.4 | 3.8 | 2,338 | 145.9 | 6.0 | 2,235 | 139.5 |
| 7.7 | 2,070 | 129.2 | 5.0 | 2,343 | 146.2 | 6.7 | 2,200 | 137.3 |
| 9.8 | 1,964 | 122.7 | 5.8 | 2,413 | 150.6 | 7.8 | 2,067 | 129.0 |
| | | | 7.25 | 2,423 | 151.2 | 9.8 | 1,955 | 122.0 |
| | | | 9.1 | 2,331 | 145.5 | | | |
| Maximum Dry Density<br>2,235 kg/m$^3$<br>Optimum Moisture Content<br>6.0% | | | Maximum Dry Density<br>2,465 kg/m$^3$<br>Optimum Moisture Content<br>7.5% | | | Maximum Dry Density<br>2,237 kg/m$^3$<br>Optimum Moisture Content<br>6.0% | | |

It is important to note that the source for the subgrade and base materials was not indicated. Therefore, it was not possible to obtain sample of the materials for further testing. However, samples of the base material and of three of the five subgrade soils were obtained from CRREL and were stored in the Geotechnical Laboratory of the New York State Department of Transportation.

### 3.3 California Bearing Ratio (CBR) of Subgrade Soils

It is generally accepted that the CBR of subgrade soil is a good indicator of its performance as a pavement subgrade material. The CBR tests were conducted in the PSPS project in order to estimate the relative performance of the built test sections under APT loading (one section relative to another). The CBR values also help relate the tested soils with other soils used in the construction of pavement subgrade.

The results of the CBR test are given in Table 3.4. The data was provided by Dr. Edel Cortez; it was not included in the project reports.

**TABLE 3.4** CBR Test Results for the Subgrade Soils

| A-4 Cells: 702, 704 and 705 | | A-6 Cells: 706, 708 and 709 | | A-7-6 This soil was not used | | A6/A-7-6 Cells: 710 | | A-7-5 Cells: 711 and 712 | |
|---|---|---|---|---|---|---|---|---|---|
| Data Provided by Dr. Edel Cortez | | | | | | Report 710 | | Report 712 | |
| Moisture Content (%) | CBR (%) | Moisture Content (%) | CBR (%) | Moisture Content (%) | CBR (%) | Moisture Content (%) | CBR (%) | Moisture Content (%) | CBR (%) |
| 7.9 | 33 | 9 | 28.2 | 22 | 15.9 | 13.4 | 16 | 18 | 65 |
| 13.4 | 35 | 15.5 | 16.1 | 22.9 | 11.9 | 15.4 | 15.4 | 20 | 53 |
| 15.9 | 12 | 20.8 | 1 | 25.3 | 6.5 | 17.2 | 13 | 22 | 42 |
| 19.2 | 1 | 22.6 | 0.3 | 34 | 2.1 | 19 | 5 | 24 | 18 |
| | | 24.8 | 0.2 | | | 21.2 | 2 | 26 | 10 |
| | | 27.1 | 0.2 | | | | | 28 | 5 |
| | | | | | | | | 30 | 3 |

No CBR test was performed on the A-2-4 soil, used in test sections 701, 703 and 707, or on the aggregate base material.

### 3.4 Hot Mix Asphalt

Very limited data on material characteristics was collected for the asphalt concrete used in the construction of the surface layer. On sections 701; 703; 705 and 706, the asphalt concrete layer, with the nominal thickness of 76.2mm (3 inch) was placed in a single lift and only one mix was used.

For the remaining test sections, (702, 704 and 707 to 712) asphalt concrete binder and surface layers were placed. A coarser mix was always used for the binder layer than for the surface layer. The nominal thickness for the binder layer was 50 mm (2 inch) and for the wearing course was 25 mm (1 inch).

In general, no asphalt mix design data was collected. In some instances, the PG binder grade, binder content and the designation of the mix are given in project reports. Three boxes of the mix used in paving test cells 705 and 706 were shipped to the Materials and Research Testing Laboratories of the Nebraska Department of Roads. Several tests were conducted on the mix:

- Sieve Analysis ( AASHTO T-30)
- Binder Content by Ignition Oven (AASHTO T-308)
- Fine Aggregate Angularity (AASHTO T-304, method A)
- Coarse Aggregate Angularity (ASTM D5821)
- Sand Equivalent (AASHTO T-176)
- Flat and Elongated Particles (ASTM D4791)
- Aggregate Specific Gravity (AASHTO T-84 and T-85)
- Moisture Sensitivity (AASHTO T-283)
- Volumetrics of samples compacted with
    - Marshall Compactor (50 and 75 blows)
    - Superpave Gyratory Compactor ($N_{max}$=134 and 152)
- Rutting under the Asphalt Pavement Analyzer, at 147°F

The detailed data of the asphalt mix testing is given in the Appendices of TS705 and 706 reports. The percent air voids recorded on the mix compacted with the Marshall hammer was 2.4% after 50 blows and 1.5% after 75 blows. This suggests that the mix was very soft and likely had low rutting resistance; the binder content of 6.3% was probably too high for the aggregates/gradation used.

Very limited information was provided for the mix used in the remaining test sections. TS 708, 709, 710, 711 and 712 were paved by Blacktop Inc., a local contractor.
The offices of Blacktop Inc. were visited on Nov 3, 2008 and information on the mix designs was requested. The engineer provided from the archives of the company the actual mix designs used for the binder and surface layers of sections TS711 and TS712; the values are reported in the last column of Table 3.5. He also provided mix designs that he indicated were identical to those used for the binder and surface layers of sections TS708, TS709 and TS710; they are also given in Table 3.5. He highlighted that the PG 58-34 binder grade given in the reports for TS 708, TS709 and TS710 is likely correct.

It is proposed to include all data in Tables 3.1 to 3.5 in the database of the PSPS project, in both Microsoft Excel and Access formats. The material characterization data is essential for understanding the possible factors that affected the performance of the experimental pavement sections tested in the PSPS experiment.

**TABLE 3.5** Asphalt Concrete Mix Design Information

| | TS702 & 704 | | | TS705 & 706* | TS 707, 708, 709 & 710** | | TS711 & 712** | |
|---|---|---|---|---|---|---|---|---|
| Mix Type | Base NH -B | Surface NH -E | | NH - C | VT-II | VT - III | VT - II | VT - III |
| Paving Date | | | | 10/25/ 2001 | | | 11/12/2003 | |
| Sieve Size (mm) | | | Sieve Size (mm) | | | | | |
| 25.4 | 100 | 100 | 25.4 | 100 | 100 | 100 | 100 | 100 |
| 19.0 | 100 | 100 | 19.0 | 100 | 99 | 100 | 98.1 | 100 |
| 12.7 | 81 | 100 | 12.7 | 97.7 | 84 | 99 | 78.4 | 98.6 |
| 9.5 | 71 | 90 | 9.5 | 88.5 | 56 | 89 | 62.1 | 84.2 |
| 4.75 | 50 | 66 | 4.75 | 66.4 | 37 | 57 | 41.3 | 58.2 |
| 2.00 | 32 | 46 | 2.36 | 56.2 | 27 | 42 | 32.7 | 46.6 |
| 0.84 | 20 | 27 | 1.18 | 47.0 | 21 | 32 | 24.9 | 35.5 |
| 0.425 | 13 | 19 | 0.6 | 34.6 | 15 | 23 | 15.5 | 22.1 |
| 0.18 | 7 | 11 | 0.3 | 22.1 | 10 | 15 | 8.0 | 11.3 |
| 0.075 | 3 | 3 | 0.15 | 13.0 | | | 3.5 | 5.0 |
| | | | 0.075 | 6.9 | 2.2 | 3.9 | 1.6 | 2.2 |
| AC Content (%) | 5.3 | 6.4 | AC Content (%) | 6.1 | 4.4 | 5.6 | 5.1 | 5.5 |
| PG Grade | 64-22 | 64-22 | PG Grade | 64-22 | 58-34 | 58-34 | 64-22 | 64-22 |

* data collected by Nebraska Department of Roads

** data obtained from Blacktop Inc.

# CHAPTER 4. EVALUATION OF PAVEMENT CONSTRUCTION DATA

The data collection during pavement construction is essential not only for understanding the possible factors that affected the performance of the experimental pavement sections tested in the PSPS experiment but also for determining the variability of the construction process. As shown in Table 2.3, more efforts were undertaken for collecting and reporting construction information for the experimental test sections TS 701 to TS707 (for the A-2-4 and A-4 soils). For the remaining sections, it is indicated in the project reports that the data were collected, but they are reported as a statistic (average value, standard deviation) or in a histogram plot, at best. The in-situ density and moisture content of the compacted granular layers and FWD tests on top of the constructed pavement were measured on all test sections. The layer thickness was measured on ten sections but complete data was reported for only three sections.

## 4.1 Test Windows

The experimental design of the PSPS project required the testing a combination of four soils and three moisture contents for each soil. This resulted in a total of twelve test cells, numbered from 701 to 712. Within each cell, APT loading was applied in up to six locations, called test windows. Since within the same cell, the wheel load was different from window to window, in order to appropriately perform the analysis of the PSPS data, the collected construction data must be assigned to each test window.

Assigning construction data to each window is not a straight forward process, since the location where the construction data was collected is rarely provided. Typically, the data is given in measuring points, but the location (coordinates) of the measuring points is not given in a diagram or a table. The number of measuring points was not consistent from cell to cell or from parameter to parameter (e.g. moisture content and layer thickness).

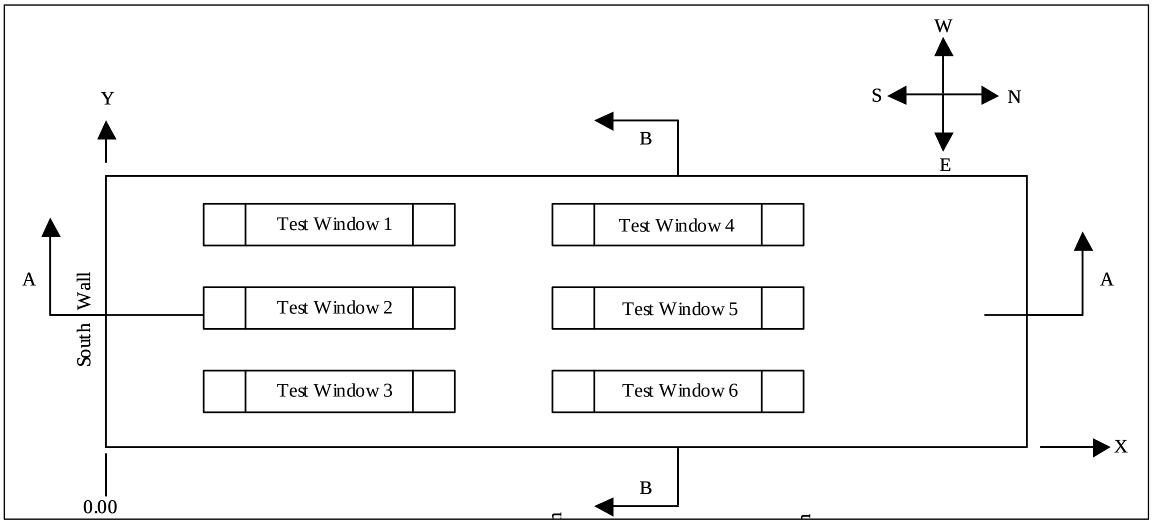
The numbering of the windows themselves was not consistent; it followed two patterns. The pattern shown in Figure 4.1a was used for test cells 702 (figure 13 in the 702 report), 704 (table C-2 in the 704 report) and 705 to 712 (figure 1a in the corresponding reports). The pattern shown in Figure 4.1b was used for test cells 701 (figure 25a in the 701 report) and 703 (figure 4 in the 703 reports).

## 4.2 In-situ Density and Moisture Content of Subgrade Soils

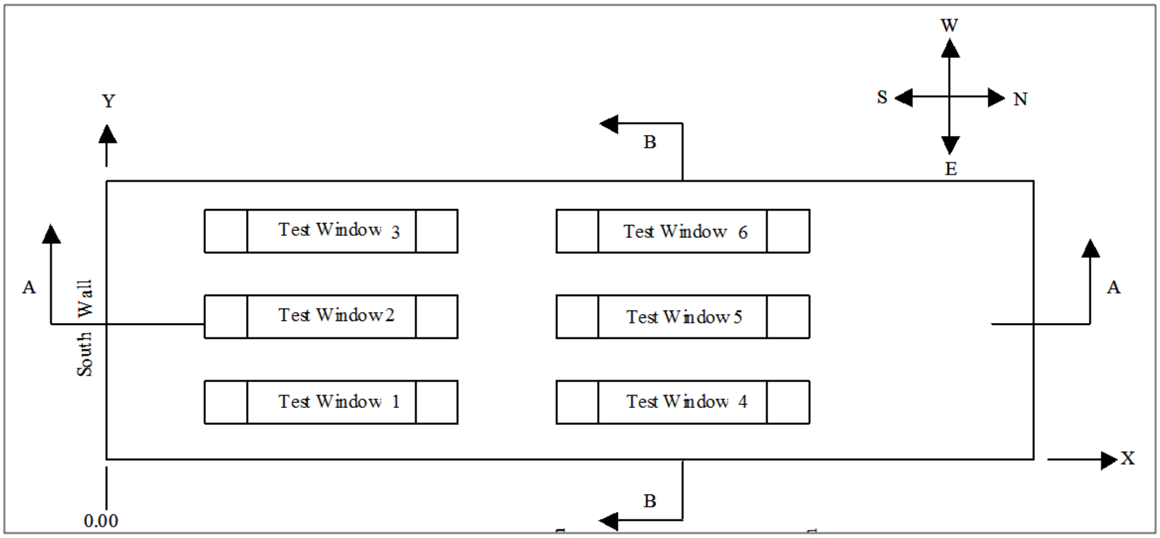
Moisture content of the subgrade soil was an experimental design parameter considered in the PSPS experiment. It was therefore critical to measure it for each layer of compacted soil and to observe the variability and the deviation from the target values. The moisture content and the wet and dry densities were measured at the same time, with a Troxler nuclear gage.

As already mentioned, the moisture content of subgrade soil was measured on all sections. However, complete data is given in project reports only for test sections TS 701 to TS706; the data for TS707 was provided by Dr. Edel Cortez.

**Figure 4.1** Location of test windows within a cell



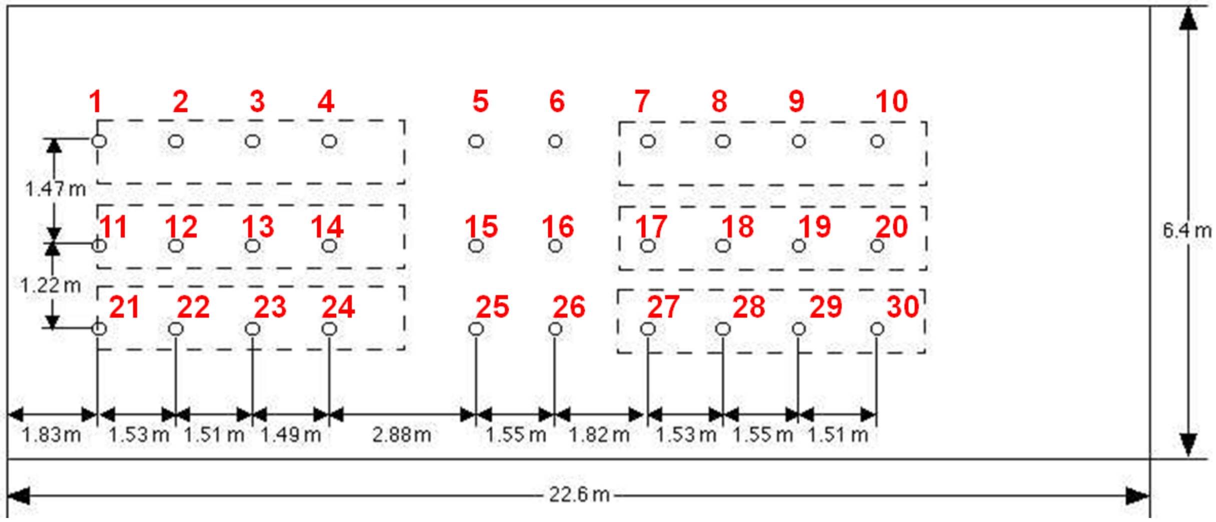
a – used for cells 702 and 704 to 712



b – used for cells 701 and 703

It is important to mention that the measurements were not done in the same location and number of points for all sections and for all soil layers. The pattern shown in Figure 4.2 was followed most of the time. However, the 30 test locations were never numbered in a figure. Dr. Cortez indicated in a conversation that the locations were always numbered starting from the top left (SW corner), going to the right (North) for the cells tested while he work on the PSPS project (cells 704 and higher). Therefore, the numbering in red was added later.

**Figure 4.2** Location of moisture and density measurements (sections 702, 704 to 712)



As shown in Figure 4.2, some of the measurement points for the in-situ moisture content and density were outside of the windows where APT loading was applied. It is therefore useful to compute the average moisture content and density values the points in the same window. They were computed as follows:

- For window W1, average for measurement points 2 to 4
- For window W2, average for measurement points 12 to 14
- For window W3, average for measurement points 22 to 24
- For window W4, average for measurement points 7 to 10
- For window W5, average for measurement points 17 to 20
- For window W6, average for measurement points 27 to 30.

Tables 4.1 and 4.2 give for each test window the average density and moisture content values for the asphalt concrete layer, base layer and the top layers of subgrade soil. It is recommended to add these average values to the database for the project, since they will allow some analysis to be done per test window and not overall per test cell. However, for the sale of completeness, it is recommended to include individual moisture and density values in the database also.

Tables 4.1 and 4.2 show that average values for density and moisture content varied from window to window. Differences of up to 10% in density of the base layer were recorded for test cells 701, 702 and 707. For the same layer of subgrade soil, the variation in density was less than 10%. However, high differences in moisture contents were recorded between the lifts of subgrade soil for the same window.

The two tables also show that in-situ density and moisture content data was not provided for test cells 708 to 712; average values for entire cells are given in project reports and are reproduced in Table 4.3. Asphalt concrete density data was measured only for test cell 706. Density and moisture data were not available for the base layer of test cell 704.

**TABLE 4.1** Average Dry Density (kg/m3)

| Cell | Window | Asphalt Layer | Base Layer | Subgrade Layer - depth (m) from the surface for top of subgrade layer | | | |
|---|---|---|---|---|---|---|---|
| | | | | 0.305 | 0.61 | 0.762 | 0.914 |
| 701 | W1 | | 1,838 | 1,994 | 1,937 | 1,971 | 1,958 |
| 701 | W2 | | 2,198 | 1,916 | 1,945 | 1,960 | 1,922 |
| 701 | W3 | | 2,094 | 1,957 | 1,957 | 1,978 | 1,952 |
| 701 | W4 | | 2,087 | 1,921 | 1,892 | 1,890 | 1,910 |
| 701 | W5 | | 2,110 | 1,962 | 1,981 | 1,943 | 1,966 |
| 701 | W6 | | 2,107 | 1,894 | 1,921 | 1,894 | 1,937 |
| 702 | W1 | | 2,191 | 1,699 | 1,617 | 1,658 | 1,721 |
| 702 | W2 | | 2,117 | 1,707 | 1,643 | 1,634 | 1,698 |
| 702 | W3 | | 1,976 | 1,676 | 1,636 | 1,648 | 1,852 |
| 702 | W4 | | 2,174 | 1,772 | 1,717 | 1,655 | 1,756 |
| 702 | W5 | | 2,042 | 1,766 | 1,778 | 1,710 | 1,784 |
| 702 | W6 | | 1,955 | 1,727 | 1,709 | 1,695 | 1,861 |
| 703 | W1 | | 2,183 | 1,902 | 1,864 | 1,803 | 1,823 |
| 703 | W2 | | 2,079 | 1,928 | 1,803 | 1,834 | 1,811 |
| 703 | W3 | | 2,025 | 1,884 | 1,917 | 1,845 | 1,847 |
| 703 | W4 | | 2,091 | 1,924 | 1,862 | 1,818 | 1,837 |
| 703 | W5 | | 2,262 | 1,925 | 1,869 | 1,859 | 1,867 |
| 703 | W6 | | 2,248 | 1,897 | 1,842 | 1,839 | 1,868 |
| 704 | W1 | | | 1,712 | 1,684 | 1,631 | 1,714 |
| 704 | W2 | | | 1,715 | 1,690 | 1,627 | 1,680 |
| 704 | W3 | | | 1,721 | 1,618 | 1,661 | 1,706 |
| 704 | W4 | | | 1,691 | 1,664 | 1,635 | 1,738 |
| 704 | W5 | | | 1,705 | 1,717 | 1,654 | 1,732 |
| 704 | W6 | | | 1,708 | 1,683 | 1,665 | 1,714 |
| 705 | W1 | | 1,942 | 1,942 | 1,672 | 1,667 | 1,646 |
| 705 | W2 | | 2,003 | 2,003 | 1,661 | 1,667 | 1,636 |
| 705 | W3 | | 1,927 | 1,927 | 1,646 | 1,647 | 1,653 |
| 705 | W4 | | 1,990 | 1,990 | 1,663 | 1,664 | 1,633 |
| 705 | W5 | | 1,961 | 1,961 | 1,647 | 1,658 | 1,642 |
| 705 | W6 | | 1,999 | 1,999 | 1,646 | 1,629 | 1,658 |
| 706 | W1 | 2,209 | 1,849 | 1,660 | 1,645 | 1,633 | 1,604 |
| 706 | W2 | 2,429 | 1,877 | 1,674 | 1,645 | 1,626 | 1,620 |
| 706 | W3 | 2,242 | 1,934 | 1,567 | 1,636 | 1,617 | 1,670 |
| 706 | W4 | 2,258 | 1,906 | 1,650 | 1,628 | 1,631 | 1,648 |
| 706 | W5 | 2,255 | 1,877 | 1,713 | 1,661 | 1,639 | 1,637 |
| 706 | W6 | 2,152 | 1,914 | 1,667 | 1,613 | 1,643 | 1,652 |
| 707 | W1 | | 2,134 | 1,952 | 1,941 | 1,926 | 1,942 |
| 707 | W2 | | 2,155 | 1,939 | 1,920 | 1,877 | 1,937 |
| 707 | W3 | | 2,019 | 1,949 | 1,926 | 1,877 | |
| 707 | W4 | | 2,219 | 1,945 | 1,952 | 1,926 | 1,940 |
| 707 | W5 | | 2,284 | 1,928 | 1,946 | 1,843 | 1,875 |
| 707 | W6 | | 2,145 | 1,948 | 1,906 | 1,832 | |

**TABLE 4.2** Average Moisture Content (%)

| Cell | Window | Base Layer | Subgrade Layer - depth (m) from the surface for top of subgrade layer | | | |
|---|---|---|---|---|---|---|
| | | | 0.305 | 0.61 | 0.762 | 0.914 |
| 701 | W1 | 2.7 | 10.8 | 10.6 | 9.1 | 7.1 |
| 701 | W2 | 2.7 | 10.7 | 11.0 | 9.3 | 7.4 |
| 701 | W3 | 3.2 | 10.4 | 10.5 | 8.7 | 8.3 |
| 701 | W4 | 2.9 | 11.1 | 10.9 | 9.6 | 6.6 |
| 701 | W5 | 2.9 | 11.2 | 10.3 | 9.0 | 7.8 |
| 701 | W6 | 3.8 | 10.6 | 11.4 | 9.0 | 7.8 |
| 702 | W1 | 2.3 | 16.8 | 14.9 | 16.0 | 16.3 |
| 702 | W2 | 2.3 | 15.8 | 15.4 | 15.5 | 15.6 |
| 702 | W3 | 2.2 | 16.6 | 17.5 | 16.3 | 15.1 |
| 702 | W4 | 2.6 | 15.8 | 15.8 | 15.6 | 16.1 |
| 702 | W5 | 2.7 | 16.7 | 15.2 | 14.9 | 15.5 |
| 702 | W6 | 2.3 | 16.6 | 15.7 | 15.7 | 15.3 |
| 703 | W1 | 3.7 | 11.8 | 15.5 | 17.6 | 16.0 |
| 703 | W2 | 3.5 | 11.1 | 16.2 | 15.6 | 15.9 |
| 703 | W3 | 3.5 | 12.1 | 13.5 | 15.0 | 14.8 |
| 703 | W4 | 3.7 | 12.6 | 14.6 | 16.4 | 15.7 |
| 703 | W5 | 3.9 | 10.3 | 14.8 | 15.0 | 14.4 |
| 703 | W6 | 3.5 | 10.2 | 16.0 | 15.3 | 13.8 |
| 704 | W1 | | 19.9 | 19.6 | 22.2 | 20.6 |
| 704 | W2 | | 20.1 | 19.2 | 21.7 | 21.2 |
| 704 | W3 | | 20.2 | 21.5 | 20.5 | 19.7 |
| 704 | W4 | | 21.2 | 20.2 | 21.7 | 19.1 |
| 704 | W5 | | 20.5 | 19.6 | 20.5 | 19.0 |
| 704 | W6 | | 19.3 | 20.4 | 21.0 | 19.6 |
| 705 | W1 | 3.4 | 22.4 | 23.2 | 22.8 | 22.4 |
| 705 | W2 | 3.4 | 22.8 | 23.0 | 22.4 | 22.8 |
| 705 | W3 | 3.3 | 22.3 | 23.2 | 23.4 | 22.3 |
| 705 | W4 | 3.5 | 23.4 | 22.9 | 23.9 | 23.4 |
| 705 | W5 | 3.5 | 22.4 | 23.2 | 22.9 | 22.4 |
| 705 | W6 | 3.3 | 22.3 | 23.4 | 23.1 | 22.3 |
| 706 | W1 | 2.8 | 18.9 | 20.4 | 19.7 | 21.0 |
| 706 | W2 | 2.9 | 18.8 | 19.7 | 21.3 | 21.7 |
| 706 | W3 | 2.9 | 20.3 | 20.4 | 21.3 | 20.9 |
| 706 | W4 | 2.9 | 18.6 | 19.6 | 21.0 | 20.9 |
| 706 | W5 | 2.8 | 18.0 | 20.1 | 20.0 | 19.6 |
| 706 | W6 | 3.2 | 18.6 | 21.7 | 21.6 | 20.5 |
| 707 | W1 | 4.3 | 11.4 | 12.6 | 11.5 | 12.2 |
| 707 | W2 | 3.7 | 12.1 | 12.9 | 11.8 | 11.8 |
| 707 | W3 | 3.3 | 12.4 | 12.9 | 11.7 | |
| 707 | W4 | 3.6 | 10.9 | 12.9 | 11.4 | 11.1 |
| 707 | W5 | 3.5 | 11.6 | 12.8 | 11.7 | 12.1 |
| 707 | W6 | 3.2 | 11.5 | 13.3 | 11.5 | |

Table 4.3 contains the statistics for the in-situ density and moisture content as given in project reports. In many cases, it is clear that the data were collected but the individual values were never reported. The statistics given for the asphalt concrete surface layer and granular base course for cell TS712 are likely wrong, since they are identical to the values reported for TS711.

**TABLE 4.3** Average in-situ density and moisture content given in project reports

| | Layer | Parameter | Experimental Cell | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | | 704 | 708 | 709 | 710 | 711 | 712 |
| In-situ Density (kg/m$^3$) | Asphalt Concrete | Average | | 2,284 | 2,304* | 2,304* | 2,300* | 2,300* |
| | | COV | | 2 | | 2.2 | | |
| | Base | Average | 2,169 | 2,158 | 2,356 | 2,284 | 2,350* | 2,350* |
| | | COV (%) | | 5.1 | 0.8 | 1.35 | 1.8* | 1.8* |
| | Subgrade | Average | | 1,716 | 1,740 | 1,697 | 1,539 | 1,575 |
| | | COV (%) | | 3 | 2.0 | 1.5 | 5.2 | 3.4 |
| In-situ Moisture Content (%) | Base | Average | 2.7 | 4.0 | 4.9 | 4.6 | 5.9* | 5.9* |
| | | COV (%) | | 15 | 7.8 | 10.3 | 5.5* | 5.5* |
| | Subgrade | Average | | 18.6 | 16.6 | 20.7 | 25.1 | |
| | | COV (%) | | 1.5 | 4.9 | 4.0 | 4.8 | |

* the values are likely erroneous; they are the same for two test cells

## 4.3 Layer Thickness

The layer thickness was measured using the rod-and-level method for the asphalt concrete, granular base and the top four lifts of subgrade soil. Unfortunately, the data was reported only for test cells 701 to 703; for the remaining cells a statistic (average and standard deviation) is reported. No additional thickness data was provided by Dr. Cortez after it was requested.

The elevation measurements were performed in 48 points, on four alignments, as shown in Figure 4.3. However, it is important to note that the numbering of the measurement points is given for TS702, but not for cells TS701 and 703. Therefore, the average layer thickness per window can be computed only for cell 702. For cells 701 and 703, the average was computed, but it was assumed that the numbering of the measurement points was changed, starting with station 1 being at the SW corner (where station 37 is in Figure 4.3). Figure 4.3 is the same as figure 7 of TS703 report, but the points were not numbered.

Figure 4.3 also shows that the measurement points were aligned outside of test windows. Therefore, the average layer thickness per window given in Table 4.4, was computed as:

- For window W1, average for measurement points 39 to 41 and 27 to 29
- For window W2, average for measurement points 27 to 29 and 15 to 17
- For window W3, average for measurement points 15 to 17 and 3 to 5
- For window W4, average for measurement points 45 to 47 and 33 to 35

- For window W5, average for measurement points 33 to 35 and 21 to 23
- For window W6, average for measurement points 21 to 23 and 9 to 11.

The values shown in Table 4.4 for test cell TS705 are those given in table 3 of the 705 report. It was indicated that these values were determined from cores extracted post-mortem. It is clear that the construction of TS705 cell, with very moist subgrade soil, led to very high variability of layer thickness. This suggests that the response and performance data collected in TS705 is of little value to the PSPS project.

**Figure 4.3** Location of elevation/thickness measurements (figure 10 in TS702 report)

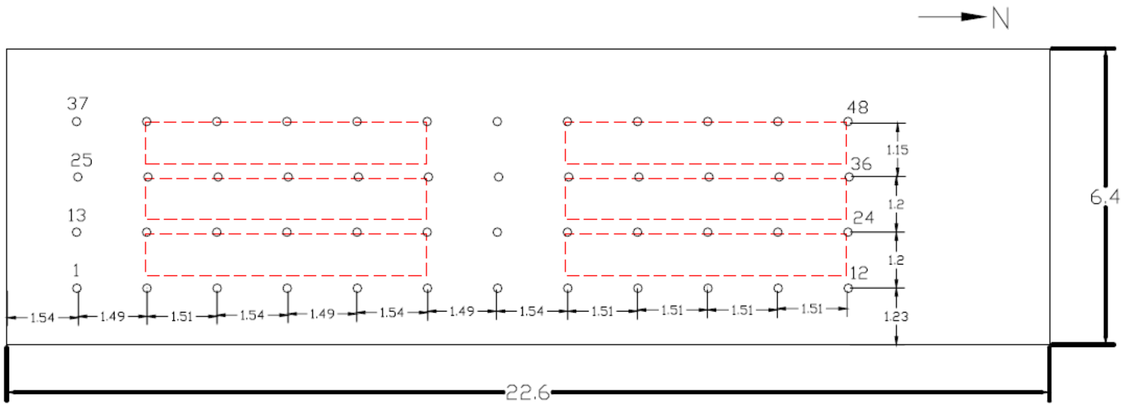


Table 4.5 lists the average layer thickness data as given in project reports. It can be observed that the same data was reported for TS708 and TS707; it is likely that the data for TS708 is erroneous. Also, the nominal thickness values were reported for cell TS704 and TS709 to TS712. This may suggest that no layer thickness measurements were performed for these experimental test cells. This lack of data makes verification of the response data difficult for these experimental test cells.

**TABLE 4.4** Average Layer Thickness (mm)

| Cell | Window | Asphalt Layer | Base Layer | Subgrade Layer - depth from the surface (m) | | | |
|---|---|---|---|---|---|---|---|
| | | | | 0.3 | 0.6 | 0.9 | 1.2 |
| 701 | W1 | 77 | 283 | 239 | 323 | 279 | 260 |
| 701 | W2 | 80 | 267 | 248 | 333 | 280 | 308 |
| 701 | W3 | 86 | 250 | 262 | 331 | 285 | 326 |
| 701 | W4 | 81 | 278 | 257 | 288 | 329 | 260 |
| 701 | W5 | 88 | 265 | 253 | 299 | 336 | 277 |
| 701 | W6 | 96 | 255 | 238 | 308 | 351 | 285 |
| 702 | W1 | 75 | 195 | 347 | 299 | 334 | 176 |
| 702 | W2 | 78 | 197 | 330 | 307 | 341 | 159 |
| 702 | W3 | 83 | 196 | 323 | 285 | 354 | 162 |
| 702 | W4 | 84 | 218 | 290 | 315 | 319 | 204 |
| 702 | W5 | 81 | 228 | 288 | 318 | 318 | 200 |
| 702 | W6 | 87 | 221 | 288 | 332 | 304 | 200 |
| 703 | W1 | | 249 | 157 | 362 | 274 | 349 |
| 703 | W2 | | 249 | 172 | 329 | 294 | 356 |
| 703 | W3 | | 253 | 201 | 303 | 290 | 361 |
| 703 | W4 | | 256 | 197 | 303 | 334 | 285 |
| 703 | W5 | | 248 | 198 | 313 | 320 | 288 |
| 703 | W6 | | 239 | 205 | 316 | 314 | 294 |
| 705 | W1 | 89* | 241 | | | | |
| 705 | W2 | 147* | 211 | | | | |
| 705 | W3 | 81* | 236 | | | | |
| 705 | W4 | 71* | 191 | | | | |
| 705 | W5 | 188* | 234 | | | | |
| 705 | W6 | 79* | 231 | | | | |

*Values measured on cores

**TABLE 4.5** Average layer thickness in project reports

| Layer | Parameter | Experimental Cell | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | 704 | 706 | 707 | 708 | 709 | 710 | 711 | 712 |
| AC | Average | 76 | | 71 | 71.1 | 76 | 76 | 76 | 76 |
| | COV (%) | | | 11 | 11 | | | | |
| Base | Average | 229 | | 226 | 226 | 228.6 | 228.6 | 228.6 | 228.6 |
| | COV (%) | | | 4 | 4 | | | | |

## 4.4 Falling Weight Deflectometer

### FWD Deflection Data

One FWD deflection data file was provided for each test cell on the DVDs. No new data were received after the data request. It was indicated by Dr. Edel Cortez that the FWD files represented tests performed on top of the constructed asphalt concrete layer only. However, there are many instances where it was indicated in the reports that FWD tests were also performed on the subgrade and base layers, but no such data was provided.

*File Format*

The format of the file was not uniform. Cells 701 to 708 and 711 had *.fwd extension; this is the old format of the Dynatest FWD file. The files for cells 709 and 710 had the same format but have the *.hwd extension, maybe because the testing was done with a Heavy Weight Deflectometer (HWD). The deflection data for cell 712 were in the new FWD deflection file format (version 25) and it was also given in a MS Access database file.

Modulus 6.0 backcalculation software import deflection data directly from the *.fwd and *.hwd files into input files they use. However, they were not able to import any of the CRREL deflection files. The error was in the header of the FWD deflection data files. The error could not be found; the backcalculation was performed successfully only after the entire header was changed. The input files for Modulus are added to the original FWD deflection data.

*Testing Dates*

Table 4.6 gives the details of the FWD equipment configuration as listed in the deflection files. The test date is recorded automatically. However, since no general log of the PSPS experiment was kept, it is not possible to identify now if the FWD testing was done on top of the subgrade or base layers, or on top of the asphalt concrete layer. Most APT facilities keep such a log to record: the construction dates of for each layer, the dates the APT testing was performed, and of the post-mortem evaluation was done. The log is very helpful since it allows relating on the same time scale the material testing, the APT testing, the response and the performance measurements.

A good example here is the FWD data given for cells 709 and 710. The notes in the FWD data file indicate that the testing was done on “top of base”. This is credible since the central deflections recorded are very high, approximately 80 mils (2.0 mm) at 6,000 lbs load level, and the backcalculation using MODULUS yielded very low values (85 ksi) for the modulus of the asphalt concrete layer. It is also possible that the reported 9.0 inch radius plate was used; as it is commonly done when testing on top of granular bases.

**TABLE 4.6** Configuration of the FWD equipment used during testing

| Cell | Test Date | Nr. of stations | Loading Plate Radius (in.) | Geophone Position (in.) | Drop Sequence |
|---|---|---|---|---|---|
| 701 | 1/25/1997 | 24 | 6 | 0; 12; 24; 36; 48; 60; 72 | 4 each at 6,000; 9,000; 12,000 and 14,500 lbs |
| 702 | | | | | |
| 703 | 2/10/1998 | 24 | 8.94 | 0; 8; 12; 24; 36; 48; 72 | 4 each at 6,000; 9,000; 12,000 and 16,000 lbs |
| 704 | | | | | |
| 705 | 11/04/2001 | 90 | 5.91 | 0; 12; 24; 36; 48; 60; 72 | 4 at 8,000 lbs |
| 706 | 1/3/2002 | 24 | 5.91 | 0; 12; 24; 36; 48; 60; 72 | 4 each at 3,000; 5,000; 7,000 and 9,000 lbs |
| 707 | 10/04/2002 | 21 | ***2.95*** | 0; 12; 24; 36; 48; 60; 72 | 4 each at 3,000; 5,000; 6,500 and 7,500 lbs |
| 708 | 10/03/2002 | 21 | ***2.95*** | 0; 12; 24; 36; 48; 60; 72 | 4 each at 3,000; 5,000; 6,000 and 7,000 lbs |
| 709 | 8/11/2003 | 21 | 9 | 0; 12; 24; 36; 48; 60; 72 | 4 each at 2,500; 4,000 and 6,000 lbs |
| 710 | 8/12/2003 | 21 | 9 | 0; 12; 24; 36; 48; 60; 72 | 4 each at 2,500 and 5,000 lbs |
| 711 | 12/03/2004 | 21 | 6 | 0; 12; 24; 36; 48; 60; 72 | 4 each at 7,000; 11,500; 15,000 and 18,000 lbs |
| 712 | 12/09/2005 | 17* | 6 | 0; 12; 24; 36; 48; 60; 72 | 4 each at 6,000; 9,000; 12,000 and 14,500 lbs |

* - stations 4 to 7 are missing

*Number of stations*

Table 4.6 clearly suggests that the testing was not done for all cells in the same corresponding location. A diagram of station location (Figure 4.4) was given in the reports for several cells and also on the data DVD, but it is obvious that was not kept the same. However, it is reasonable to assume that the testing was done in three alignments, corresponding to the centerlines of windows 1 and 4, 2 and 5 and 3 and 6, respectively. For most cells, the FWD tests were performed in 7 or 8 stations for each alignment.

For cell 705, it is likely that the FWD tests were performed every foot (12 inches); this resulted in a total of 90 stations. For cells 701 to 704 and 706, the FWD tests were performed on two alignments, between the test windows as shown in Figure 4.5. This figure originates in Figure 5 in TS707 report; the FWD test locations are not numbered.

Since the FWD tests were performed between the test windows, the FWD data recorded for one cell cannot be split and assigned to the six windows.

It seems that, on each alignment, the tests were performed always starting from South going North. Also, it seems that the first alignment was to the East of the test cell (windows 3 and 6).

**Figure 4.4** Location of FWD test locations for TS 707 to TS712

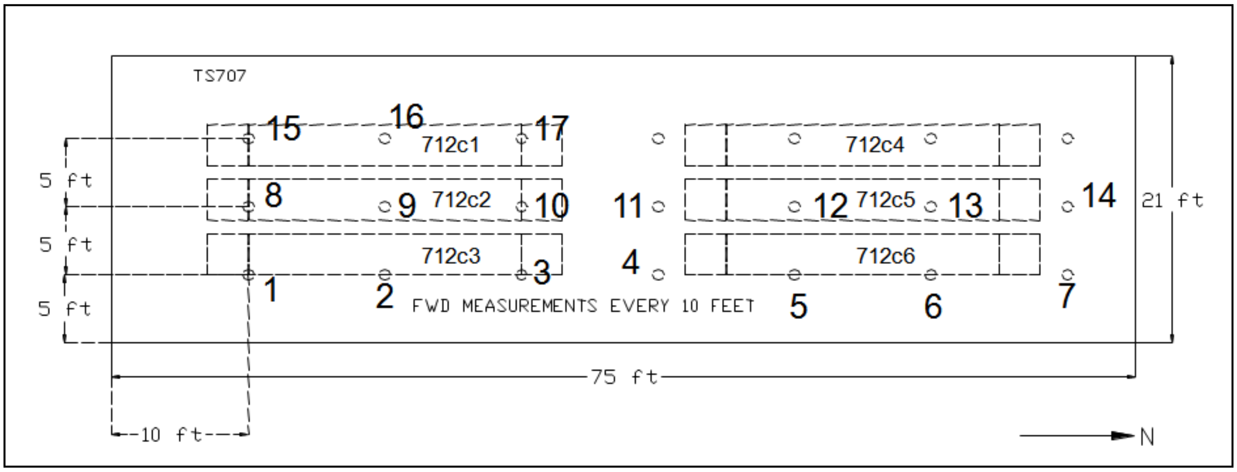
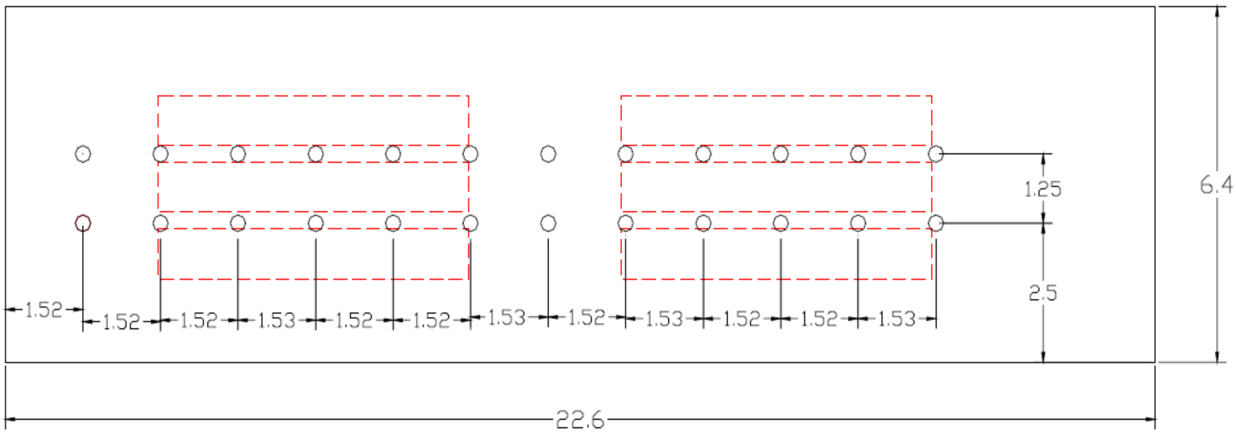


**Figure 4.5** Location of FWD test locations for TS701 to TS704 and TS706 (figure 17 in TS703 report)



FWD TEST POINTS

### *Testing Configuration*

Table 4.6 gives the details of the FWD equipment configuration as listed in the deflection files. The radius of the loading plate and the position of the geophones are entered by the FWD equipment operator.

It is obvious from Table 4.6 that the operator erroneously recorded the plate radius as 2.95 inches when testing cells 707 and 708; the smallest plate that can be attached to the FWD equipment has the radius of 5.91 inches. The 5.91 or 6 inches (due to round up error) radius plate is the most common plate used for testing flexible pavement structures. It was assumed that the operator mistakenly considered the diameter as 5.91 inches (instead of the radius) and then recorded the radius as half of that, or 2.95 inches. This error was corrected in the file. However, it cannot be determined if the radius of the loading plate recorded for cells 703, 704, 709 and 710 was 9 inches or the standard plate with the radius of 5.91 or 6 inches was used. As discussed previously, it is likely that a 9.0 inch radius plate was used for the tests done on cells 709 and 710, but it cannot be assumed the same for cells 703 and 704. Therefore, the original value of 9.0 inches was not changed.

For most FWD testing, the equal spacing between geophones of 12 inches was used; this is the spacing initially recommended by Dynatest for testing flexible pavements. The spacing recommended by the LTPP program for flexible pavements was used only for cells 703 and 704.

The drop sequence used varied from cell to cell. This was very reasonable since lower FWD loads must be used for the cells with wetter soil. It is however, unclear why very high loads were used when testing cells 711 and 712. These cells had a soft, wet soil, so lower loads should have been be used.

### *Layer Moduli Backcalculation*

The balcalculation of layer moduli was performed using MODULUS 6.0 program. The backcalculation was performed with MODULUS by changing, for each layer, the upper and lower moduli limits until the average backcalculated moduli of that layer for one test cell was close to the average of the two limits. The backcalculation was performed for all twelve test cells, but only for a single deflection bowl for each FWD measurement point, the bowl corresponding to the last drop at a load level close to 9,000 lbs. The backcalculation was done at once for all the measurement points in a test cell, using the reported average layer thicknesses for test cells 701, 702, 703, 707, 708 and the nominal layer thicknesses for the remaining test sections.

The results of the backcalculation are given in Appendix A. The tables show that a better backcalculation was obtained for the test cells for which the average layer thickness was used instead of the nominal layer thickness; the average Absolute Error/Sensor is lower.

*Proposed Data to be Retained*

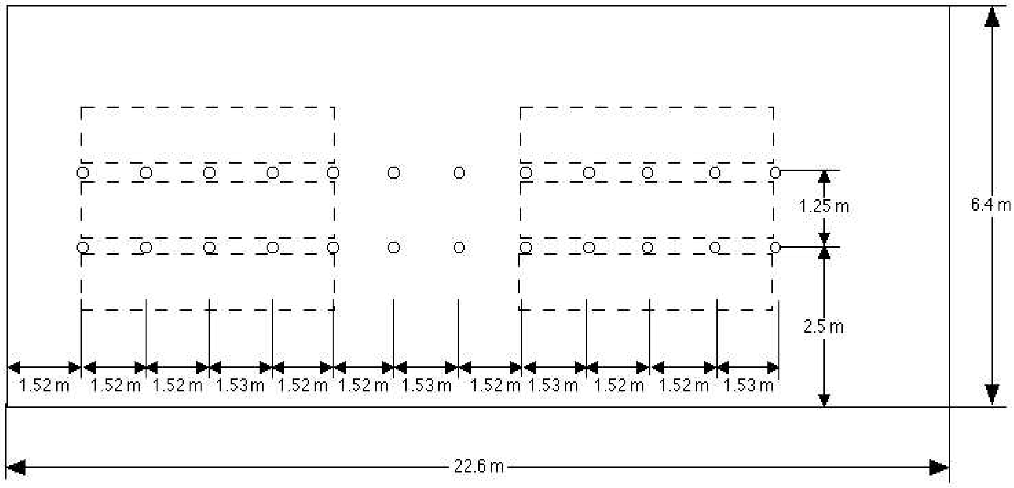
It is proposed that the FWD data collected for all test cells. However, for test cells TS701 to TS707 it was noted that the locations of the FWD stations were either outside of the test windows or were unknown. The following data was retained for all load drops:

- Cell number, measurement point, load level and drop number, air and pavement surface temperatures, diameter of the load plate, location of the geophones and the measured FWD load and deflection,.
- Remarks were added for deflection bowls that have decreasing deflections. If the last drop had non-decreasing deflections, which happened several times for TS709 and TS710, data was flagged in this case. The non-decreasing deflections can be attributed to the extremely weak pavement or to the use of the 12 inch spacing between geophones; the LTPP protocol for FWD testing of flexible pavements should have been used instead.
- Backcalculated layer moduli from Appendix A.

## 4.5 Dynamic Cone Penetrometer (DCP)

Dynamic Cone Penetrometer tests were performed for construction quality control only for test cell TS701, in 24 stations, as shown in Figure 4.6. The data was used for estimating the CBR of the compacted soil; it is given in table A-4 in the TS701 report. However, since the measurement locations are not numbered, and are between the test windows, it is proposed that the CBR-from-DCP data should not be retained for the PSPS project database.

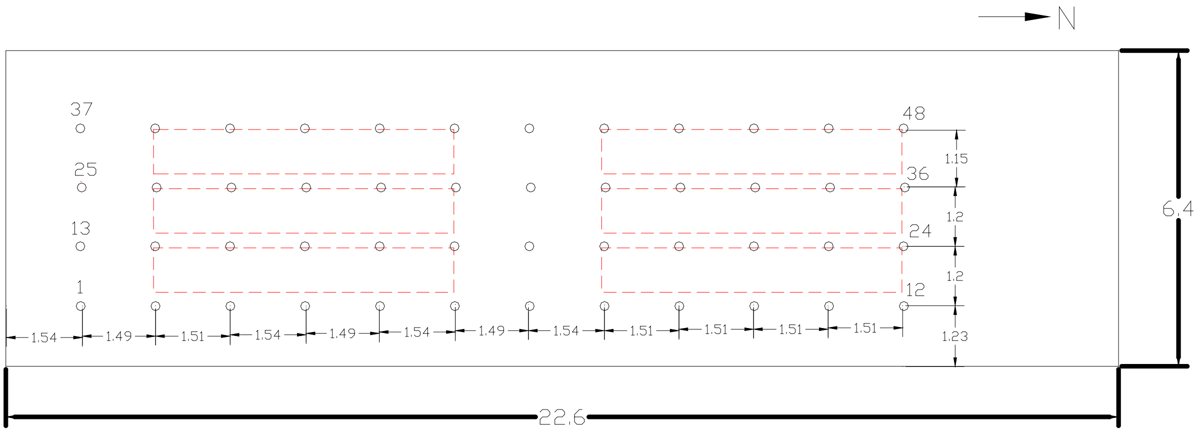
**Figure 4.6** Location of DCP test locations for TS701 (figure 20 in TS701 report)



## 4.6 CLEGG Hammer

Testing with the CLEGG hammer was conducted in 48 stations for TS701, 702 and 704, as shown in Figure 4.6. CELGG hammer testing was also performed for TS706, in 60 test points. However, no diagram of the test locations is provided.  The CLEGG hammer data was used for estimating the CBR of the compacted soil; it is given in Table 4.7 for the upper 1.2 meters of subgrade. It is proposed that the CBR-from-CLEGG hammer data should be retained for the PSPS project database only for test cells TS701, TS702 and TS704. For TS706, the data was retained in the database but  notes were added indicating that the measurement locations are unknown.

**Figure 4.7.** CLEGG hammer test points for 701, 702 and 704 (fig. 9 in TS704 report)



## 4.7 Vane Shear

Vane Shear tests were performed for construction quality control only for test cell TS705, in four layers, in 36 stations each, as shown in figure 16 of TS705 report. However, individual test data was not provided and, therefore, no Vane Shear data should be retained for the PSPS database. The only information provided in the TS705 report is a histogram (figure 17), which gives: number of test points = 144; average Vane Shear = 36.9kPa and the coefficient of variation (COV) =25.2%.

**TABLE 4.7** CBR of subgrade soil estimated for CLEGG hammer tests

| | TS701 | | | | TS702 | | | | TS704 | | | | TS706 | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Depth from AC surface (m) | | | | | | | | | | | | | | |
| Point | 1.07 | 0.91 | 0.8 | 0.6 | 1.07 | 0.91 | 0.76 | 0.61 | 1.1 | 0.9 | 0.8 | 0.6 | 1.19 | 0.7 | 0.43 |
| 1 | 8 | 10 | 6 | 3 | 4.5 | 4.5 | 5.7 | 5.7 | 1.1 | 1.1 | 1.8 | 0.6 | 3 | 3 | 4 |
| 2 | 8 | 10 | 8 | 6 | 8.5 | 5.7 | 4.5 | 4.5 | 1.8 | 2.5 | 1.1 | 1.1 | 2 | 3 | 3 |
| 3 | 8 | 14 | 14 | 8 | 10.1 | 5.7 | 5.7 | 5.7 | 2.5 | 1.8 | 0.3 | 0.6 | 2 | 4 | 3 |
| 4 | 18 | 16 | 12 | 4 | 8.5 | 3.4 | 8.5 | 4.5 | 1.8 | 1.8 | 0.3 | 0.6 | 2 | 3 | 3 |
| 5 | 18 | 12 | 14 | 12 | 8.5 | 4.5 | 10.1 | 8.5 | 1.8 | 1.8 | 1.1 | 1.1 | 3 | 3 | 3 |
| 6 | 16 | 14 | 10 | 7 | 5.7 | 4.5 | 10.1 | 8.5 | 1.1 | 1.8 | 1.1 | 1.1 | 3 | 3 | 3 |
| 7 | 18 | 12 | 12 | 12 | 7 | 4.5 | 7 | 8.5 | 1.1 | 1.8 | 1.1 | 1.1 | 3 | 3 | 3 |
| 8 | 23 | 14 | 12 | 10 | 8.5 | 4.5 | 11.8 | 5.7 | 1.8 | 2.5 | 0.6 | 1.1 | 3 | 2 | 4 |
| 9 | 23 | 16 | 14 | 12 | 8.5 | 5.7 | 5.7 | 8.5 | 1.8 | 3.4 | 0.6 | 1.1 | 2 | 2 | 4 |
| 10 | 20 | 16 | 12 | 10 | 10.1 | 3.4 | 7 | 7 | 1.1 | 2.5 | 1.1 | 0.6 | 2 | 3 | 4 |
| 11 | 23 | 20 | 16 | 10 | 7 | 4.5 | 11.8 | 8.5 | 1.8 | 1.8 | 1.1 | 1.1 | 2 | 3 | 3 |
| 12 | 23 | 18 | 18 | 7 | 5.7 | 4.5 | 11.8 | 4.5 | 2.5 | 4.5 | 1.1 | 1.1 | 3 | 3 | 4 |
| 13 | 7 | 10 | 16 | 4 | 7 | 3.4 | 7 | 4.5 | 1.1 | 1.8 | 0.3 | 0.6 | 2 | 3 | 3 |
| 14 | 7 | 14 | 12 | 10 | 11.8 | 7 | 5.7 | 5.7 | 1.8 | 1.8 | 1.8 | 1.1 | 2 | 4 | 4 |
| 15 | 8 | 18 | 14 | 10 | 4.5 | 7 | 5.7 | 8.5 | 2.5 | 2.5 | 0.3 | 1.1 | 3 | 3 | 3 |
| 16 | 23 | 25 | 7 | 10 | 7 | 8.5 | 10.1 | 11.8 | 2.5 | 1.1 | 0.6 | 1.1 | 2 | 3 | 3 |
| 17 | 23 | 25 | 20 | 12 | 7 | 10.1 | 7 | 4.5 | 1.8 | 1.8 | 0.6 | 0.6 | 2 | 4 | 3 |
| 18 | 25 | 28 | 14 | 12 | 10.1 | 5.7 | 7 | 5.7 | 2.5 | 1.1 | 0.3 | 1.1 | 2 | 3 | 3 |
| 19 | 40 | 23 | 10 | 12 | 8.5 | 8.5 | 11.8 | 8.5 | 2.5 | 1.8 | 0.3 | 1.8 | 4 | 3 | 3 |
| 20 | 37 | 20 | 20 | 10 | 11.8 | 8.5 | 11.8 | 8.5 | 1.8 | 1.8 | 1.8 | 1.1 | 2 | 4 | 3 |
| 21 | 31 | 16 | 14 | 12 | 7 | 8.5 | 8.5 | 4.5 | 1.8 | 2.5 | 0.6 | 1.1 | 3 | 5 | 3 |
| 22 | 34 | 16 | 12 | 10 | 13.7 | 10.1 | 11.8 | 4.5 | 1.8 | 0.6 | 0.6 | 1.8 | 3 | 4 | 3 |
| 23 | 40 | 23 | 16 | 12 | 13.7 | 10.1 | 10.1 | 3.4 | 1.8 | 0.6 | 1.8 | 1.8 | 3 | 4 | 3 |
| 24 | 25 | 18 | 20 | 12 | | 8.5 | 10.1 | 5.7 | 2.5 | 3.4 | 0.6 | 1.1 | 4 | 3 | 4 |
| 25 | 10 | 8 | 6 | | 10.1 | 4.5 | 7 | 4.5 | 1.1 | 1.8 | 1.1 | 1.8 | 3 | 3 | 3 |
| 26 | 7 | 8 | 10 | | 11.8 | 4.5 | 8.5 | 11.8 | 1.8 | 2.5 | 0.6 | 1.8 | 3 | 3 | 4 |
| 27 | 14 | 18 | 7 | | 13.7 | 8.5 | 7 | 8.5 | 2.5 | 1.8 | 0.6 | 1.1 | 2 | 3 | 5 |
| 28 | 20 | 20 | 8 | | 17.9 | 8.5 | 8.5 | 11.8 | 2.5 | 2.5 | 0.3 | 0.6 | 3 | 2 | 4 |
| 29 | 16 | 25 | 14 | | 10.1 | 11.8 | 13.7 | 7 | 1.8 | 1.8 | 0.6 | 1.1 | 3 | 3 | 4 |
| 30 | 23 | 23 | 12 | | 10.1 | 10.1 | 10.1 | 8.5 | 2.5 | 1.1 | 1.8 | 1.8 | 3 | 3 | 5 |
| 30 | 23 | 23 | 12 | | 10.1 | 10.1 | 10.1 | 8.5 | 2.5 | 1.1 | 1.8 | 1.8 | 3 | 3 | 5 |
| 31 | 18 | 20 | 18 | | 11.8 | 8.5 | 8.5 | 4.5 | 2.5 | 1.8 | 0.3 | 1.8 | 2 | 3 | 2 |
| 32 | 25 | 18 | 23 | | 11.8 | 7 | 7 | 10.1 | 2.5 | 2.5 | 0.3 | 1.1 | 2 | 4 | 2 |
| 33 | 28 | 23 | 10 | | 11.8 | 7 | 7 | 11.8 | 1.8 | 3.4 | 1.1 | 1.1 | 2 | 3 | 2 |

**TABLE 4.7 –** Continued

| | TS701 | | | | TS702 | | | | TS704 | | | | TS706 | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Depth from AC surface (m) | | | | | | | | | | | | | | |
| Point | 1.07 | 0.91 | 0.8 | 0.6 | 1.07 | 0.91 | 0.76 | 0.61 | 1.1 | 0.9 | 0.8 | 0.6 | 1.19 | 0.7 | 0.43 |
| 34 | 25 | 23 | 18 | 14 | 10.1 | 8.5 | 8.5 | 8.5 | 2.5 | 3.4 | 1.1 | 0.6 | 3 | 3 | 3 |
| 35 | 28 | 23 | 18 | 16 | 8.5 | 10.1 | 11.8 | 10.1 | 2.5 | 2.5 | 0.3 | 0.6 | 2 | 4 | 3 |
| 36 | 25 | 23 | 10 | 14 | 10.1 | 2.5 | 5.7 | 7 | 1.1 | 4.5 | 0.3 | 1.1 | 4 | 3 | 3 |
| 37 | 8 | 10 | 6 | 7 | 11.8 | 2.5 | 7 | 5.7 | 1.1 | 3.4 | 0.3 | 1.1 | 3 | 3 | 4 |
| 38 | 8 | 18 | 6 | 10 | 11.8 | 3.4 | 7 | 8.5 | 1.1 | 3.4 | 0.3 | 1.1 | 3 | 3 | 3 |
| 39 | 12 | 12 | 18 | 8 | 15.8 | 5.7 | 8.5 | 10.1 | 1.8 | 2.5 | 1.1 | 1.8 | 3 | 3 | 3 |
| 40 | 16 | 10 | 10 | 12 | 11.8 | 7 | 8.5 | 7 | 2.5 | 1.8 | 1.1 | 1.1 | 2 | 2 | 3 |
| 41 | 14 | 10 | 10 | 10 | 11.8 | 8.5 | 10.1 | 13.7 | 2.5 | 1.8 | 0.6 | 1.1 | 2 | 3 | 3 |
| 42 | 12 | 8 | 14 | 10 | 11.8 | 8.5 | 8.5 | 7 | 2.5 | 1.8 | 1.1 | 1.1 | 2 | 3 | 4 |
| 43 | 23 | 10 | 16 | 12 | 10.1 | 7 | 8.5 | 5.7 | 2.5 | 1.8 | 0.3 | 1.1 | 3 | 3 | 4 |
| 44 | 20 | 16 | 16 | 14 | 10.1 | 5.7 | 13.7 | 10.1 | 2.5 | 2.5 | 0.6 | 0.6 | 2 | 3 | 4 |
| 45 | 20 | 18 | 16 | 16 | 10.1 | 7 | 5.7 | 8.5 | 3.4 | 4.5 | 1.8 | 0.6 | 2 | 4 | 5 |
| 46 | 18 | 20 | 16 | 14 | 8.5 | 5.7 | 8.5 | 4.5 | 2.5 | 3.4 | 0.6 | 1.1 | 3 | 3 | 3 |
| 47 | 25 | 20 | 14 | 10 | 8.5 | 8.5 | 10.1 | 8.5 | 2.5 | 3.4 | 0.6 | 1.1 | 3 | 3 | 3 |
| 48 | 20 | 20 | 16 | 10 | 11.8 | 8.5 | 8.5 | 4.5 | 1.8 | 3.4 | 0.6 | 0.6 | 3 | 4 | 2 |
| 49 | | | | | | | | | | | | | 2 | 3 | 3 |
| 50 | | | | | | | | | | | | | 4 | 3 | 3 |
| 51 | | | | | | | | | | | | | 2 | 3 | 3 |
| 52 | | | | | | | | | | | | | 3 | 3 | 3 |
| 53 | | | | | | | | | | | | | 3 | 3 | 3 |
| 54 | | | | | | | | | | | | | 3 | 2 | 3 |
| 55 | | | | | | | | | | | | | 2 | 3 | 3 |
| 56 | | | | | | | | | | | | | 2 | 3 | 3 |
| 57 | | | | | | | | | | | | | 3 | 4 | 3 |
| 58 | | | | | | | | | | | | | 3 | 4 | 4 |
| 59 | | | | | | | | | | | | | 2 | 3 | 4 |
| 60 | | | | | | | | | | | | | 3 | 3 | 4 |

# CHAPTER 5. APT TESTING DATA

## 5.1 Test Dates and Wheel Loads

If, for each test window, the wheel loads are given in each test cell report as well as in the Excel database, the dates the APT testing was conducted are rarely given. The APT test dates are useful in relating the temperature recorded by the temperature sensors and the moisture content recorded by the Vitel Hydra moisture gages with the APT testing time of each test window.

Table 5.1 gives the date interval each test window was subjected to APT loading. It is important to note that the dates listed for a test window correspond to the dates the APT loading started and ended on that test window; it is unknown if the machine was stopped for longer periods of time between these dates for maintenance and/or repairs.

The wheel loads listed in Table 5.1 correspond to the average values. The wheel load of the HVS machine does not remain constant while the wheel passes over the pavement. However, the measurements for some test windows showed that the wheel load had a coefficient of variation of less than 2.0%. Because of this, it is recommended for practical purposes to retain only the average wheel load values (Table 5.1) for the PSPS database.

## 5.2 Tire inflation pressure and lateral wheel wander

The tire inflation pressure has been recorded for several test cells, but not for test windows. The values ranged around 690kPa (100 psi) and the recorded variations were less than 4.0%. Therefore, it is recommended to retain for the PSPS database only the average inflation pressure value. Another reason for retaining this value is that the average contact pressure between the tire and the pavement surface is not equal to the tire inflation pressure.

The lateral wheel wander used in the APT loading is an important parameter since it determines the shape of the transverse surface profile and the values of the accumulated permanent deformation in the pavement structure. For the entire PSPS experiment the same lateral wander pattern was used: uniform lateral wander with the maximum lateral position from the centerline of ±0.3m (12in.) in 50mm (2in.) increments. The APT test were conducted in uni-directional mode at 13km/hour (8 mph); the average number of load repetitions being 700 per hour. The dimensions of the APT loading wheel are given in the summary report for the project.

**TABLE 5.1.** Test Dates and Wheel Loads for each Test Window

| Cell | | Test Window | | | | | |
|---|---|---|---|---|---|---|---|
| | | 1 | 2 | 3 | 4 | 5 | 6 |
| 701 | Load (kN) | 40 | 89 | 103.5 | 89 | - | - |
| | Start date | 4/10/97 | 8/20/97 | 9/4/97 | 7/9/97 | - | - |
| | End date | 7/1/97 | 9/2/97 | 9/10/97 | 8/11/97 | - | - |
| 702 | Load (kN) | 67 | 81 | 63 | 61 | 54 | 71 |
| | Start date | | | | | | |
| | End date | | | | | | |
| 703 | Load (kN) | - | 62.3 | 62.3 | - | 80 | 53.4 |
| | Start date | - | 5/4/98 | 10/15/98 | - | 4/17/98 | 5/11/98 |
| | End date | - | 5/8/98 | 11/16/98 | - | 4/28/98 | 10/10/98 |
| 704 | Load (kN) | 54 | 45 | 49 | 45 | 40 | 40 |
| | Start date | 11/23/98 | 6/7/99 | 5/17/99 | 12/7/98 | 7/13/99 | 4/21/99 |
| | End date | 12/4/98 | 7/6/99 | 5/24/99 | 12/14/98 | 10/19/99 | 5/12/99 |
| 705 | Load (kN) | 26 | 41 | 22 | - | 54 | - |
| | Start date | 12/20/01 | 12/10/01 | 1/22/02 | - | 11/25/01 | - |
| | End date | 12/21/01 | 12/18/01 | 1/23/02 | - | 11/27/01 | - |
| 706 | Load (kN) | 27 | 40 | 22 | 22 | 27 | 40 |
| | Start date | 2/21/02 | 3/7/02 | 3/18/02 | 2/14/02 | 2/28/02 | 3/14/02 |
| | End date | 2/27/02 | 3/11/02 | 3/26/02 | 2/21/02 | 3/6/02 | 3/15/02 |
| 707 | Load (kN) | 62 | 40 | 80 | 53 | 80 | 67 |
| | Start date | 11/26/02* | 1/8/03* | 4/15/03* | 10/29/02* | 12/18/02* | 4/2/03* |
| | End date | 12/17/02* | 2/20/03* | 4/21/03* | 11/22/02* | 1/3/03* | 4/14/03* |
| 708 | Load (kN) | 40 | 26.7 | 31.1 | 53.4 | 40 | 31.1 |
| | Start date | 4/28/03 | 5/9/03 | 5/23/03 | 4/22/03 | 5/1/03 | 5/20/03 |
| | End date | 4/30/03 | 5/20/03 | 5/29/03 | 4/24/03 | 5/5/03 | 5/23/03 |
| 709 | Load (kN) | 26.7 | 40 | 53.4 | 31.1 | 40 | 20 |
| | Start date | 5/4/04 | 3/30/04 | 4/19/04 | 3/22/04 | 4/22/04 | 4/5/04 |
| | End date | 5/19/04 | 4/1/04 | 4/21/04 | 3/26/04 | 4/29/04 | 4/14/04 |
| 710 | Load (kN) | 27 | 40 | 20.5 | 40 | 20.0 | 33.4 |
| | Start date | 1/12/04 | 2/11/04 | 2/5/04 | 1/26/04 | 1/28/04 | 2/18/04 |
| | End date | 1/22/04 | 2/13/04 | 2/9/04 | 1/27/04 | 2/2/04 | 4/4/04 |
| 711 | Load (kN) | 26.7 | 97.9 | 80 | 80 | 40 | 97.9 |
| | Start date | 2/7/05 | 8/3/06 | 11/16/05 | 9/19/06 | 6/6/05 | 9/7/06 |
| | End date | 4/18/05 | 9/5/06 | 12/7/05 | 10/15/06 | 11/9/05 | 9/18/06 |
| 712 | Load (kN) | 80 | 89 | 93.4 | 97.9 | 40 | 97.9 |
| | Start date | 12/8/05 | 4/28/06 | 2/21/06 | 11/17/06* | 3/1/06 | 10/30/06* |
| | End date | 2/16/06 | 5/12/06 | 2/28/06 | 11/27/06* | 4/26/06 | 11/15/06* |

*Dates were obtained from profile file dates not from reports

### 5.3 Temperature and moisture content

Efforts were undertaken to collect the temperature and moisture content at various locations in the pavement structure. However, due to the lack of the clear protocol, most of the data have been lost.

Table 2.4 shows the availability of the data. In essence, the temperature or moisture data was provided in three forms:

- *As a statistic*. In this case the average temperature or moisture content is given in the reports for the entire test cell. In some cases (e.g. test cell 707), the average temperature is given for each test window, but no depth is given (see Table 5.2).
- *As a chart*. In this case, the temperature at various depths is plotted versus the date. The depth for each thermocouple, corresponding for each series, is not always given. Therefore no data can be extracted
- *As data table*. This case is only for test cell 707. The table, reproduced in Table 5.3, does not indicate the depth for each sensor; it wasn't given in the report appendices either.
- *As a raw data table*. This case is only for test cell 703, for which Dr. Cortez provided the data. The data provided were used to compute the values shown in Table 5.4 and 5.5. This is the only test cell with complete temperature and moisture data.

In general, it can be concluded that the provided temperature and moisture data are insufficient and of little help. In some cells, no temperature sensors were installed in the asphalt layer. Also, surface and air temperature measurements were recorded manually for some test cells. Most, if not all, APT research projects record the temperature in the asphalt concrete layer, at least at the surface and mid-depth, since the stiffness of this layer greatly depends on temperature.

Dr. Cortez provided a spreadsheet with the temperature data for section 706, used for a figure in the 706 report. However, it was found that the dates the temperature values were recorded were after March 25, 2002, when testing of cell 706 ended.

It is important to note that the data and the charts given in the reports suggest that the moisture content in the subgrade soil did not change much during the APT testing. This is expected since the pavement structures were built in concrete pits and the asphalt concrete surface layer paved wall-to-wall did not allow the moisture in the subgrade soil to decrease. However, variation in moisture contents with depth has been recorded, confirming the similar conclusion on the moisture content measured during construction.

**TABLE 5.2.** Mean subsurface temperatures in the test cell 707 (table 5 in the 707 report)

| Test window | Mean temperature (°C) | COV |
|---|---|---|
| 707C1 | 19.2 | 2.0 |
| 707C2 | 19.1 | 3.8 |
| 707C3 | 20.0 | 3.2 |
| 707C4 | 19.5 | 3.2 |
| 707C5 | 18.7 | 2.8 |
| 707C6 | 19.7 | 2.6 |

**TABLE 5.3** Mean temperatures recorded for test cell 707

| Test window | Thermocouple | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | M1 | M2 | M3 | M4 | M5 | M6 | M7 | M8 | M9 |
| 707C1 | 15.6 | 21.0 | 19.4 | 14.9 | 21.2 | 11.7 | 16.5 | 12.5 | 15.6 |
| 707C2 | 15.5 | 21.0 | 19.3 | 14.9 | 21.3 | 11.7 | 16.7 | 12.5 | 15.6 |
| 707C3 | 15.5 | 20.9 | 19.3 | 15.1 | 21.4 | 11.8 | 16.9 | 12.6 | 15.8 |
| 707C4 | 15.7 | 21.0 | 19.4 | 15.0 | 21.2 | 11.7 | 16.5 | 12.6 | 15.7 |
| 707C5 | 15.5 | 20.9 | 19.3 | 14.9 | 21.2 | 11.7 | 16.6 | 12.5 | 15.6 |
| 707C6 | 15.5 | 20.9 | 19.3 | 15.1 | 21.3 | 11.8 | 16.8 | 12.6 | 15.7 |

**TABLE 5.4** Average temperatures during APT loading for test cell 703

| Test Window | Depth from surface (m) | | | | | | | | Surface | Air |
|---|---|---|---|---|---|---|---|---|---|---|
| | 1.31 | 1 | 0.68 | 0.51 | 0.64 | 0.33 | 0.21 | 0.07 | | |
| 703C2 | 16.82 | 16.83 | 16.95 | 17.02 | 16.91 | 17.14 | 17.50 | 17.69 | | 18.72 |
| 703C3 | 18.50 | 18.53 | 18.51 | 18.51 | 18.53 | 18.47 | 18.43 | 18.43 | 21.18 | 18.83 |
| 703C5 | 16.86 | 16.80 | 16.88 | 16.93 | 16.90 | 16.95 | 16.99 | 17.01 | 17.46 | 17.10 |
| 703C6 | 18.45 | 18.66 | 18.86 | 19.03 | 18.90 | 19.13 | 19.28 | 19.36 | 20.99 | 19.81 |

**TABLE 5.5** Average moisture content during APT loading for test cell 703

| Test Window | Depth from surface (m) | | | | | |
|---|---|---|---|---|---|---|
| | 0.36 | 0.61 | 0.91 | 1.09 | 1.52 | 1.78 |
| 703C2 | 13.12 | 13.18 | 14.23 | 14.25 | 6.17 | 0.59 |
| 703C3 | 12.87 | 13.82 | 14.07 | 14.35 | 6.26 | 0.65 |
| 703C5 | 13.43 | 14.27 | 14.25 | 14.58 | 6.20 | 0.59 |
| 703C6 | 12.84 | 12.53 | | 14.02 | 6.16 | 0.62 |

# CHAPTER 6. POST-MORTEM EVALUATION DATA

The evaluation of the pavement structure after the APT testing is useful in determining the deformation in each pavement layer and if the properties of the materials have changed during loading. This forensic analysis also helps identify the main cause for the failure of the pavement structure. As shown in Table 2.5, post-mortem forensic analysis was done only for seven out of twelve test cells. The same evaluation procedure was not used for all seven cells.

## 6.1 Layer Thickness

Measurements of layer thickness help with finding out the contribution of each layer to the total pavement deformation. Typically, trenches are cut across the pavement structure and the transverse profiles at the surface and at the interface between the surface and base layers are recorded. Then the thickness of the asphalt layers is determined by subtracting the later profile from the former.

Table 6.1 gives the layer thickness data given in tabular form for test cell 707. This is the only cell for which the post-mortem thickness data is given in a table. For test cells 707 to 712 the thickness data is shown in two charts for each test window. From these charts, the thicknesses measured at the centerline of the test windows were extracted. The extracted data is given in Table 6.2.

**TABLE 6.1** Post-mortem thickness data for test section 707

| Test Window | Distance from centerline of the section (m) [- is East] | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | -0.61 | -0.46 | -0.30 | -0.15 | 0.00 | 0.15 | 0.30 | 0.46 | 0.61 |
| Thickness of AC layer (mm) | | | | | | | | | |
| 707C1 | 108 | 108 | 102 | 102 | 95 | 102 | 102 | 108 | 114 |
| 707C2 | 102 | 102 | 102 | 102 | 95 | 102 | 108 | 102 | 102 |
| 707C3 | 102 | 95 | 95 | 102 | 95 | 89 | 95 | 102 | 102 |
| 707C4 | 95 | 95 | 89 | 89 | 83 | 89 | 89 | 95 | 95 |
| 707C5 | 89 | 89 | 89 | 83 | 83 | 83 | 89 | 89 | 95 |
| 707C6 | 95 | 95 | 89 | 89 | 89 | 89 | 95 | 95 | 95 |
| Thickness of base layer (mm) | | | | | | | | | |
| 707C1 | 241 | 235 | 229 | 229 | 229 | 229 | 235 | 229 | 229 |
| 707C2 | 229 | 229 | 229 | 241 | 229 | 235 | 229 | 229 | 235 |
| 707C3 | 229 | 235 | 241 | 235 | 229 | 235 | 229 | 229 | 235 |
| 707C4 | 241 | 241 | 241 | 235 | 241 | 241 | 248 | 241 | 248 |
| 707C5 | 235 | 235 | 229 | 235 | 235 | 229 | 235 | 241 | 241 |
| 707C6 | 241 | 241 | 241 | 235 | 235 | 241 | 241 | 248 | 241 |

**TABLE 6.2** Post-mortem layer thickness at the centerline of the test window

| Test Window | Test Cell | | | | |
|---|---|---|---|---|---|
| | 708* | 709 | 710 | 711 | 712 |
| Thickness of AC layer (mm) | | | | | |
| C1 | 64 | 76 | 68 | 66 | 78 |
| C2 | 70 | 82 | 77 | 70 | 79 |
| C3 | 62 | 82 | 82 | 76 | 82 |
| C4 | 95 | 71 | 71 | 100 | 105 |
| C5 | 94 | 95 | 79 | 100 | 85 |
| C6 | 62 | 73 | 76 | 78 | 105 |
| Thickness of base layer (mm) | | | | | |
| C1 | 269 | 223 | 205 | 230 | 222 |
| C2 | 267 | 215 | 197 | 242 | 210 |
| C3 | 271 | 220 | 209 | 215 | 210 |
| C4 | 258 | 196 | 190 | 220 | 250 |
| C5 | 262 | 170 | 200 | 228 | 270 |
| C6 | 264 | 165 | 232 | 246 | 180 |

## 6.2 Moisture Content and Density

The dry density and moisture content of the aggregate base and the subgrade soil were measured for test cells 707 to 712 using a Troxler nuclear density gage lowered in the cut trenches. The results of the measurements are given in charts in the corresponding project reports. The values were extracted from the charts and are given in Tables 6.3 and 6.4.

Table 6.3 shows that the charts for moisture content for test cell 712 were identical between them and, with one chart from the report for test cell 711. Therefore, it is very likely that the data reported for test cell 712 is erroneous.

In addition to the measurements with the Troxler nuclear gage, density measurements were performed with the sand-cone method only for test cell 708, and only in the base course. These values were not included in the database.

## 6.3 Mechanical Properties of Subgrade Soil

As shown in Table 2.5, DCP tests were performed for test cells 707 to 712; the data for test cell 710 is not given. The results show only in graphical form the change in estimated CBR of the subgrade with depth; no data is provided.

Vane Shear tests were performed only for test cells 708 to 710. As for the DCP, the results are shown only in charts; no data is given. Light Falling Weight (L-FWD) tests were performed only for test cell 708; the data should not be retained for the database.

**TABLE 6.3** Moisture Content determined in post-mortem trenches

| Test Window | Test Cell | | | | | |
|---|---|---|---|---|---|---|
| | 707 | 708* | 709 | 710 | 711 | 712 |
| Top of Base | | | | | | |
| C1 | 3.4 | 3.6 | 3.3 | 2.4 | 1.6 | 1.6 |
| C2 | 3.5 | 3.9 | 3.6 | 2.2 | 2.2 | 2.2 |
| C3 | 3.7 | 3.7 | 3.3 | 2.3 | 2.0 | 2.0 |
| C4 | 3.8 | 3.8 | 4.0 | 2.4 | 4.6 | 1.6 |
| C5 | 3.5 | 3.9 | 3.8 | 2.3 | 4.4 | 2.2 |
| C6 | 3.9 | 3.5 | 3.2 | 3.0 | 3.7 | 2.0 |
| Top of Subgrade | | | | | | |
| C1 | 10.8 | 19.0 | 17.8 | 18.6 | 20.3 | 20.3 |
| C2 | 11.1 | 19.2 | 16.7 | 18.1 | 17.2 | 17.2 |
| C3 | 10.9 | 19.8 | 17.6 | 18.8 | 20.2 | 20.2 |
| C4 | 10.8 | 18.6 | 16.6 | 17.7 | 22.5 | 20.3 |
| C5 | 11.6 | 20.0 | 16.8 | 18.2 | 23.2 | 17.2 |
| C6 | 10.9 | 19.0 | 17.5 | 18.6 | 24.8 | 20.2 |
| 0.6 m below AC | | | | | | |
| C1 | 10.9 | 19.9 | 16.7 | 20.2 | | |
| C2 | 11 | 20.0 | 16.3 | 19.3 | | |
| C3 | 10.8 | 21.0 | 16.6 | 20.2 | | |
| C4 | 11.3 | 18.8 | 15.0 | 19.8 | | |
| C5 | 11.1 | 19.5 | 16.3 | 19.3 | | |
| C6 | 10.5 | 19.2 | 16.6 | 20.4 | | |
| 0.9 m below AC | | | | | | |
| C1 | | | 17.5 | 19.7 | 22.2 | 22.2 |
| C2 | | | 17.3 | 19.1 | 20.2 | 20.2 |
| C3 | | | 18.0 | 20.9 | 23.2 | 23.2 |
| C4 | | | 16.2 | 19.0 | 25.0 | 22.2 |
| C5 | | | 15.9 | 19.7 | 24.6 | 20.2 |
| C6 | | | 17.8 | 19.3 | 24.3 | 23.2 |

**TABLE 6.4** Dry density determined in post-mortem trenches

| Test Window | Test Cell | | | | | |
|---|---|---|---|---|---|---|
| | 707 | 708* | 709 | 710 | 711 | 712 |
| Top of Base | | | | | | |
| C1 | 1905 | 1900 | 2330 | 2210 | 2290 | 2195 |
| C2 | 1933 | 1850 | 2275 | 2210 | 2445 | 2420 |
| C3 | 1962 | 1970 | 2225 | 2230 | 2315 | 2360 |
| C4 | 1888 | 1860 | 2335 | 2230 | 2275 | 2400 |
| C5 | 2003 | 1800 | 2145 | 2175 | 2390 | 2315 |
| C6 | 1901 | 1895 | 2320 | 2225 | 2565 | 2375 |
| Top of Subgrade | | | | | | |
| C1 | 1748 | 1620 | 1675 | 1735 | 1710 | 1530 |
| C2 | 1707 | 1600 | 1780 | 1745 | 1615 | 1525 |
| C3 | 1726 | 1580 | 1750 | 1670 | 1630 | 1585 |
| C4 | 1641 | 1445 | 1670 | 1730 | 1640 | 1550 |
| C5 | 1716 | 1475 | 1755 | 1725 | 1605 | 1580 |
| C6 | 1713 | 1500 | 1705 | 1775 | 1570 | 1590 |
| 0.6 m below AC | | | | | | |
| C1 | 1755 | 1505 | 1660 | 1625 | | |
| C2 | 1737 | 1545 | 1630 | 1575 | | |
| C3 | 1768 | 1525 | 1655 | 1635 | | |
| C4 | 1700 | 1430 | 1660 | 1565 | | |
| C5 | 1679 | 1410 | 1705 | 1550 | | |
| C6 | 1694 | 1440 | 1715 | 1625 | | |
| 0.9 m below AC | | | | | | |
| C1 | | | 1600 | 1595 | 1585 | 1505 |
| C2 | | | 1640 | 1620 | 1525 | 1560 |
| C3 | | | 1570 | 1615 | 1553 | 1495 |
| C4 | | | 1600 | 1615 | 1585 | 1505 |
| C5 | | | 1630 | 1605 | 1520 | 1560 |
| C6 | | | 1575 | 1640 | 1550 | 1495 |

# CHAPTER 7. EVALUATION OF PAVEMENT RESPONSE DATA (Stresses, Strains, Displacements)

## 7.1 Evaluation of the Raw Response Data Submitted on DVDs

The raw pavement response data submitted on DVDs was inspected in detail. The availability stress/strain/displacement data submitted on DVDs is given in Table 7.1. The table should be read as follows:

- The numbers in the cells corresponding to PASSES mean that profile measurements were taken at this number of passes.
- If the cell is not shaded, it means that no response data is given in the DVDs for that number of passes.
- The three colors of shading cells indicate that the response is recorded in three different formats. The yellow shade is the predominant format. Dr. Cortez provided the header labels only for this format.
- No stress data is reported in the database or the reports for cell 710, even though the report indicates that stress measurements were made for this test cell.

After inspecting the data submitted in electronic format it was concluded that the summarized response data provided in the Excel database cannot be verified from raw data because:

- The response data is computed from the raw signal data by subtracting from the data collected under load, the so-called "no-load" signal data, the data collected with the bogie of the HVS machine passing at about 100 mm above the pavement surface. The "no-load" signal data is not always given.
- The calibration factors, (which relate deformations or stresses to voltage) are given in the reports only for cells 701 and 703. In order to verify the reported strain data, the calibration factors for all sensors used in electronic format are needed. However, they were never provided by Dr. Cortez.
- The data on DVDs shows that, most of the time, three replicate runs were performed when the strain/stress data was recorded. However, in the Excel database, only one value of the three is reported. It is unclear if it is the average of the three or only one of the recorded values; no explanation was found in the reports.
- For about one third of the files, the headers are not explained and are not the same as those in the remaining files.
- The true location of the sensors is not always given in project reports; they were given for the cells tested toward the beginning of the PSPS project.
- The raw data is a mix of raw voltage data and response data. Unfortunately, it is not specified in each file which data is reported.

Therefore, the further efforts were dedicated to the evaluation of the response data submitted in the Excel files.

## **TABLE** 7.1 Availability of Raw Pavement Response Data

| Cell | Window | kips | kN | Passes | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| A-2-4<br>W10 | 701C1 | 9 | 40 | - | 500 | 1,000 | 2,500 | 5,000 | 10,000 | 20,000 | 44,509 | 52,493 | 53,493 | 63,900 | 99,011 | 151,565 | 200,000 | 283,480 |
| | 701C2 | 20 | 89 | 10 | 500 | 1,000 | 2,500 | 5,000 | 10,000 | 27,260 | 51,400 | 103,455 | 135,000 | 135,230 | 149,614 | | | |
| | 701C3 | 23 | 103.5 | 10 | 500 | 1,000 | 2,500 | 5,000 | 15,000 | 30,000 | 40,000 | | | | | | | |
| | 701C4 | 20 | 89 | 10 | 500 | 1,000 | 2,500 | 5,000 | 10,000 | 22,700 | 55,000 | 95,394 | 172,526 | | | | | |
| A-2-4<br>W12 | 707C1 | 13.4 | 62 | 0 | 250 | 500 | 1,000 | 5,000 | 10,000 | 25,000 | 50,000 | 106,000 | | | | | | |
| | 707C2 | 8.9 | 40 | 0 | 250 | 1,000 | 5,000 | 25,000 | 100,000 | 256,000 | 504,000 | 1,000,000 | | | | | | |
| | 707C3 | 18.0 | 80 | 0 | 250 | 1,000 | 5,000 | 25,000 | 50,000 | | | | | | | | | |
| | 707C4 | 11.8 | 53 | 0 | 250 | 500 | 1,000 | 2,500 | 5,000 | 10,000 | 50,000 | 102,000 | 250,000 | | | | | |
| | 707C5 | 18.0 | 80 | 0 | 250 | 500 | 1,000 | 2,500 | 5,000 | 10,000 | 25,000 | 50,000 | | | | | | |
| | 707C6 | 15.0 | 67 | 0 | 250 | 1,000 | 5,000 | 25,000 | 50,000 | 100,000 | | | | | | | | |
| A-2-4<br>W15 | 703C2 | 14 | 62.3 | 0 | 500 | 1,000 | 2,500 | 5,000 | 10,000 | 25,000 | 50,000 | | | | | | | |
| | 703C3 | 14 | 62.3 | 0 | 500 | 1,000 | 2,500 | 5,000 | 10,000 | 25,000 | 50,000 | 105,000 | 222,340 | 376,750 | | | | |
| | 703C5 | 18 | 80 | 0 | 500 | 1,000 | 2,500 | 5,000 | 10,000 | 25,000 | 50,000 | 104,720 | | | | | | |
| | 703C6 | 12 | 53 | 0 | 500 | 1,000 | 2,500 | 5,000 | 10,000 | 25,000 | 48,772 | 92,550 | 152,510 | 196,700 | 496,555 | 951,065 | 1,356,500 | |
| A-4<br>W17 | 702C1 | 15.0 | 67 | 0 | 500 | 1,000 | 2,500 | 5,000 | 10,000 | 25,000 | 37,060 | 51,431 | | | | | | also in Excel |
| | 702C2 | 18.1 | 81 | 0 | 500 | 1,000 | 2,500 | 5,000 | 10,000 | 10,000 | 23,000 | 46,500 | 57,075 | | | | | also in Excel |
| | 702C3 | 14.1 | 63 | 0 | 500 | 1,000 | 2,500 | 5,000 | 10,700 | 25,000 | 56,036 | 103,308 | | | | | | also in Excel |
| | 702C4 | 13.6 | 61 | 0 | 1,000 | 2,500 | 5,000 | 10,000 | 25,000 | 39,686 | 52,000 | 79,764 | 158,900 | 212,455 | | | | also in Excel |
| | 702C5 | 12.1 | 54 | 0 | 500 | 1,000 | 2,500 | 2,500 | 2,500 | 25,000 | 50,000 | 105,800 | 229,697 | 240,627 | 425,313 | 750,230 | 1,037,634 | also in Excel |
| | 702C6 | 15.9 | 71 | 0 | 500 | 1,000 | 2,500 | 5,000 | 10,000 | 25,000 | 51,500 | 81,725 | 119,525 | | | | | also in Excel |
| A-4<br>W19 | 704C1 | 12.0 | 54 | 0 | 500 | 1,000 | 2,500 | 5,000 | 10,900 | 23,947 | | | | | | | | passes not given |
| | 704C2 | 10.0 | 45 | 0 | 500 | 1,000 | 2,500 | 6,000 | 13,000 | 22,930 | 57,075 | 120,000 | | | | | | |
| | 704C3 | 10.9 | 49 | 0 | 500 | 1,000 | 6,000 | 12,000 | 25,751 | 41,800 | 81,850 | | | | | | | |
| | 704C4 | 10.0 | 45 | 0 | 1,000 | 2,500 | 5,000 | | | | | | | | | | | passes not given |
| | 704C5 | 8.9 | 40 | 0 | 500 | 1,000 | 2,500 | 5,000 | 10,000 | 25,000 | 50,000 | 117,340 | 250,000 | 505,281 | 780,122 | | | passes not given |
| | 704C6 | 8.9 | 40 | 0 | 500 | 1,000 | 2,500 | 5,000 | 8,600 | 22,500 | 50,000 | 100,500 | 250,100 | | | | | |

## **TABLE** 7.1 - CONTINUED

| Cell | Window | kips | kN | Passes | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| A-4<br>W23 | 705C1 | 6 | 26 | 0 | 200 | | | | | | | | |
| | 705C2 | 9 | 40 | 0 | 500 | 800 | | | | | | | |
| | 705C3 | 5 | 22 | 0 | 100 | 250 | | | | | | | |
| | 705C5 | 12 | 53 | 0 | 500 | 950 | | | | | | | |
| A-6<br>W16 | 709C1 | 6 | 26.7 | 0 | 250 | 1,000 | 5,000 | 10,000 | 25,000 | 35,000 | 50,000 | 75,000 | |
| | 709C2 | 9 | 40 | 0 | 250 | 1,000 | 2,500 | 5,000 | | | | | |
| | 709C3 | 12 | 53.4 | 0 | 250 | 1,000 | 1,500 | | | | | | |
| | 709C4 | 7 | 31.1 | 0 | 250 | 1,000 | 5,000 | 10,000 | 22,000 | | | | |
| | 709C5 | 9 | 40 | 0 | 250 | 500 | 800 | | | | | | |
| | 709C6 | 4.5 | 20 | 0 | 250 | 1,000 | 5,000 | 10,000 | 25,000 | | | | |
| A-6<br>W19 | 708C1 | 9 | 40 | 0 | 250 | 500 | 1,000 | 2,500 | | | | | |
| | 708C2 | 6 | 26.7 | 0 | 250 | 1,000 | 2,500 | 5,000 | 10,000 | 25,000 | 65,000 | | |
| | 708C3 | 7 | 31.1 | 0 | 250 | 600 | 1,000 | 2,500 | 5,000 | 10,000 | | | |
| | 708C4 | 12 | 53.4 | 0 | 250 | 1,000 | 2,500 | | | | | | |
| | 708C5 | 9 | 40 | 0 | 250 | 1,000 | 2,500 | 5,000 | | | | | |
| | 708C6 | 7 | 31.1 | 0 | 250 | 1,000 | 2,500 | 5,000 | 10,000 | 35,000 | | | |
| A-6<br>W22 | 706C1 | 6 | 27 | 0 | 100 | 500 | 1,000 | 5,000 | | | | | |
| | 706C2 | 9 | 40 | 0 | 100 | 500 | 1,000 | 2,500 | | | | | |
| | 706C3 | 4.9 | 22 | 0 | 250 | 500 | 1,000 | 2,500 | 5,000 | | | | |
| | 706C4 | 4.9 | 22 | 0 | 100 | 500 | 1,000 | 5,000 | 10,000 | 25,000 | | | |
| | 706C5 | 6 | 27 | 0 | 100 | 500 | 1,000 | 5,000 | 10,000 | | | | |
| | 706C6 | 9 | 40 | 0 | 250 | 500 | | | | | | | |

**TABLE 7.1** - CONTINUED

| Cell | Window | kips | kN | Passes | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| A-6<br>A-7-6<br>W21 | 710C1 | 6.0 | 27.0 | 0 | 250 | 1,000 | 2,500 | 5,000 | 10,000 | 25,000 | 50,000 | | | | | | |
| | 710C2 | 9.0 | 40.0 | 0 | 100 | 500 | 1,000 | 1,700 | 3,000 | | | | | | | | |
| | 710C3 | 4.6 | 20.5 | 0 | 250 | 500 | 1,000 | 5,000 | 10,000 | | | | | | | | |
| | 710C4 | 9.0 | 40.0 | 0 | 250 | 1,000 | | | | | | | | | | | |
| | 710C5 | 4.5 | 20.0 | 0 | 250 | 500 | 1,000 | 5,000 | | | | | | | | | |
| | 710C6 | 7.5 | 33.4 | 0 | 250 | 500 | 1,000 | 4,240 | | | | | | | | | |
| A-7-5<br>W25 | 711C1 | 6.0 | 26.7 | 0 | 250 | 1,000 | 5,000 | 10,000 | 25,000 | 50,000 | 100,000 | 250,000 | 500,000 | | | | |
| | 711C2 | 22 | 97.9 | 0 | 250 | 30,000 | 90,000 | 315,000 | | | | | | | | | |
| | 711C3 | 18.0 | 80.0 | 0 | 250 | 1,000 | 5,000 | 10,000 | 25,000 | 100,000 | 200,000 | | | | | | |
| | 711C4 | 18.0 | 80.0 | 0 | 250 | 57,150 | 88,000 | 326,300 | | | | | | | | | problems with profiles |
| | 711C5 | 22.0 | 97.9 | 0 | 250 | 1,000 | 5,000 | 10,000 | 25,000 | 50,000 | 100,000 | 250,000 | 500,000 | 560,000 | 600,000 | 750,000 | |
| | 711C6 | 22.0 | 97.9 | 0 | 250 | 1,000 | 81,400 | 205,550 | | | | | | | | | problems with profiles |
| A-7-5<br>W20 | 712C1 | 18 | 80 | 0 | 250 | 1,000 | 10,000 | 100,000 | 110,000 | 300,000 | | | | | | NO_LOAD data is missing | |
| | 712C2 | 20.0 | 89.0 | 0 | 250 | 1,000 | 5,000 | 34,000 | 65,000 | 108,000 | 168,000 | | | | | NO_LOAD data is missing | |
| | 712C3 | 21.0 | 93.4 | 0 | 250 | 1,000 | 10,000 | 25,000 | 50,000 | 64,000 | | | | | | NO_LOAD data is missing | |
| | 712C4 | 22.0 | 97.9 | 0 | 250 | 1,000 | 47,087 | 72,500 | 147,200 | 180,800 | | | | | | NO_LOAD data is missing | |
| | 712C5 | 9.0 | 40.0 | 0 | 250 | 1,000 | 25,000 | 100,000 | 294,000 | 463,000 | | | | | | NO_LOAD data is missing | |
| | 712C6 | 22.0 | 97.9 | 0 | 250 | 1,000 | 100,000 | 121,300 | | | | | | | | NO_LOAD data is missing | |

## 7.2 Availability of Response Data Submitted in Excel files

The response and performance data for the twelve test cells have been reported in twelve Excel files, one file for each test cell. Each file had the response data organized in worksheets, corresponding to each variable measured. Thus, an individual sheet contains the data for a single response variable (e.g. resilient vertical strain) for all test windows tested in that cell. The first worksheet contains the wheel load data, followed by a sheet with the rutting data and then worksheets with response data.

The availability of the data in the Excel files is given in Table 7.2. The table shows a complete set of response data is not reported for all tested windows. Possible reasons for missing data include the lack of sensors, faulty sensors, erroneous measurements or lost data. It is important to note that no stress data (vertical, longitudinal or transverse) was reported for test cell 710 and that only vertical stresses were reported for test cell 703.

**TABLE 7.2** Availability of Data in the Excel Database

| | | Experimental Cell | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 701 | 702 | 703 | 704 | 705 | 706 | 707 | 708 | 709 | 710 | 711 | 712 |
| Windows tested | | 4 | 6 | 4 | 6 | 4 | 6 | 6 | 6 | 6 | 6 | 6 | 6 |
| Rutting (from profiler) | | 1,2,4 | all | all | all | all | all | All | all | all | all | all | all |
| Vertical Deformation | Resilient | | | | | | | | | | | | |
| | Permanent | 1,2,4 | all | 2,3,6 | all | all | all | All | all | all | all | all | all |
| Longitudinal Deformation | Resilient | | | | | | | | | | | | |
| | Permanent | 1,2,4 | all | 2,3,6 | all | all | all | All | all | all | all | 1,2,4,5,6 | all |
| Transverse Deformation | Resilient | | | | | | | | | | | | |
| | Permanent | 1,2,4 | all | 2,3,6 | all | all | all | All | all | all | all | 1,2,4,5,6 | all |
| Vertical Strain | Resilient | 1,2,3,4 | all | all | all | all | all | All | all | all | all | all | all |
| | Permanent | 1,2,4 | all | all | all | all | all | All | all | all | all | all | all |
| Longitudinal Strain | Resilient | 1,2,4 | all | all | all | all | all | All | all | all | all | | |
| | Permanent | 1,2 | all | all | all | all | all | All | all | all | all | 1,2,4,5,6 | all |
| Transverse Strain | Resilient | 1,2,4 | all | all | all | all | all | All | all | all | all | | |
| | Permanent | 1,2 | all | all | all | all | all | All | all | all | all | 1,2,4,5,6 | all |
| Vertical Stress | Dynamic | 1,2,3 | 1,2 | 2,5,6 | all | all | all | All | 1,2,3,4,5 | all | | all | all |
| Longitudinal Stress | Dynamic | 2,3 | 1,2 | 2,5,6 | 1 | all | all | All | 1,2,3,4,5 | all | | 2,3,5 | all |
| Transverse Stress | Dynamic | 2,3 | 1,2 | 2,5,6 | 1 | all | all | All | all | all | | 1,2,3,5 | all |

### 7.3 Assessment of the Response Data Submitted in the Excel files

The response and performance data reported in twelve Excel files were analyzed for reasonableness, and the erroneous data were marked for removal. The following rules have been used for erroneous data identification:

A. The stresses and strains (vertical, longitudinal and transverse) in the subgrade soil must decrease with depth.
B. All stresses must always be compressive (negative). The vertical strains must be compressive while horizontal strains must be tensile (positive).
C. The strains and deformations must increase with the number of loading passes applied or at least show a consistent trend.
D. When similar wheel loads were used, the corresponding stresses and strains should be higher for the test window with the higher moisture content in the subgrade soil.
E. For any given test window, the stresses and strains must keep the same sign throughout the APT loading.
F. No data should be retained for pavement structures that failed in less than 5,000 load repetitions.

Rules A and B follow the general, agreed-upon principles of distribution of stresses and strains in the lower layers of a pavement structure. Some stresses and strains generated in the horizontal direction by a rolling wheel load may be lower in the asphalt concrete layer than in the base or top of the subgrade layers, but no horizontal stresses or strains were measured in the asphalt concrete layer in the PSPS project.

Rule C is based on the concept that the deterioration of the materials taking place during APT loading leads to higher deformations and strains in the lower layers of the pavement structure. However, the same principles cannot be applied to stresses. Stresses in all directions (vertical, horizontal) typically increase at the beginning of the APT experiment and then stabilize.

A good example of such a case is the vertical stress recorded for test cell 711. As shown in Figure 7.1, the vertical stress increased with the number of applied passes only for test window 711C6. This is abnormal and was observed only for this test window out of the 66 tested in the PSPS experiment. It can only be explained by the very high wheel load applied, 97.9kN; more than twice the legal limit for single axles. This high load caused un-characteristic failure of the pavement structure.

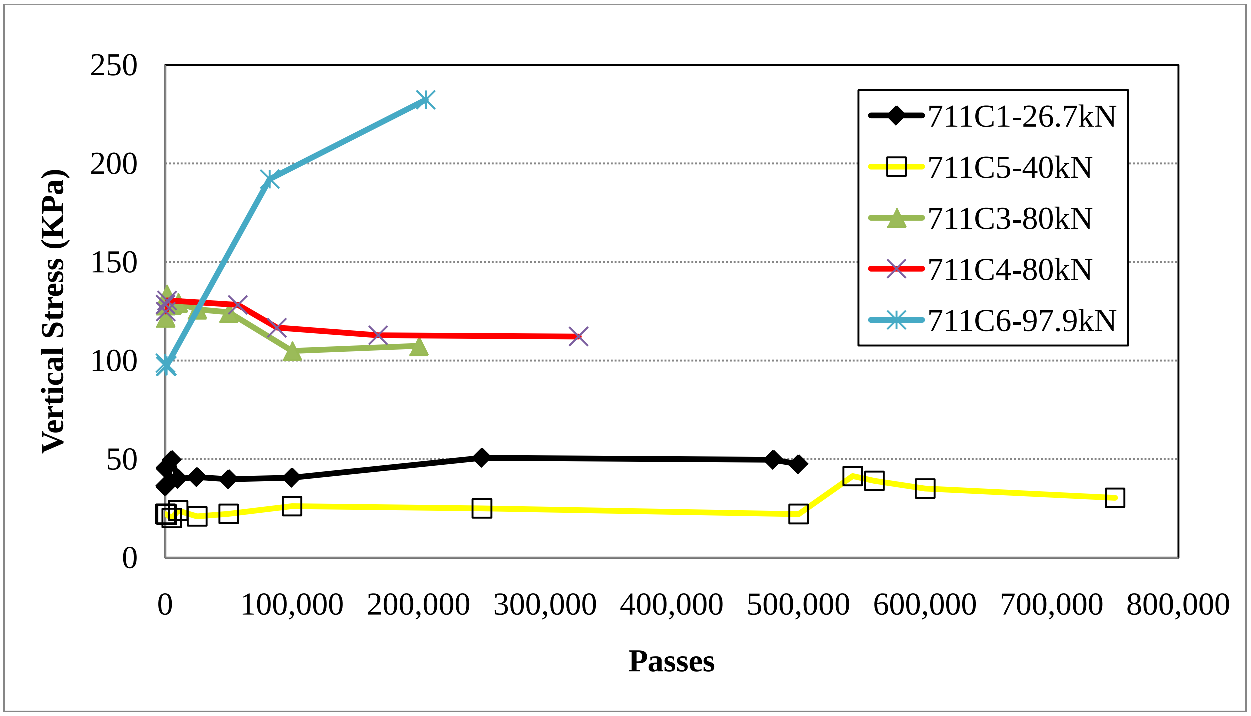
Rule D relies on the fact that, for a given soil, the stiffness decreases when the moisture content increases. Rule E relies on the fact that the data acquisition system and the sensor wires remain connected during APT testing of a test window. Thus, reversal of polarities for sensor cables to cause a change in sign should not take place; a change in sign could indicate a faulty sensor.

However, it was observed in many instances that the sign of a response variable remained consistent throughout the APT loading of a test window, but it was opposite from that of the corresponding variable for other test windows of the same cell. This is an indication of polarity change for that sensor. Therefore, the sign for all values of that variable should be changed for consistency to the sign indicated by Rule B.

Rule F was established on the idea that no in-situ pavement structures built following construction specifications fails in less than 5,000 load cycles, unless a catastrophic event, such as flood or slope instability takes place. Retaining the data recorded in such cases in the PSPS database would bias the models developed, because it reflects situations that happen very rarely for in-situ pavement structures. By consequence, it is proposed to flag in the database the data recorded for:

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

**Figure 7.1** Vertical Stresses at the Top of the Subgrade Soil – Test Cell 711



A principle that was followed in the data assessment was that, for the windows of the same test cell, the corresponding response variables do not necessarily have to increase with the increase in applied wheel load. As shown in Figure 7.1, the vertical stress recorded for windows C5, where the applied load was 40kN was less than that recorded for windows c1, where the applied load was 26.7kN. This can be explained by the difference in layer thickness and/or material stiffness. However, it is likely that the stress cell was not properly installed. A stress cell not installed properly will always record a lower stress than the true value.

## 7.4 Assembly of the MS Access database

After the response and performance data reported in twelve Excel files were analyzed for reasonableness based on the six rules previously presented, and the erroneous data were marked for removal, the data was assembled in an MS Access database to facilitate further analysis. The database contains all the data, but error codes or explanations were used in a separate field, typically the last field of each table, to indicate the reason for considering the data as erroneous. In this manner, no data has been discarded, but erroneous data can be easily removed or ignored when performing further data analysis.

In addition to the response data, the MS Access database also contains:

- all assembled material characterization data (gradation, moisture-density data, resilient modulus data)
- all construction information data (layer thickness, moisture content and density of the as-compacted granular layers, backcalculated layer moduli, etc)
- all APT loading data. Unfortunately, insufficient temperature and moisture data was available and thus, it was not included in the database.
- Limited in-situ density, moisture and stiffness data collected on the subgrade soil layer during the post-mortem analysis.

The data included in the MS Access database is stored in tables. For each table, the meaning of data on each field, along with the measuring units, where applicable, are given in Appendix B. The tables are listed in alphabetical order such that they can be found with ease.

# CHAPTER 8 LABORATORY DETERMINATION OF RESILIENT MODULUS OF SUBGRADE SOIL

The PSPS aimed to develop new subgrade criteria models to be used in the design of flexible pavement structures. The laboratory testing conducted to determine the properties of subgrade soil, the key material, included:

- gradation analysis;
- Standard Proctor Tests to determine the optimum moisture content and maximum dry density
- Liquid Limit and Plastic Limit tests for the soil classification;
- CBR tests (only on three out of the five soils).

In-situ testing of the constructed subgrade included density and moisture measurements and FWD tests on top of the constructed pavement structures and a limited number of DCP and Clegg Hammer tests on the compacted soil.

In order to validate any current or future models for pavement response or performance, or to develop new models using the data collected in the PSPS experiment, the Resilient Modulus ($M_R$) of the soils used in the construction of the PSPS experimental pavements must be measured. Sufficient quantities of three soils (A-4, A-6 and A-7-5) used in the construction of the PSPS test sections were retrieved from stockpiles at CRREL for this purpose. The soils were dried and processed for the resilient modulus testing.

The Mechanistic-Empirical Design Guide (M-E PDG) uses the Resilient Modulus determined in the triaxial test as the material property to be used for the characterization of subgrade soils and granular base and subbase materials for Level 1 design. The AASHTO T 307 "Determining the Resilient Modulus of Soils and Aggregate Materials" is recommended as the test procedure to be followed for the determination of the Resilient Modulus. The most advanced design methods in Europe and Australia also use Resilient Modulus to characterize unbound foundation materials and subgrade soils. Therefore, an important task of this research project is to determine the Resilient Modulus of the subgrade soils following the AASHTO T 307 protocol.

## 8.1. Selection of the test conditions

The relative density levels and moisture content for which the soil samples are prepared must be selected before the resilient modulus testing program is commenced. Most often, samples cannot be prepared for high moistures content and high dry density values since the soil may require more water than for the fully saturated soil and thus, during the compaction in the steel molds, water is squeezed out of the samples. Low values for dry density coupled with medium to high values for moisture content may lead to very soft samples that do not maintain their shape while being transported and installed in the triaxial cell or that exhibit high deformation during triaxial loading. In this case, the resilient modulus test is stopped before all loading sequences are completed.

The selection of the relative density levels and moisture content for which the soil samples were prepared and tested was based on:

- The optimum moisture content and the maximum dry density
- The moisture content and dry density measured in-situ during the construction of the test sections
- Preliminary tests on trial combination of moisture and density

Trial samples of the A-6 soil at the moisture content of 19% and dry density equal to the maximum value given in project reports were prepared. Since the samples were very soft and will likely not last in the repeated triaxial Resilient Modulus test, the Standard Proctor tests (AASHTO T 99) were redone for all three soils. The results are given in Table 8.1.

**TABLE 8.1** Results of the Standard Proctor tests (AASHTO T 99)

| A–4 soil | | | | A-6 soil | | A-7-5 soil | | | |
|---|---|---|---|---|---|---|---|---|---|
| Sample 1 | | Sample 2 | | Sample 1 | | Sample 1 | | Sample 2 | |
| MC (%) | DD (kg/m$^3$) | MC (%) | DD (kg/m$^3$) | MC (%) | DD (kg/m$^3$) | MC (%) | DD (kg/m$^3$) | MC (%) | DD (kg/m$^3$) |
| 8.04 | 1,983 | 7.04 | 1,954 | 12.15 | 1,789 | 11.99 | 1,733 | 11.95 | 1,746 |
| 9.49 | 2,007 | 9.10 | 1,992 | 13.98 | 1,792 | 14.09 | 1,786 | 14.00 | 1,811 |
| 11.97 | 1,984 | 10.75 | 2,027 | 15.30 | 1,862 | 15.49 | 1,863 | 15.84 | 1,871 |
| 13.58 | 1,916 | 12.86 | 1,937 | 17.36 | 1,822 | 17.02 | 1,862 | 17.77 | 1,818 |
| 14.21 | 1,886 | 4.75 | 1,888 | 18.66 | 1,779 | 18.45 | 1,798 | 19.85 | 1,754 |
| | | 17.00 | 1,833 | | | | | | |

Figure 8.1 shows the results of the new Proctor tests along with the Proctor test results given in project reports for the A-4 soil. The figure clearly shows that the results given in reports were likely innacurate, and that the testing procedure recommended by AASHTO T 99 standard was not followed well. The test standard requires an increase of moisture in the sample in increments of approximately 2%. However, the figure shows that no density data was recorded for moisture content around 10 and 12%. This likely led to an erroneous estimation of the maximum dry density (1,780 kg/m$^3$) and optimum moisture content (17% - quite high for an A-4 soil). The new Proctor tests estimate the Optimum Moisture Content (OMC) of 10% and a maximum dry density (MDD) of 2,010 kg/m$^3$.

Figure 8.1 also shows that most of the in-situ density and moisture data were closer to the Proctor curve given in the PSPS project reports. The data is likely correct since the desired moisture content for TS704 and TS705 was 19% and 25% respectively. As expected, at these high mositure contents, the achieved dry density after the in-situ compaction is much lower than the optimum dry density.

The proposed levels of compaction and moisture contents are given in Table 8.2 and shown in Figure 8.1. Considering the difficulties encountered during the HVS testing of the A-4 soil in TS705, the highest moisture content recomended for the resilient modulus testing is 17%.

Figure 8.2 shows the results of the new Proctor tests along with the Proctor test results given in project reports for the A-6 soil. Both sets of tests indicated an OMC of 16%. However, higher MDD was achieved in the new Proctor test (1,865 kg/m$^3$) instead of 1,791 kg/m$^3$ given in project reports.

The proposed levels of compaction and moisture contents are given in Table 8.2 and shown in Figure 8.2. Considering the difficulties encountered during the HVS testing of the A-6 soil in TS706, only one density level is recommended for moisture content of 22%.

**Figure 8.1.** Dry Density vs. Moisture Content for the A-4 soil

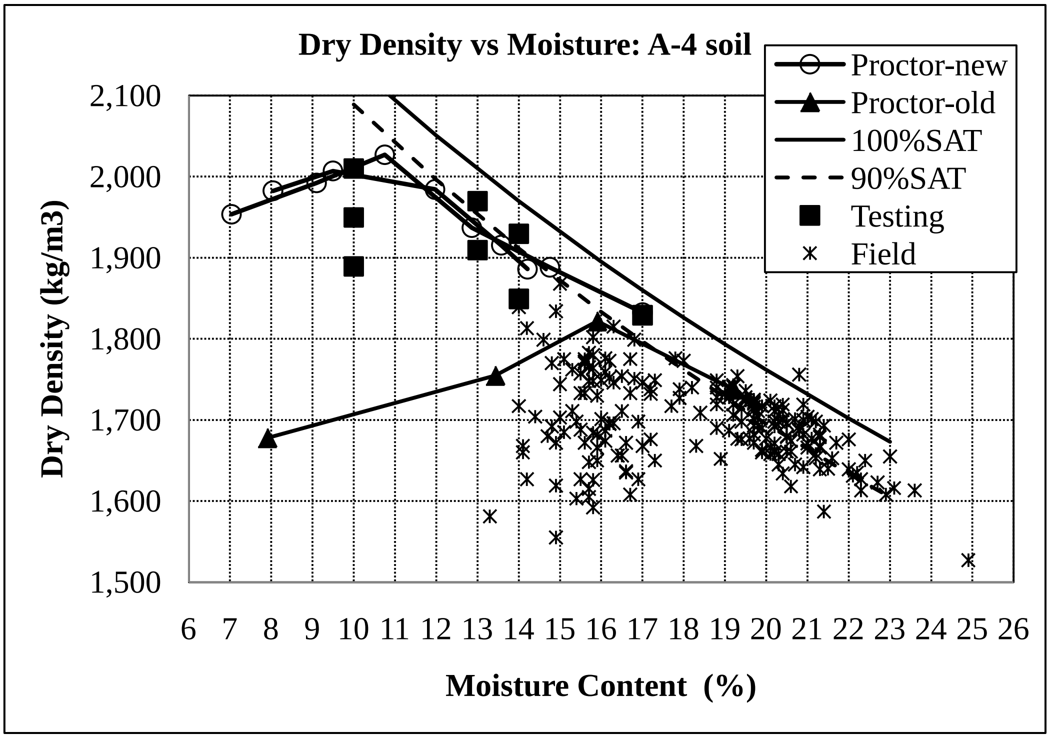


**Figure 8.2.** Dry Density vs. Moisture Content for the A-6 soil

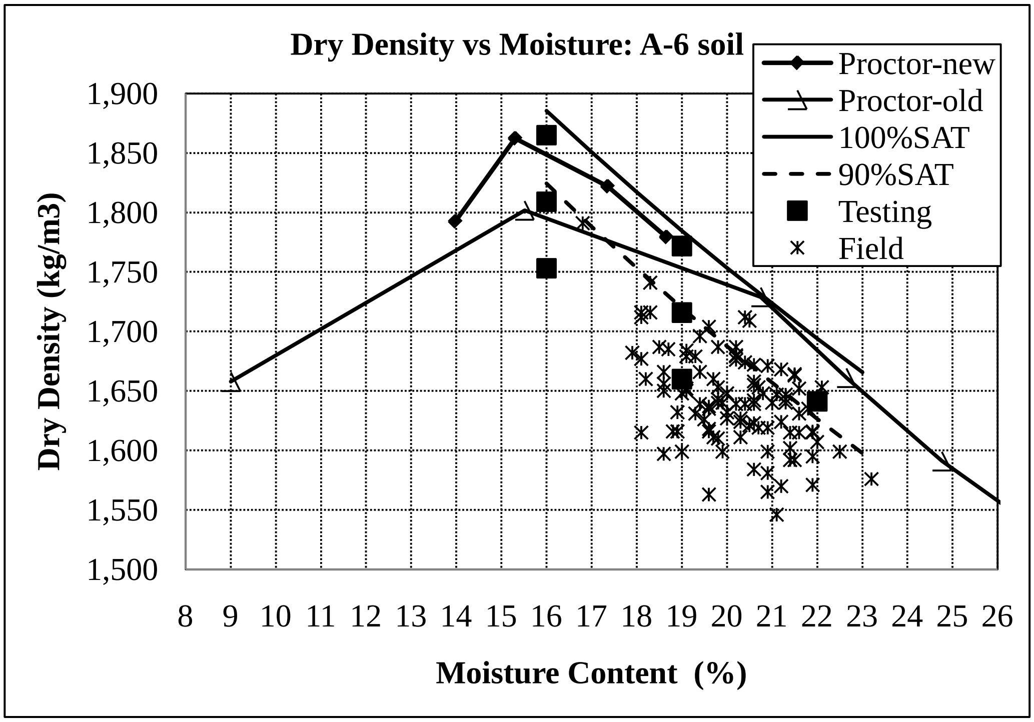


**Figure 8.3**. Dry Density vs. Moisture Content for the A-7-5 soil

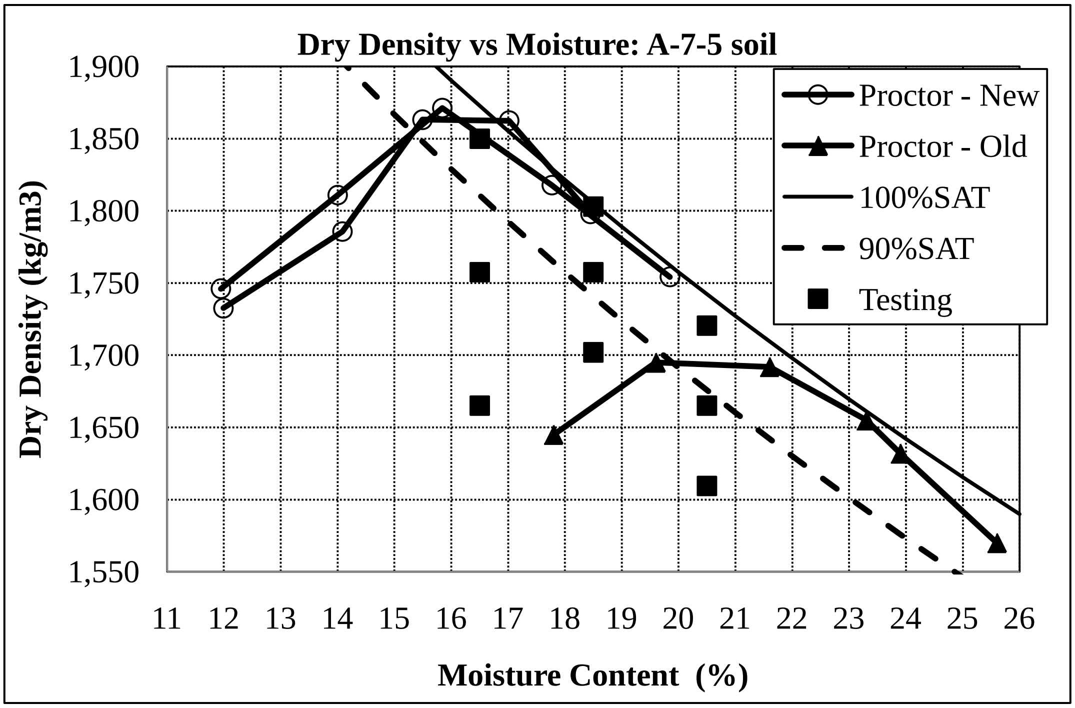


Figure 8.3 shows the results of two new Proctor tests along with the Proctor test results given in project reports for the A-7-5 soil; no in-situ mositure and density data was reported for this soil. The new Proctor tests estimate the OMC of 16.5% and a MDD of 1,850 kg/m$^3$. The values are less than expected for an A-7-5 soil. Considering that the HVS loading was successful when this soil was tested at 20.5% moisture content (TS712), the proposed levels of compaction and moisture content are best on the new Proctor test results but should include the moisture content of 20.5%. The proposed levels of compaction and moisture contents are given in Table 8.2 and shown in Figure 8.3.

## 8.2 Resilient Modulus Tests

The resilient modulus of each soil sample was determined in the laboratory using a repeated load tri-axial testing machine. The Universal Testing Machine (UTM) manufactured by Industrial Process Controls of Melbourne, Australia was used for this purpose. The test protocol for determining the Resilient Modulus followed the AASHTO T 307 test method.

The UTM test configuration consisted of four main components: the Computer Data Acquisition System (CDAS), the hydraulic system, a PC, and the tri-axial cell. The CDAS records the signals from the transducers, digitizes the information, and then passes the information along to the PC. The CDAS also controls the testing frame and transducers, along with adjusting and applying the load through the actuator. The hydraulic system allows for strict control of the loading, and therefore, precise control of the stresses incurred by the sample. The hydraulic system is connected to the actuator through an electrically controlled hydraulic servo valve. The force applied to the sample is determined using a load cell mounted in line with the loading shaft. The triaxial cell consists of an air-tight chamber, a loading arm, and a sample platform.

The tri-axial cell used in these tests was 150-mm in diameter and 300-mm tall. Confining pressure for the tri-axial test is provided by means of pressurized air. A separate air tank with a pneumatic value is connected to the triaxial cell. Using the pressure sensor, the computer system maintains a static pressure during the testing. Figure 6.4 shows the tri-axial cell used to determine the resilient modulus of the soil samples.

Soil samples were prepared at the desired levels of compaction (relative density) and moisture contents. Three samples were prepared for each combination of relative density - moisture content, as indicated in Table 8.2.

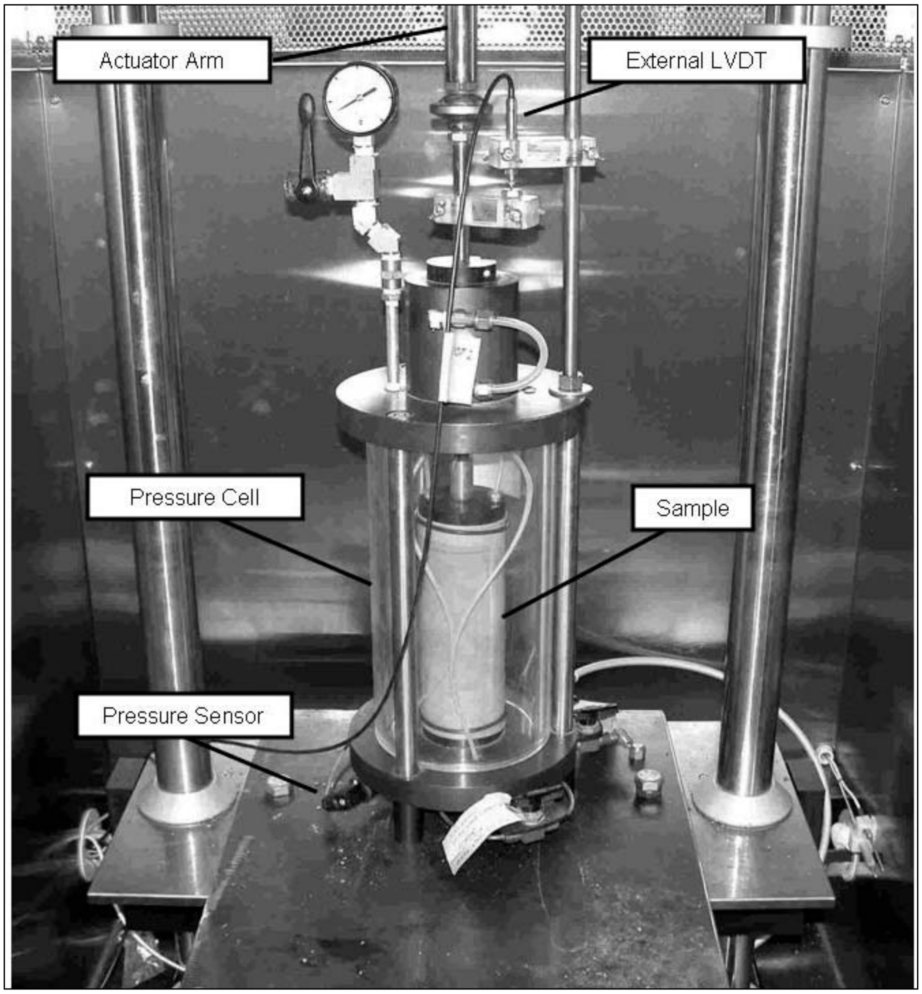
**TABLE 8.2** Proposed Factorial for Resilient Modulus Testing

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

After the soil had been dried and mechanically ground, the quantities of soil and water needed to obtain the desired moisture content and relative density level were determined. This was done by first testing the moisture content of the soil (although it had been dried and stored in sealed containers, some moisture might have been present). Next, the weight of water and the weight of soil required were calculated for a little more than the quantity of material needed for preparing the samples, based on the volume of the sample and molds, the desired relative density and the moisture content. The dry soil and water were mixed thoroughly and left to rest at least two hours before the samples were compacted.

After the desired quantity of wet soil needed for each sample was weighed, the soil samples were compacted in steel molds using a static press in three lifts, as specified in the AASHTO T 307 protocol. The samples were then extracted carefully using a hydraulic jack. The final sample size was 71 mm in diameter with a height of 145 mm. This sample size was selected based on the size of the triaxial cell.

**Figure 8.4** Tri-axial Cell



Once the samples had been extracted, they were placed in a rubber membrane. The covered sample was then placed in the tri-axial cell and porous stones were placed above and below the specimen. After the sample was placed in the tri-axial cell, the cell was sealed and placed inside the testing machine. Then, the hydraulic actuator was connected to the loading arm of the tri-axial cell. After the actuator was adjusted to contact the specimen, the external LVDT was placed and adjusted to ensure maximum stroke availability.

The testing procedure for all samples followed the AASHTO T 307-07 (2007) protocol. Each sample was conditioned prior to the testing sequence. The sample was conditioned for 1,000 load repetitions using a deviator stress of 21 kPa and a confining pressure of 21 kPa. After the initial conditioning, all samples were tested at a combination of five levels of deviator stress (13.8 kPa, 27.6 kPa, 41.4 kPa, 55.2 kPa and 68.9 kPa) and three levels of maximum stress (41.4 kPa, 27.6 kPa and 13.8 kPa) which resulted in the 15 loading sequences given in Table 8.3.

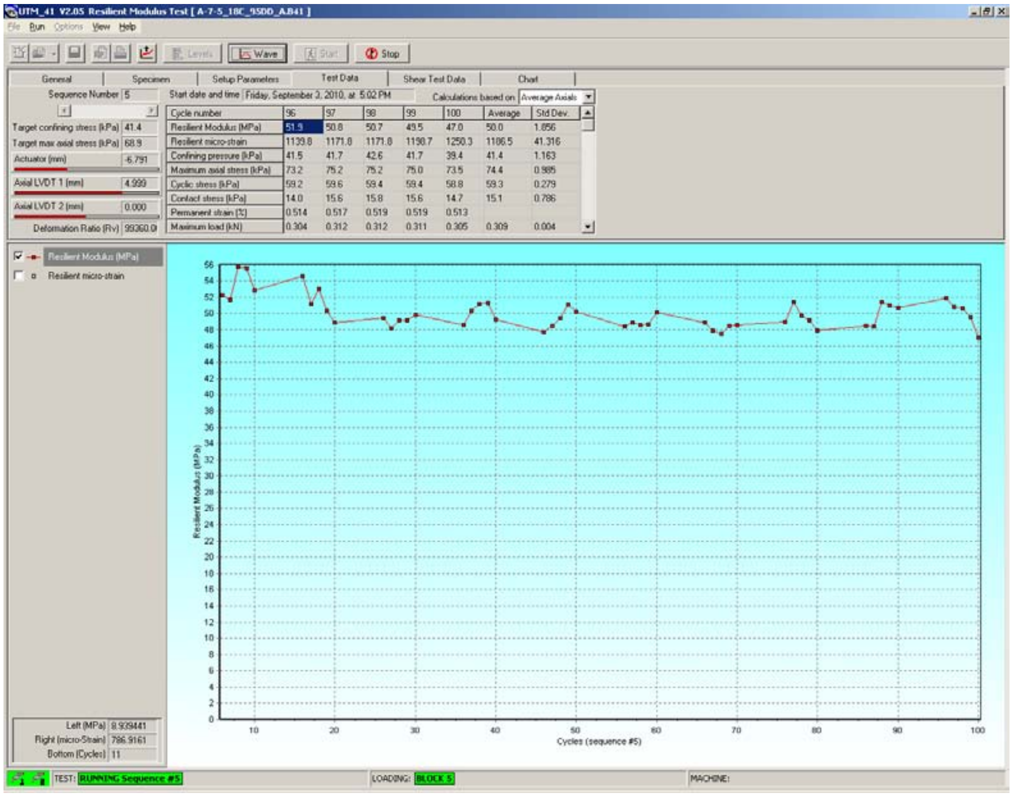
**TABLE 8.3** Loading Sequence during the Tri-axial Resilient Modulus Test

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

During each test sequences, 100 load repetitions were applied to the sample. The values recorded for the last five repetitions were averaged to calculate the resilient modulus for each loading sequence. Figure 8.5 shows an example of the typical test results for one of the loading sequence.

For each test, resilient modulus, resilient strain, permanent strain, confining pressure, cyclical stress, and contact stress were recorded for each load repetition. Only the values corresponding to the 96th to 100th loading cycles were used in calculating the final resilient modulus at each sequence. Figure 8.6 shows the haversine wave shape for one load pulse. The duration of the load pulse is 0.1 seconds followed by a rest period of 0.9 seconds.

**Figure 8.5** Screen Capture Showing the Resilient Modulus Test Result



Sequence Number 5

Start date and time Friday, September 3, 2010, at 5:02 PM

Calculations based on Average Axials

Target confining stress (kPa) 41.4

Target max axial stress (kPa) 68.9

Actuator (mm) -6.791

Axial LVDT 1 (mm) 4.999

Axial LVDT 2 (mm) 0.000

Deformation Ratio (Rv) 99360.0

| Cycle number | 96 | 97 | 98 | 99 | 100 | Average | Std Dev. |
|---|---|---|---|---|---|---|---|
| Resilient Modulus (MPa) | 51.9 | 50.8 | 50.7 | 49.5 | 47.0 | 50.0 | 1.856 |
| Resilient micro-strain | 1139.8 | 1171.8 | 1171.8 | 1190.7 | 1250.3 | 1186.5 | 41.316 |
| Confining pressure (kPa) | 41.5 | 41.7 | 42.6 | 41.7 | 39.4 | 41.4 | 1.163 |
| Maximum axial stress (kPa) | 73.2 | 75.2 | 75.2 | 75.0 | 73.5 | 74.4 | 0.985 |
| Cyclic stress (kPa) | 59.2 | 59.6 | 59.4 | 59.4 | 58.8 | 59.3 | 0.279 |
| Contact stress (kPa) | 14.0 | 15.6 | 15.8 | 15.6 | 14.7 | 15.1 | 0.786 |
| Permanent strain (%) | 0.514 | 0.517 | 0.519 | 0.519 | 0.513 | | |
| Maximum load (kN) | 0.304 | 0.312 | 0.312 | 0.311 | 0.305 | 0.309 | 0.004 |

Left (MPa) 8.939441

Right (micro-Strain) 786.9161

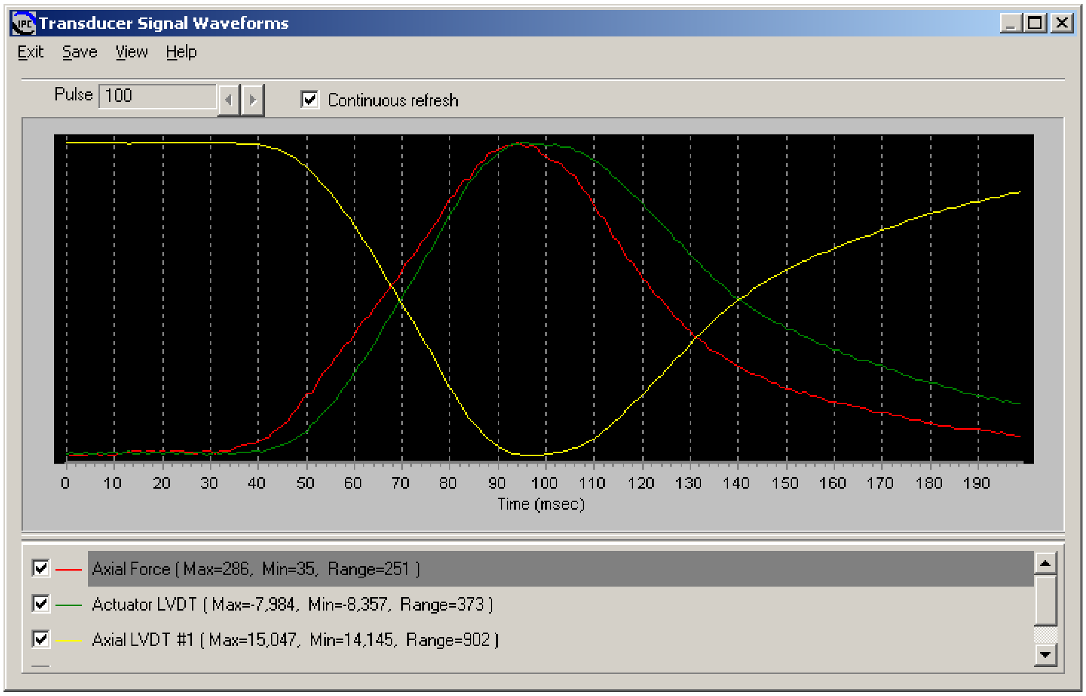
Bottom (Cycles) 11

TEST: RUNNING Sequence #5

LOADING: BLOCK 5

MACHINE:

**Figure 8.6** Wave shape of the Loading Pulse



Pulse 100

☑ Continuous refresh

☑ Axial Force ( Max=286, Min=35, Range=251 )

☑ Actuator LVDT ( Max=-7,984, Min=-8,357, Range=373 )

☑ Axial LVDT #1 ( Max=15,047, Min=14,145, Range=902 )

### 8.3 Laboratory Resilient Modulus Test Results

Resilient modulus tests were performed in the laboratory on the soil samples. Three replicate samples were tested for each moisture content – relative density level combination listed in Table 6.2. The results obtained on each sample along with the loading conditions (confining pressure, maximum deviatoric stress) are given in the Access database. For the sake of brevity, only the resilient modulus results obtained for each tested sample is given in Appendix C.

Figures 8.7 to 8.9 show the average resilient moduli values measured on the A-4 soil at three moisture contents (10%; 13% and 14%). Each point represents the average of three corresponding values, from three replicate samples. The figures shows that the compaction level, shown in the figure's legend as the relative dry density (dry density divided by the maximum dry density), affects the resilient modulus; the higher the compaction levels, the higher the resilient modulus.

Figures 8.10 and 8.11 show the average resilient moduli values measured on the A-6 soil at 16% and 19% moisture contents while figures 8.12 to 8.14 show the average moduli for the A-7-5 soil. If the resilient modulus increased with the compaction level for the A-6 soil, it did not increase for the A-7-5 soil at 20.5% moisture content. It is clear that the resilient modulus test on the A-7-5 soil at 93% dry density and 20.5% moisture content must be repeated.

It is important to note that:

- Several samples were manufactured of A-4 soil at 17% moisture content. The soil was very wet and soft, and the samples could not even be transported and placed in the triaxial cell without being damaged. Even at 13% and 14% moisture content, some samples were soft and were damaged while testing because the large permanent deformation accumulated during cyclic loading. Figure 8.14 shows two deformed samples made of A-4 soil at 14% moisture content at the left and right of a sample of the same soil but at 10% moisture content.
- It was attempted to test samples of A-6 soil for the moisture content of 22%. The soil was so wet, that water was coming out of the sample during compaction.
- Even though difficulties were encountered when testing some of the A-7-5 soil samples, especially at low compaction levels, samples of this soil were manufactured at 23% moisture content. However, the samples were very soft, too soft to be tested; the soil had the consistency of soft play dough.
- The general observation that can be made was that no soil sample can be successfully tested at moisture content higher than 4 percent above the optimum moisture content. Even the fabrication of the samples is often difficult to perform.
- At moisture contents above optimum, the variability of the resilient modulus test results increases.

**Figure 8.7** Laboratory Resilient Modulus Results – A-4 Soil at 10% Moisture Content

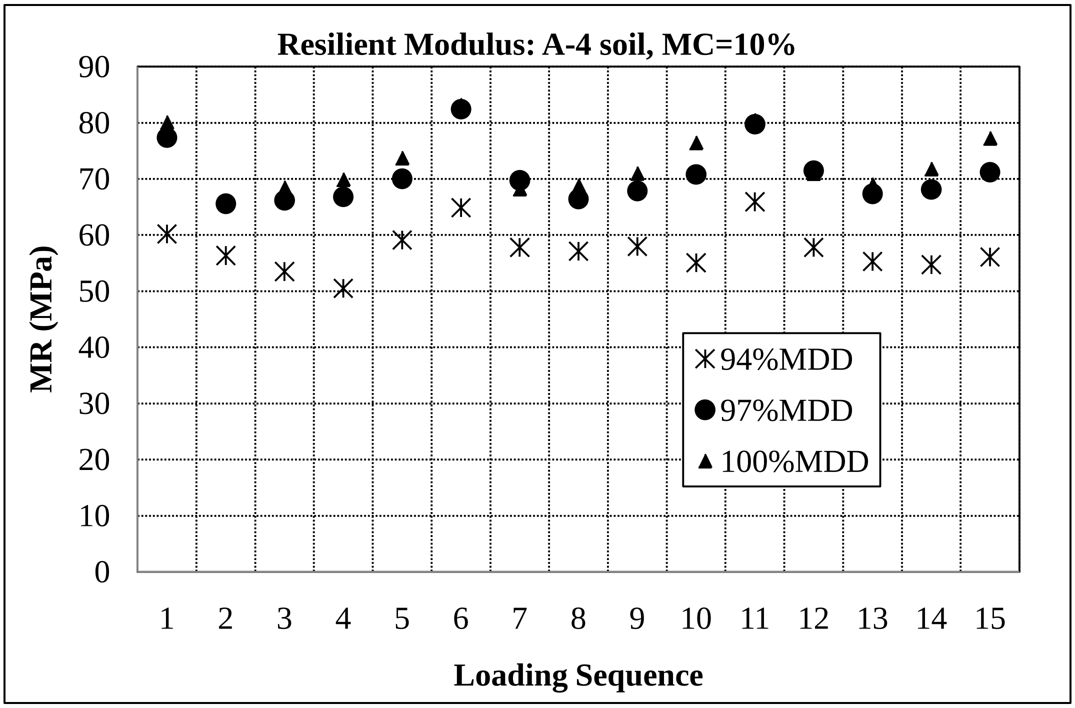


**Figure 8.8** Laboratory Resilient Modulus Results – A-4 Soil at 13% Moisture Content

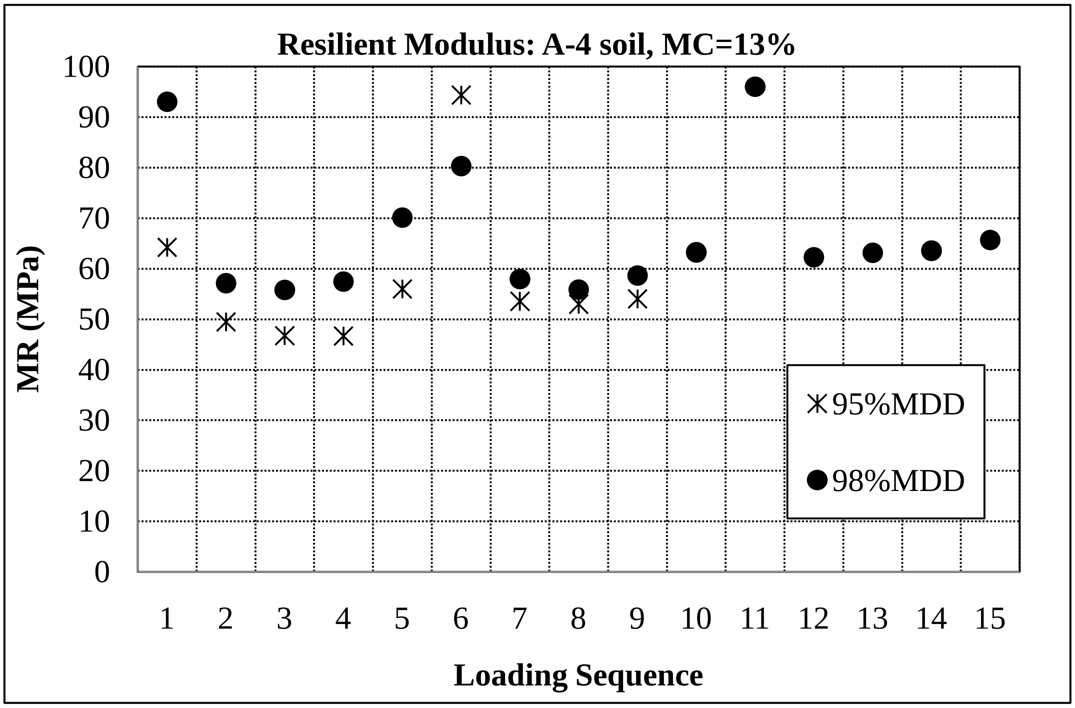


**Figure 8.9** Laboratory Resilient Modulus Results – A-4 Soil at 14% Moisture Content

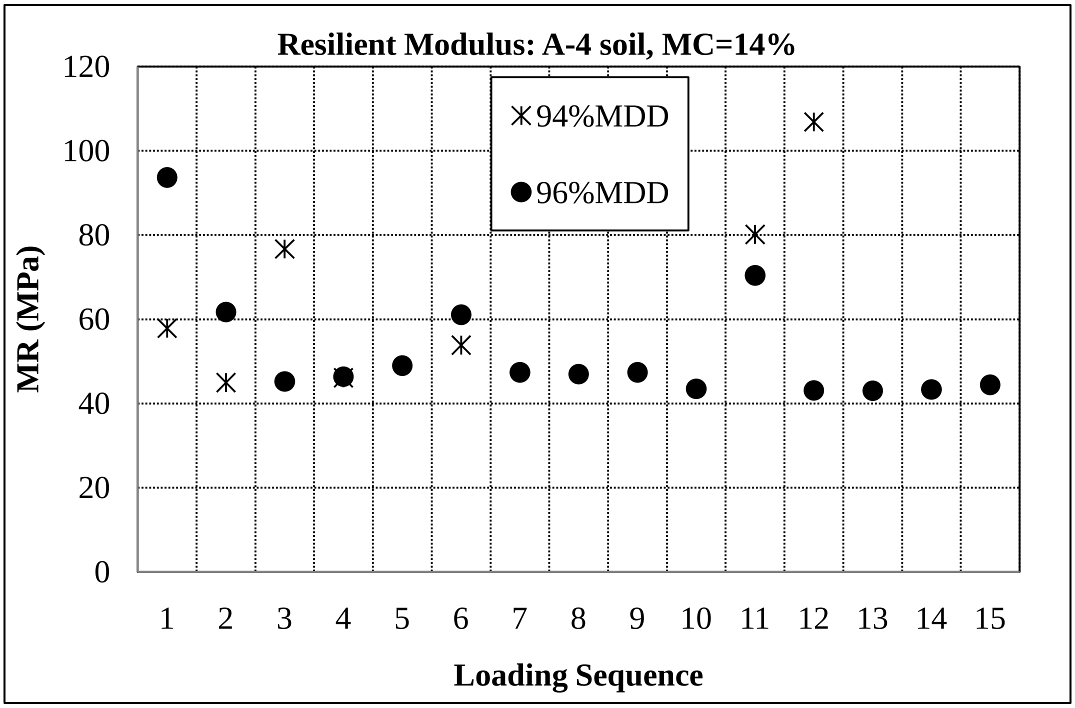


**Figure 8.10** Laboratory Resilient Modulus Results – A-6 Soil at 16% Moisture Content

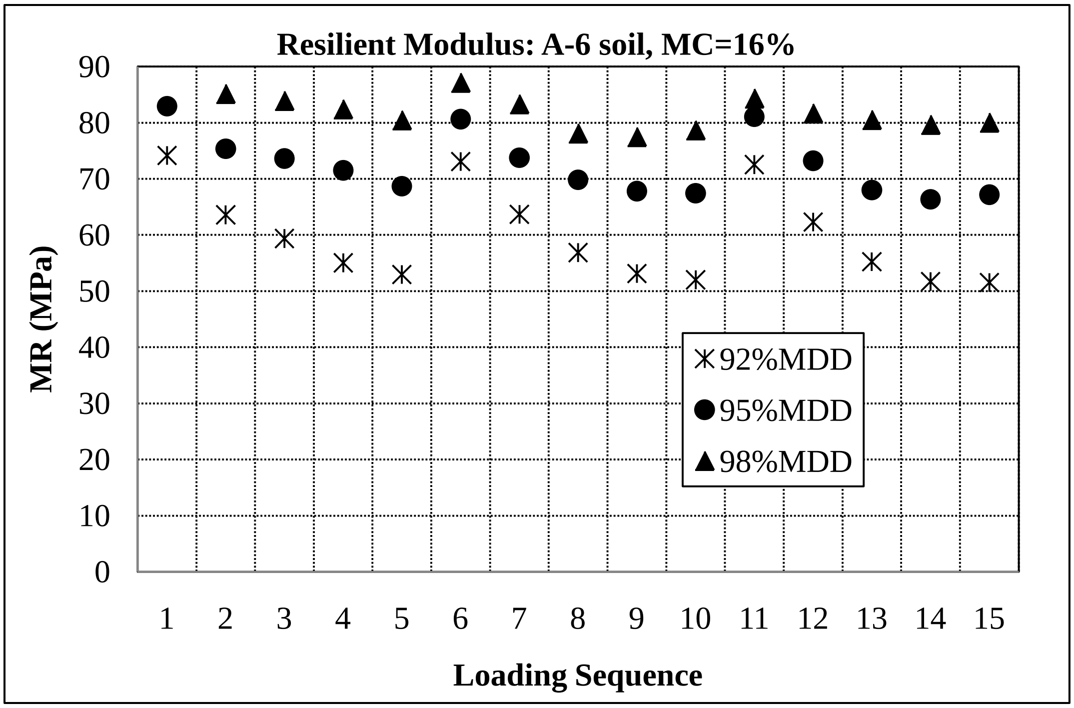


**Figure 8.11** Laboratory Resilient Modulus Results – A-6 Soil at 19% Moisture Content

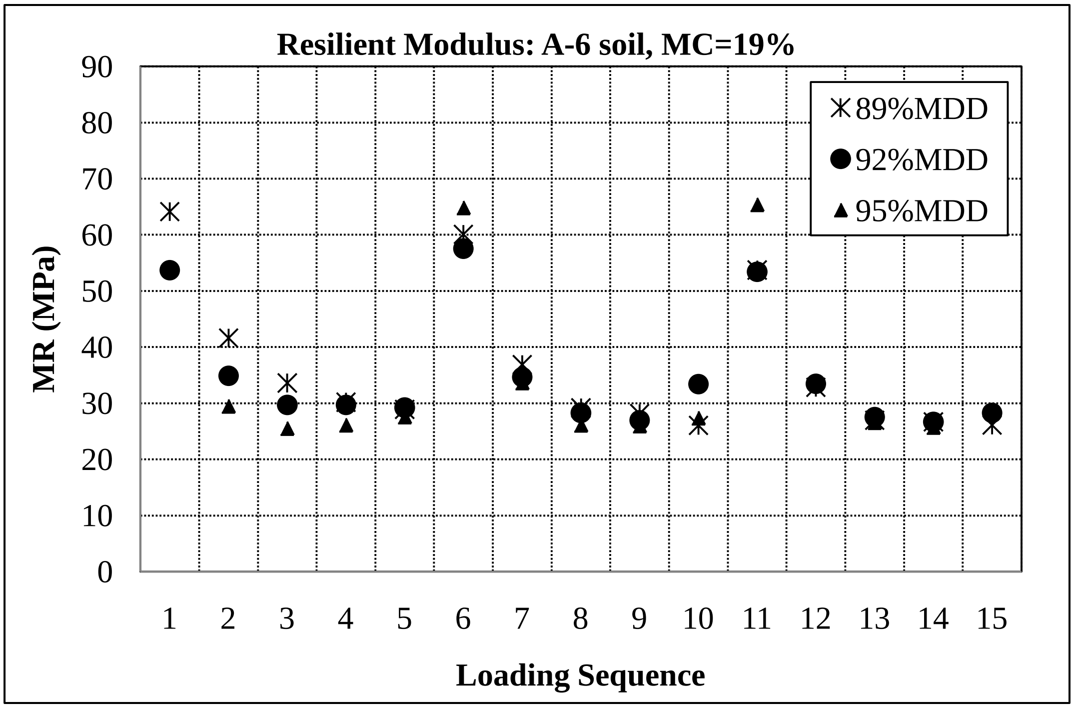


**Figure 8.12** Laboratory Resilient Modulus Results – A-7-5 Soil at 16.5% Moisture Content

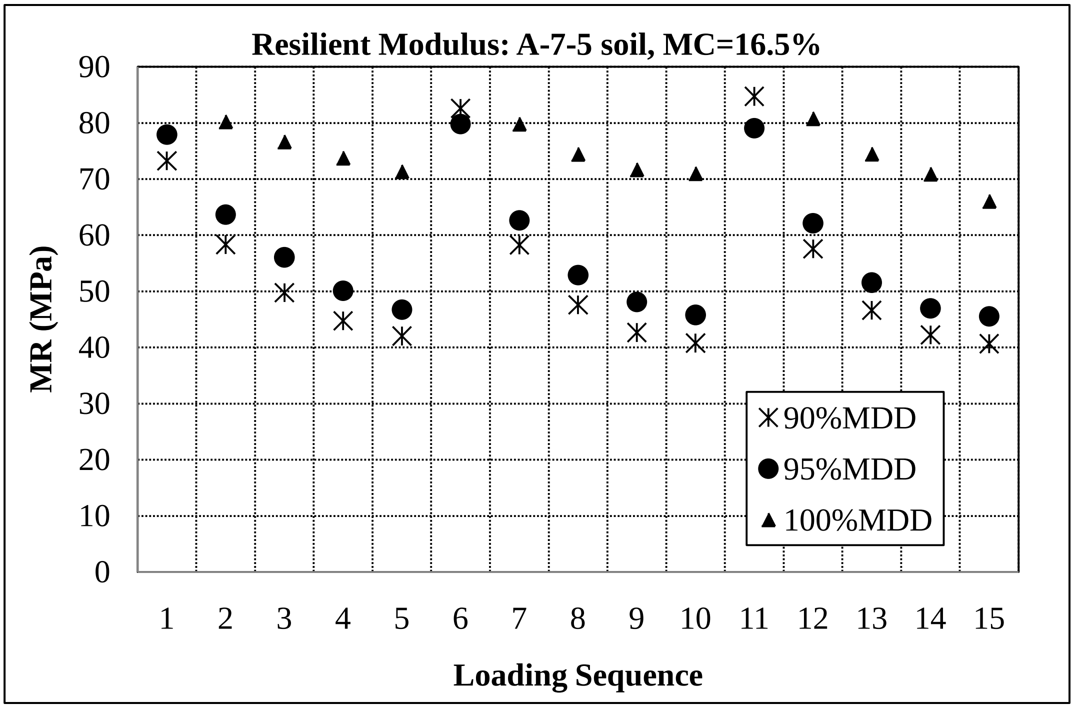


**Figure 8.13** Laboratory Resilient Modulus Results – A-7-5 Soil at 18.5% Moisture Content

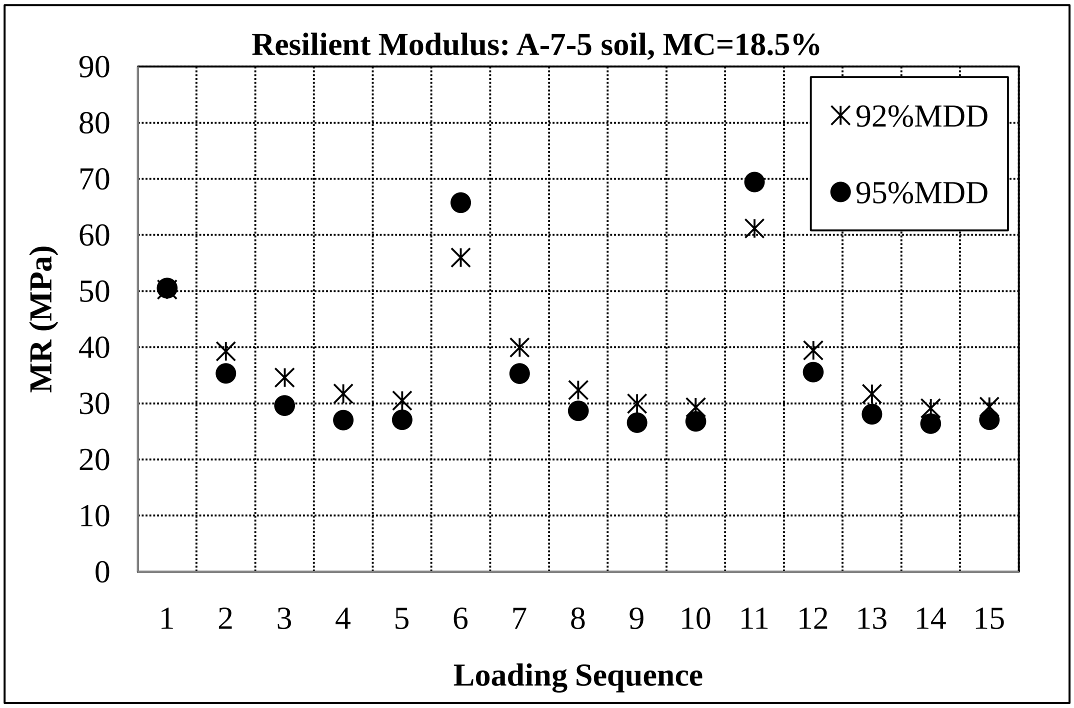


**Figure 8.14** Laboratory Resilient Modulus Results – A-7-5 Soil at 20.5% Moisture Content

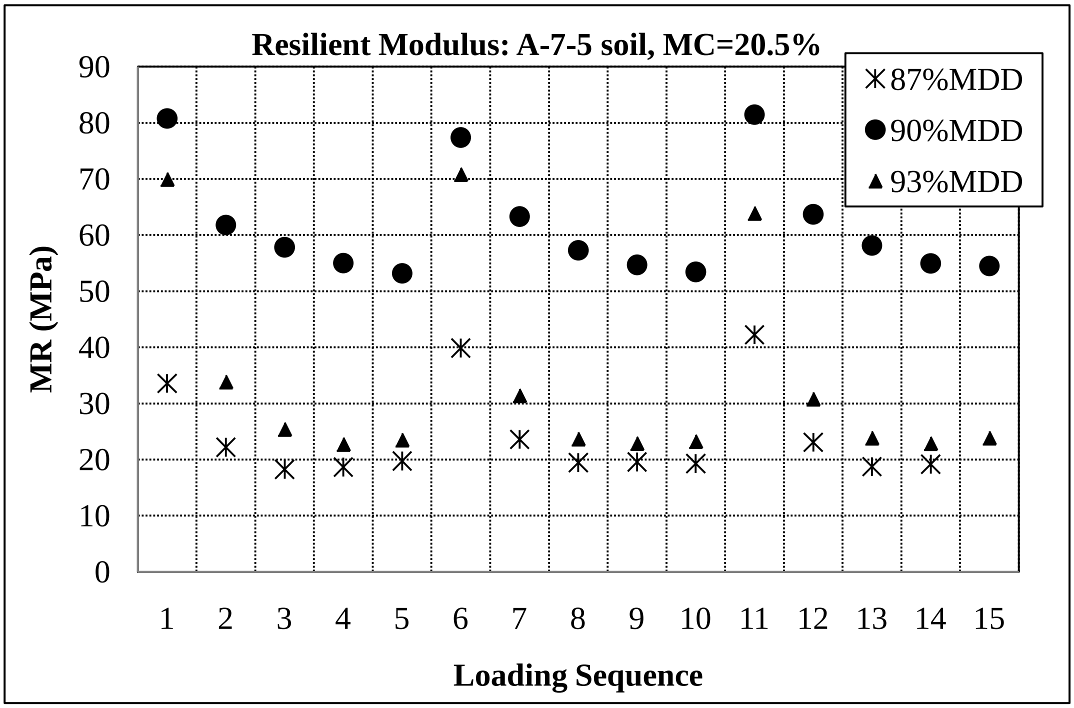


**Figure 8.15** Deformed Soil Samples at High Moisture Content

09/06/2010

## 8.4 Development of Non-Linear Stiffness Model for Soil

Subgrade soils exhibit a stress dependent behavior; their stiffness is affected by the magnitude of the stresses applied. Many stress dependency models are available in the literature. However, the most commonly used is the model incorporated in the M-E PDG (NCHRP, 2004). In this model, the resilient modulus of granular materials, $M_R$, is dependent on the confining stress, $\sigma_3$, and the octahedral shear stress, $\tau_{oct}$, as shown in Equation 6.1.

$$M_R = K_1 \cdot p_a \cdot (\theta / p_a)^{K_2} \cdot [(\tau_{oct} / p_a) + 1]^{K_3} \tag{6.1}$$

where,

$M_R$ = Resilient Modulus,

$K_1$, $K_2$, and $K_3$ = Regression Constants,

$\Theta$ = bulk stress = $\sigma_v + 2^*\sigma_3$

$\rho_a$ = normalizing stress (atmospheric pressure)

$\sigma_3$ = Confining Stress, and

$\tau_{oct}$ = Octahedral Shear Stress = $\{[2^*(\sigma_v - \sigma_3)^2]^{0.5}\}/3$

$\sigma_v$ = Maximum Axial Stress

The three constants, $K_1$, $K_2$ and $K_3$ in the model are characteristics of each soil, which change with moisture content and compaction level. Since the model above is extensively used by many researchers, the values of the $K_1$, $K_2$ and $K_3$ constants were calculated for each of the three soils tested and for each moisture content – compaction level combination. The coefficients and the coefficient of determination ($R^2$ values) for each moisture density combination of all soils are given in Table 8.4. They were estimated using non-linear regression analysis by fitting the model given in Equation 6.1 to the average value of the resilient modulus measured values calculated for the three replicate soil samples.

**TABLE 8.4** Models for Deviator Stress Effects on Stiffness

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

# CHAPTER 9. WORK PLAN FOR FUTURE RESEARCH

This chapter presents a proposed work plan developed for the in-depth analysis of the data obtained in the PSPS project. It provides a brief background on further studies related to modeling of permanent deformation in unbound pavement layers as well as a proposed framework for the data analysis in the form of a work plan organized by tasks. The framework was developed based on the assessed availability and quality of the data from the PSPS study, already discussed in previous chapters, and on the studies found during the literature search.

The PSPS study is unique in that it is the only research study that has provided permanent deformation data in the subgrade soil recorded under accelerated pavement testing, for a large factorial of soil type and moisture contents. The valuable data this study has recorded can lead to verification of existing models as well as the development of advanced and new models for the accumulation of permanent deformation in subgrade soil layer. This may significantly improve mechanistic-empirical design methods for flexible pavement structures and provide sound and validated models for inclusion in mechanistic design models for pavement structures. It is therefore imperative to conduct an in-depth analysis of the data obtained in this study.

## 9.1 Background on Rutting and Permanent Deformation Models

Rutting is the formation of longitudinal depressions in the wheel paths with small amounts of upheaval on the sides of the ruts due to the load induced permanent deformation in the pavement layers. This permanent deformation can occur in the subgrade, the base or subbase layers, or in the asphalt concrete layers. The magnitude of rutting and the contribution of each layer to the total permanent deformation depend on the magnitude and the lateral position of the wheel loads, the stresses in the individual pavement layers and the relative strength of the pavement layers. This later factor may change with temperature in the asphalt concrete layers and moisture regime in the unbound granular layers. Rutting develops progressively with the number of traffic load applications and is caused by the densification and shear deformation of the materials in the pavement structure.

Although rutting can occur in any layer of the pavement structure, almost all rutting prediction models assume that rutting is primarily related to the vertical compressive strain ($\varepsilon_v$) at the top of the subgrade soil layer. Historically, this correspondence was developed in the 1960s and the 1970s, as the result of field observations of the failure of flexible pavements with relatively thin asphalt concrete layers. However, experience has proved later that the permanent deformation may develop in the unbound base and subbase layers as well as in the asphalt concrete layers, especially for structures with thick asphalt concrete layers, where the subgrade is well protected by the pavement layers above. A method to estimate the contribution of each layer to rutting of hot mix asphalt pavements based on the shape of the transverse profile at the pavement surface was developed as part of NCHRP Project 1-34A (White et al., 2002).

Many field studies have indicated that rutting may occur in the asphalt concrete surface layer only. This indicates a mix design problem, rather than a structural design deficiency. Extensive work has been conducted on this topic as part of the SHRP’s Superpave Program. The implementation of the Superpave mix design and binder characterization methods has significantly reduced the occurrence of rutting in asphalt concrete layers.

A comprehensive discussion on the development of rutting in flexible pavements is given by Ullitz (2000), Long et al. (2002) and Huang (2003). They indicated that rutting and/or permanent deformation is typically modeled by:

- Estimating of permanent deformation with the layer materials modeled using visco-elastic, visco-elasto-plastic or plastic models. These models are derived based on fundamental principles of visco-elasticity and plasticity.
- Computing the permanent deformation using empirical relations developed from distress data, collected on in-service pavements. These models are typically incorporated in a pavement management system environment and have a low degree of accuracy.
- Estimating the number of load repetitions that will generate a certain permanent deformation or rut depth defined as failure criteria using transfer functions. These transfer functions typically relate the number of load repetitions to the magnitude of stresses or strains at critical locations in the layered system.

Table 9.1 lists the major transfer functions, equations that relate the vertical compressive strain ($\varepsilon_v$) at the top of the subgrade soil layer with the number of repetitions ($N_r$) of the load generating that strain, that induce a rut depth equal to a failure limit (e.g. 20 mm).

**TABLE 9.1** Transfer functions for subgrade rutting models

1. Chevron Model (20 mm rut depth)

$N_r = 1.077 * 10^{18} * (\varepsilon_v)^{-4.4843}$

2. Shell Model (terminal serviceability = 2.5)

$N_r = 6.15 * 10^{-7} * (\varepsilon_v)^{-4}$ at 50% reliability
$N_r = 1.945 * 10^{-7} * (\varepsilon_v)^{-4}$ at 85% reliability
$N_r = 1.05 * 10^{-7} * (\varepsilon_v)^{-4}$ at 95% reliability

3. South African Model (failure of the subgrade)

$N_r = 1.077 * 10^{18} * (A - 10 * \log \varepsilon_v)^{-4.4843}$
A = 33.5 for a terminal rut depth of 10mm and 36.5 for a terminal rut depth of 20 mm

3. Asphalt Institute Model $N_r = 10^M$ where $M = 1 / [0.25*(-1.553-\log \varepsilon_v)]$

4. U.S. Army Corp of Engineers Model

$N_r = 10{,}000 * [(0.0002347 + 0.00245 \log E_s) / \varepsilon_v]^B$ where $B = 0.0658 * E_s^{0.559}$

$N_r$ – number of loads until failure of the subgrade
$\varepsilon_v$ - vertical strain at the top of the subgrade layer
$E_s$ – subgrade resilient modulus

The models developed above were derived based on observed deformation of in-service pavement structures. However, the models are empirical and do not always reflect the contribution of the other pavement layers to rutting.

When incorporated in mechanistical-empirical design procedure for flexible pavements, the models given in Table 9.1 were used to compute the cumulative pavement damage. The cumulative damage is computed with the aid of Miner's law. The law was developed originally to predict metal fatigue but has been applied to other materials and forms of distress. The Miner's law is expressed by the following relationship:

$$D = \sum_{i=1}^{k} n_i / N_i$$

$n_i$ - number of applied loads in condition i
$N_i$ - number of allowable repetitions in condition i

For each load conditions, the Miner's law calculated the corresponding damage fraction consumed. The life of the pavement is considered consumed when the total damage, D, equals or exceeds unity. Although Miner's law is incorporated in most mechanistical-empirical design methods, according to Wirshing and Yao (1976), it fails to predict accurately pavement material behavior because it does not account for the order the loads are applied and ignores the presence of an endurance limit.

Major limitations of these transfer functions are:

- are empirical in nature,
- are valid only for the subgrade soils they were derived for,
- are valid only for the lateral wheel wander and the tire inflation pressure they were derived for,
- are valid only if the same definition of rut depth is used (e.g. relative to a horizontal imaginary line or a 1.2 m straight edge),
- do not include the plastic limits or gradation of the subgrade soil
- ignore the contribution of upper pavement layers to the permanent deformation at pavement surface.

The NCHRP 1-37A pavement design model (NCHRP, 2004) contains models for predicting permanent deformation in each pavement layer. The average vertical resilient strain in each layer/sublayer is computed for each analysis period of the entire design period with a linear elastic program for each axle load configuration. Rutting distress is predicted in absolute terms and not computed based on Miner's law; the incremental distress computed for each analysis period is directly accumulated over the entire target design life of the pavement.

The model used for unbound materials has the form:

$$\delta_a (N) = \beta_1 * (\varepsilon_0 / \varepsilon_r) * \varepsilon_v * h * EXP[-( \rho/N)^{\beta}]$$

where:
$\delta_a$ – Permanent deformation for the layer/sublayer
$\beta_1$ - Calibration factor for the unbound granular and subgrade materials
$\varepsilon_0$ , $\beta$ and $\rho$ – Material properties, with $\log \beta = -0.6119 - 0.017638 * w_c$
$\varepsilon_r$ – Resilient strain imposed in laboratory test to obtain the above listed material properties
$\varepsilon_v$ – Average vertical resilient strain in the layer/sublayer
h – Thickness of the layer/sublayer $w_c$ – water content in the layer/sublayer
N – Number of traffic repetitions

All parameters, except for $\beta_1$, were computed function of the resilient modulus of the layer/sublayer and water content, estimated based on the ground water table depth. The final calibrated model parameters, derived from the permanent deformation data collected on 88 LTPP sections in 28 states were:

$\beta_{1GB} = 1.673$ for unbound granular base and
$\beta_{1SG} = 1.35$ for unbound subgrade soil.

The NCHRP 1-37A model for rutting in unbound materials was developed by modifying the models proposed by Tseng and Lytton (1989), which had been developed originally based on laboratory tests and not on field measured permanent deformation data. However, the modifications have significantly altered the original models in that:

- The same shape of the model was proposed for unbound foundation materials and for subgrade soils
- The factor of bulk and deviatoric stresses were eliminated.
- The shape of the model was changed to reduce the scatter in the prediction of the permanent deformation during calibration with LTPP data, even though the LTPP database had no permanent deformation data measured in individual pavement layers. The permanent deformation in individual pavement layers was estimated based on an artificially selected contribution of each layer to the total permanent deformation.

The permanent deformation model for unbound materials incorporated in the NCHRP 1-37A pavement design model is empirical. However, a desirable feature is that it includes directly the effect of moisture content in the computation of permanent deformation, and not indirectly, through its effect on the resilient modulus of the foundation layers.

The most common procedure for studying the evolution of permanent deformation under cyclic loading for granular materials is to perform triaxial laboratory tests, in which the material is subjected to a large number of cycles at one stress level. Then an empirical model is derived from the permanent deformation ($\varepsilon_p$ or PD) vs. number of cycles (N) curve. Well known relationships have been proposed by:

Barksdale (1972), $\varepsilon_p = a + b * \log N$

Sweere (1990) $\varepsilon_p = a * N^b$
Hornych et al. (1998): $\varepsilon_p = a * [1 - (N/100)^{-b}]$

Van Niekerk et al. (2000) and Van Niekerk (2002):

- for aggregates $\varepsilon_p = a * (N/1000)^b + c * (EXP[d*N/1000]-1)$
  c = 0 if the accumulation of permanent deformation is stable
- for sand: $\varepsilon_p = a * (N/1000)^b$

Theyse et al. (2000)
$\varepsilon_p$ or PD = a*[EXP(b*N) – 1] - c*[EXP(-d*N) – 1] – unstable case

$\varepsilon_p$ or PD = $m*N + c*N / [1 + (c*N/a)^b ]^{1/b}$ – stable case

Theyse et al. (1997)
$PD = a * N^c * [EXP(b*\sigma_v) – 1]$

Gidel (2001): $\varepsilon_p = a*[1– (N/100)^{-b} ]*[L_{max}/p_a]^n /[m + s /p_{max} - q_{max}/p_{max}]$

Where:

$L_{max} = [q_{max}{}^2 + p_{max}{}^2 ]^{0.5}$   $p_a$ = 100kPa
a, b, c, d, n – model parameters
m, s – parameters of the failure line of the material, of equation q = m*p+s
p – deviatoric stress;   q – confining stress
$\sigma_v$ – vertical stress at the top of the pavement foundation
N – number of load repetitions

An interesting model is proposed by Nunez et al (2004). They have performed cyclic triaxial tests on three granular material with the maximum aggregate size of 25 mm, and identified three segments on the permanent deformation versus the number of load cycles curve (Figure 9.1):

- an initial permanent strain ($\varepsilon_{pi}$ ), accumulated in the very beginning of the test after $N_i$ cycles, reflecting some kind of post-compaction;
- a second stage with permanent deformation accumulating very slowly, for which a constant strain rate (CSR) may be computed;
- an increasing strain rate stage, observed if the deviatoric, ($\sigma_d$), exceeds a certain threshold , ($\sigma_{1,f}$ ) , which may cause specimen's failure.

The model is simple and allows an easy calculation of the permanent strain with the formula:

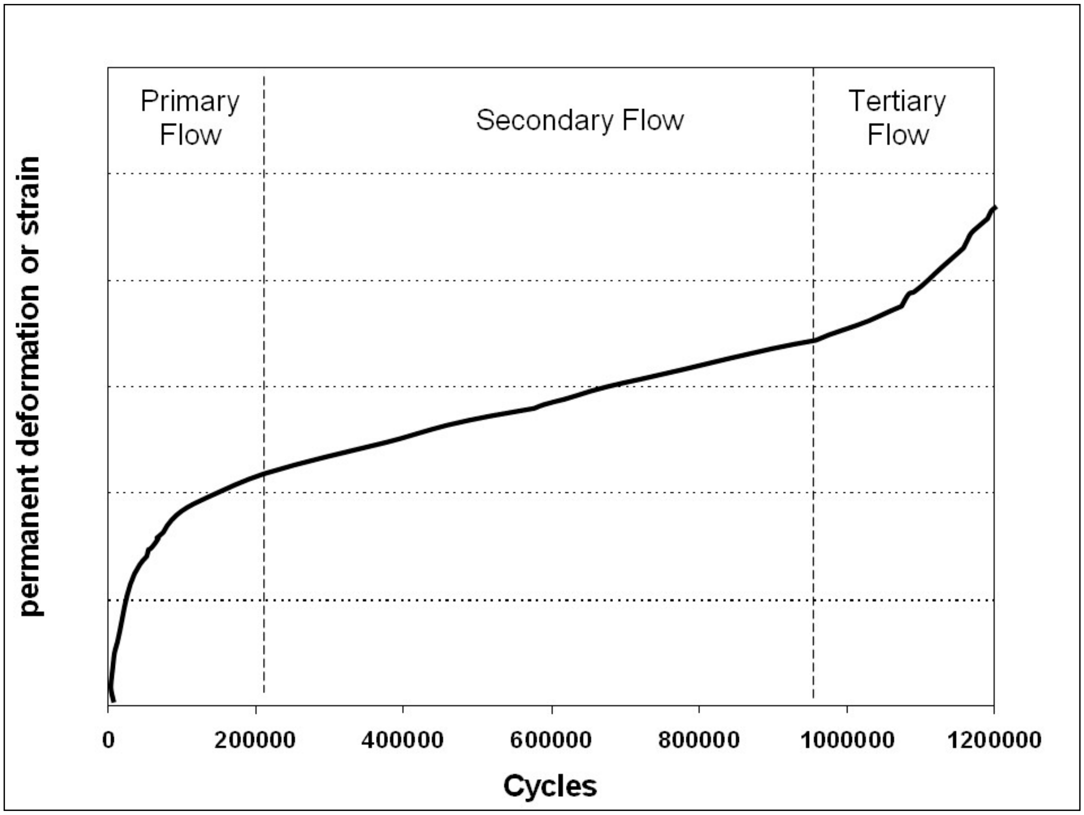
$\varepsilon_p = \varepsilon_{pi} + CSR * (N-N_i)$

The parameters can be determined from the results of cyclic triaxial tests performed at several levels of deviatoric stress with the following formulas:

$\varepsilon_{pi} = a * EXP[b* \sigma_d]$   or   $\varepsilon_{pi} = f * EXP[g* \sigma_d / \sigma_{1,f} ]$
$CSR = c * EXP[d* \sigma_d]$   or   $CSR = h * EXP[i* \sigma_d / \sigma_{1,f} ]$

A separate set of material constants, a, b, c, d, e, f, g, h and i must be determined for each density level and moisture content.

**Figure 9.1**. Typical evolution of accumulated permanent deformation



All the models presented previously were derived from the results of cyclic triaxial tests on granular materials for bases and subbases. The original models proposed by Tseng an Lytton (1989), which were modified and adopted in the NCHRP 1-37A model for permanent deformation in unbound materials, were also developed based on laboratory tests on granular materials. No model was found to be derived from measured permanent deformation of an unbound granular layer, from neither in-service nor APT pavement structure. For subgrade soils, such a model was developed at the Danish Road Institute (Zhang et al, 1998) in the DRTM1 experiment, and was validated for the DRTM2 experiment. The energy-density model has the following form:

$$\varepsilon_{pz} = a * (N)^b * [0.5*(\sigma_z / p) * \varepsilon_z ]^c$$

where

$\varepsilon_{pz}$ – vertical plastic strain at a depth z (microstrain)
$\varepsilon_z$ - vertical dynamic elastic strain at depth z, (microstrain)
N – number of load repetitions
$\sigma_z$ – vertical stress at depth z (MPa)
p – reference stress (MPa) taken as atmospheric pressure (0.1 MPa)
a, b, c – constants

For silty clayey sand, the constants were: a = 0.453, b = 0.341 and c = 0.868.

When the model was tested, it was revealed that at the same number of load repetitions, the calculated plastic strains in a pavement with a stiff subgrade were larger than for a soft subgrade, which is incorrect. The model was later improved by Odermatt (2000), who analyzed the permanent deformation data from DRTM1 and CRREL's TS01 and TS02 APT sections. The improved model has the form:

$$\varepsilon_{pz} = a * (N)^b * (\sigma_z / p)^c * \varepsilon_z^{\,d}$$

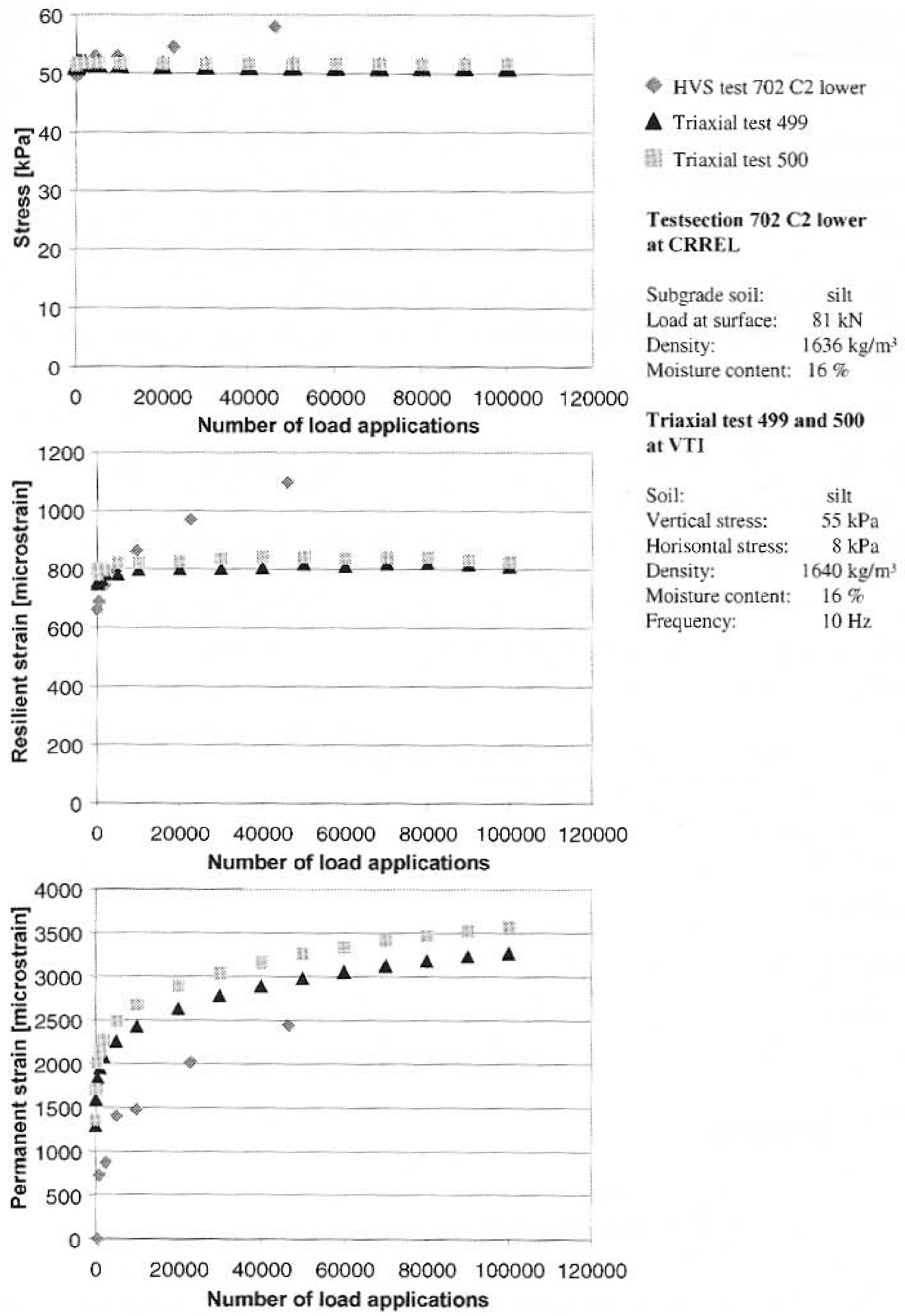
Odermatt (2000) estimated the four constants from permanent deformation data measured in the three APT projects. He also performed an extensive repeated triaxial testing program to compute the constants in the equation above and to study the influence of compaction, moisture content and loading frequency on the accumulation of permanent deformation. In the triaxial tests he subjected the same subgrade soils used in the three APT tests, to over 500,000 cycles of deviatoric stress, at constant confining stress. He then found that the permanent deformations predicted with the laboratory derived constants and the field measured permanent deformations do not match. An example of the results is provided in Figure 9.2. The possible justifications for the mismatch were (Odermatt, 2000):

- A reorientation of the principal stresses takes place during shear in the APT test with a rolling wheel. The principal stresses do not rotate in the triaxial test.
- Mean values of densities and moisture content from the APT tests were used in the triaxial tests.
- Some permanent strain measurements in the APT tests were unreliable.
- Horizontal stresses are difficult to measure in the APT tests
- A static confining pressure is applied in the triaxial tests, while in the APT tests, the horizontal stresses vary as the wheel passes a point in the material.

The trends of the accumulation of permanent strain also differed. The initial permanent strain (after the first 1,000 cycles) is higher in the cyclic triaxial test than in the APT test. This may be explained by the fact that, in the APT and in-service pavements, some permanent strain accumulated during the compaction and placement of the upper layers. This initial stage cannot be simulated in the laboratory tests. Also, the rate of increase in permanent strain after the accumulation of the initial strain is typically smaller for the cyclic triaxial test. A possible explanation is that, during the laboratory tests, the confining stress is not pulsating; it is kept constant throughout the test.

Odermatt's work suggests that no model derived solely from cyclic triaxial test data can estimate accurately the accumulation of permanent deformation in subgrade soils under a rolling wheel. Laboratory tests can be used solely to determine shift or correction factors that reflect the relative influence of moisture, compaction level and freeze-thaw cycles on the accumulation of permanent vertical strain and deformation.

**Figure 9.2** Comparison of Predicted and measured permanent strain (Odermatt, 2000)



Theyse (1997) presented a conceptual model for developing a model for the evolution of permanent deformation of unbound pavement layers. The objective of the work was to develop permanent deformation models for incorporation into the South African Pavement Mechanistic Design Method (SAMDM) based on permanent deformation data collected during HVS trials in South Africa over a long period of time. It was therefore implicitly assumed that specific loading conditions to APT experiments (reduced wheel speed, high frequency of loading, short duration of the experiments) are likely to have small effects on the development of permanent deformation in typical South African structures, which have relatively thin hot-mix-asphalt surface layers and well-compacted unbound granular layers.

The model assumes that the permanent deformation of an unbound pavement layer, the dependent variable, depends on a number of independent variables and is fully controlled by these variables. The independent variables may be grouped as primary and secondary independent variables. The two primary independent variables are defined as the stress condition (stress or strain level) and the number of stress repetitions. Without either one of these variables, there will not be any traffic induced permanent deformation in a pavement structure. The secondary independent variables (material type or material shear strength and moisture content) will not cause any permanent deformation by themselves, but they will influence the magnitude of the permanent deformation. Their influence was not discussed in the paper by Theyse (1997).

Even though the model serves a pavement design process and does not predict the performance of an in-service pavement structure when the performance of the same structure under APT condition is known, the conceptual model contains elements useful for such purpose. The same conceptual model can be used for the analysis of the permanent deformation data at the PSPS project.

Permanent deformation data must be recorded for each pavement layer at regular intervals during the APT experiment. Multi-Depth Deflectometers (MDD) are used for this purpose. The MDDs consists of a stack of Linear Variable Displacement Transducers (LVDTs). The LVDTs are housed in modules that can be fixed at a predetermined depth in the pavement structure, usually at layer interfaces. A reference core runs through the LVDT modules and is anchored at a depth of 2.5 – 3 meters (Theyse, 1998). An example of the recorded evolution of permanent deformation is given in Figure 9.3.

Empirical equations for predicting the permanent deformation in each unbound pavement layer are developed from MDD permanent deformation data. The proposed equation for unbound foundation layers has the form:

$$PD = a * N^c * [EXP(b*\sigma_z) - 1]$$

a, b, c – model parameters, obtained by fitting the function to MDD deformation data (e.g. from Figure 9.3)

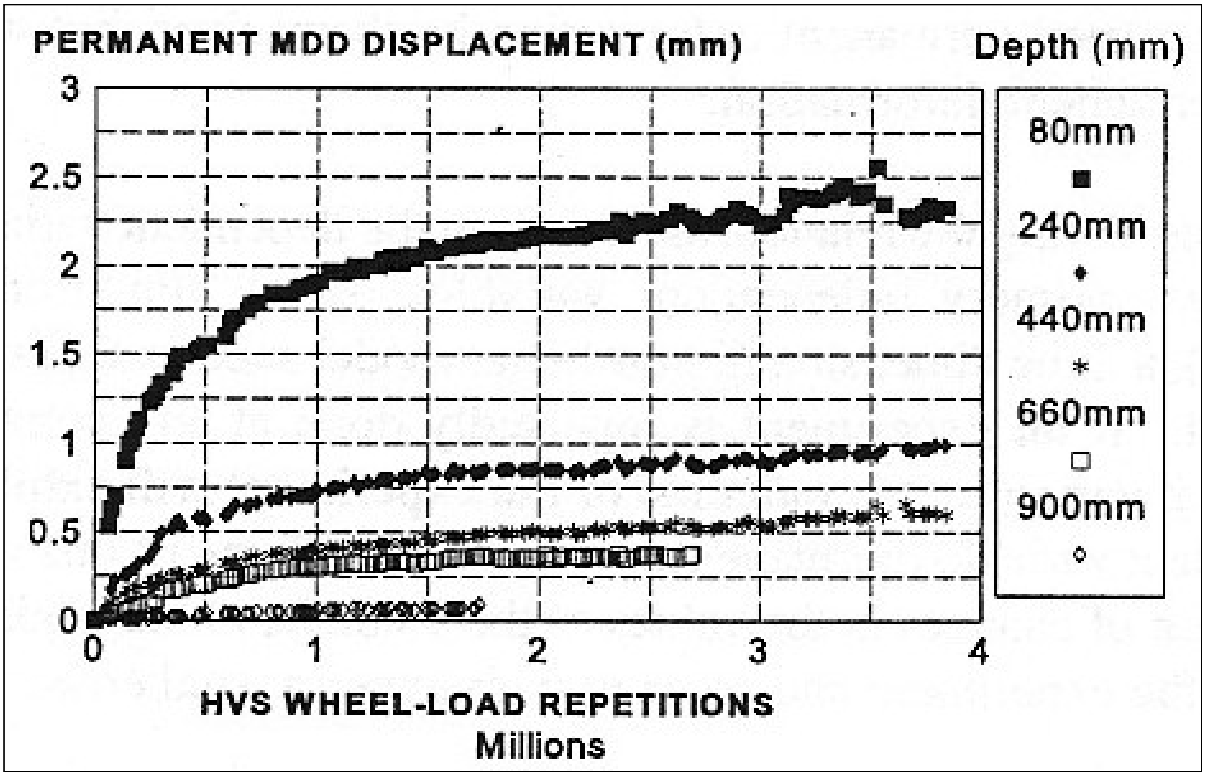
N – number of repetitions (E80 standard axles)

$\sigma_z$ – vertical stress at the top of the pavement foundation computed with a linear elastic structural program, with elastic layer moduli backcalculated from deflection data measured by the MDDs.

Theyse's conceptual model is interesting and presents the advantage of utilizing an empirical equation with parameters that can be backcalculated from APT permanent deformation data. The equation does not use strain or stress data, which cannot always be measured accurately in APT experiments. However, the main limitations are:

- The conceptual model has not been validated with permanent deformation data from an in-service pavement.
- The conceptual model can be applied only to unbound granular layers.

**Figure 9.3**. Permanent downward displacement of MDD modules with increasing load repetitions (Theyse, 1998)



## 9.2. Premise for the Proposed Work Plan

The proposed work plan is drafted based on the following facts:

a. The PSPS study provided valuable data for the validation and development of models for permanent deformation in the subgrade soil layers. It is the only APT study that delivered, for a relatively large factorial of subgrade soil type, moisture content, wheel load level the evolution with the number of applied passes of:
    - Vertical permanent deformation and strain
    - Vertical dynamic (resilient) strain
    - Vertical and horizontal dynamic stresses.

These variables were recorded simultaneously at the same depths within the subgrade layer.

b. Construction and pavement performance data is also available for most PSPS tested pavement structures not only in terms of average values per tested structure but also in precise locations.
c. The quality of response, performance, testing and construction data has been assessed already and only good data has been retained in the database.
d. Extensive laboratory tests to determine the properties of the subgrade soils have already been conducted. Samples of three subgrade soils are available; additional testing of these soils is possible if additional parameters are needed.
e. Development of both empirical and mechanistic models for the development of permanent deformation in subgrade soils must be conducted in order to maximize the use of the valuable data resulted from the PSPS study.

### 9.3. Outline of the Proposed Work Plan

The objective of the in-depth analysis of the PSPS data is to validate existing and to develop new and advanced models for the permanent deformation in subgrade soil layers. To achieve this objective the following tasks must be conducted:

*TASK 1 – Review of PSPS products*

In this task, a detailed review of all products of the PSPS study (project reports, data assessment report and database) must be conducted. The research team must become very knowledgeable on all details of the project. The research team must know in greatest detail how the experiment was conducted, what data was collected, what laboratory material characterization tests were performed and what the project database contains.

*TASK 2 – Development of Empirical Models for Permanent Deformation in Subgrade Soils*

This task will aim at developing new empirical models and obtaining the coefficient for existing models by conducting statistical analysis of the data included in the PSPS database. Several models should be studied:

- The model currently incorporated in M-E PDG
- All other empirical models presented in the “background” section of this chapter
- New empirical models. These models should predict the incremental vertical permanent deformation as function of:
    - the already accumulated permanent deformation,
    - the resilient vertical strain
    - the vertical and horizontal stresses

The influence of soil type, moisture content and relative dry density should be studied to identify if they affect the coefficients of the model. Further refinement of the models may be necessary to incorporate these variables.

It is recommended that multi-linear and non-linear regression analysis be employed for this work. Several statistical packages (e.g. SAS) can be effectively employed to accomplish this since the PSPS data is already organized in a MS Access database. Thus, the data manipulation can be easily done.

### *TASK 3 – Advanced Laboratory Testing of Subgrade Soils*

It is recommended repeated triaxial test with suction measurements to determine the accumulation of permanent deformation be conducted in this task in order to:

- Determine if the deformation accumulates in the laboratory tests in similar way as in the APT test. If such a similarity exists, the accuracy and effectiveness of mechanistic-empirical pavement design methods will be significantly improve.
- Obtain experimental data that will allow the determination of parameters for mechanistic model that calculate permanent deformation in the subgrade soils. Several models including the Drucker-Prager and modified Drucker-Prager are currently available.

It is recommended that repeated triaxial test with pulsating confining pressure be conducted in this task. This test replicates better the field conditions since in any point within the subgrade layer the confining pressure is not constant when the loading wheel passes on top of the pavement, but it increases and decreases in the same time with the vertical, deviatoric stress. This may explain Odermatt's failure to match the permanent deformation model derived in the laboratory tests with the values measured in TS701 and TS702 test cells; the confining pressure was kept constant in his tests.

It is also recommended that the test be conducted for a factorial combination of soil type (3 soils), moisture content (OMC and OMC+3% only), relative dry density level (2 levels), confining stress (2 levels) and deviatoric stress (2 levels) to capture the influence of these variables on the accumulation of permanent deformation. The confining and deviatoric stresses will be selected for each soil considering the vertical and horizontal stresses recorded in the corresponding PSPS sections.

It is important to note that there is no standard test procedure for the repeated tri-axial test on soils, either with or without pulsating confining pressure. A major unknown is the number of pre-conditioning loading cycles that should be applied before the permanent deformation measurements is started.

### *TASK 4 – Finite Element Modeling of Permanent Deformation Accumulation*

The work to be conducted in this task aims at verifying if mechanistic models are effective in predicting the permanent deformation in subgrade soil layer. The work will consist of:

a) Modeling of the accumulation of permanent deformation in laboratory tested samples. This must be done in order to derive the coefficients or parameters of the model for each soil type, moisture content and relative dry density. Here, FEM will be used to model the deformation in a cylindrical soil sample subjected to a combination of pulsating confining and deviatoric stresses.
b) Using the permanent deformation versus cycles of load applications obtained in the laboratory tests in Task 3 and the FEM modeling will allow the derivation of the mechanistic model coefficients through back-estimation. These coefficients will be different for different soils, moisture contents and relative dry densities.
c) FEM modeling of the accumulation of permanent deformation in the APT experiment using the coefficients or parameters derived in b). It is recommended to use the layer thicknesses determined in the locations where the emu gages were installed in the PSPS sections.

d) Comparison of deformations obtained in the FEM analysis and the APT experiment to validate the mechanistic models.

*TASK 5 - Final Report*

A report that will give detailed information on the laboratory tests, the analytical modeling, and the recommended prediction models for the permanent deformation of subgrade soils must be prepared in this task.

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# APPENDIX A

# BACKCALCULATED LAYER MODULI

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701 AVERAGE THICKNESS                          TTI  MODULUS  ANALYSIS  SYSTEM  (SUMMARY REPORT)                    (Version 6.0)
-----------------------------------------------------------------------------------------------------------------------------------
  District: 701                                                                         MODULI RANGE(psi)
  County  :                                                    Thickness(in)        Minimum        Maximum     Poisson Ratio Values
  Highway/Road:                                 Pavement:           3.30             300,000        650,000          H1: v = 0.35
                                                Base:              10.50              30,000         90,000          H2: v = 0.35
                                                Subbase:            0.00                                             H3: v = 0.00
                                                Subgrade:          70.15(by DB)               15,200                 H4: v = 0.45
-----------------------------------------------------------------------------------------------------------------------------------
             Load    Measured Deflection (mils):                                Calculated Moduli values (ksi):        Absolute Dpth to
  Station   (lbs)    R1       R2       R3       R4       R5       R6       R7     SURF(E1)  BASE(E2)  SUBB(E3)  SUBG(E4) ERR/Sens Bedrock
-----------------------------------------------------------------------------------------------------------------------------------
    1.000    9,193  18.11   10.93     4.84     2.31     1.61     1.29     1.08     543.9       47.3        0.0      10.9      18.64   79.2
    2.000    9,111  18.00    9.74     3.96     1.97     1.38     1.12     0.91     378.8       46.7        0.0      13.0      20.76   87.1
    3.000    9,152  15.97    9.04     3.90     1.81     1.25     1.01     0.84     523.4       51.4        0.0      13.8      19.21   75.4
    4.000    9,152  14.81    8.30     3.58     1.71     1.22     0.98     0.81     510.3       58.8        0.0      14.7      19.90   79.6
    5.000    9,049  14.58    8.09     3.34     1.63     1.16     0.97     0.76     504.5       57.1        0.0      15.4      20.90   83.4
    6.000    9,065  14.43    7.81     3.13     1.51     1.10     0.92     0.74     489.1       55.6        0.0      16.5      21.85   81.3
    7.000    9,000  15.72    7.87     3.02     1.49     1.09     0.88     0.72     359.4       50.0        0.0      16.9      22.49   75.6
    8.000    8,980  14.93    7.83     3.15     1.54     1.10     0.84     0.73     423.0       54.2        0.0      16.2      20.97   83.7
    9.000    8,983  14.00    7.46     3.09     1.53     1.10     0.85     0.73     449.8       61.1        0.0      16.4      20.71   86.4
   10.000    9,008  12.66    7.03     3.24     1.59     1.12     0.87     0.74     508.8       77.1        0.0      15.8      18.37   84.7
   11.000    9,013  13.18    7.54     3.34     1.61     1.05     0.93     0.75     602.2       65.6        0.0      15.6      18.14   81.3
   12.000    8,906  12.52    6.79     2.91     1.48     1.11     0.76     0.73     493.5       72.9        0.0      17.0      20.18   92.9
   13.000    8,775  17.82   10.80     4.52     2.30     1.65     1.29     1.05     510.3       46.3        0.0      10.7      20.14   92.3
   14.000    8,758  17.84   10.08     4.26     2.00     1.35     1.07     0.88     450.7       43.0        0.0      12.0      18.99   76.8
   15.000    8,761  15.87    8.70     3.65     1.78     1.23     1.01     0.79     430.9       51.5        0.0      13.7      19.97   83.1
   16.000    8,742  15.95    8.20     3.17     1.60     1.12     0.96     0.77     367.2       48.4        0.0      15.5      21.93   77.4
   17.000    8,758  14.86    7.63     3.01     1.53     1.13     0.88     0.74     375.6       54.7        0.0      16.2      22.15   83.5
   18.000    8,778  15.20    7.45     2.97     1.48     1.08     0.85     0.70     321.3       53.9        0.0      16.8      21.88   87.2
   19.000    8,712  13.69    6.88     2.87     1.49     1.10     0.78     0.69     352.2       65.0        0.0      16.9      20.91   98.8
   20.000    8,737  13.82    7.36     3.07     1.53     1.07     0.85     0.70     440.2       60.6        0.0      16.1      20.24   87.8
   21.000    8,717  13.30    6.89     2.97     1.54     1.09     0.86     0.70     387.7       69.2        0.0      16.3      20.15   98.5
   22.000    8,737  12.86    7.24     3.24     1.61     1.13     0.86     0.71     529.7       70.3        0.0      15.3      18.60   87.2
   23.000    8,704  12.08    6.89     3.01     1.51     1.07     0.86     0.70     592.4       72.9        0.0      16.2      19.55   89.4
   24.000    8,709  11.96    6.78     2.90     1.43     0.98     0.76     0.64     622.3       69.0        0.0      17.1      18.98   85.6
------------------------------------------------------------------------------------------------------------------------------------
  Mean:              14.76    8.06     3.38     1.67     1.18     0.94     0.78     465.3       58.4        0.0      15.2      20.23   84.0
  Std. Dev:           1.88    1.23     0.54     0.25     0.17     0.14     0.11      83.9        9.8        0.0       1.9       1.26    6.0
  Var Coeff(%):      12.74   15.32    16.03    14.79    14.09    15.17    13.96      18.0       16.8        0.0      12.4       6.25    7.2
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702 AVERAGE THICKNESS                    TTI  MODULUS  ANALYSIS  SYSTEM  (SUMMARY REPORT)                          (Version 6.0)
-----------------------------------------------------------------------------------------------------------------------------------
  District:                                                                             MODULI RANGE(psi)
  County  :                                                     Thickness(in)          Minimum        Maximum    Poisson Ratio Values
  Highway/Road:                                  Pavement:          3.30                200,000        450,000        H1: v = 0.35
                                                 Base:              8.00                 20,000        110,000        H2: v = 0.35
                                                 Subbase:           0.00                                              H3: v = 0.00
                                                 Subgrade:         68.97(by DB)                 9,200                 H4: v = 0.45
-----------------------------------------------------------------------------------------------------------------------------------
            Load    Measured Deflection (mils):                                Calculated Moduli values (ksi):        Absolute Dpth to
  Station   (lbs)    R1       R2       R3       R4       R5       R6       R7     SURF(E1)  BASE(E2)  SUBB(E3)  SUBG(E4) ERR/Sens Bedrock
-----------------------------------------------------------------------------------------------------------------------------------
    1.000    7,963  20.19    14.24     7.36     3.63     2.35     1.79     1.35     403.2      76.0       0.0       6.0     15.67   84.8
    2.000    7,725  28.25    16.68     6.77     3.05     2.04     1.55     1.25     255.4      28.4       0.0       6.8     22.08   70.7
    3.000    7,845  24.03    13.04     5.63     2.71     1.85     1.47     1.17     211.4      42.2       0.0       8.2     21.99   80.1
    4.000    7,861  19.29    11.69     5.49     2.61     1.69     1.29     1.06     298.1      62.6       0.0       8.4     19.08   78.4
    5.000    7,869  16.37    10.06     4.89     2.43     1.61     1.23     0.99     343.8      84.2       0.0       9.2     18.86   86.8
    6.000    7,812  17.35    10.56     4.88     2.37     1.56     1.23     1.00     330.9      69.7       0.0       9.2     19.90   82.1
    7.000    7,790  17.82    10.67     5.00     2.32     1.48     1.22     0.94     317.8      64.7       0.0       9.3     19.33   75.1
    8.000    7,798  16.33     9.89     4.61     2.23     1.51     1.18     0.96     346.2      75.4       0.0       9.8     20.28   81.5
    9.000    7,738  16.26     9.76     4.38     2.19     1.52     1.18     0.96     336.3      73.8       0.0      10.0     21.45   88.1
   10.000    7,575  17.43    10.43     4.62     2.17     1.49     1.18     0.95     326.3      60.3       0.0       9.6     21.49   76.7
   11.000    7,641  18.34    10.37     4.54     2.24     1.54     1.17     0.96     278.1      58.3       0.0       9.7     21.71   85.1
   12.000    7,653  18.32    10.51     4.63     2.13     1.42     1.14     0.89     299.4      54.5       0.0       9.9     21.17   73.9
   13.000    7,636  18.85    12.49     6.13     3.04     1.96     1.46     1.18     344.5      72.0       0.0       7.0     17.27   86.0
   14.000    7,562  17.36    11.02     5.18     2.49     1.69     1.30     1.05     342.8      70.6       0.0       8.4     19.78   80.2
   15.000    7,497  20.65    11.77     5.05     2.35     1.59     1.23     1.01     264.1      45.5       0.0       8.8     21.65   75.2
   16.000    7,600  16.07     9.77     4.51     2.21     1.44     1.17     0.94     345.0      73.8       0.0       9.7     19.91   83.8
   17.000    7,570  16.22     9.93     4.55     2.16     1.44     1.10     0.91     346.6      70.2       0.0       9.7     20.06   78.3
   18.000    7,497  16.49     9.80     4.39     2.07     1.40     1.10     0.89     331.5      64.4       0.0      10.0     21.01   77.3
   19.000    7,546  14.69     9.08     4.23     2.05     1.40     1.10     0.90     381.6      82.7       0.0      10.2     20.38   81.9
   20.000    7,530  15.17     9.38     4.49     2.12     1.38     1.08     0.90     372.6      79.3       0.0       9.8     18.87   77.6
   21.000    7,551  15.29     9.50     4.42     2.07     1.39     1.10     0.89     380.5      75.4       0.0      10.0     20.05   76.4
   22.000    7,493  15.13     9.24     4.28     2.05     1.36     1.05     0.87     365.0      76.3       0.0      10.2     19.85   79.8
   23.000    7,538  15.20     9.23     4.24     2.06     1.35     1.05     0.85     358.6      76.3       0.0      10.3     19.85   82.3
   24.000    7,543  16.98     9.65     4.08     1.95     1.33     1.05     0.85     318.6      56.1       0.0      10.8     22.17   79.3
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  Mean:             17.84    10.78     4.93     2.36     1.57     1.23     0.99     329.1      66.4       0.0       9.2     20.16   80.3
  Std. Dev:          3.07     1.80     0.82     0.40     0.25     0.18     0.13      44.1      13.5       0.0       1.2      1.55    4.3
  Var Coeff(%):     17.24    16.71    16.67    16.86    15.92    14.68    13.18      13.4      20.4       0.0      12.9      7.68    5.4
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703 AVERAGE THICKNESS                     TTI  MODULUS  ANALYSIS  SYSTEM  (SUMMARY REPORT)                          (Version 6.0)
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  District:                                                                        MODULI RANGE(psi)
  County  :                                                Thickness(in)          Minimum        Maximum    Poisson Ratio Values
  Highway/Road:                             Pavement:          3.30               250,000        550,000        H1: v = 0.35
                                            Base:              9.80                20,000         80,000        H2: v = 0.35
                                            Subbase:           0.00                                             H3: v = 0.00
                                            Subgrade:         49.93(by DB)                14,000                H4: v = 0.45
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             Load    Measured Deflection (mils):                           Calculated Moduli values (ksi):        Absolute Dpth to
  Station   (lbs)    R1      R2      R3      R4      R5      R6      R7    SURF(E1)  BASE(E2)  SUBB(E3)  SUBG(E4) ERR/Sens Bedrock
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    1.000    9,617  20.80   14.47   10.23    3.44    1.80    1.31    0.87    325.5      38.6       0.0      12.0     16.32   55.9
    2.000    9,599  19.87   13.96    9.67    3.26    1.66    1.20    0.78    345.8      39.0       0.0      12.8     16.13   56.1
    3.000    9,552  21.74   14.85   10.39    3.31    1.64    1.14    0.76    304.9      33.6       0.0      12.6     16.50   52.1
    4.000    9,443  20.67   14.43   10.05    3.22    1.63    1.12    0.75    338.4      34.6       0.0      12.7     16.75   52.5
    5.000    9,479  18.20   12.26    8.67    3.13    1.53    1.00    0.64    315.8      46.7       0.0      13.6     13.43   63.8
    6.000    9,472  18.69   12.52    9.09    3.41    1.65    1.08    0.70    299.9      48.4       0.0      12.5     12.30   70.4
    7.000    9,544  16.61   11.57    8.48    3.24    1.63    1.09    0.71    397.8      55.4       0.0      13.0     12.44   74.5
    8.000    9,406  16.16   10.87    7.69    2.83    1.50    1.08    0.70    324.4      56.9       0.0      14.4     15.21   66.9
    9.000    9,406  15.39   10.10    7.07    2.69    1.50    1.08    0.72    288.1      65.0       0.0      15.0     16.41   73.6
   10.000    9,508  15.21   10.49    7.56    2.76    1.44    0.99    0.65    410.8      58.6       0.0      15.0     14.18   65.6
   11.000    9,424  15.16   10.52    7.59    2.85    1.46    1.01    0.66    412.3      59.4       0.0      14.5     13.39   70.7
   12.000    9,435  14.00    9.81    7.06    2.57    1.28    0.88    0.55    485.9      60.0       0.0      16.2     13.49   65.2
   13.000    9,290  20.39   13.49    9.16    3.00    1.60    1.16    0.78    254.5      38.1       0.0      13.3     17.77   53.9
   14.000    9,315  17.61   11.83    8.38    2.87    1.53    1.13    0.74    316.6      47.4       0.0      13.9     16.37   57.6
   15.000    9,279  18.82   12.41    8.36    2.73    1.51    1.09    0.70    265.1      41.8       0.0      14.5     18.61   53.8
   16.000    9,206  20.13   13.19    8.83    2.71    1.44    1.03    0.69    258.2      35.3       0.0      14.6     18.82   50.4
   17.000    9,290  17.97   12.00    8.41    3.00    1.58    1.11    0.72    286.9      48.3       0.0      13.5     15.60   62.2
   18.000    9,290  16.13   11.14    7.98    2.95    1.54    1.07    0.72    370.0      54.8       0.0      13.7     14.11   67.7
   19.000    9,242  15.84   10.97    7.89    2.93    1.50    1.04    0.67    385.9      55.0       0.0      13.8     13.64   68.5
   20.000    9,242  15.69   10.77    7.69    2.77    1.43    1.01    0.65    377.2      54.2       0.0      14.5     14.55   63.6
   21.000    9,217  14.20    9.52    6.96    2.73    1.48    1.03    0.69    349.9      71.1       0.0      14.6     13.95   81.8
   22.000    9,261  13.36    9.51    7.01    2.77    1.45    1.01    0.65    504.1      70.8       0.0      14.5     12.55   84.2
   23.000    9,188  14.52    9.91    7.23    2.74    1.44    1.02    0.70    388.3      63.8       0.0      14.6     13.75   72.7
   24.000    9,188  15.37   10.52    7.46    2.60    1.31    0.94    0.56    389.7      52.1       0.0      15.5     14.94   59.4
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  Mean:             17.19   11.71    8.29    2.94    1.52    1.07    0.70    349.8      51.2       0.0      14.0     15.05   63.0
  Std. Dev:          2.47    1.65    1.05    0.26    0.12    0.09    0.07     65.4      11.2       0.0       1.0      1.88    8.8
  Var Coeff(%):     14.39   14.10   12.65    8.79    7.56    8.24    9.75     18.7      21.8       0.0       7.4     12.49   14.0
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704 - Nominal Thicknesses                   TTI  MODULUS  ANALYSIS  SYSTEM  (SUMMARY REPORT)                       (Version 6.0)
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  District:                                                                        MODULI RANGE(psi)
  County  :                                                Thickness(in)          Minimum        Maximum    Poisson Ratio Values
  Highway/Road:                             Pavement:           3.00               200,000       600,000        H1: v = 0.35
                                            Base:               9.00                30,000        90,000        H2: v = 0.40
                                            Subbase:            0.00                                            H3: v = 0.00
                                            Subgrade:          51.03(by DB)                14,000               H4: v = 0.45
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             Load    Measured Deflection (mils):                           Calculated Moduli values (ksi):        Absolute Dpth to
  Station   (lbs)    R1      R2      R3      R4      R5      R6      R7    SURF(E1)  BASE(E2)  SUBB(E3)  SUBG(E4) ERR/Sens Bedrock
-----------------------------------------------------------------------------------------------------------------------------------
    1.000     9,617 20.80   14.47   10.23    3.44    1.80    1.31    0.87    391.1      42.9       0.0      12.3     17.38   55.9
    2.000     9,599 19.87   13.96    9.67    3.26    1.66    1.20    0.78    427.6      42.9       0.0      13.1     17.23   56.1
    3.000     9,552 21.74   14.85   10.39    3.31    1.64    1.14    0.76    357.3      38.0       0.0      12.7     17.35   52.1
    4.000     9,443 20.67   14.43   10.05    3.22    1.63    1.12    0.75    410.3      38.5       0.0      12.8     17.68   52.5
    5.000     9,479 18.20   12.26    8.67    3.13    1.53    1.00    0.64    361.1      53.0       0.0      13.9     14.81   63.8
    6.000     9,472 18.69   12.52    9.09    3.41    1.65    1.08    0.70    333.9      55.7       0.0      12.9     13.57   70.4
    7.000     9,544 16.61   11.57    8.48    3.24    1.63    1.09    0.71    431.0      65.1       0.0      13.4     13.51   74.5
    8.000     9,406 16.16   10.87    7.69    2.83    1.50    1.08    0.70    366.1      64.9       0.0      15.0     16.62   66.9
    9.000     9,406 15.39   10.10    7.07    2.69    1.50    1.08    0.72    324.8      73.8       0.0      15.8     17.90   73.6
   10.000     9,508 15.21   10.49    7.56    2.76    1.44    0.99    0.65    463.1      67.2       0.0      15.4     15.38   65.6
   11.000     9,424 15.16   10.52    7.59    2.85    1.46    1.01    0.66    454.1      69.1       0.0      14.9     14.68   70.7
   12.000     9,435 14.00    9.81    7.06    2.57    1.28    0.88    0.55    553.7      68.8       0.0      16.6     14.62   65.2
   13.000     9,290 20.39   13.49    9.16    3.00    1.60    1.16    0.78    302.0      41.8       0.0      13.6     18.84   53.9
   14.000     9,315 17.61   11.83    8.38    2.87    1.53    1.13    0.74    364.1      53.3       0.0      14.3     17.49   57.6
   15.000     9,279 18.82   12.41    8.36    2.73    1.51    1.09    0.70    317.1      45.5       0.0      14.8     19.64   53.8
   16.000     9,206 20.13   13.19    8.83    2.71    1.44    1.03    0.69    287.8      39.9       0.0      14.6     19.58   50.4
   17.000     9,290 17.97   12.00    8.41    3.00    1.58    1.11    0.72    329.0      54.4       0.0      13.9     16.97   62.2
   18.000     9,290 16.13   11.14    7.98    2.95    1.54    1.07    0.72    414.6      63.1       0.0      14.1     15.47   67.7
   19.000     9,242 15.84   10.97    7.89    2.93    1.50    1.04    0.67    430.6      63.6       0.0      14.2     14.91   68.5
   20.000     9,242 15.69   10.77    7.69    2.77    1.43    1.01    0.65    434.7      61.5       0.0      15.0     15.80   63.6
   21.000     9,217 14.20    9.52    6.96    2.73    1.48    1.03    0.69    379.4      83.1       0.0      15.2     15.40   81.8
   22.000     9,261 13.36    9.51    7.01    2.77    1.45    1.01    0.65    533.8      84.4       0.0      14.9     13.58   84.2
   23.000     9,188 14.52    9.91    7.23    2.74    1.44    1.02    0.70    422.6      74.5       0.0      15.1     15.05   72.7
   24.000     9,188 15.37   10.52    7.46    2.60    1.31    0.94    0.56    458.4      58.4       0.0      15.9     16.07   59.4
-----------------------------------------------------------------------------------------------------------------------------------
  Mean:              17.19   11.71    8.29    2.94    1.52    1.07    0.70    397.8      58.5       0.0      14.4     16.23   63.0
  Std. Dev:           2.47    1.65    1.05    0.26    0.12    0.09    0.07     68.2      13.8       0.0       1.1      1.80    8.8
  Var Coeff(%):      14.39   14.10   12.65    8.79    7.56    8.24    9.75     17.1      23.6       0.0       7.8     11.08   14.0
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705 - Nominal Thicknesses                     TTI  MODULUS  ANALYSIS  SYSTEM  (SUMMARY REPORT)                       (Version 6.0)
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  District:                                                                        MODULI RANGE(psi)
  County  :                                                Thickness(in)          Minimum        Maximum    Poisson Ratio Values
  Highway/Road:                             Pavement:          3.00               100,000      1,300,000        H1: v = 0.35
                                            Base:              9.00                10,000        120,000        H2: v = 0.40
                                            Subbase:           0.00                                             H3: v = 0.00
                                            Subgrade:         90.50(by DB)                 3,000                H4: v = 0.45
------------------------------------------------------------------------------------------------------------------------------------
             Load    Measured Deflection (mils):                           Calculated Moduli values (ksi):        Absolute Dpth to
  Station   (lbs)    R1      R2      R3      R4      R5      R6      R7     SURF(E1)  BASE(E2)  SUBB(E3)  SUBG(E4) ERR/Sens Bedrock
------------------------------------------------------------------------------------------------------------------------------------
    1.000    8,132  51.56   34.65   18.60   10.12    4.41    1.42    0.74    555.6      10.5       0.0       3.5     12.29   74.7 *
    2.000    7,722  48.26   32.69   16.37    8.04    3.41    1.40    0.86    459.7      11.3       0.0       3.8     11.26   73.1 *
    3.000    7,348  38.74   26.63   13.87    6.95    3.05    1.17    0.93    620.8      12.8       0.0       4.3     10.36   75.5 *
    6.000    7,086  69.71   47.31   25.74   13.60    5.72    1.32    0.08    163.9      10.0       0.0       2.3     29.78   71.3 *
    7.000    7,099  54.48   40.04   27.07   16.45    8.38    3.57    1.06    921.7      10.0       0.0       2.0      6.53   87.8 *
    8.000    7,364  44.42   31.19   19.70   12.51    7.20    3.39    0.84    542.5      23.4       0.0       2.5      3.07   94.1
    9.000    7,711  33.07   25.55   16.94   11.01    6.45    3.36    1.41   1300.0      30.7       0.0       2.9      2.11  103.9 *
   10.000    7,838  32.93   24.70   16.41   10.98    6.58    3.32    1.09    297.4      57.6       0.0       3.0      3.43   99.8
   11.000    7,718  37.72   26.81   16.39   10.48    5.78    2.59    0.55    862.9      23.2       0.0       3.2      3.86   91.7
   12.000    7,078  42.53   30.08   17.15    9.86    4.78    1.59    0.57    847.3      10.0       0.0       3.2      8.70   80.5 *
   16.000    7,690  47.08   30.83   19.68   11.65    6.65    4.16    2.03    186.6      31.8       0.0       2.7      3.38  109.2
   17.000    8,286  29.67   22.51   15.52   10.56    6.63    3.67    1.62    229.0      92.2       0.0       3.1      1.51  110.1
   18.000    8,333  59.13   21.51   15.10   10.27    6.49    3.71    1.63    104.0      30.1       0.0       3.5     19.20  110.1 *
   19.000    8,603  93.83   25.00   16.70   10.68    6.25    3.37    1.26    109.7      11.0       0.0       3.7     25.64  103.3 *
   20.000    6,490  55.65   26.17   17.40   11.02    6.59    2.86    0.86    100.0      20.1       0.0       2.7      9.49   90.1 *
   21.000    7,083  45.70   32.84   20.21   12.25    6.56    2.99    0.88    849.3      13.4       0.0       2.5      2.67   91.7
   22.000    7,388  85.00   29.34   19.96   13.87    8.59    4.54    1.77    100.0      11.7       0.0       2.7     24.72  103.7 *
   23.000    7,369 118.36   31.75   20.15   13.13    7.93    4.43    1.96    100.0      10.0       0.0       2.4     24.56  107.7 *
   24.000    7,459 107.11   25.41   16.97   11.64    7.76    4.83    2.18    100.0      10.0       0.0       3.0     33.14  110.2 *
   25.000    7,491  67.68   22.53   15.04   10.57    7.15    4.55    2.56    109.2      14.2       0.0       3.6     29.03  129.5 *
   26.000    7,507  29.72   19.36   14.08   10.23    6.95    4.39    2.63    363.0      84.5       0.0       2.8      5.72  141.6
   27.000    7,197  31.65   22.13   14.63   10.26    6.67    4.00    2.16    325.8      61.1       0.0       2.8      3.41  124.2
   28.000    7,281  29.40   21.88   15.02   10.38    6.62    3.85    1.92    263.3      77.0       0.0       2.8      0.71  117.3
   29.000    7,396  27.98   21.91   15.43   10.26    6.41    3.67    1.85    362.8      74.7       0.0       2.8      2.61  118.1
   30.000    7,006  26.98   22.18   16.03   10.82    6.50    3.44    1.59    103.4     120.0       0.0       2.6      5.34  106.4 *
   31.000    7,301  34.43   25.70   16.68   10.54    6.28    3.30    1.33   1070.8      27.8       0.0       2.8      0.93  104.5
   32.000    7,615  61.75   21.42   14.42    9.74    6.44    3.67    1.56    116.8      16.4       0.0       3.9     25.67  108.1 *
   33.000    7,702  82.95   20.84   14.83   10.17    6.45    3.65    1.67    112.7      11.3       0.0       3.8     31.86  112.2 *
   34.000    7,456  95.65   23.07   15.72   10.35    6.20    3.26    1.34    100.0      10.0       0.0       3.3     28.41  105.3 *
   35.000    7,409  31.51   24.81   16.93   11.23    6.63    3.34    1.16   1300.0      32.9       0.0       2.8      3.76  100.8 *
   36.000    7,245  35.46   28.36   18.65   11.90    6.72    3.23    0.93   1300.0      21.5       0.0       2.6      4.04   96.2 *
   37.000    7,456  33.83   25.80   17.51   11.80    7.35    4.10    1.83    192.4      68.6       0.0       2.5      1.51  109.7
   38.000    7,118  27.43   22.91   16.44   11.48    7.46    4.41    2.27   1300.0      54.7       0.0       2.4      2.41  120.0 *
   40.000    7,849  17.22   14.43   11.56    8.30    5.85    3.63    2.10   1300.0     120.0       0.0       3.7      7.19  137.0 *
   41.000    8,055  13.83   12.08    9.86    7.61    5.41    3.55    2.00   1300.0     120.0       0.0       4.3     14.67  133.3 *
   42.000    7,869  13.85   12.44   10.08    7.70    5.39    3.45    1.95   1300.0     120.0       0.0       4.5     15.90  133.6 *
   43.000    7,992  14.40   13.06   10.34    7.70    5.26    3.26    1.74   1300.0     120.0       0.0       4.3     11.14  126.1 *
   44.000    9,212  51.63   15.15   11.43    8.38    5.58    3.30    1.63    185.9      23.5       0.0       6.2     33.16  118.7 *
   45.000    8,437  18.17   15.75   11.86    8.51    5.56    3.20    1.61   1300.0     120.0       0.0       3.8      4.78  119.9 *
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  46.000    7,186  46.62    29.52    18.64    12.42     7.32     3.88     1.71    136.5       34.9        0.0        2.5        3.51  104.6
  47.000    7,078  34.63    23.41    15.79    10.74     6.87     3.89     1.79    232.4       54.8        0.0        2.7        3.00  111.4
  48.000    7,197  26.73    21.01    15.22    10.50     6.71     3.83     1.88    150.6      120.0        0.0        2.7        1.80  116.6 *
  49.000    7,289  27.40    21.76    15.79    10.92     6.93     3.92     1.97    452.4       78.1        0.0        2.6        3.20  116.1
  50.000    7,221  27.55    22.21    16.02    11.08     6.89     3.71     1.66    122.7      120.0        0.0        2.6        3.70  108.6 *
  51.000    7,158  29.68    24.06    17.14    11.65     7.13     3.91     1.87   1300.0       41.4        0.0        2.5        3.37  110.7 *
  52.000    7,475  28.72    22.82    16.42    11.59     7.49     4.37     2.13   1300.0       54.6        0.0        2.5        1.67  115.9 *
  53.000    7,559  23.17    19.62    14.96    10.64     7.10     4.23     2.29    546.0      120.0        0.0        2.6        3.92  126.4 *
  54.000    7,602  21.80    18.26    13.94    10.13     6.69     3.95     1.98    757.9      119.1        0.0        2.7        4.00  119.2
  55.000    7,650  21.99    18.22    13.50     9.61     6.40     3.98     2.11   1300.0       94.0        0.0        2.9        2.04  124.1 *
  56.000    7,313  18.76    15.65    11.89     8.80     6.04     3.78     2.05   1300.0      120.0        0.0        3.0        2.34  127.1 *
  57.000    7,324  18.67    15.67    11.86     8.68     5.86     3.60     1.91   1300.0      120.0        0.0        3.0        2.83  124.6 *
  58.000    7,038  18.62    15.78    11.97     8.72     5.80     3.49     1.84   1300.0      113.0        0.0        2.9        3.64  123.9 *
  59.000    7,186  20.10    16.88    12.49     8.90     5.83     3.31     1.57   1300.0       91.9        0.0        3.0        4.24  115.0 *
  60.000    7,857  18.51    15.44    11.70     8.30     5.29     3.08     1.59   1300.0      116.0        0.0        3.6        4.53  122.1 *
  61.000    7,221  46.34    33.19    19.87    11.57     6.24     2.87     0.73    821.2       12.6        0.0        2.6        1.65   92.0
  62.000    6,837  36.08    26.87    16.87    10.59     6.23     3.35     1.28    856.1       24.8        0.0        2.6        0.49  102.5
  63.000    7,070  34.67    27.37    17.45    10.78     6.31     3.39     1.25   1300.0       21.6        0.0        2.7        0.86  101.6 *
  64.000    7,086  30.39    23.41    15.59     9.95     5.77     3.00     1.24   1300.0       29.9        0.0        3.0        2.24  103.7 *
  65.000    7,380  28.15    22.84    15.61    10.10     5.83     2.96     1.26   1300.0       37.8        0.0        3.1        5.09  101.7 *
  66.000    7,165  28.88    23.18    15.93    10.26     5.87     3.02     1.19   1300.0       32.9        0.0        3.0        4.17  102.9 *
  67.000    7,424  29.70    23.43    16.09    10.71     6.59     3.70     1.76   1300.0       40.6        0.0        2.8        1.59  113.8 *
  68.000    7,480  25.21    21.43    15.58    10.96     7.18     4.33     2.44   1300.0       71.2        0.0        2.5        3.03  130.2 *
  69.000    7,329  31.21    25.36    17.65    11.83     7.47     4.32     2.25   1300.0       39.9        0.0        2.4        1.59  119.3 *
  70.000    7,666  32.57    25.97    16.64    10.85     6.79     4.04     2.11   1300.0       34.4        0.0        2.8        1.88  120.1 *
  71.000    7,928  26.89    20.95    14.10     9.64     6.24     3.76     2.03   1175.2       59.2        0.0        3.2        0.98  125.0
  72.000    8,039  20.85    17.68    12.96     9.20     6.13     3.76     1.93   1300.0      106.8        0.0        3.2        2.79  121.1 *
  73.000    7,714  23.54    19.30    11.90     6.11     4.04     3.53     1.95   1300.0       47.0        0.0        4.3       11.95   94.2 *
  74.000    7,833  20.19    16.61    12.21     8.57     5.37     3.03     1.52   1300.0       93.2        0.0        3.6        4.35  116.7 *
  75.000    7,401  23.09    15.18    10.90     7.53     4.73     2.71     1.36    294.6      100.7        0.0        4.0        3.37  119.2
  76.000    6,725  51.51    34.09    19.91    11.03     5.19     1.67     0.16    470.8       10.0        0.0        2.7       10.37   79.4 *
  77.000    6,657  48.19    33.37    19.08    10.56     5.05     1.69     0.04    551.5       10.0        0.0        2.7        9.14   80.1 *
  78.000    6,352  63.70    40.69    20.35    10.20     4.16     1.28     0.92    122.2       10.0        0.0        2.6       22.78   69.8 *
  79.000    6,892  51.87    35.07    20.14    11.17     5.07     1.70     0.97    482.5       10.0        0.0        2.7       10.68   76.9 *
  80.000    7,062  56.47    37.21    19.31     9.94     4.38     1.36     1.13    330.4       10.0        0.0        2.9       16.37   74.5 *
  81.000    6,713  49.29    35.01    20.33    11.35     5.41     1.76     0.36    563.4       10.0        0.0        2.6       10.64   79.4 *
  82.000    6,852  51.59    35.56    20.28    11.57     5.60     1.85     0.17    522.3       10.0        0.0        2.6        9.15   79.7 *
  83.000    6,924  45.80    34.05    21.03    13.16     7.04     2.72     0.30   1087.2       10.0        0.0        2.4        6.06   84.4 *
  84.000    6,435  59.56    42.56    23.46    12.87     5.81     1.64     0.59    296.3       10.0        0.0        2.2       19.30   75.2 *
  85.000    6,447  62.04    43.77    22.54    11.58     4.91     1.33     0.07    175.0       10.0        0.0        2.4       25.72   71.3 *
  86.000    6,609  50.72    35.04    19.19    10.86     5.37     2.13     0.37    495.4       10.0        0.0        2.6        4.35   83.3 *
  87.000    6,678  44.04    31.74    18.44    11.27     6.22     2.78     0.52    705.7       14.1        0.0        2.5        2.95   90.1
  88.000    6,744  49.61    37.69    23.19    13.93     7.10     2.83     0.39    832.3       10.0        0.0        2.2        6.37   84.9 *
  89.000    6,148  67.20    41.47    20.15    10.43     4.73     1.65     0.59    100.0       10.0        0.0        2.4       14.14   74.7 *
  90.000    6,598  52.71    30.70    15.63     8.70     4.25     1.69     0.56    213.7       11.4        0.0        3.2        4.69   82.4
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 Mean:             41.26    25.74    16.50    10.51     6.14     3.19     1.40    706.6       48.0        0.0        3.0        8.74  102.5
 Std. Dev:         21.31     7.88     3.45     1.67     1.04     0.95     0.66    490.0       41.1        0.0        0.7        9.01   19.8
 Var Coeff(%):     51.65    30.62    20.91    15.90    17.00    29.67    46.86     69.3       85.6        0.0       22.0      103.00   19.3
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706 - Nominal Thicknesses                 TTI  MODULUS  ANALYSIS  SYSTEM  (SUMMARY REPORT)                        (Version 6.0)
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  District:                                                                                   MODULI RANGE(psi)
  County  :                                                              Thickness(in)         Minimum        Maximum    Poisson Ratio Values
  Highway/Road:                                      Pavement:              3.00               200,000        850,000        H1: v = 0.35
                                                     Base:                  9.00                 5,000         45,000        H2: v = 0.40
                                                     Subbase:               0.00                                             H3: v = 0.00
                                                     Subgrade:            112.30(by DB)                 4,500                H4: v = 0.45
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             Load    Measured Deflection (mils):                                       Calculated Moduli values (ksi):       Absolute Dpth to
  Station   (lbs)    R1      R2      R3      R4      R5      R6      R7    SURF(E1)  BASE(E2)  SUBB(E3)  SUBG(E4) ERR/Sens Bedrock
------------------------------------------------------------------------------------------------------------------------------------
    1.000    8,739  55.50   31.19   12.41    7.26    4.67    3.30    2.69    207.6      12.5       0.0        5.1     10.57   83.2
    2.000    8,548  53.40   33.03   14.19    7.81    4.85    2.95    1.88    350.5      10.8       0.0        4.6      6.90  117.3
    3.000    8,902  53.11   32.63   15.14    9.09    5.48    3.02    1.54    306.4      14.8       0.0        4.4      4.21  108.0
    4.000    8,751  50.79   31.47   14.81    9.31    5.55    2.98    1.65    302.9      16.6       0.0        4.4      4.22  300.0
    5.000    8,672  46.07   29.43   14.39    8.69    5.28    2.99    1.54    387.7      17.9       0.0        4.6      3.71  112.9
    6.000    8,421  58.77   37.76   17.52    9.93    5.76    3.10    1.87    398.6       9.3       0.0        3.8      2.96  103.6
    7.000    8,651  52.01   32.31   15.36    9.23    5.88    3.59    2.07    271.6      17.1       0.0        4.2      6.28  128.0
    8.000    8,770  44.58   26.38   12.63    8.04    5.17    3.25    1.99    208.6      24.4       0.0        5.0      7.30  139.1
    9.000    8,704  43.03   27.32   12.23    6.29    4.63    3.39    2.44    404.4      16.5       0.0        5.4     12.46   92.7
   10.000    8,603  40.78   28.83   14.77    8.33    5.31    3.57    2.30    689.1      18.2       0.0        4.5      6.57  135.1
   11.000    8,588  46.91   31.35   16.26    9.50    5.84    3.63    2.31    471.3      17.6       0.0        4.1      4.23  134.3
   12.000    8,719  42.20   27.65   14.98    9.23    5.79    3.63    2.26    371.7      26.8       0.0        4.3      4.15  138.8
   13.000    8,783  40.26   28.27   16.09    9.61    5.91    3.74    2.34    710.0      23.5       0.0        4.2      2.96  137.7
   14.000    8,643  58.44   36.72   17.26    9.81    5.98    3.76    2.41    306.6      12.5       0.0        3.8      5.53  129.0
   15.000    8,926  38.13   26.68   14.63    9.08    5.70    3.87    2.70    615.1      28.7       0.0        4.5      5.01  150.4
   16.000    8,759  31.28   21.76   12.03    7.69    5.24    3.67    2.61    593.0      42.1       0.0        5.1      7.46  212.7
   17.000    8,683  51.22   29.65   12.33    6.27    4.37    2.95    2.02    292.1      11.7       0.0        5.4     10.73   89.2
   18.000    8,481  52.35   32.98   15.66    9.15    5.77    3.37    1.91    315.8      14.9       0.0        4.1      5.39  117.3
   19.000    8,516  48.44   31.89   16.35    9.44    5.81    3.36    1.98    451.3      15.9       0.0        4.1      3.47  116.3
   20.000    8,715  47.10   30.38   15.50    9.43    5.87    3.47    1.91    352.3      20.4       0.0        4.2      4.17  121.2
   21.000    8,433  41.92   29.90   15.89    9.10    5.77    3.59    2.01    718.4      17.6       0.0        4.1      4.93  147.6
   22.000    8,433  46.44   32.83   17.87    9.70    5.92    3.50    2.17    780.4      12.5       0.0        3.9      3.24  112.0
   23.000    8,588  41.99   28.29   15.13    8.92    5.37    3.27    1.97    558.4      20.0       0.0        4.4      2.95  126.8
   24.000    9,247  34.33   23.02   11.41    6.94    4.65    3.04    2.01    551.0      30.5       0.0        5.9      7.87  158.4
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  Mean:             46.63   30.07   14.79    8.66    5.44    3.37    2.11    442.3      18.9       0.0        4.5      5.72  124.3
  Std. Dev:          7.14    3.69    1.80    1.09    0.49    0.29    0.32    169.8       7.5       0.0        0.5      2.62   28.8
  Var Coeff(%):     15.31   12.28   12.21   12.55    8.96    8.54   15.39     38.4      39.5       0.0       12.0     45.77   23.1
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707 AVERAGE THICKNESS                     TTI  MODULUS  ANALYSIS  SYSTEM  (SUMMARY REPORT)                          (Version 6.0)
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  District:                                                                        MODULI RANGE(psi)
  County  :                                                Thickness(in)          Minimum        Maximum    Poisson Ratio Values
  Highway/Road:                             Pavement:           2.80               200,000        400,000        H1: v = 0.35
                                            Base:               8.90                25,000         80,000        H2: v = 0.35
                                            Subbase:            0.00                                             H3: v = 0.00
                                            Subgrade:          41.88(by DB)                 8,400                H4: v = 0.45
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             Load    Measured Deflection (mils):                           Calculated Moduli values (ksi):        Absolute Dpth to
  Station   (lbs)    R1      R2      R3      R4      R5      R6      R7    SURF(E1)  BASE(E2)  SUBB(E3)  SUBG(E4) ERR/Sens Bedrock
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    1.000    7,642  25.54   13.10    4.00    2.04    1.57    1.21    0.97    219.2      36.8       0.0       6.7     41.36   49.8
    1.000    8,808  29.43   15.20    4.81    2.43    1.81    1.44    1.11    213.7      39.0       0.0       6.4     39.89   51.4
    1.000    8,953  29.57   15.35    4.92    2.49    1.87    1.47    1.16    213.7      40.5       0.0       6.3     39.41   52.2
    3.000    8,959  26.19   14.22    4.57    2.18    1.65    1.28    1.02    249.2      46.4       0.0       6.8     39.50   52.4
    3.000    9,754  26.69   14.31    4.66    2.20    1.61    1.29    1.07    262.8      49.5       0.0       7.4     39.13   53.3
    3.000    7,894  21.64   11.45    3.74    1.72    1.23    1.01    0.85    260.8      48.1       0.0       7.6     39.10   53.5
    5.000    7,840  19.85   10.43    3.50    1.63    1.19    0.96    0.80    279.5      54.1       0.0       8.0     38.64   55.5
    7.000    7,740  19.82    9.54    3.04    1.58    1.16    0.93    0.76    271.2      48.2       0.0       9.1     41.61   52.1
    7.000   10,731  25.89   12.07    3.87    2.07    1.50    1.19    0.99    282.2      50.5       0.0       9.9     42.44   52.5
    9.000   10,937  24.99   13.83    4.89    2.13    1.51    1.23    1.07    316.3      64.2       0.0       8.0     37.99   60.8
   11.000   10,868  25.29   13.55    4.79    2.26    1.63    1.25    1.07    304.0      64.5       0.0       7.9     37.67   60.8
   13.000   10,751  24.14   12.39    4.31    2.13    1.57    1.17    1.01    304.0      65.2       0.0       8.7     37.84   59.0
   15.000   10,541  30.76   14.20    4.19    2.13    1.61    1.29    1.09    265.2      34.8       0.0       9.2     44.35   48.7
   17.000   10,554  25.69   13.80    4.70    2.02    1.44    1.11    1.06    292.1      56.0       0.0       8.2     39.15   56.8
   19.000   10,602  24.33   12.51    4.09    1.94    1.46    1.14    1.00    305.7      57.3       0.0       9.2     39.06   53.7
   21.000   10,484  27.24   12.81    3.59    1.74    1.34    1.10    0.91    357.0      34.0       0.0      10.8     44.90   47.5
   23.000   10,367  27.03   13.27    4.02    1.81    1.35    1.13    0.92    302.0      40.9       0.0       9.5     41.36   49.7
   25.000   10,553  22.14   11.95    4.43    2.00    1.41    1.15    0.95    337.4      74.2       0.0       8.5     36.74   68.0
   27.000   10,252  29.11   12.74    3.83    1.79    1.30    0.98    0.78    287.1      32.5       0.0      10.2     44.64   49.4
   29.000   10,854  28.46   14.03    4.54    2.22    1.63    1.26    1.03    264.6      48.1       0.0       8.6     40.22   52.9
   31.000   10,868  23.40   12.26    4.39    2.10    1.48    1.19    1.00    320.7      70.2       0.0       8.7     37.13   62.5
   33.000   10,780  22.50   12.19    4.36    2.06    1.46    1.17    0.99    345.8      73.5       0.0       8.6     37.20   62.4
   35.000   10,591  25.59   12.49    3.87    1.90    1.42    1.13    0.96    302.0      48.1       0.0       9.9     41.68   50.7
   37.000   10,536  25.33   13.07    4.23    1.96    1.43    1.17    0.94    298.5      53.1       0.0       9.0     39.18   53.0
   39.000   10,555  22.11   12.07    4.20    1.94    1.50    1.14    0.97    345.7      70.7       0.0       8.8     38.45   59.1
   41.000   10,449  28.59   12.99    3.80    1.94    1.35    1.03    0.83    289.4      35.6       0.0      10.1     45.35   48.5
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  Mean:             25.44   12.92    4.21    2.02    1.48    1.17    0.97    288.1      51.4       0.0       8.5     40.15   53.6
  Std. Dev:          2.95    1.32    0.47    0.22    0.17    0.13    0.10     38.6      12.9       0.0       1.2      2.51    4.7
  Var Coeff(%):     11.59   10.22   11.23   11.05   11.58   11.09   10.65     13.4      25.2       0.0      14.0      6.25    8.8
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708 AVERAGE THICKNESS                            TTI  MODULUS  ANALYSIS  SYSTEM  (SUMMARY REPORT)                 (Version 6.0)
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  District:                                                                        MODULI RANGE(psi)
  County  :                                                Thickness(in)          Minimum        Maximum    Poisson Ratio Values
  Highway/Road:                             Pavement:          2.80                60,000       160,000        H1: v = 0.35
                                            Base:              8.90                 5,000        30,000        H2: v = 0.35
                                            Subbase:           0.00                                            H3: v = 0.00
                                            Subgrade:         38.37(by DB)                 2,800               H4: v = 0.45
-----------------------------------------------------------------------------------------------------------------------------------
             Load    Measured Deflection (mils):                           Calculated Moduli values (ksi):        Absolute Dpth to
  Station   (lbs)    R1      R2      R3      R4      R5      R6      R7     SURF(E1)  BASE(E2)  SUBB(E3)  SUBG(E4) ERR/Sens Bedrock
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    1.000    7,045  46.08   22.06    6.85    4.29    3.02    2.10    1.68    106.7      21.3       0.0       3.1     47.05   49.8
    2.000    6,968  48.75   21.28    6.29    4.17    3.00    2.20    1.59    102.4      15.9       0.0       3.6     50.52   48.0
    3.000    7,056  41.63   19.80    6.26    3.85    2.89    2.09    1.58    117.1      24.0       0.0       3.4     46.19   50.8
    4.000    7,063  42.24   20.41    6.74    4.28    3.15    2.28    1.72    119.7      26.3       0.0       3.1     44.35   53.4
    5.000    6,708  58.62   28.40    8.47    4.58    3.50    2.56    2.00     83.8      14.0       0.0       2.5     46.95   47.7
    6.000    6,399  67.79   31.21    7.97    4.14    3.41    2.53    1.87     86.4       8.0       0.0       2.7     51.03   44.6
   13.000    6,715  53.88   28.30    9.23    4.57    3.31    2.30    1.71     94.7      18.2       0.0       2.3     41.70   51.9
   15.000    7,086  43.98   20.86    7.09    4.23    3.25    2.53    2.01    111.8      25.0       0.0       3.0     43.64   55.7
   17.000    6,957  46.91   21.65    6.61    3.92    3.15    2.36    1.82    103.3      18.5       0.0       3.4     47.52   49.1
   19.000    7,112  38.83   18.99    6.11    3.78    2.89    2.26    1.80    130.8      27.6       0.0       3.5     44.49   51.9
   21.000    6,646  56.13   30.71    9.30    3.96    3.09    2.62    1.93     97.5      14.6       0.0       2.3     43.41   48.1
   23.000    6,725  56.50   29.99    9.03    4.36    3.32    2.56    1.92     92.0      15.4       0.0       2.4     43.27   48.0
   25.000    6,843  48.80   24.18    7.67    4.34    3.41    2.73    2.15    100.1      20.0       0.0       2.7     44.01   50.6
   27.000    6,420  65.20   32.17    8.55    4.25    3.44    2.68    1.90    100.1       8.7       0.0       2.5     49.20   44.9
   29.000    6,995  41.43   21.22    7.24    4.54    3.32    2.32    1.77    149.1      29.1       0.0       2.7     40.61   56.0
   31.000    6,915  46.52   21.52    6.87    4.13    3.00    2.23    1.67    100.1      20.3       0.0       3.2     46.51   51.2
   33.000    6,991  44.34   20.79    6.33    3.76    2.79    2.15    1.61    110.1      20.0       0.0       3.5     47.38   49.1
   35.000    6,648  50.37   26.76    8.33    4.01    3.13    2.42    1.81    101.6      17.9       0.0       2.5     42.22   49.5
   37.000    6,841  49.23   24.92    7.94    4.26    3.13    2.35    1.85    101.4      19.8       0.0       2.7     43.26   50.8
   39.000    6,511  59.88   32.27    9.83    4.13    3.27    2.46    1.80     88.3      13.3       0.0       2.2     44.00   48.2
   41.000    6,682  51.69   28.50    9.81    4.31    3.07    2.02    1.44    103.3      19.6       0.0       2.2     41.87   56.0
-----------------------------------------------------------------------------------------------------------------------------------
  Mean:             50.42   25.05    7.74    4.18    3.17    2.37    1.79    104.8      18.9       0.0       2.8     45.20   50.1
  Std. Dev:          7.91    4.57    1.23    0.24    0.20    0.20    0.17     15.1       5.6       0.0       0.5      2.90    3.1
  Var Coeff(%):     15.69   18.25   15.84    5.73    6.23    8.55    9.33     14.4      29.6       0.0      16.6      6.41    6.1
-----------------------------------------------------------------------------------------------------------------------------------
```

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------------------------------------------------------------------------------------------------------------------------------------
709 - Nominal Thicknesses               TTI  MODULUS  ANALYSIS  SYSTEM  (SUMMARY REPORT)                          (Version 6.0)
------------------------------------------------------------------------------------------------------------------------------------
  District:                                                                         MODULI RANGE(psi)
  County  :                                                Thickness(in)           Minimum        Maximum    Poisson Ratio Values
  Highway/Road:                             Pavement:            3.00                40,000       140,000        H1: v = 0.35
                                            Base:                9.00                 2,000        10,000        H2: v = 0.40
                                            Subbase:             0.00                                            H3: v = 0.00
                                            Subgrade:           34.94(by DB)                 2,300               H4: v = 0.45
------------------------------------------------------------------------------------------------------------------------------------
             Load    Measured Deflection (mils):                            Calculated Moduli values (ksi):         Absolute Dpth to
  Station   (lbs)    R1      R2      R3      R4      R5      R6      R7     SURF(E1)  BASE(E2)  SUBB(E3)  SUBG(E4) ERR/Sens Bedrock
------------------------------------------------------------------------------------------------------------------------------------
     1.000    5,915  84.18   49.09    7.69    3.37    2.60    1.71    1.30     120.4       2.5       0.0       2.5     71.30   47.1
     2.000    6,358  89.50   36.59    8.76    3.29    2.01    1.54    0.93      40.8       6.0       0.0       2.2     63.06   44.0
     3.000    6,284  77.74   37.85    8.73    3.91    2.51    1.42    1.04      53.6       7.8       0.0       2.0     61.41   43.9
     4.000    6,155  82.26   44.16    8.61    4.22    2.86    1.88    1.27      58.9       6.4       0.0       1.9     62.48   44.5
     5.000    5,996  88.17   69.64    6.56    2.56    1.88    0.91    0.85     117.0       2.0       0.0       2.5     93.83   55.4 *
     7.000    6,358  89.31   39.52    7.75    4.27    2.62    1.85    1.24      94.9       2.9       0.0       2.9     64.59   44.9
     9.000    6,734  86.91   50.88    9.13    4.07    3.38    2.30    1.38      72.7       5.9       0.0       2.0     61.53   45.3
    10.000    6,642  84.85   50.48    8.86    4.07    3.39    2.27    1.38      75.8       5.9       0.0       2.0     62.18   45.6
    11.000    6,210  89.40   53.41    5.52    2.47    1.89    1.04    0.96     109.2       2.0       0.0       3.2     85.24   55.6 *
    12.000    6,450  92.39   63.79    7.05    3.76    2.69    1.31    0.98     125.7       2.0       0.0       2.7     83.62   53.1 *
    13.000    6,476  95.14   61.39    6.54    3.83    3.04    1.24    0.93     113.2       2.0       0.0       2.8     82.94   54.2 *
    17.000    6,125  87.30   35.18    6.83    3.38    3.07    2.29    1.56      75.3       3.1       0.0       3.1     59.51   45.2
    18.000    6,144  71.72   38.00    8.29    4.34    3.14    2.23    1.65      62.1       8.5       0.0       2.0     56.79   44.0
    19.000    6,125  79.30   48.41    9.92    3.53    2.95    2.04    1.17      75.8       6.4       0.0       1.8     56.53   43.7
    20.000    5,996  80.08   49.89   10.26    3.31    3.05    1.87    0.87      77.8       6.0       0.0       1.7     58.80   43.5
------------------------------------------------------------------------------------------------------------------------------------
  Mean:              85.22   48.55    8.03    3.63    2.74    1.73    1.17      84.9       4.6       0.0       2.3     68.25   46.9
  Std. Dev:           6.14   10.44    1.34    0.58    0.49    0.47    0.25      26.8       2.3       0.0       0.5     12.07    4.1
  Var Coeff(%):       7.21   21.50   16.68   15.87   18.07   26.94   21.81      31.5      50.4       0.0      20.7     17.69    8.7
------------------------------------------------------------------------------------------------------------------------------------
```

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-----------------------------------------------------------------------------------------------------------------------------------
710 - Nominal Thicknesses                    TTI  MODULUS  ANALYSIS  SYSTEM  (SUMMARY REPORT)                        (Version 6.0)
-----------------------------------------------------------------------------------------------------------------------------------
  District:                                                                        MODULI RANGE(psi)
  County  :                                                Thickness(in)          Minimum        Maximum     Poisson Ratio Values
  Highway/Road:                             Pavement:          3.00                20,000       120,000         H1: v = 0.35
                                            Base:              9.00                 1,000        20,000         H2: v = 0.40
                                            Subbase:           0.00                                             H3: v = 0.00
                                            Subgrade:         34.96(by DB)                3,000                 H4: v = 0.45
-----------------------------------------------------------------------------------------------------------------------------------
             Load    Measured Deflection (mils):                           Calculated Moduli values (ksi):          Absolute Dpth to
  Station   (lbs)    R1      R2      R3      R4      R5      R6      R7    SURF(E1)  BASE(E2)  SUBB(E3)  SUBG(E4) ERR/Sens Bedrock
-----------------------------------------------------------------------------------------------------------------------------------
    1.000    5,000  87.06   37.38    4.78    2.62    2.14    1.67    1.23     52.7       2.5       0.0       2.7     68.82   51.5
    2.000    4,225  77.14   40.13    3.98    2.85    1.93    1.48    1.19    103.8       1.0       0.0       3.5     74.18   55.9 *
    3.000    4,502  55.83   25.07    5.29    3.41    2.46    1.86    1.35     49.0       7.2       0.0       2.3     60.17   44.5
    4.000    4,649  47.19   19.41    5.26    3.38    2.44    1.94    1.30     49.4      11.1       0.0       2.5     54.44   45.6
    5.000    4,594  47.96   20.26    5.14    3.31    2.45    1.89    1.26     50.2      10.2       0.0       2.5     55.78   44.8
    7.000    4,206  60.46   22.54    4.93    3.39    2.38    1.73    1.12     34.2       5.5       0.0       2.5     60.83   44.4
    8.000    4,383  67.00    6.34    5.16    3.13    2.45    1.82    1.06     30.3       3.0       0.0      10.1     80.43  256.6 *
   10.000    4,557  50.74   24.19    6.56    3.97    2.96    2.07    1.48     53.8      11.1       0.0       1.9     52.05   45.1
   11.000    4,612  48.79   23.66    6.24    3.72    2.76    2.07    1.43     58.1      11.4       0.0       2.0     52.08   44.8
   12.000    4,494  62.57   30.35    6.16    3.70    2.89    2.10    1.48     48.6       6.4       0.0       1.9     59.81   44.3
   13.000    4,151  62.85   24.37    5.53    3.83    2.64    1.91    1.20     33.0       5.8       0.0       2.2     60.40   44.0
   16.000    4,612  69.25   31.54    4.83    3.15    2.19    1.61    1.26     79.2       2.8       0.0       2.8     66.67   48.3
   18.000    4,679  58.25   26.26    6.25    3.49    2.69    1.81    1.16     47.0       8.1       0.0       2.1     57.09   44.0
   19.000    4,457  70.10   35.03    5.25    3.10    2.04    1.51    1.04     81.1       2.6       0.0       2.6     68.53   48.1
   20.000    4,132  80.15   41.22    3.27    2.72    1.95    1.24    0.84     85.3       1.1       0.0       3.5     76.40   60.9 *
   21.000    4,778  52.10   21.34    5.37    2.98    1.89    1.37    0.89     47.5       9.2       0.0       2.6     58.67   44.7
-----------------------------------------------------------------------------------------------------------------------------------
  Mean:             62.34   26.82    5.25    3.30    2.39    1.76    1.21     56.4       6.2       0.0       3.0     62.90   47.0
  Std. Dev:         12.11    8.91    0.84    0.39    0.34    0.26    0.19     20.5       3.7       0.0       2.0      8.70   10.7
  Var Coeff(%):     19.42   33.21   16.07   11.94   14.32   14.64   15.57     36.4      60.0       0.0      65.6     13.82   22.7
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711 - Nominal Thicknesses                   TTI  MODULUS  ANALYSIS  SYSTEM  (SUMMARY REPORT)                       (Version 6.0)
-----------------------------------------------------------------------------------------------------------------------------------
  District:                                                                        MODULI RANGE(psi)
  County  :                                                Thickness(in)          Minimum        Maximum    Poisson Ratio Values
  Highway/Road:                             Pavement:          3.00                40,000       340,000        H1: v = 0.35
                                            Base:              9.00                10,000        70,000        H2: v = 0.40
                                            Subbase:           0.00                                            H3: v = 0.00
                                            Subgrade:         76.47(by DB)                11,000               H4: v = 0.45
-----------------------------------------------------------------------------------------------------------------------------------
             Load    Measured Deflection (mils):                          Calculated Moduli values (ksi):       Absolute Dpth to
  Station   (lbs)    R1      R2      R3      R4      R5      R6      R7     SURF(E1)  BASE(E2)  SUBB(E3)  SUBG(E4) ERR/Sens Bedrock
-----------------------------------------------------------------------------------------------------------------------------------
    2.000    7,825  24.89   10.79    4.08    2.59    1.44    1.81    1.48    145.3      33.1       0.0      11.0     23.29   71.7
    4.000    7,701  26.92   10.52    3.76    2.51    1.97    1.52    1.24     92.2      29.7       0.0      11.5     28.55   62.1
    6.000    7,509  26.68   10.59    3.78    2.45    1.89    1.48    1.17     96.5      28.8       0.0      11.2     27.47   61.9
    8.000    7,441  29.03   12.43    4.18    2.68    1.44    1.39    1.25    131.8      22.9       0.0      10.0     22.64   55.5
   10.000    7,441  27.93   10.46    3.77    2.45    1.85    1.44    1.16     77.9      27.3       0.0      11.3     27.90   63.2
   12.000    7,463  20.12    8.70    3.85    2.53    1.89    1.46    1.16    168.7      49.3       0.0      11.1     26.35  168.1
   14.000    7,407  19.23    8.68    4.02    2.55    1.82    1.36    1.06    195.4      53.8       0.0      10.7     23.63  285.7
   16.000    7,554  26.76   12.73    3.74    2.93    1.60    1.54    1.33    190.7      24.2       0.0      10.3     28.41   48.4
   18.000    7,373  28.25   11.50    3.89    2.25    1.69    1.39    1.12    120.5      23.0       0.0      10.9     24.24   56.1
   20.000    7,441  24.27    9.97    3.88    2.48    1.87    1.50    1.22    121.5      33.8       0.0      11.0     26.80   78.8
   22.000    7,384  19.93    9.60    4.09    2.57    1.95    1.55    1.26    220.3      48.7       0.0      10.1     23.19  123.8
   24.000    7,475  16.94    8.25    3.83    2.50    1.92    1.50    1.19    289.6      66.0       0.0      10.8     23.68  296.8
   26.000    7,282  18.85    8.36    3.80    2.58    1.99    1.57    1.28    196.4      54.8       0.0      10.7     27.08  223.4
   28.000    7,373  18.83    8.54    3.91    2.54    1.93    1.46    1.14    206.7      55.3       0.0      10.7     25.06  244.3
   30.000    7,893  33.49   11.02    4.17    2.65    1.83    1.39    1.07     50.9      24.0       0.0      11.4     27.61   71.8
   32.000    7,169  25.20   10.56    3.98    2.28    1.65    1.28    1.02    124.9      28.7       0.0      10.6     22.84   70.9
   34.000    7,147  21.53    9.79    3.51    2.33    1.73    1.37    1.09    175.8      35.3       0.0      11.1     25.79   62.5
   36.000    7,181  20.95    9.91    3.98    2.38    1.78    1.37    1.09    192.7      40.3       0.0      10.3     22.09   89.3
   38.000    7,113  16.02    8.09    3.83    2.41    1.77    1.35    1.05    314.9      67.0       0.0      10.5     21.25  300.0
   40.000    7,068  20.28    9.49    3.89    2.41    1.78    1.36    1.05    189.9      42.6       0.0      10.3     22.99   98.5
   42.000    7,011  23.61    8.84    3.71    2.41    1.73    1.30    0.99     75.2      36.2       0.0      11.3     27.87  112.5
-----------------------------------------------------------------------------------------------------------------------------------
  Mean:             23.32    9.94    3.89    2.50    1.79    1.45    1.16    160.8      39.3       0.0      10.8     25.18   88.5
  Std. Dev:          4.56    1.33    0.16    0.15    0.16    0.12    0.12     67.9      14.0       0.0       0.4      2.35   42.2
  Var Coeff(%):     19.54   13.33    4.19    5.99    8.72    8.09   10.12     42.2      35.7       0.0       4.1      9.33   47.9
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712 - Nominal Thicknesses               TTI  MODULUS  ANALYSIS  SYSTEM  (SUMMARY REPORT)                      (Version 6.0)
----------------------------------------------------------------------------------------------------------------------------------
  District:                                                                        MODULI RANGE(psi)
  County  :                                                Thickness(in)          Minimum        Maximum    Poisson Ratio Values
  Highway/Road:                             Pavement:           3.00               150,000       450,000        H1: v = 0.35
                                            Base:               9.00                20,000        60,000        H2: v = 0.40
                                            Subbase:            0.00                                            H3: v = 0.00
                                            Subgrade:          87.84(by DB)                11,000               H4: v = 0.45
-----------------------------------------------------------------------------------------------------------------------------------
             Load    Measured Deflection (mils):                           Calculated Moduli values (ksi):       Absolute Dpth to
  Station   (lbs)    R1      R2      R3      R4      R5      R6      R7    SURF(E1)  BASE(E2)  SUBB(E3)  SUBG(E4) ERR/Sens Bedrock
-----------------------------------------------------------------------------------------------------------------------------------
    1.001    9,510  27.55   13.65    5.54    3.17    2.33    1.82    1.40    235.1      37.1       0.0      10.8     18.39   93.7
    2.001    9,420  29.24   13.60    5.04    2.96    2.22    1.75    1.30    202.7      30.6       0.0      11.5     19.68   67.6
    3.001    9,589  26.41   14.76    5.70    2.84    2.08    1.69    1.30    426.4      30.7       0.0      11.0     18.73   76.5
    4.001    9,533  24.30   13.08    5.19    2.86    2.15    1.66    1.30    351.4      39.8       0.0      11.5     18.86   84.9
    5.001    9,567  23.57   12.71    5.60    3.16    2.29    1.77    1.40    328.1      49.2       0.0      10.8     17.01  140.3
    6.001    9,533  24.27   13.19    5.50    2.99    2.20    1.74    1.40    350.6      42.3       0.0      11.0     17.95  108.0
    7.001    9,567  23.13   13.02    6.12    3.17    2.26    1.75    1.40    382.7      50.7       0.0      10.4     15.27   97.4
    8.001    9,352  29.57   14.84    5.72    3.19    2.41    1.91    1.50    238.6      31.0       0.0      10.2     19.41   76.0
    9.001    9,408  28.65   14.40    5.74    3.07    2.24    1.78    1.40    249.0      32.4       0.0      10.5     18.14   86.3
   10.001    9,533  24.23   13.43    5.63    3.00    2.34    1.64    1.40    374.7      42.2       0.0      10.8     18.04  107.2
   11.001    9,465  23.30   11.89    4.85    2.71    2.06    1.65    1.30    300.3      43.8       0.0      12.3     19.11   96.3
   12.001    9,420  22.15   12.21    5.41    2.98    2.20    1.77    1.40    366.6      51.5       0.0      11.1     17.52  123.8
   13.001    9,408  24.47   12.95    5.37    3.00    2.14    1.78    1.60    311.0      42.0       0.0      11.1     17.90  104.7
   14.001    9,408  24.07   13.74    5.90    3.03    2.24    1.69    1.40    419.9      41.1       0.0      10.5     16.99   94.6
   15.001    9,352  26.65   13.30    5.41    3.23    2.43    1.88    1.40    237.1      39.4       0.0      10.6     19.04   94.7
   16.001    9,397  24.43   12.73    5.39    3.00    2.24    1.68    1.30    294.3      43.4       0.0      11.1     17.81  118.7
   17.001    9,476  21.05   11.51    5.09    2.92    2.16    1.67    1.30    369.8      56.4       0.0      11.7     17.50  155.6
------------------------------------------------------------------------------------------------------------------------------------
  Mean:             25.12   13.24    5.48    3.02    2.23    1.74    1.38    319.9      41.4       0.0      11.0     18.08   99.8
  Std. Dev:          2.48    0.91    0.32    0.14    0.10    0.08    0.08     68.7       7.6       0.0       0.5      1.07   20.5
  Var Coeff(%):      9.87    6.91    5.87    4.62    4.63    4.49    5.85     21.5      18.4       0.0       4.7      5.93   20.6
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# APPENDIX B

## DICTIONARY FOR THE DATA INCLUDED IN THE MICROSOFT ACCESS DATABASE

The data included in the MS Access database is stored in tables. For each table, the meaning of data on each field, along with the measuring units, where applicable, is given below.

TABLE: APT_Loading

| | |
|---|---|
| Cell | The name of the PSPS experimental cell, from 701 to 712 |
| Window | Test window within the experimental cell, from 1 to 6. Not all experimental cells have all 6 test windows |
| Load_kN | Wheel load used (kN) |
| Start date | The date the APT loading on that cell & test window started |
| End date | The date the APT loading on that cell & test window ended |
| Remarks | Remarks regarding the APT loading used |

TABLE: Backcalculated_Moduli

| | |
|---|---|
| Cell | The name of the PSPS experimental cell, from 701 to 712 |
| Point | The point where the FWD measurements were performed. See Figures 4.4 and 4.5 |
| Load | FWD load, in lbs |
| D0 | Deflection measured by the central geophone (geophone 1), in mils |
| D2 | Deflection measured by geophone 2, in mils |
| D3 | Deflection measured by geophone 3, in mils |
| D4 | Deflection measured by geophone 4, in mils |
| D5 | Deflection measured by geophone 5, in mils |
| D6 | Deflection measured by geophone 6, in mils |
| D7 | Deflection measured by geophone 7, in mils |
| E-AC | Backcalculated Modulus for the Asphalt Concrete surface layer, in ksi |
| E-Base | Backcalculated Modulus for the aggregate base layer, in ksi |
| E-Subgrade | Backcalculated Modulus for the subgrade soil layer, in ksi |
| Err/Sensor | Total error per sensor, in percentage<br>=100*SUM[(1 – Dcalculated / Dmeasured)^2] |
| Depth-Bedrock | Estimated depth to bedrock, in inches |

TABLE: Construction_Average_Layer_Thickness

| | |
|---|---|
| Cell | The name of the PSPS experimental cell, from 701 to 712 |
| Window | Test window within the experimental cell, from 1 to 6. Not all experimental cells have all 6 test windows |
| Asphalt | Average thickness of the asphalt concrete surface layer within each test window, in mm |
| Base | Average thickness of the granular base layer within each test window, in mm |
| Soil_Layer1_Thickness | Average thickness of the top layer of subgrade soil within each test window, in mm |
| Soil_Layer2_Thickness | Average thickness of the second layer of subgrade soil within each test window, in mm |
| Soil_Layer3_Thickness | Average thickness of the third layer of subgrade soil within each test window, in mm |
| Soil_Layer4_Thickness | Average thickness of the fourth layer of subgrade soil within each test window, in mm |

TABLE: Construction_Average_Density_MC

| | |
|---|---|
| Cell | The name of the PSPS experimental cell, from 701 to 712 |
| Window | Test window within the experimental cell, from 1 to 6. Not all experimental cells have all 6 test windows |
| Asphalt_Density | Average bulk density of the asphalt concrete surface layer within each test window, in kg/m$^3$ |
| Base_DD | Average dry density for the granular base layer, in kg/m$^3$. |
| Base_MC | Average moisture content for the granular base layer, in percents. |
| Soil_Layer1_Depth | Depth from the pavement surface to the top of the subgrade soil lift where the measurements were performed with the nuclear gage during construction, in mm, for the top lift of subgrade soil. |
| Soil_Layer1-DD | Average dry density for the top lift of subgrade soil within each test window, in kg/m$^3$. |
| Soil_Layer1-MC | Average moisture content for the top lift of subgrade soil within each test window, in percents. |
| Soil_Layer2_Depth | Depth from the pavement surface to the top of the subgrade soil lift where the measurements were performed with the nuclear gage during construction, in mm, for the second lift of subgrade soil. |
| Soil_Layer2-DD | Average dry density for the second lift of subgrade soil within each test window, in kg/m$^3$. |
| Soil_Layer2-MC | Average moisture content for the second lift of subgrade soil within each test window, in percents. |
| Soil_Layer3_Depth | Depth from the pavement surface to the top of the subgrade soil lift where the measurements were performed with the nuclear gage during construction, in mm, for the third lift of subgrade soil. |
| Soil_Layer3-DD | Average dry density for the third lift of subgrade soil within each test window, in kg/m$^3$. |
| Soil_Layer3-MC | Average moisture content for the third lift of subgrade soil within each test window, in percents. |
| Soil_Layer4_Depth | Depth from the pavement surface to the top of the subgrade soil lift where the measurements were performed with the nuclear gage during construction, in mm, for the fourth lift of subgrade soil. |
| Soil_Layer4-DD | Average dry density for the fourth lift of subgrade soil within each test window, in kg/m$^3$. |
| Soil_Layer4-MC | Average moisture content for the fourth lift of subgrade soil within each test window, in percents. |

TABLE: Construction_CBR_Clegg

| | |
|---|---|
| Cell | The name of the PSPS experimental cell, from 701 to 712 |
| Point | The point where the Clegg hammer tests were performed during construction. See Figure 4.7 |
| X | The X coordinate (in meters) for the point where the Clegg hammer tests was performed, measured from the left bottom corner of the test pit. See Figure 4.7 |
| Y | The Y coordinate (in meters) for the point where the Clegg hammer tests was performed, measured from the left bottom corner of the test pit. See Figure 4.7 |
| SoilLayer1_Depth | Depth from the pavement surface to the top of the subgrade soil layer where the Clegg hammer tests were performed during construction, in mm, for the top lift of subgrade soil. |
| SoilLayer1_Clegg_CBR | Estimated CBR for the top lift of subgrade soil |
| SoilLayer2_Depth | Depth from the pavement surface to the top of the subgrade soil layer where the Clegg hammer tests were performed during construction, in mm, for the second lift of subgrade soil. |
| SoilLayer2_Clegg_CBR | Estimated CBR for the second lift of subgrade soil |
| SoilLayer3_Depth | Depth from the pavement surface to the top of the subgrade soil layer where the Clegg hammer tests were performed during construction, in mm, for the third lift of subgrade soil. |
| SoilLayer3_Clegg_CBR | Estimated CBR for the third lift of subgrade soil |
| SoilLayer4_Depth | Depth from the pavement surface to the fourth of the subgrade soil layer where the Clegg hammer tests were performed during construction, in mm, for the top lift of subgrade soil. |
| SoilLayer4_Clegg_CBR | Estimated CBR for the fourth lift of subgrade soil |

TABLE: Construction_Density_MC

| | |
|---|---|
| Cell | The name of the PSPS experimental cell, from 701 to 712 |
| Point | The point where the density measurements were performed during construction. See Figures 4.2 |
| X | The X coordinate (in meters) for the point where the layer density was recorded, measured from the left bottom corner of the test pit. See Figures 4.2 |
| Y | The X coordinate (in meters) for the point where the layer density was recorded, measured from the left bottom corner of the test pit. See Figures 4.2 |
| ASPHALT | Bulk density for the asphalt concrete layer, in kg/m$^3$. |
| BASE_DD | Dry density for the granular base layer, in kg/m$^3$. |
| BASE_MC | Moisture content for the granular base layer, in percents. |
| Soil_Layer1_Depth | Depth from the pavement surface to the top of the subgrade soil layer where the density and moisture content measurements were performed with the nuclear gage during construction, in mm, for the top lift of subgrade soil. |
| Soil_Layer1_DD | Dry density for the top lift of subgrade soil, in kg/m$^3$. |
| Soil_Layer1_MC | Moisture content for the top lift of subgrade soil, in percents. |
| Soil_Layer2_Depth | Depth from the pavement surface to the top of the subgrade soil layer where the density and moisture content measurements were performed with the nuclear gage during construction, in mm, for the top lift of subgrade soil. |
| Soil_Layer2_DD | Dry density for the second lift of subgrade soil, in kg/m$^3$. |
| Soil_Layer2_MC | Moisture content for the second lift of subgrade soil, in percents. |
| Soil_Layer3_Depth | Depth from the pavement surface to the top of the subgrade soil layer where the density and moisture content measurements were performed with the nuclear gage during construction, in mm, for the third lift of subgrade soil. |
| Soil_Layer3_DD | Dry density for the third lift of subgrade soil, in kg/m$^3$. |
| Soil_Layer3_MC | Moisture content for the third lift of subgrade soil, in percents. |
| Soil_Layer4_Depth | Depth from the pavement surface to the top of the subgrade soil layer where the density and moisture content measurements were performed with the nuclear gage during construction, in mm, for the fourth lift of subgrade soil. |
| Soil_Layer4_DD | Dry density for the fourth lift of subgrade soil, in kg/m$^3$. |
| Soil_Layer4_MC | Moisture content for the fourth lift of subgrade soil, in percents. |

TABLE: Construction_Layer_Thickness

| | |
|---|---|
| Cell | The name of the PSPS experimental cell, from 701 to 712 |
| Point | The point where the layer thickness was measured during construction. See Figure 4.3 |
| X | The X coordinate (in meters) for the point where the layer thickness was recorded, measured from the left bottom corner of the test pit. See Figure 4.3 |
| Y | The Y coordinate (in meters) for the point where the layer thickness was recorded, measured from the left bottom corner of the test pit. See Figure 4.3 |
| Asphalt | Thickness of the asphalt concrete surface layer, in mm |
| Base | Thickness of the granular base layer, in mm |
| Soil_Layer1_Thickness | Thickness of the top layer of subgrade soil, in mm |
| Soil_Layer2_Thickness | Thickness of the second layer of subgrade soil, in mm |
| Soil_Layer3_Thickness | Thickness of the third layer of subgrade soil, in mm |
| Soil_Layer4_Thickness | Thickness of the fourth layer of subgrade soil, in mm |

TABLE: Experiment_Factorial

| | |
|---|---|
| Cell | The name of the PSPS experimental cell, from 701 to 712 |
| Soil | The Soil (AASHTO Soil class) used in the experimental cell |
| Target_MC | Moisture Content (%) |
| Moisture_Description | Description of the target moisture content for the experimental cell in relation to the optimum moisture content of the soil used |

TABLE: FWD_Deflections

| | |
|---|---|
| Cell | The name of the PSPS experimental cell, from 701 to 712 |
| Point | The point where the FWD measurements were performed. See Figures 4.4 and 4.5 |
| X | The X coordinate (in meters) for the point where the FWD measurements were performed, measured from the left bottom corner of the test pit. See Figures 4.4 and 4.5 |
| Y | The Y coordinate (in meters) for the point where the FWD measurements were performed, measured from the left bottom corner of the test pit. See Figures 4.4 and 4.5 |
| LoadLevel | FWD load level, from the lightest load (1) to the heaviest load (4) |
| Drop_Number | The number of replicate load drop at the same load level |
| Air_Temp | Temperature of the air at the time the FWD tests were performed, in °F |
| Pav_Surf_Temp | Temperature recorded at the pavement surface at the time the FWD tests were performed, in °F |
| Radius_in | Radius of the FWD load plate, in inches. |
| Location_Geo1 | Distance between geophone 1 and the center of the load plate, in inches. It is always 0.0 for this geophone, because it is mounted at the center of the load plate |
| Location_Geo2 | Distance between geophone 2 and the center of the load plate, in inches. |
| Location_Geo3 | Distance between geophone 3 and the center of the load plate, in inches. |
| Location_Geo4 | Distance between geophone 4 and the center of the load plate, in inches. |
| Location_Geo5 | Distance between geophone 5 and the center of the load plate, in inches. |
| Location_Geo6 | Distance between geophone 6 and the center of the load plate, in inches. |
| Location_Geo7 | Distance between geophone 7 and the center of the load plate, in inches. |
| Load-lbs | FWD load, in lbs |
| Deflect-Geo1 | Deflection measured by the central geophone (geophone 1), in mils |
| Deflect-Geo2 | Deflection measured by geophone 2, in mils |
| Deflect-Geo3 | Deflection measured by geophone 3, in mils |
| Deflect-Geo4 | Deflection measured by geophone 4, in mils |
| Deflect-Geo5 | Deflection measured by geophone 5, in mils |
| Deflect-Geo6 | Deflection measured by geophone 6, in mils |
| Deflect-Geo7 | Deflection measured by geophone 7, in mils |
| Remarks | Remarks regarding the FWD deflection measurements for each specific cell, location and load level. |

TABLE: HMA_Design

| | |
|---|---|
| Cell | Experimental cell the HMA design was used |
| Paving Date | Paving date |
| Mix Type | Mix class or type |
| Info_Source | Source that provided the mix design data |
| 25_4 | Percent passing the 25.4mm (1 inch) sieve |
| 19 | Percent passing the 19.1mm (3/4 inch) sieve |
| 12_7 | Percent passing the 19.1mm (3/4 inch) sieve |
| 9_5 | Percent passing the 9.52mm (3/8 inch) sieve |
| 4_75 | Percent passing the 4.75mm (#4) sieve |
| 2_36 | Percent passing the 2.0mm sieve |
| 2 | Percent passing the 2.0mm sieve |
| 1_18 | Percent passing the 1.18mm (#16) sieve |
| 0_84 | Percent passing the 0.84mm sieve |
| 0_6 | Percent passing the 0.6mm sieve |
| 0_425 | Percent passing the 0.425 mm sieve |
| 0_3 | Percent passing the 0.3mm (#50) sieve |
| 0_18 | Percent passing the 0.18mm sieve |
| 0_15 | Percent passing the 0.15mm (#100) sieve |
| 0_075 | Percent passing the 0.75mm (#200) sieve |
| AC Content | Gravimetric binder content (%) |
| PG Grade | Superpave PG grade |

TABLE: Lab_CBR

| | |
|---|---|
| Soil | Soil (AASHTO Soil class) |
| MC | Moisture Content (%) |
| CBR | California Bearing Ratio – CBR (%) |

TABLE: Lab_Proctor

| | |
|---|---|
| Soil | Soil (AASHTO Soil class) |
| Cell | Cell |
| MC | Moisture Content (%) |
| DD | Dry Density (kg/m$^3$) |
| Procedure | Proctor Procedure used (Standard or Modified) |
| Date | Date the Proctor test was performed |
| Maximum | Yes for Maximum Dry Density / No for raw moisture vs density data |
| Source | Source that provided the Proctor test data |

TABLE: Lab_Resilient_Modulus

| | |
|---|---|
| Soil | Soil (AASHTO Soil class) |
| MC | Moisture Content (%) |
| Relative_DD | Relative Dry Density (%) |
| Sample | Replicate sample code (A, B or C) |
| Sequence | Loading sequence, 1 to 15, see Table 8.3 |
| Confining_pressure | Confining Pressure, in kPa |
| Maximum_axial_stress | Maximum axial stress, in kPa |
| Cyclic_stress | Cyclic stress (difference between the maximum axial stress and the contact stress), in kPa |
| MR_Average | Average value of the resilient modulus measured for the 96th to the 100th cycle of each loading sequence |
| MR_STD | Standard Deviation of the resilient modulus values measured for the 96th to the 100th cycle of each loading sequence |
| Comments | “Bad data” indicates erroneous values |

TABLE: Longitudinal_Permanent_Deformation

| | |
|---|---|
| Cell | The name of the PSPS experimental cell, from 701 to 712 |
| Window | Test window within the experimental cell, from 1 to 6. Not all experimental cells have all 6 test windows |
| Layer | Layer for which the longitudinal permanent deformation is recorded |
| Depth_original | The depth given in the project reports |
| Depth_Gage_Top | Depth from the pavement surface where the upper gage used to determine the longitudinal permanent deformation was installed, in mm. |
| Depth_Gage_Bottom | Depth from the pavement surface where the lower gage used to determine the longitudinal permanent deformation was installed, in mm. |
| Passes | Number of passes of the HVS machine when the response measurements were recorded |
| Longitudinal_Perm-Deformation | Longitudinal permanent deformation, in mm. |
| Removal-Code | 1 – inconsistent value; 2 – value too big; 3 – value too small; 4 – value with wrong sign; a – good value; |

TABLE: Longitudinal_Permanent_Strain

| | |
|---|---|
| Cell | The name of the PSPS experimental cell, from 701 to 712 |
| Window | Test window within the experimental cell, from 1 to 6. Not all experimental cells have all 6 test windows |
| Layer | Layer for which the longitudinal permanent strain was recorded |
| Depth | Depth from the pavement surface for which the strain is estimated, in mm |
| Passes | Number of passes of the HVS machine when the response measurements were recorded |
| Longitudinal_Permanent_Strain | Longitudinal permanent strain, in microstrain. |
| Removal_Code | 1 – inconsistent value; 2 – value too big; 3 – value too small; 4 – value with wrong sign; a – good value; |

TABLE: Longitudinal_Resilient_Strain

| | |
|---|---|
| Cell | The name of the PSPS experimental cell, from 701 to 712 |
| Window | Test window within the experimental cell, from 1 to 6. Not all experimental cells have all 6 test windows |
| Layer | Layer for which the longitudinal resilient strain is recorded |
| Depth | Depth from the pavement surface for which the strain is estimated, in mm |
| Passes | Number of passes of the HVS machine when the response measurements were recorded |
| Longitudinal_Resilient_Strain | Longitudinal resilient strain, in microstrain. |
| Removal_Code | 1 – inconsistent value; 2 – value too big; 3 – value too small; 4 – value with wrong sign; a – good value; |

TABLE: Longitudinal_Stress

| | |
|---|---|
| Cell | The name of the PSPS experimental cell, from 701 to 712 |
| Window | Test window within the experimental cell, from 1 to 6. Not all experimental cells have all 6 test windows |
| Depth | Depth from the pavement surface where the cell was installed, in mm |
| Passes | Number of passes of the HVS machine when the response measurements were recorded |
| Longitudinal_Stress | Longitudinal dynamic stress, in kPa |
| Removal_Code | 1 – inconsistent value; 2 – value too big; 3 – value too small; 4 – value with wrong sign; a – good value; |

TABLE: Post-Mortem_CBR

| | |
|---|---|
| Cell | The name of the PSPS experimental cell, from 701 to 712 |
| Window | Test window within the experimental cell, from 1 to 6. Not all experimental cells have all 6 test windows |
| Depth | Depth of the cone penetration form the pavement surface, in mm |
| Post-Mortem-CBR | CBR of subgrade soil estimated from the DCP measurements done in the trenches cut during post-mortem evaluation, in percents |

TABLE: Soil_Description

| | |
|---|---|
| Soil | Soil (AASHTO Soil class) |
| OMC | Optimum Moisture Content (%) |
| MDD | Maximum Dry Density (kg/m$^3$) |
| LL | Liquid Limit (%) |
| PI | Plasticity Index |
| Pass#10 | Percent Passing #10 (2.0mm) sieve |
| Pass#200 | Percent Passing #200 (0.075mm) sieve |
| Pass0.002mm | Percent smaller than 2.0 microns |
| Specific_Gravity | Specific Gravity = density in g/cm$^3$ |

TABLE: Soil_Gradation

| Soil | Soil (AASHTO Soil class) |
|---|---|
| 38_1 | Percent passing the 38.1mm (1 ½ inch) sieve |
| 25_4 | Percent passing the 25.4mm (1 inch) sieve |
| 19_1 | Percent passing the 19.1mm (3/4 inch) sieve |
| 9_52 | Percent passing the 9.52mm (3/8 inch) sieve |
| 4_75 | Percent passing the 4.75mm (#4) sieve |
| 2 | Percent passing the 2.0mm sieve |
| 0_84 | Percent passing the 0.84mm sieve |
| 0_42 | Percent passing the 0.42mm sieve |
| 0_25 | Percent passing the 0.25mm (#60) sieve |
| 0_149 | Percent passing the 0.149mm (#100) sieve |
| 0_074 | Percent passing the 0.74mm (#200) sieve |
| 0_0289 | Percent smaller than 28.9 microns |
| 0_0257 | Percent smaller than 25.7 microns |
| 0_0214 | Percent smaller than 21.4 microns |
| 0_0186 | Percent smaller than 18.6 microns |
| 0_0163 | Percent smaller than 16.3 microns |
| 0_0151 | Percent smaller than 15.1microns |
| 0_0111 | Percent smaller than 11.1 microns |
| 0_0097 | Percent smaller than 9.7 microns |
| 0_0088 | Percent smaller than 8.8 microns |
| 0_008 | Percent smaller than 8.0 microns |
| 0_007 | Percent smaller than 7.0 microns |
| 0_0063 | Percent smaller than 6.3 microns |
| 0_0059 | Percent smaller than 5.9 microns |
| 0_0051 | Percent smaller than 5.1 microns |
| 0_0043 | Percent smaller than 4.3 microns |
| 0_003 | Percent smaller than 3.0 microns |
| 0_0027 | Percent smaller than 2.7 microns |
| 0_0023 | Percent smaller than 2.3 microns |
| 0_0013 | Percent smaller than 1.3 microns |
| 0_0012 | Percent smaller than 1.2 microns |
| 0_0011 | Percent smaller than 1.1 microns |

TABLE: Surface_Permanent_Deformation

| | |
|---|---|
| Cell | The name of the PSPS experimental cell, from 701 to 712 |
| Window | Test window within the experimental cell, from 1 to 6. Not all experimental cells have all 6 test windows |
| Passes | Number of passes of the HVS machine when the profile was recorded |
| Profile 1 ….Profile20 | The maximum permanent deformation (downward movement of the point at the pavement surface) measured in each of the twenty transverse profiles recorded in one session. |
| Average | Average of the twenty maximum permanent deformations recorded in one session |

TABLE: Transverse_Permanent_Deformation

| | |
|---|---|
| Cell | The name of the PSPS experimental cell, from 701 to 712 |
| Window | Test window within the experimental cell, from 1 to 6. Not all experimental cells have all 6 test windows |
| Layer | Layer for which the transverse permanent deformation is recorded |
| Depth_Reported | The depth given in the project reports |
| Depth_Gage_Top | Depth from the pavement surface where the upper gage used to determine the transverse permanent deformation was installed, in mm. |
| Depth_Gage_Bottom | Depth from the pavement surface where the lower gage used to determine the transverse permanent deformation was installed, in mm. |
| Passes | Number of passes of the HVS machine when the response measurements were recorded |
| Transverse_Perm-Deformation | Transverse permanent deformation, in mm. |
| Removal-Code | 1 – inconsistent value; 2 – value too big; 3 – value too small; 4 – value with wrong sign; a – good value; |

TABLE: Transverse_Permanent_Strain

| | |
|---|---|
| Cell | The name of the PSPS experimental cell, from 701 to 712 |
| Window | Test window within the experimental cell, from 1 to 6. Not all experimental cells have all 6 test windows |
| Layer | Layer for which the transverse permanent strain was recorded |
| Depth | Depth from the pavement surface for which the strain is estimated, in mm |
| Passes | Number of passes of the HVS machine when the response measurements were recorded |
| Transverse_Permanent_Strain | Transverse permanent strain, in microstrain. |
| Removal_Code | 1 – inconsistent value; 2 – value too big; 3 – value too small; 4 – value with wrong sign; a – good value; |

TABLE: Transverse_Resilient_Strain

| | |
|---|---|
| Cell | The name of the PSPS experimental cell, from 701 to 712 |
| Window | Test window within the experimental cell, from 1 to 6. Not all experimental cells have all 6 test windows |
| Layer | Layer for which the transverse resilient strain is recorded |
| Depth | Depth from the pavement surface for which the strain is estimated, in mm |
| Passes | Number of passes of the HVS machine when the response measurements were recorded |
| Transverse_Resilient_Strain | Transverse resilient strain, in microstrain. |
| Removal_Code | 1 – inconsistent value; 2 – value too big; 3 – value too small; 4 – value with wrong sign; a – good value; |

TABLE: Transverse_Stress

| | |
|---|---|
| Cell | The name of the PSPS experimental cell, from 701 to 712 |
| Window | Test window within the experimental cell, from 1 to 6. Not all experimental cells have all 6 test windows |
| Depth | Depth from the pavement surface was the pressure cell was installed, in mm |
| Passes | Number of passes of the HVS machine when the response measurements were performed |
| Transverse_Stress | Transverse dynamic stress, in kPa. |
| Removal_Code | 1 – inconsistent value; 2 – value too big; 3 – value too small; 4 – value with wrong sign; a – good value; |

TABLE: Vertical _Permanent_Deformation

| | |
|---|---|
| Cell | The name of the PSPS experimental cell, from 701 to 712 |
| Window | Test window within the experimental cell, from 1 to 6. Not all experimental cells have all 6 test windows |
| Depth_original | The depth given in the project reports |
| Depth_Gage_Top | Depth from the pavement surface where the upper gage used to determine the transverse permanent deformation was installed, in mm |
| Depth_Gage_Bottom | Depth from the pavement surface where the lower gage used to determine the transverse permanent deformation was installed, in mm. |
| Passes | Number of passes of the HVS machine when the response measurements were recorded |
| Ver_Perm-Deformation | Transverse permanent deformation, in mm. |
| Removal_Code | 1 – inconsistent value; 2 – value too big; 3 – value too small; 4 – value with wrong sign; a – good value; |

TABLE: Vertical_Permanent_Strain

| | |
|---|---|
| Cell | The name of the PSPS experimental cell, from 701 to 712 |
| Window | Test window within the experimental cell, from 1 to 6. Not all experimental cells have all 6 test windows |
| Layer | Layer for which the vertical permanent strain was recorded |
| Depth | Depth from the pavement surface for which the strain is estimated, in mm |
| Passes | Number of passes of the HVS machine when the response measurements were recorded |
| Vertical_Permanent_Strain | Vertical permanent strain, in microstrain. |
| Removal_Code | 1 – inconsistent value; 2 – value too big;<br>3 – value too small; 4 – value with wrong sign<br>a – good value; |

TABLE: Vertical_Resilient_Strain

| | |
|---|---|
| Cell | The name of the PSPS experimental cell, from 701 to 712 |
| Window | Test window within the experimental cell, from 1 to 6. Not all experimental cells have all 6 test windows |
| Layer | Layer for which the transverse resilient strain is recorded |
| Depth | Depth from the pavement surface for which the strain is estimated, in mm |
| Passes | Number of passes of the HVS machine when the response measurements were recorded |
| Vertical_Resilient_Strain | Transverse resilient strain, in microstrain. |
| Remove_Code | 1 – inconsistent value; 2 – value too big;<br>3 – value too small; 4 – value with wrong sign<br>a – good value; |

TABLE: Vertical_Stress

| | |
|---|---|
| Cell | The name of the PSPS experimental cell, from 701 to 712 |
| Window | Test window within the experimental cell, from 1 to 6. Not all experimental cells have all 6 test windows |
| Depth | Depth from the pavement surface at which the pressure cell was installed and the stress was measured, in mm |
| Passes | Number of passes of the HVS machine when the response measurements were performed |
| Vertical_Stress | Vertical dynamic stress, in kPa. |
| Remove_Code | 1 – inconsistent value; 2 – value too big;<br>3 – value too small; 4 – value with wrong sign; a – good value; |

# APPENDIX C

# LABORATORY RESILIENT MODULUS TEST RESULTS

**TABLE C1:** Laboratory Resilient Modulus Test Results for the A-4 Soil at 10% Moisture Content

| Loading Sequence | **Relative Density (%)** | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 94 | | | | 97 | | | | 100 | | | |
| | SAMPLE | | | Average | SAMPLE | | | Average | SAMPLE | | | Average |
| | A | B | C | | A | B | C | | A | B | C | |
| 1 | 60.63 | 55.40 | 64.60 | *60.21* | 86.45 | 59.32 | 86.25 | *77.34* | 72.48 | 65.40 | 102.45 | *80.11* |
| 2 | 53.85 | 53.20 | 61.97 | *56.34* | 70.45 | 58.78 | 67.53 | *65.59* | 57.87 | 56.48 | 83.13 | *65.83* |
| 3 | 50.51 | 51.64 | 58.37 | *53.51* | 72.43 | 59.73 | 66.34 | *66.17* | 63.78 | 56.71 | 84.94 | *68.47* |
| 4 | 37.39 | 52.64 | 61.45 | *50.49* | 72.00 | 59.78 | 68.66 | *66.82* | 66.66 | 61.63 | 81.45 | *69.91* |
| 5 | | 56.00 | 62.26 | *59.13* | 75.08 | 62.11 | 72.89 | *70.03* | 72.98 | 61.18 | 87.09 | *73.75* |
| 6 | | 60.09 | 69.67 | *64.88* | 88.38 | 62.71 | 96.18 | *82.42* | 71.89 | 69.04 | 108.68 | *83.20* |
| 7 | | 53.05 | 62.55 | *57.80* | 73.75 | 60.47 | 74.99 | *69.74* | 62.36 | 58.92 | 83.42 | *68.23* |
| 8 | | 53.13 | 61.08 | *57.11* | 70.05 | 57.39 | 71.77 | *66.40* | 65.73 | 59.62 | 81.17 | *68.84* |
| 9 | | 53.05 | 62.90 | *57.98* | 71.94 | 59.67 | 71.98 | *67.86* | 67.75 | 64.71 | 80.56 | *71.01* |
| 10 | | 56.43 | 53.67 | *55.05* | 76.41 | 62.59 | 73.40 | *70.80* | 74.17 | 68.46 | 86.79 | *76.47* |
| 11 | | 59.83 | 72.02 | *65.92* | 86.46 | 63.05 | 89.77 | *79.76* | 71.21 | 73.64 | 96.64 | *80.49* |
| 12 | | 55.87 | 59.76 | *57.82* | 74.06 | 59.20 | 81.15 | *71.47* | 65.40 | 61.01 | 86.54 | *70.98* |
| 13 | | 54.30 | 56.27 | *55.28* | 72.23 | 57.75 | 72.05 | *67.35* | 64.26 | 62.57 | 80.22 | *69.02* |
| 14 | | 54.74 | | *54.74* | 73.13 | 59.83 | 71.39 | *68.12* | 69.19 | 63.59 | 82.61 | *71.80* |
| 15 | | 56.09 | | *56.09* | 76.13 | 62.96 | 74.53 | *71.21* | 74.18 | 68.99 | 88.64 | *77.27* |

**TABLE C2:** Laboratory Resilient Modulus Test Results for the A-4 Soil at 13% Moisture Content

| Loading Sequence | **Relative Density (%)** | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | 95 | | | | 98 | | | |
| | SAMPLE | | | Average | SAMPLE | | | Average |
| | A | B | C | | A | B | C | |
| 1 | 92.57 | 52.23 | 47.90 | *64.24* | 87.87 | 81.10 | 110.18 | *93.05* |
| 2 | 58.09 | 44.02 | 46.25 | *49.45* | 60.20 | 53.82 | 57.39 | *57.14* |
| 3 | 51.78 | 41.85 | 46.60 | *46.74* | 56.28 | 56.13 | 55.05 | *55.82* |
| 4 | 52.64 | 40.17 | 47.19 | *46.67* | 56.83 | 59.09 | 56.41 | *57.44* |
| 5 | 56.01 | | | *56.01* | 61.56 | 78.67 | | *70.11* |
| 6 | 81.87 | | 106.88 | *94.37* | 84.24 | 76.38 | | *80.31* |
| 7 | 53.56 | | | *53.56* | 59.18 | 56.71 | | *57.94* |
| 8 | 52.98 | | | *52.98* | 60.07 | 51.66 | | *55.86* |
| 9 | 54.04 | | | *54.04* | 62.88 | 54.46 | | *58.67* |
| 10 | | | | | 63.45 | 63.02 | | *63.24* |
| 11 | | | | | 85.36 | 106.72 | | *96.04* |
| 12 | | | | | 62.31 | 62.22 | | *62.26* |
| 13 | | | | | 65.50 | 60.82 | | *63.16* |
| 14 | | | | | 65.72 | 61.42 | | *63.57* |
| 15 | | | | | 68.42 | 62.93 | | *65.68* |

**TABLE C3:** Laboratory Resilient Modulus Test Results for the A-4 Soil at 14% Moisture Content

| Loading Sequence | **Relative Density (%)** | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | 94 | | | | 96 | | | |
| | SAMPLE | | | Average | SAMPLE | | | Average |
| | A | B | C | | A | B | C | |
| 1 | 50.99 | 75.96 | 46.61 | *57.85* | 121.59 | 95.36 | 64.06 | *93.67* |
| 2 | 41.55 | 55.51 | 37.81 | *44.96* | 81.98 | 57.07 | 46.06 | *61.70* |
| 3 | 42.26 | 146.97 | 40.83 | *76.68* | 49.63 | 43.46 | 42.57 | *45.22* |
| 4 | 43.90 | 49.30 | 45.12 | *46.11* | 50.48 | 47.59 | 41.03 | *46.37* |
| 5 | | | | | 52.59 | 49.02 | 45.39 | *49.00* |
| 6 | 53.86 | | | *53.86* | 60.84 | 64.52 | 57.89 | *61.08* |
| 7 | | | | | 50.08 | 47.83 | 44.27 | *47.39* |
| 8 | | | | | 50.60 | 49.15 | 41.10 | *46.95* |
| 9 | | | | | 51.04 | | 43.73 | *47.38* |
| 10 | | | | | | | 43.49 | *43.49* |
| 11 | 80.16 | | | *80.16* | | | 70.42 | *70.42* |
| 12 | 106.88 | | | *106.88* | | | 43.09 | *43.09* |
| 13 | 50.99 | 75.96 | 46.61 | *57.85* | | | 43.01 | *43.01* |
| 14 | 41.55 | 55.51 | 37.81 | *44.96* | | | 43.33 | *43.33* |
| 15 | 42.26 | 146.97 | 40.83 | *76.68* | | | 44.44 | *44.44* |

**TABLE C4:** Laboratory Resilient Modulus Test Results for the A-6 Soil at 16% Moisture Content

| Loading Sequence | **Relative Density (%)** | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 92 | | | | 95 | | | | 98 | | | |
| | SAMPLE | | | Average | SAMPLE | | | Average | SAMPLE | | | Average |
| | A | B | C | | A | B | C | | A | B | C | |
| 1 | 70.78 | 58.81 | 92.88 | *74.15* | 71.48 | 90.48 | 86.84 | *82.93* | 66.72 | 126.89 | 88.24 | *93.95* |
| 2 | 60.28 | 57.10 | 73.37 | *63.58* | 64.27 | 84.67 | 77.13 | *75.36* | 60.53 | 98.16 | 96.87 | *85.19* |
| 3 | 56.50 | 53.47 | 68.15 | *59.38* | 57.05 | 89.88 | 73.96 | *73.63* | 60.34 | 96.46 | 95.03 | *83.95* |
| 4 | 53.15 | 50.25 | 61.71 | *55.04* | 53.95 | 89.53 | 71.09 | *71.52* | 58.43 | 93.61 | 95.30 | *82.45* |
| 5 | 50.53 | 49.16 | 59.16 | *52.95* | 50.55 | 87.64 | 67.86 | *68.68* | 56.43 | 91.39 | 93.65 | *80.49* |
| 6 | 74.18 | 56.32 | 88.73 | *73.07* | 79.80 | 85.90 | 76.20 | *80.63* | 60.55 | 116.90 | 84.08 | *87.17* |
| 7 | 62.31 | 54.97 | 73.80 | *63.69* | 63.84 | 84.77 | 72.64 | *73.75* | 57.12 | 101.17 | 91.76 | *83.35* |
| 8 | 54.67 | 50.44 | 65.49 | *56.87* | 55.81 | 84.06 | 69.58 | *69.82* | 53.55 | 90.64 | 90.23 | *78.14* |
| 9 | 51.15 | 47.12 | 61.08 | *53.12* | 51.77 | 84.18 | 67.49 | *67.81* | 52.80 | 88.44 | 91.28 | *77.51* |
| 10 | 49.73 | 47.50 | 58.85 | *52.03* | 49.91 | 85.79 | 66.62 | *67.44* | 53.35 | 91.08 | 91.68 | *78.70* |
| 11 | 74.76 | 59.74 | 83.15 | *72.55* | 76.43 | 85.35 | 81.41 | *81.07* | 59.74 | 105.43 | 87.93 | *84.37* |
| 12 | 59.12 | 53.80 | 74.06 | *62.33* | 65.40 | 82.46 | 71.83 | *73.23* | 57.57 | 98.44 | 89.10 | *81.70* |
| 13 | 52.27 | 49.09 | 64.30 | *55.22* | 55.09 | 81.32 | 67.66 | *68.02* | 55.20 | 95.46 | 90.99 | *80.55* |
| 14 | 48.38 | 46.93 | 59.83 | *51.71* | 51.15 | 81.62 | 66.27 | *66.35* | 54.35 | 92.71 | 91.98 | *79.68* |
| 15 | 49.06 | 46.17 | 59.36 | *51.53* | 49.67 | 86.36 | 65.49 | *67.17* | 54.92 | 92.85 | 92.44 | *80.07* |

**TABLE C5:** Laboratory Resilient Modulus Test Results for the A-6 Soil at 19% Moisture Content

| Loading Sequence | **Relative Density (%)** | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 89 | | | | 92 | | | | 95 | | | |
| | SAMPLE | | | Average | SAMPLE | | | Average | SAMPLE | | | Average |
| | A | B | C | | A | B | C | | A | B | C | |
| 1 | 58.67 | 68.30 | 65.40 | *64.12* | 62.61 | 57.45 | 41.00 | *53.69* | 71.71 | 40.53 | 50.28 | *54.17* |
| 2 | 36.68 | 42.73 | 45.39 | *41.60* | 36.36 | 36.82 | 31.53 | *34.90* | 34.53 | 23.31 | 30.66 | *29.50* |
| 3 | 29.36 | 35.30 | 36.15 | *33.60* | 30.65 | 30.57 | 27.93 | *29.72* | 28.20 | 22.32 | 26.10 | *25.54* |
| 4 | 26.77 | 31.81 | 31.97 | *30.18* | 28.37 | 33.77 | 27.01 | *29.72* | 27.86 | 24.72 | 25.83 | *26.14* |
| 5 | 26.81 | 30.89 | 29.05 | *28.92* | 30.28 | 30.77 | 26.63 | *29.23* | 30.44 | 25.12 | 27.22 | *27.60* |
| 6 | 53.85 | 68.44 | 57.91 | *60.07* | 71.75 | 53.03 | 47.85 | *57.54* | 82.24 | 56.12 | 56.12 | *64.83* |
| 7 | 30.92 | 43.44 | 36.31 | *36.89* | 40.33 | 30.66 | 32.98 | *34.65* | 39.18 | 28.91 | 32.88 | *33.66* |
| 8 | 25.34 | 33.64 | 28.50 | *29.16* | 32.24 | 26.06 | 26.48 | *28.26* | 28.72 | 23.77 | 25.87 | *26.12* |
| 9 | 24.47 | 31.97 | 27.98 | *28.14* | 28.38 | 26.88 | 25.63 | *26.96* | 28.03 | 24.54 | 25.40 | *25.99* |
| 10 | 24.35 | 28.01 | 25.80 | *26.05* | 46.31 | 27.33 | 26.56 | *33.40* | 29.07 | 26.39 | 26.70 | *27.39* |
| 11 | 51.21 | 51.37 | 58.61 | *53.73* | 54.78 | 58.13 | 47.36 | *53.42* | 77.67 | 63.81 | 54.67 | *65.38* |
| 12 | 29.96 | 35.17 | 33.43 | *32.85* | 31.15 | 36.91 | 32.39 | *33.48* | 38.78 | 30.65 | 32.61 | *34.01* |
| 13 | 25.65 | 28.25 | 27.03 | *26.98* | 28.02 | 28.65 | 25.93 | *27.53* | 29.26 | 24.86 | 25.64 | *26.59* |
| 14 | 25.13 | 27.59 | 27.27 | *26.66* | 27.66 | 27.07 | 25.26 | *26.66* | 27.29 | 25.47 | 24.45 | *25.74* |
| 15 | | 28.36 | 23.87 | *26.11* | 29.29 | 28.75 | 26.79 | *28.28* | 29.73 | 28.28 | 26.76 | *28.26* |

**TABLE C6:** Laboratory Resilient Modulus Test Results for the A-7-5 Soil at 16.5% Moisture Content

| Loading Sequence | **Relative Density(%)** | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 90 | | | | 95 | | | | 100 | | | |
| | SAMPLE | | | | SAMPLE | | | | SAMPLE | | | |
| | A | B | C | Average | A | B | C | Average | A | B | C | Average |
| 1 | 98.54 | 59.35 | 61.85 | *73.25* | 56.09 | 79.59 | 98.15 | *77.94* | 117.86 | 82.21 | 75.42 | *91.83* |
| 2 | 65.12 | 55.38 | 54.57 | *58.36* | 50.75 | 67.25 | 72.99 | *63.67* | 90.87 | 79.51 | 70.26 | *80.21* |
| 3 | 53.32 | 49.78 | 46.22 | *49.77* | 46.12 | 58.66 | 63.40 | *56.06* | 85.00 | 76.20 | 68.69 | *76.63* |
| 4 | 46.70 | 47.03 | 40.53 | *44.76* | 42.86 | 50.67 | 56.80 | *50.11* | 79.35 | 73.02 | 68.85 | *73.74* |
| 5 | 41.93 | 46.52 | 37.70 | *42.05* | 39.83 | 47.09 | 53.37 | *46.76* | 73.81 | 70.41 | 69.75 | *71.32* |
| 6 | 112.32 | 69.81 | 65.62 | *82.58* | 60.96 | 79.46 | 98.96 | *79.79* | 112.78 | 88.27 | 80.22 | *93.76* |
| 7 | 66.07 | 56.42 | 52.26 | *58.25* | 52.46 | 63.34 | 72.15 | *62.65* | 93.75 | 74.00 | 71.63 | *79.79* |
| 8 | 50.88 | 49.15 | 42.82 | *47.62* | 45.90 | 53.10 | 59.75 | *52.92* | 83.99 | 71.12 | 68.16 | *74.42* |
| 9 | 43.51 | 46.07 | 38.42 | *42.67* | 42.05 | 48.24 | 54.11 | *48.13* | 76.47 | 70.66 | 67.89 | *71.67* |
| 10 | 40.97 | 44.83 | 36.57 | *40.79* | 39.89 | 45.91 | 51.64 | *45.81* | 72.41 | 70.58 | 69.96 | *70.98* |
| 11 | 120.68 | 68.83 | 64.68 | *84.73* | 61.69 | 81.00 | 94.52 | *79.07* | 118.07 | 83.35 | 81.04 | *94.15* |
| 12 | 65.47 | 55.46 | 51.76 | *57.56* | 54.03 | 62.32 | 70.04 | *62.13* | 95.37 | 74.75 | 72.17 | *80.76* |
| 13 | 49.75 | 48.75 | 41.39 | *46.63* | 45.21 | 51.79 | 57.70 | *51.57* | 83.03 | 70.73 | 69.60 | *74.46* |
| 14 | 43.47 | 45.85 | 37.35 | *42.22* | 41.06 | 47.10 | 52.81 | *46.99* | 75.01 | 69.75 | 67.90 | *70.89* |
| 15 | 40.59 | 45.03 | 36.44 | *40.69* | 40.00 | 45.22 | 51.42 | *45.55* | 60.09 | 69.30 | 68.74 | *66.04* |

**TABLE C7:** Laboratory Resilient Modulus Test Results for the A-7-5 Soil at 18.5% Moisture Content

| Loading Sequence | **Relative Density (%)** | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | 92 | | | | 95 | | | |
| | SAMPLE | | | Average | SAMPLE | | | Average |
| | A | B | C | | A | B | C | |
| 1 | 54.90 | 47.05 | 48.85 | *50.26* | 44.16 | 46.49 | 60.93 | *50.53* |
| 2 | 39.57 | 37.33 | 40.95 | *39.28* | 31.43 | 35.50 | 39.12 | *35.35* |
| 3 | 35.35 | 32.72 | 35.67 | *34.58* | 26.82 | 29.82 | 32.17 | *29.60* |
| 4 | 32.68 | 29.26 | 33.18 | *31.71* | 24.65 | 27.42 | 28.97 | *27.01* |
| 5 | 31.08 | 28.66 | 31.70 | *30.48* | 25.00 | 27.26 | 28.94 | *27.07* |
| 6 | 62.19 | 51.32 | 54.35 | *55.95* | 50.27 | 55.30 | 91.67 | *65.75* |
| 7 | 41.56 | 37.40 | 40.85 | *39.94* | 32.25 | 36.25 | 37.41 | *35.30* |
| 8 | 33.93 | 29.86 | 33.28 | *32.36* | 26.19 | 29.47 | 30.32 | *28.66* |
| 9 | 30.93 | 28.24 | 30.68 | *29.95* | 24.88 | 27.12 | 27.70 | *26.56* |
| 10 | 30.02 | 27.69 | 30.15 | *29.29* | 25.05 | 26.99 | 28.29 | *26.78* |
| 11 | 70.22 | 53.14 | 60.09 | *61.15* | 52.14 | 60.45 | 95.69 | *69.43* |
| 12 | 41.31 | 36.28 | 40.70 | *39.43* | 32.14 | 36.67 | 37.82 | *35.54* |
| 13 | 33.70 | 28.99 | 32.36 | *31.68* | 25.44 | 28.94 | 29.79 | *28.06* |
| 14 | 30.64 | 27.01 | 29.73 | *29.12* | 24.43 | 26.85 | 27.93 | *26.40* |
| 15 | 30.27 | 27.78 | 30.10 | *29.39* | 25.10 | 27.25 | 28.81 | *27.06* |

**TABLE C8:** Laboratory Resilient Modulus Test Results for the A-7-5 Soil at 20.5% Moisture Content

| Loading Sequence | **Relative Density (%)** | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 87 | | | | 90 | | | | 93 | | | |
| | SAMPLE | | | Average | SAMPLE | | | Average | SAMPLE | | | Average |
| | A | B | C | | A | B | C | | A | B | C | |
| 1 | 33.28 | 36.33 | 31.07 | *33.56* | 72.74 | 93.07 | 76.49 | *80.77* | 65.06 | 75.42 | 69.27 | *69.92* |
| 2 | 19.12 | 26.83 | 20.66 | *22.20* | 51.02 | 69.83 | 64.50 | *61.78* | 39.26 | 28.21 | 34.02 | *33.83* |
| 3 | 15.90 | 21.12 | 17.75 | *18.26* | 42.80 | 69.10 | 61.58 | *57.83* | 28.54 | 21.33 | 26.33 | *25.40* |
| 4 | 17.38 | 20.85 | 17.73 | *18.65* | 35.72 | 69.47 | 59.76 | *54.99* | 24.19 | 20.73 | 23.24 | *22.72* |
| 5 | 19.28 | 21.29 | 18.66 | *19.74* | 32.62 | 68.25 | 58.70 | *53.19* | 24.34 | 23.33 | 22.82 | *23.50* |
| 6 | 38.25 | 43.65 | 37.68 | *39.86* | 72.50 | 88.30 | 71.32 | *77.37* | 55.62 | 99.37 | 57.34 | *70.78* |
| 7 | 22.95 | 25.67 | 22.12 | *23.58* | 47.76 | 79.34 | 62.81 | *63.30* | 30.93 | 34.12 | 29.12 | *31.39* |
| 8 | 18.85 | 21.31 | 18.22 | *19.46* | 37.77 | 75.53 | 58.54 | *57.28* | 23.30 | 25.26 | 22.46 | *23.67* |
| 9 | 18.86 | 21.28 | 18.56 | *19.57* | 33.29 | 72.36 | 58.45 | *54.70* | 22.38 | 23.69 | 22.56 | *22.88* |
| 10 | | | 19.28 | *19.28* | 32.53 | 69.38 | 58.38 | *53.43* | 23.73 | 22.63 | 23.33 | *23.23* |
| 11 | | | 42.22 | *42.22* | 81.83 | 89.80 | 72.72 | *81.45* | 54.39 | 85.28 | 51.92 | *63.87* |
| 12 | | | 23.08 | *23.08* | 50.17 | 75.76 | 65.19 | *63.71* | 29.80 | 34.10 | 28.46 | *30.78* |
| 13 | | | 18.73 | *18.73* | 38.27 | 76.38 | 59.74 | *58.13* | 22.40 | 26.31 | 22.80 | *23.84* |
| 14 | | | 19.18 | *19.18* | 33.87 | 72.55 | 58.38 | *54.93* | 21.31 | 25.02 | 22.27 | *22.87* |
| 15 | | | | | 32.97 | 71.98 | 58.51 | *54.49* | 23.42 | 24.58 | 23.54 | *23.85* |