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16. Abstract

VESYS5 is a probabilistic and mechanistic flexible pavement analysis computer program. It predicts the asphalt pavement performance (rutting, fatigue cracking, present serviceability index [PSI], etc.) with time. Also, it has been successfully used to analyze the asphalt pavement performance under the field traffic and under accelerated pavement testing loads. However, it works only in DOS operation systems and routine use is impractical due to its complicated input and output. These defects significantly block the application of VESYS5. In the past year the Texas Transportation Institute has upgraded and enhanced the VESYS5 to the Windows® version with user-friendly input and output interface. This report summarizes the input parameters of the enhanced VESYS5 program. These input parameters include climate, pavement structure, material properties, and traffic data. In addition, this report also documents the test protocols on material properties such as modulus and permanent deformation property. Finally, a case study is provided to demonstrate the inputs and outputs of the enhanced VESYS5.

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INPUT PARAMETERS OF ENHANCED VESYS5

by

Fujie Zhou
Research Associate
Texas Transportation Institute

and

Tom Scullion
Research Engineer
Texas Transportation Institute

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Project 9-1502
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TEXAS TRANSPORTATION INSTITUTE
The Texas A&M University System
College Station, Texas 77843-3135

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CHAPTER 1

INTRODUCTION

VESYS5 is a probabilistic and mechanistic flexible pavement analysis computer program. For more than 30 years, Mr. Bill Kenis led FHWA's effort to develop the VESYS series. VESYS5 is one program in the powerful VESYS family. It is based on the elastic model of layered homogeneous material in half-infinite space with some viscoelastic-plastic theory applications. It predicts asphalt pavement performance (rutting, fatigue cracking, PSI, etc.) with time. Also, it has been successfully used to analyze asphalt pavement performance under field traffic and under accelerated pavement testing loads (*1, 2, 3*). In addition, its running speed is very fast. However, it works only in DOS operating systems and routine use is impractical due to its complicated input and output. These defects significantly hamper the application of VESYS5. Thus, this project is to upgrade the DOS version of VESYS5 into the user-friendly Windows® version.

This report documents key input parameters of the upgraded Windows version of VESYS5. Chapter 1 presents a short introduction. Chapter 2 documents the key input parameters. A brief summary is made in Chapter 3. Appendices A and B present the laboratory test protocols used to measure the important input parameters related to material properties. A case study is provided in Appendix C to demonstrate the enhanced VESYS5 program.

CHAPTER 2

INPUT PARAMETERS OF ENHANCED VESYS5

The Windows version of enhanced VESYS5 provides a user-friendly input and output interface and significantly improves the usability of the existing VESYS5 program. The enhanced VESYS5 has simplified user input and visualized output based on thoroughly studying and examining the input of VESYS5. Input data are categorized into four types: "General Information, Climate, Structure and Material Property, and Traffic." Output data include summary of input data, graphic output of performance data (total rutting, layer rutting, fatigue cracking, and present serviceability index [PSI]), and tabulated performance data. Figure 1 presents the flowchart and main interface of the enhanced VESYS5 program. Four types of input parameters will be discussed in this chapter.

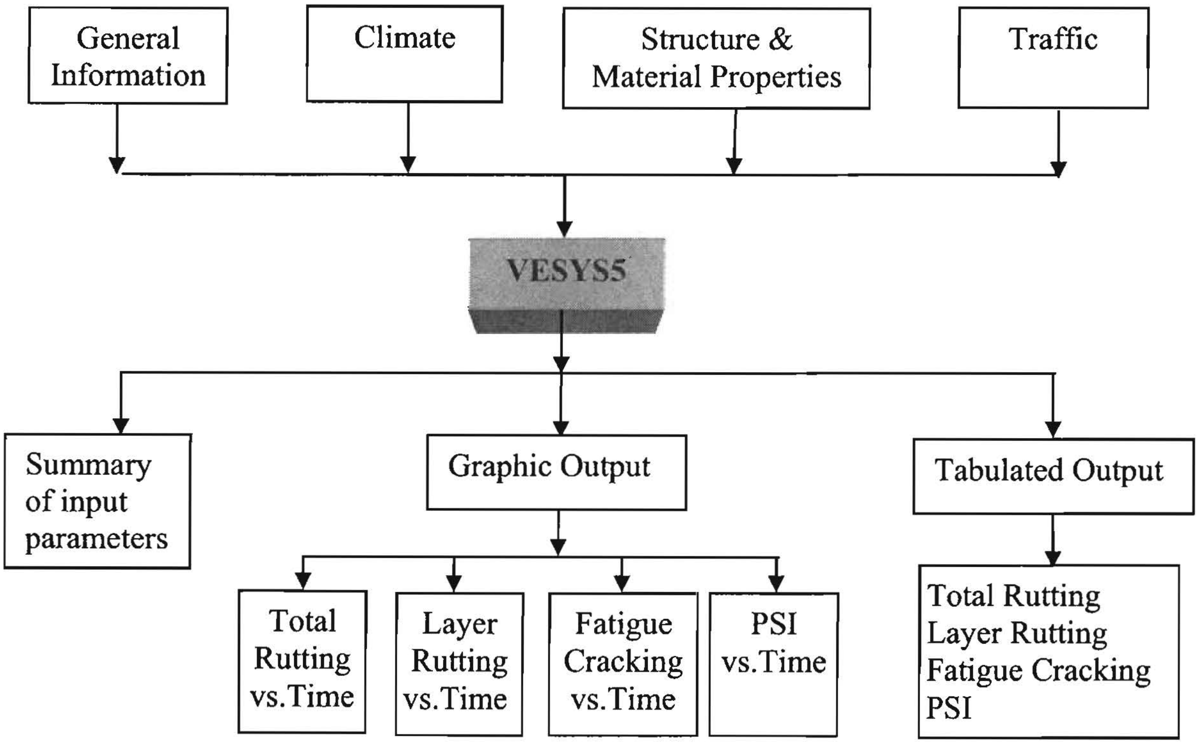


Figure 1a. Flowchart of Enhanced VESYS5.

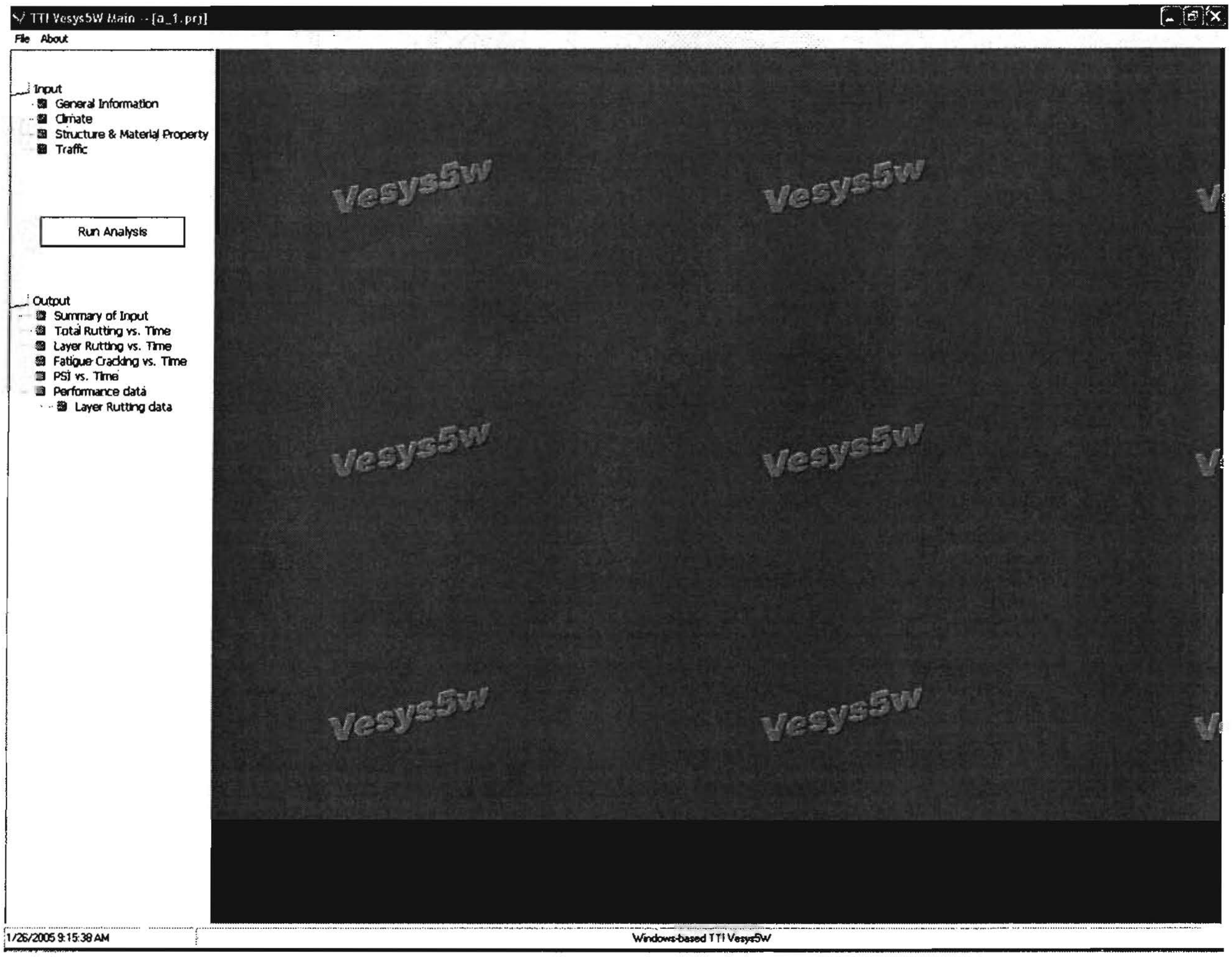
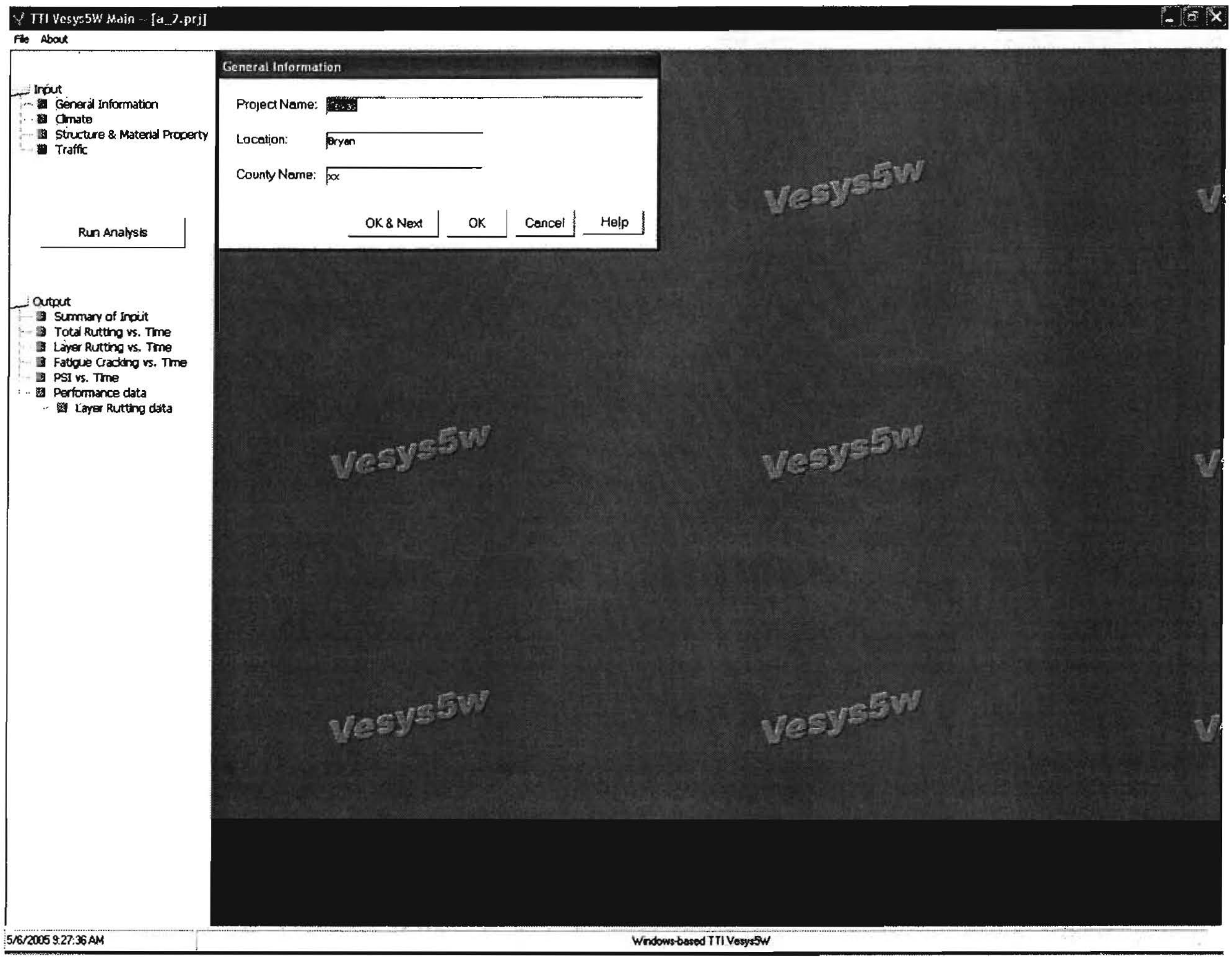


Figure 1b. Main Input and Output Interface of Enhanced VESYS5.

GENERAL INFORMATION

While some VESYS5 program parameters are mandatory, the input of general information is optional. The general information shown in Figure 2 includes project name, location, and county. The title of the output reports displays project name information.



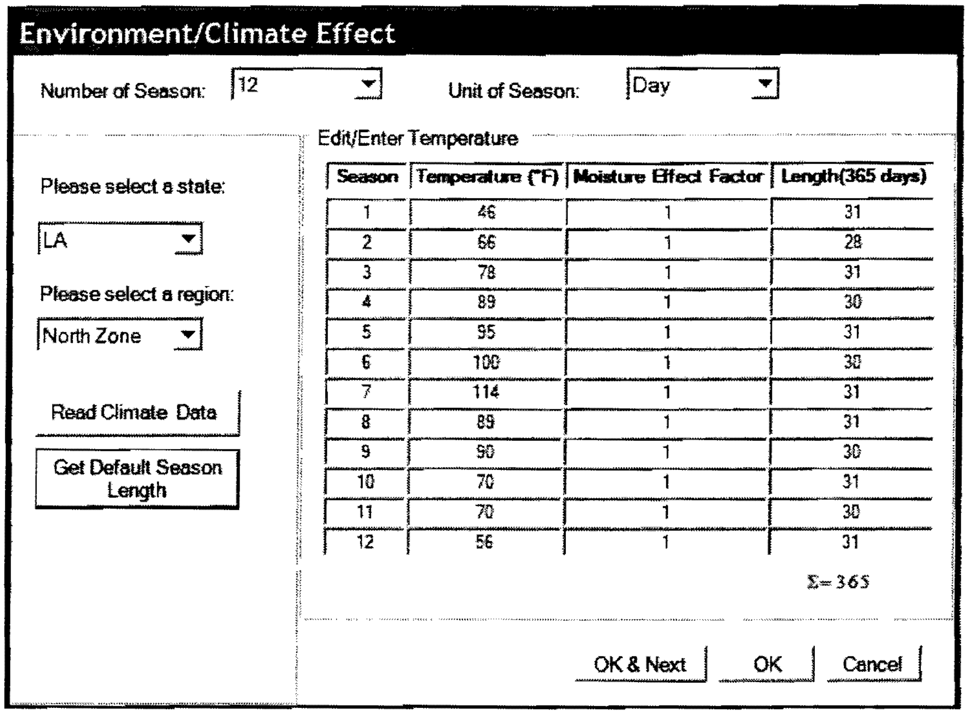
Project Name: [illegible]
Location: Bryan
County Name: xx

5/6/2005 9:27:36 AM

Figure 2. Input Parameters of General Information.

CLIMATE INPUT

Climate data **MUST** be entered before "Structure & Material Property" and "Traffic" data." Figure 3 shows required input data. However, only part of the data are mandatory in the VESYS5 program. Required data are number of seasons, unit of season, season length, and moisture effect factor. Both state and region selections are optional. Please note the importance of carefully selecting the number of seasons and the unit of season because this is the important information for generating the program input and is directly related to the following "Structure & Material Property" and "Traffic" input.



Number of Season: 12
Unit of Season: Day
Please select a state: LA
Please select a region: North Zone

Edit/Enter Temperature

Season	Temperature (°F)	Moisture Effect Factor	Length(365 days)
1	46	1	31
2	66	1	28
3	78	1	31
4	89	1	30
5	95	1	31
6	100	1	30
7	114	1	31
8	89	1	31
9	90	1	30
10	70	1	31
11	70	1	30
12	56	1	31

$\Sigma = 365$

Figure 3. Input Parameters of Climate.

The number of seasons ranges from 1 to 12, with a default value of 12. There are two options for unit of season: day and month. Users can specify the length of each season, but the summary of seasons per year should be 12 months or 365 days. The enhanced VESYS5 displays the calculation of total length, while users enter the season length. The moisture effect factor is set to consider the influence of moisture on base, subbase, and subgrade. The default moisture effect factor is 1 for all seasons; however, users can modify it. Each season's moisture effect factor affects the modulus of the base layer, subbase layer, and subgrade for that season. The moduli values of base, subbase, and subgrade used in the pavement performance analysis are calculated by the moisture effect factor by multiplying the moduli entered in the following "Structure & Material Property" section.

The "Read Climate Data" button is active and allows users to select "State" and "Region" only if the number of seasons equals 12. After selecting the state and region, click the "Read Climate Data" button; the program reads the default temperature of that state and region and displays the data. Users can modify the temperature data. The "Get Default Season Length" button provides users a simple way to calculate the average length of season based on the number of seasons and unit.

STRUCTURE & MATERIAL PROPERTY INPUT

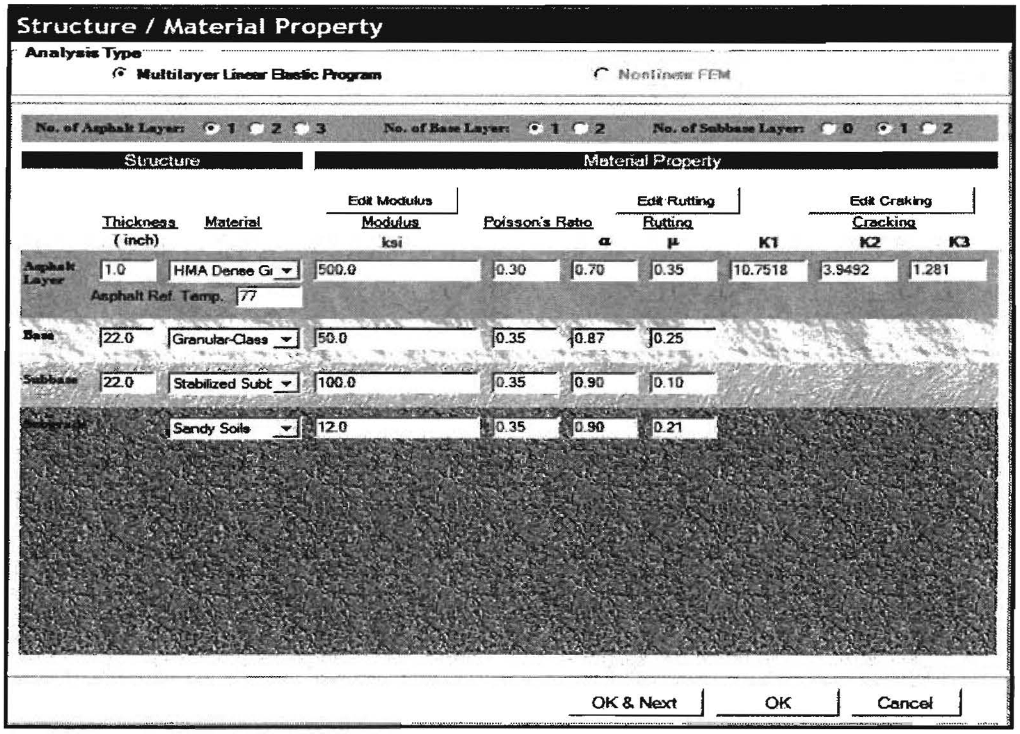
"Structure & Material Property" has been especially organized for users to easily input pavement structural and material information. As mentioned previously, users must finish entering and save climate data before starting "Structure & Material Property" input, since season temperature, moisture effect factor, and number of seasons will be used in calculating "Structure & Material Property" data. The following discusses input parameters.

- **Analysis Type**

Only multilayer linear elastic analysis is available in enhanced VESYS5.

- **Defining Layers**

The enhanced VESYS5 clearly defines pavement layers with a user-friendly Graphical User Interface (GUI). There are four types of layers: asphalt, base, subbase, and subgrade. Users can define the number of layers for each type of layer, except the subgrade layer, by clicking the radio button corresponding to each type. The default number of layers is 4, as illustrated in Figure 4.



Analysis Type
● Multilayer Linear Elastic Program ○ Nonlinear FEM

No. of Asphalt Layer: ● 1 ○ 2 ○ 3 No. of Base Layer: ● 1 ○ 2 No. of Subbase Layer: ○ 0 ● 1 ○ 2

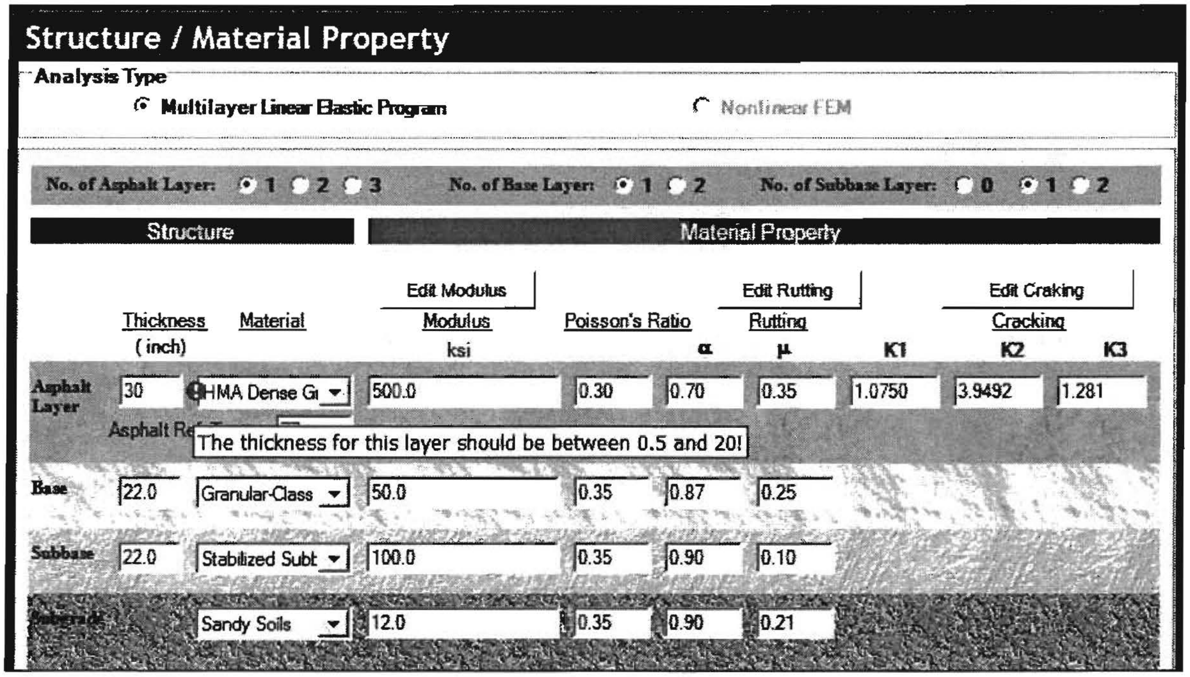
	Thickness (inch)	Material	Modulus ksi	Poisson's Ratio	Rutting α	Rutting μ	Cracking K1	Cracking K2	Cracking K3
Asphalt Layer	1.0	HMA Dense Gi	500.0	0.30	0.70	0.35	10.7518	3.9492	1.281
Base	22.0	Granular-Class	50.0	0.35	0.87	0.25			
Subbase	22.0	Stabilized Subt	100.0	0.35	0.90	0.10			
Subgrade		Sandy Soils	12.0	0.35	0.90	0.21			

Asphalt Ref. Temp. 77

Figure 4. Overview of "Structure & Material Property."

- **Thickness**

The enhanced VESYS5 defines the valid range of thickness. Thickness of asphalt layers is 0.5–20 inches, and thickness of other layers is 4–25 inches. The program checks the input value. If the input value is not valid, a red flashing icon appears near the thickness textbox (Figure 5). Pointing the cursor to the flashing icon displays valid range information.



Analysis Type: ● Multilayer Linear Elastic Program ○ Nonlinear FEM

No. of Asphalt Layer: ● 1 ○ 2 ○ 3 No. of Base Layer: ● 1 ○ 2 No. of Subbase Layer: ○ 0 ● 1 ○ 2

	Thickness (inch)	Material	Modulus ksi	Poisson's Ratio	Rutting α	Rutting μ	K1	Cracking K2	K3
Asphalt Layer	30	HMA Dense Gi	500.0	0.30	0.70	0.35	1.0750	3.9492	1.281
Base	22.0	Granular-Class	50.0	0.35	0.87	0.25			
Subbase	22.0	Stabilized Subt	100.0	0.35	0.90	0.10			
Subgrade		Sandy Soils	12.0	0.35	0.90	0.21			

The thickness for this layer should be between 0.5 and 20!

Figure 5. Illustration of Thickness Check Function.

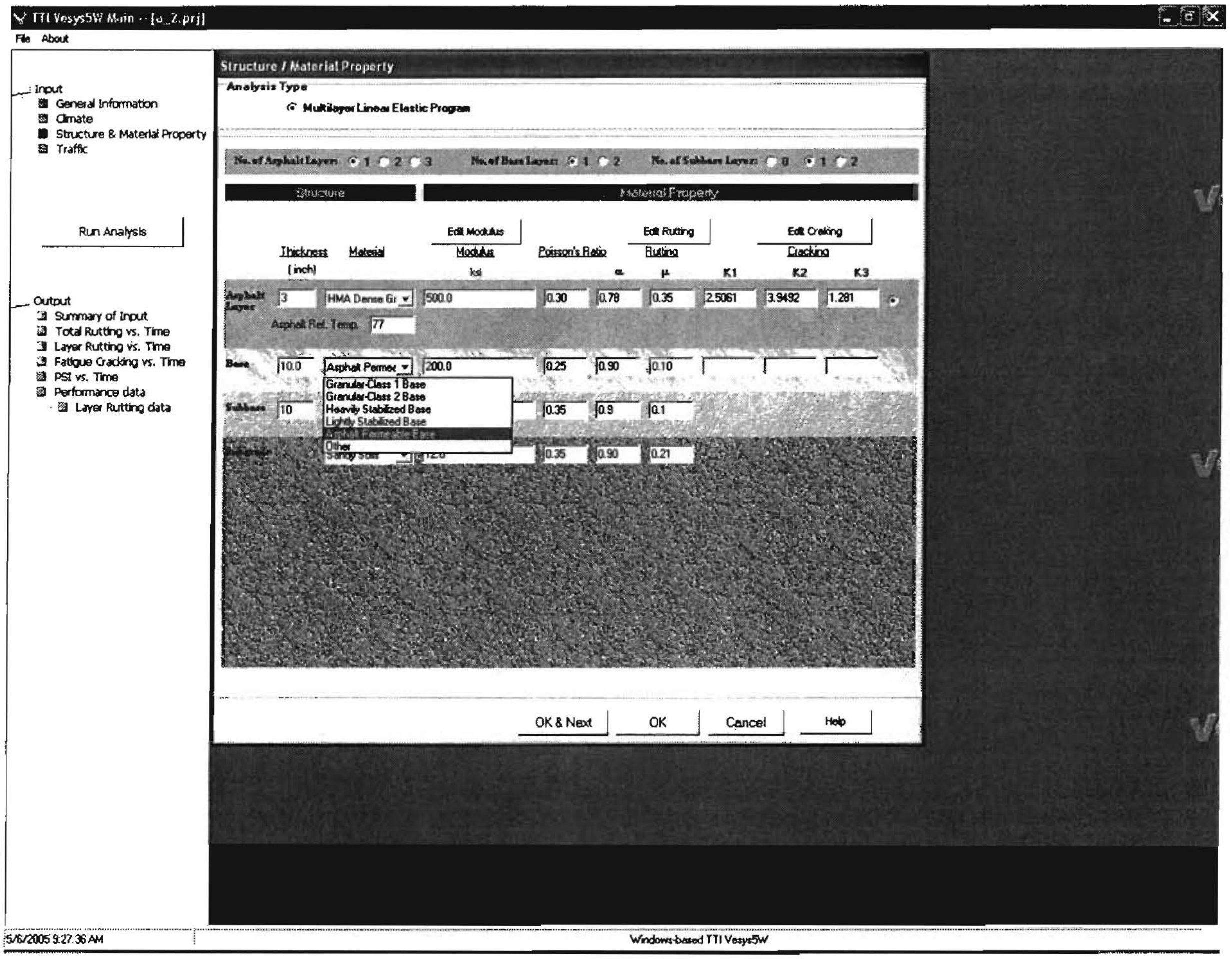
- **Material**

Material information for each layer helps users to define the material property. Users can select the material type for a specific layer from the layer's dropdown list (Figure 6). After selecting the material, users will see the material property data of that layer entered automatically. The enhanced VESYS5 defines and calculates the layer's material property based on the material type and layer thickness entered. Table 1 presents detailed default material type and associated properties for each layer.

Table 1. Default Material Properties Built in the Enhanced VESYS5.

Material Type		Modulus (ksi)	Poisson's Ratio	μ	α	K₁	K₂	K₃
Asphalt	HMA* Dense Graded A	300	0.3	0.35	0.78	*	3.9492	1.281
	HMA Dense Graded B	400	0.3	0.35	0.78			
	HMA Dense Graded C	500	0.3	0.35	0.78			
	HMA Dense Graded D	500	0.3	0.35	0.78			
	Rut Resistant HMA	900	0.3	0.30	0.89			
	Fatigue Resistant HMA	600	0.3	0.30	0.76			
	Modified HMA	1000	0.3	0.30	0.89			
	Other	1200	0.3	0.30	0.89			
Base/ Subbase	Granular-Class 1 Base	70	0.35	0.20	0.90			
	Granular-Class 2 Base	50	0.35	0.25	0.87			
	Heavily Stabilized Base	200	0.25	0.10	0.95			
	Lightly Stabilized Base	125	0.30	0.15	0.95			
	Asphalt Permeable Base	300	0.35	0.25	0.85			
	Other	100	0.30	0.10	0.90			
Soils	Gravelly Soils	16	0.35	0.20	0.90			
	Sandy Soils	12	0.35	0.21	0.90			
	High PI* Clay	4	0.40	0.30	0.89			
	Low PI Clay	8	0.40	0.28	0.90			
	Other	8	0.40	0.30	0.90			

Note: $*, k_1 = \dfrac{0.00432}{0.000398 + \dfrac{0.003602}{1 + e^{(11.02 - 3.49 - h_{ac})}}}$, h_{ac} is the thickness of asphalt layer(s). Hot-Mix Asphalt (HMA); Plasticity Index (PI).



Analysis Type: ● Multilayer Linear Elastic Program

No. of Asphalt Layer: ● 1 ○ 2 ○ 3　No. of Base Layer: ● 1 ○ 2　No. of Subbase Layer: ○ 0 ● 1 ○ 2

	Thickness (inch)	Material	Modulus ksi	Poisson's Ratio	Rutting α	Rutting μ	Cracking K1	Cracking K2	Cracking K3
Asphalt Layer	3	HMA Dense Gr	500.0	0.30	0.78	0.35	2.5061	3.9492	1.281
Base	10.0	Asphalt Permea	200.0	0.25	0.90	0.10			
Subbase	10			0.35	0.9	0.1			
Subgrade		Sandy Soil	12.0	0.35	0.90	0.21			

Asphalt Ref. Temp. 77

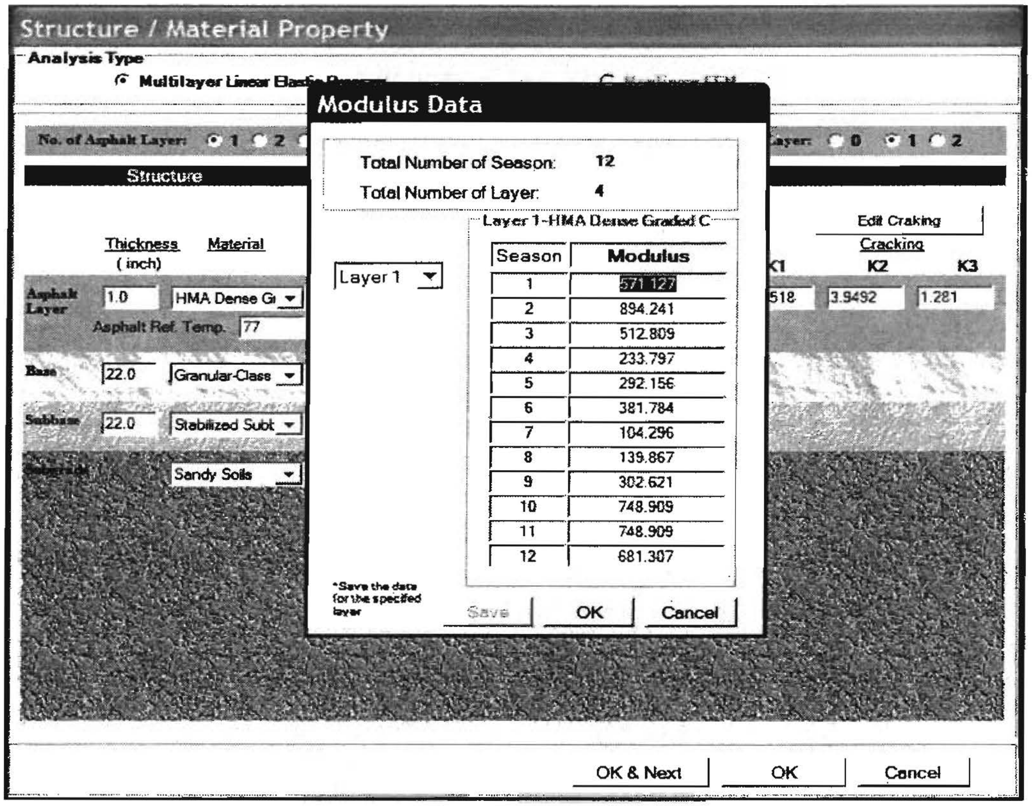
Granular-Class 1 Base
Granular-Class 2 Base
Heavily Stabilized Base
Lightly Stabilized Base
Asphalt Permeable Base
Other

Figure 6. Illustration of Default Material Type.

- **Modulus**

Modulus of each pavement layer is a mandatory parameter for the enhanced VESYS5 program. The modulus value is used for calculating the pavement response under traffic load. ASTM D3497 "Standard Test Method for Dynamic Modulus of Asphalt Mixtures" can be used to determine the modulus of asphalt mixtures. Appendix A presents the recommended laboratory test protocol for resilient moduli of base, subbase, and subgrade. The default modulus values of typical pavement materials are provided in the program and are presented in Table 1. For asphalt materials, the default modulus value corresponds to the temperature of 77 °F. The default moduli value of base, subbase, and subgrade materials correspond to the optimum moisture content. Users can modify the default modulus value of each layer.

Actually, the VESYS5 program requires the seasonal modulus value of each pavement layer. The enhanced VESYS5 automatically calculates the seasonal modulus of asphalt layer based on the reference modulus entered in the screen for that layer and each season's temperature defined in "Climate." The seasonal moduli of other layers are calculated based on the input value of modulus in the "Material & Structure" screen and moisture effect factor (Figure 3). Click the "Edit Modulus" button to open the modulus data screen (Figure 7). Users can view or modify the seasonal modulus of each layer from this screen. Please note the number of season displayed in the modulus data screen is the same as the number defined in the "Climate" screen (Figure 3). Users can continue to edit the modulus of pavement layer by clicking the "Save" button on the current editing layer of the modified Modulus Data. Click "OK" to save the Modulus Data of the current layer and close this screen. Make sure to click the "Save" button to save the modulus data for each layer.



Modulus Data

Total Number of Season: 12
Total Number of Layer: 4

Asphalt Layer: 1.0, HMA Dense Gr
Asphalt Ref. Temp. 77
Base: 22.0, Granular-Class
Subbase: 22.0, Stabilized Subt
Subgrade: Sandy Soils
K1: 518; K2: 3.9492; K3: 1.281

Layer 1-HMA Dense Graded C

Season	Modulus
1	571.127
2	894.241
3	512.809
4	233.797
5	292.156
6	381.784
7	104.296
8	139.867
9	302.621
10	748.909
11	748.909
12	681.307

*Save the data for the specifed layer

Figure 7. Editing Interface of Seasonal Modulus.

- **Poisson's Ratio**

The enhanced VESYS5 also requires Poisson's ratio. The default Poisson's ratio is given based on the layer's material type (Table 1). The valid range of Poisson's ratio is 0.1–0.44. The program automatically checks the input value.

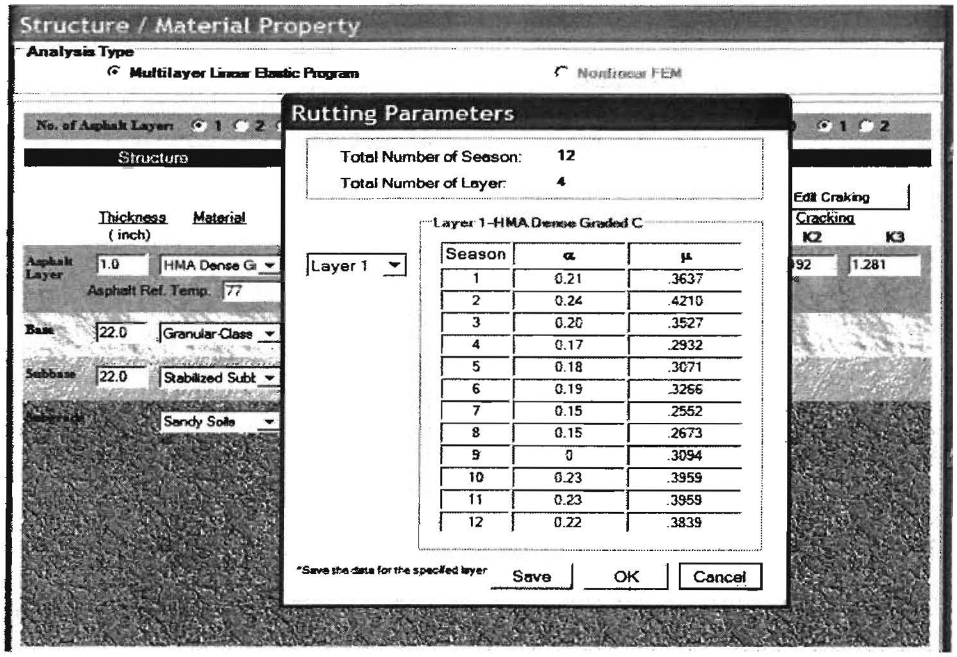
- **Permanent Deformation (Rutting) Property**

The VESYS rutting model is used to predict the rutting development of asphalt pavement. The rutting parameters include ALPHA and GNU. Similar to modulus data, they are mandatory. ALPHA and GNU values are normally determined by repeated load tests. Appendix B presents the associated laboratory test protocols. The program provides the default ALPHA and GNU values based on material types. Each season's ALPHA/GNU values for asphalt layers are calculated based on the reference temperature, ALPHA/GNU input of each layer, and the season's temperature from the climate screen. Clicking the "Edit Rutting" button allows users to open, view, or edit the ALPHA and GNU values of each season for specified layers (Figure 8). If the *calculated* rutting data is beyond the 0.1–0.95 range, the program limits it to this range in order to make the original VESYS5 program execute smoothly.

The range of ALPHA defined by program is as follows:

- Asphalt Layer: 0.7–0.95. If the input value ranges from 0.1 to 0.95, user will get a warning, but will still be allowed to save the data.
- Base and Subbase Layers: 0.7–0.9.
- Subgrade Layer: 0.5–1.

The range of GNU is 0 to 0.5. The program will validate the input ALPHA and GNU values. If the input is invalid, a red flashing icon appears to notify users.



Asphalt Layer: 1.0, HMA Dense G
Asphalt Ref. Temp. 77
Base: 22.0, Granular Class
Subbase: 22.0, Stabilized Subt
Subgrade: Sandy Soils
K2: 92
K3: 1.281

Total Number of Season: 12
Total Number of Layer: 4
Layer 1
Layer 1-HMA Dense Graded C

Season	α	μ
1	0.21	.3637
2	0.24	.4210
3	0.20	.3527
4	0.17	.2932
5	0.18	.3071
6	0.19	.3266
7	0.15	.2552
8	0.15	.2673
9	0	.3094
10	0.23	.3959
11	0.23	.3959
12	0.22	.3839

*Save the data for the specified layer

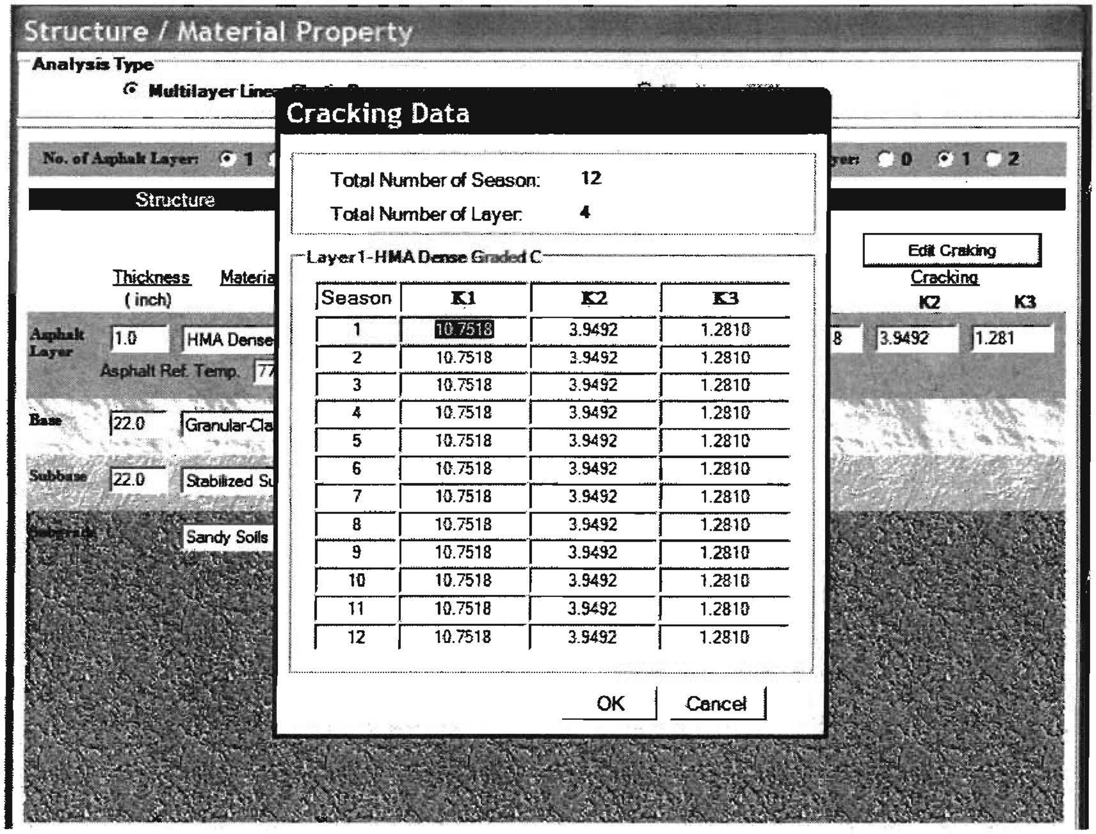
Figure 8. Illustration of Editing Alpha and Gnu.

- **Fatigue Cracking Property**

The enhanced VESYS5 uses the traditional fatigue cracking equation (Equation 1) to predict fatigue cracking performance.

$$N_f = K_1 \left(\frac{1}{\varepsilon} \right)^{K_2} \left(\frac{1}{E} \right)^{K_3} \tag{1}$$

Fatigue cracking parameters include K_1, K_2, and K_3, which can be determined based on the American Association of State Highway and Transportation Officials (AASHTO) TP8-94, Method for Determining the Fatigue Life of Compacted Hot Mix Asphalt (HMA) Subjected to Repeated Flexural Bending. Also, the program builds the default values based on the fatigue cracking equation in AASHTO 2002 Design Guide. The program automatically calculates the default K_1 based on the thickness of all asphalt layers. K_2 and K_3 are given and displayed after users pick up the last layer of asphalt layers. All three parameters can be modified. Clicking the "Edit Cracking" button allows users to view and edit each season's K_1, K_2 and K_3 data (Figure 9).



Total Number of Season: 12

Total Number of Layer: 4

Layer1-HMA Dense Graded C

Season	K1	K2	K3
1	10.7518	3.9492	1.2810
2	10.7518	3.9492	1.2810
3	10.7518	3.9492	1.2810
4	10.7518	3.9492	1.2810
5	10.7518	3.9492	1.2810
6	10.7518	3.9492	1.2810
7	10.7518	3.9492	1.2810
8	10.7518	3.9492	1.2810
9	10.7518	3.9492	1.2810
10	10.7518	3.9492	1.2810
11	10.7518	3.9492	1.2810
12	10.7518	3.9492	1.2810

Figure 9. Illustration of Editing Fatigue Cracking Parameters: K_1, K_2, and K_3.

Traffic Data

Traffic load information **MUST** be specified in order to run the enhanced VESYS5. Traffic Data input includes the information of axle load and repeated load. Thus, it takes two steps to finish the traffic data input. First, select the axle type (or truck type). Second, users need to specify the daily repetitions corresponding to the selected axle or truck. The following paragraphs discuss these two steps.

- **Axle Load Data**

The information describing axle load data (such as tire pressure and weight of axle/2) is needed in this input category. The enhanced VESYS5 classifies the potential axles as two levels (Level 2: specific axle and Level 1: specific truck). Based on the purpose of analysis, users can select the applicable level.

- **Level 2: Specific Axle**

Level 2: specific axle is the default option when users open the traffic screen the first time. Four types of axles are available: single, tandem, tridem, and quad axle(s). After users select an axle type, the right side of the screen displays the corresponding input information for the selected axle type (Figure 10).

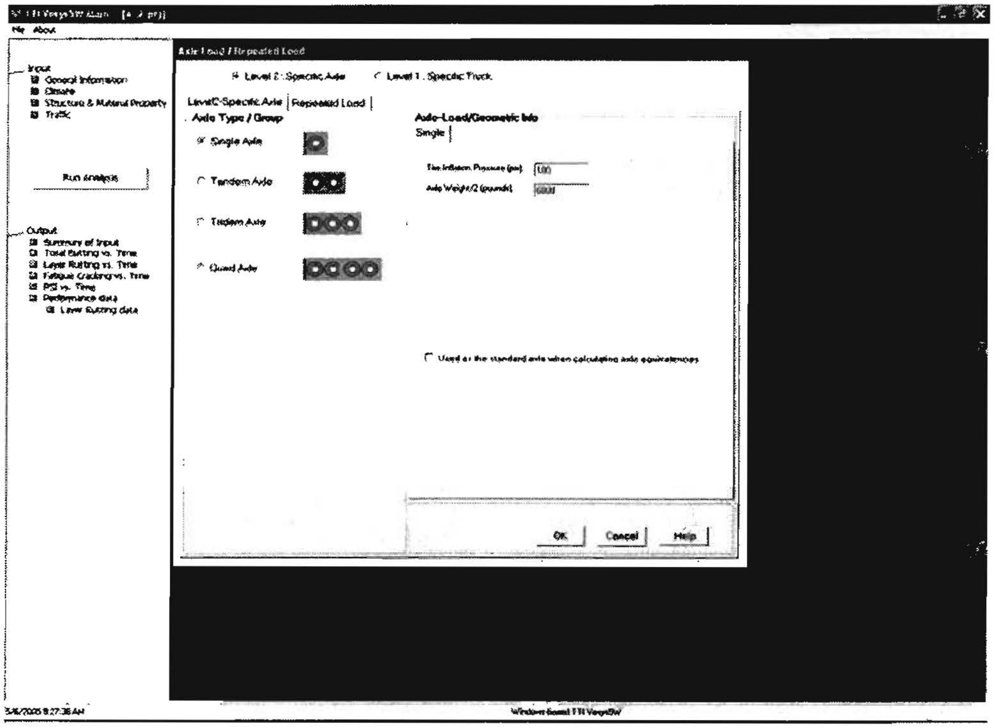


Figure 10. Input Screen of Traffic Input-Level 2: Specific Axle.

The parameters describing the axle load include “Tire Inflation Pressure” and “Axle Weight/2.” Except for single axle, the axle spacing also needs to be specified. “Inter-Axle Spacing” is the distance between the adjacent two axles. Please note that the “Axle Weight/2” is half the weight of the axle load. For example, for a 34 kip tandem load, Axle Weight/2 should be 8.5 kip (34/2/2 = 8.5 kip).

- **Level 1: Specific Truck**

In some cases, users may use multiple groups of multiple-axle loads for the pavement performance analysis. The enhanced VESYS5 defines the multiple-axle group as the different truck types (Figure 11). The enhanced VESYS5 defines 10 truck types plus trailer combinations. The picture of each type of truck shows users the definition of that truck clearly and visually. Select a type of truck, and enter the required axle load information for the selected truck on the right side of the screen. The basic information about axle loads is the same as described in the Level 2 section.

In addition, the trailer will appear if users choose trucks 4, 5, 6, or 7. Users can add the trailer to the current truck by selecting the check box. The trailer tab appears in the “Axle-Load/Geometric Info” section, and the information about the trailer axle is the same as described in the Level 2 section.

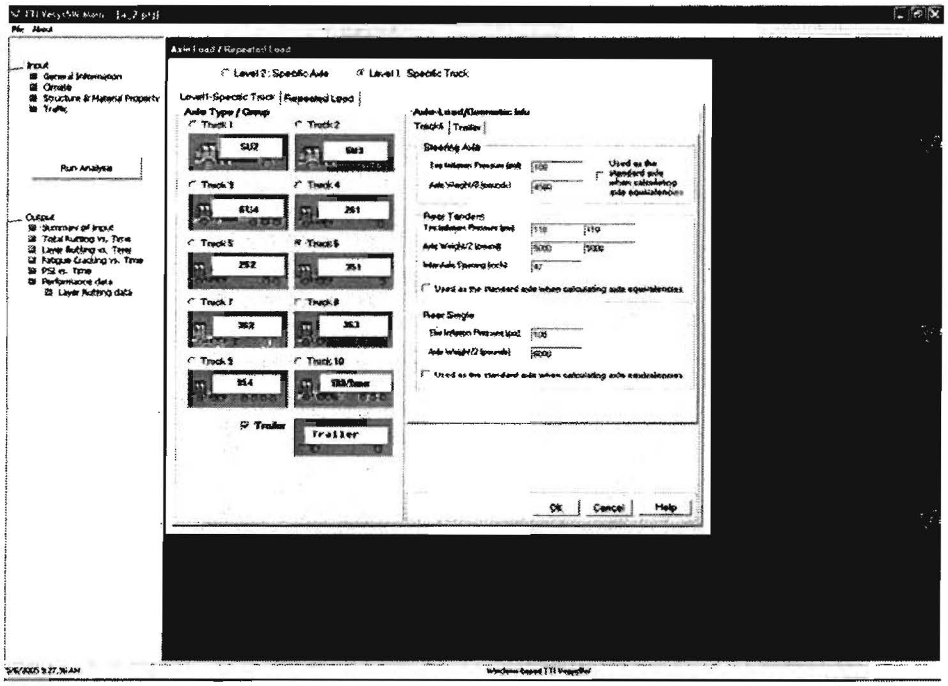


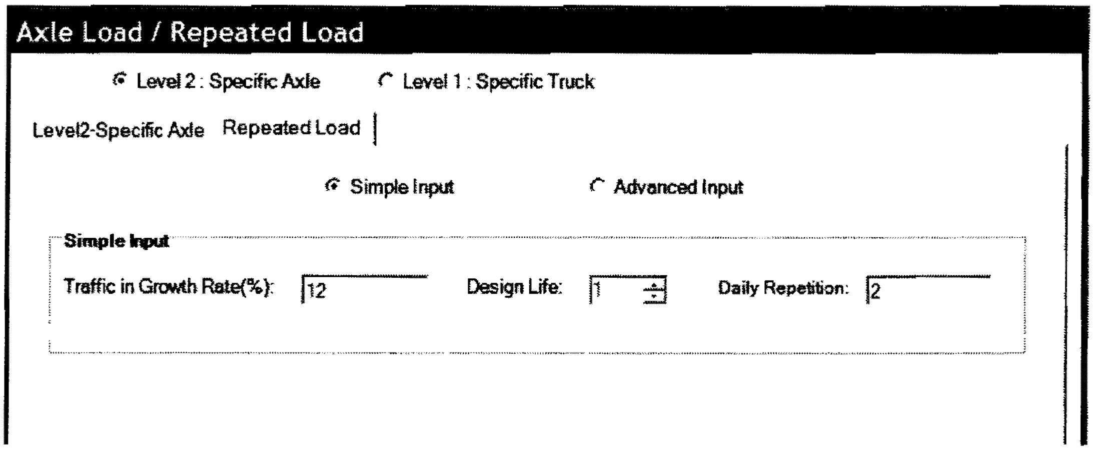
Figure 11. Input Screen of Traffic Input-Level 1: Specific Truck.

- **Repeated Load**

Users may enter the repeated load data information in two ways. The simple input is for general pavement performance analysis, and the advanced input is for Accelerated Pavement Test (APT) data analysis. They are presented in the following.

- **Simple Input**

This method is the simple way to enter the repeated load information. Users only need to enter the growth rate, design life, and daily repetitions of the axle or truck previously specified (Figure 12). The program automatically calculates repeated data described above.



● Level 2 : Specific Axle ○ Level 1 : Specific Truck

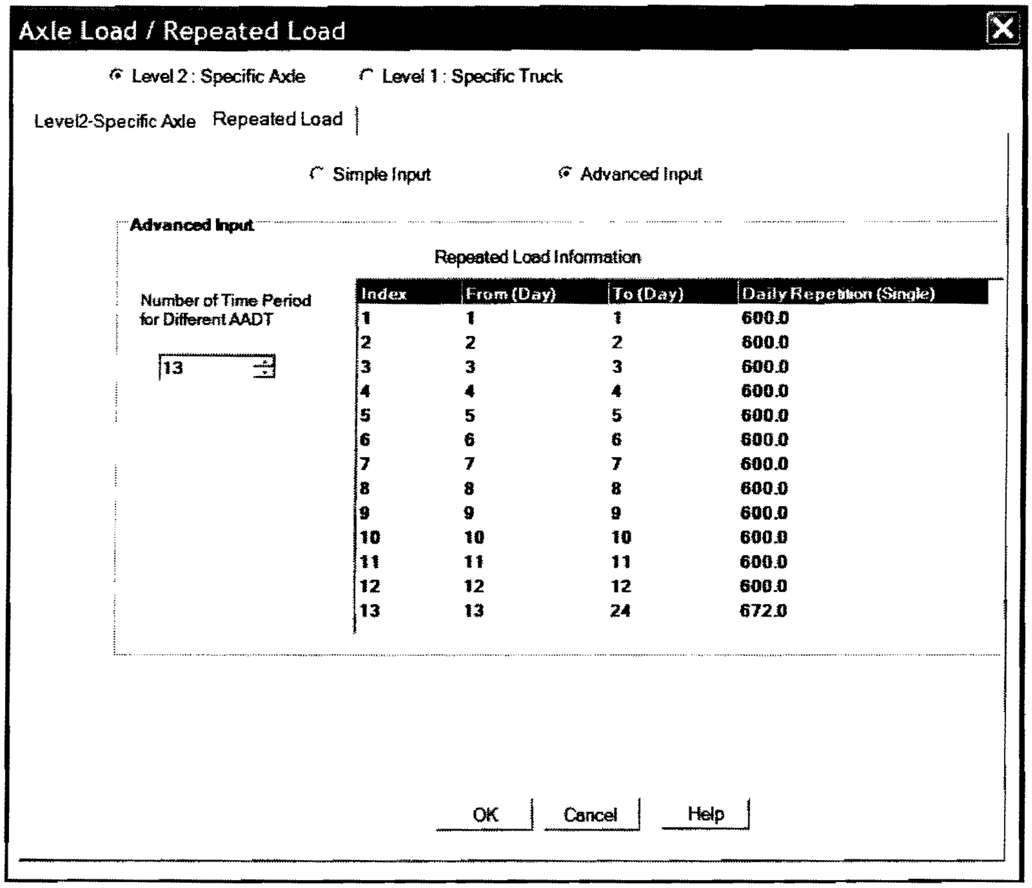
● Simple Input ○ Advanced Input

Traffic in Growth Rate(%): 12 Design Life: 1 Daily Repetition: 2

Figure 12. Repeated Load: Simple Input.

- **Advanced Input**

For the Advanced Input (Figure 13), users should specify the specific daily repetitions of the selected axle or truck within each season that has been defined in previous "Climate" zone. This function is especially designed for the APT performance prediction. It should be mentioned that the minimum daily repetitions of axles or trucks is 100.



● Level 2 : Specific Axle ○ Level 1 : Specific Truck

○ Simple Input ● Advanced Input

Advanced Input

Number of Time Period for Different AADT: 13

Repeated Load Information

Index	From (Day)	To (Day)	Daily Repetition (Single)
1	1	1	600.0
2	2	2	600.0
3	3	3	600.0
4	4	4	600.0
5	5	5	600.0
6	6	6	600.0
7	7	7	600.0
8	8	8	600.0
9	9	9	600.0
10	10	10	600.0
11	11	11	600.0
12	12	12	600.0
13	13	24	672.0

Figure 13. Repeated Load: Advanced Input.

CHAPTER 3

SUMMARY

This report documents the enhanced VESYS5 Windows version program input parameters. The input data required are classified into four categories: General Information, Climate, Structure & Material Property, and Traffic Data. It is well known that the toughest task is to determine the material properties including modulus, rutting and fatigue properties, etc. One of the special features of the enhanced VESYS5 program is that the default values of material properties have been built into the program. These default values are based on substantial literature review and laboratory testing. In addition, the laboratory test protocols have also been recommended to determine these material properties. Also, a case study is provided in Appendix C to demonstrate the enhanced VESYS5 program.

REFERENCES

1. Kenis, W. J. and W. Wang, Calibrating Mechanistic Flexible Pavement Rutting Models from Full Scale Accelerated Tests, *Proceedings of the 8th International Conference on Asphalt Pavements*, Vol. 1, pp. 663-672, Seattle, Washington.
2. Chen, Dar-Hao, Huang-Hsiung Lin, and F. Hugo, Application of VESYS3AM in Characterization of Permanent Deformation, *Journal of Pavement Engineering,* 2001.
3. Chen, Dar-Hao, Weijun Wang, F. Zhou, B. Kenis, S. Nazarian, and T. Scullion, *Rutting Prediction Using Calibrated Model with TxMLS and AASHTO Road Data*, 2nd International Conference on Accelerated Pavement Testing, September 26-29, 2004, Minneapolis, Minnesota.

APPENDIX A

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

1. Scope

1.1 This test method describes the laboratory preparation and testing procedures for the determination of permanent deformation and resilient modulus (M_r) of unbound granular base/subbase materials and subgrade soils for pavement performance prediction. The stress conditions used in the test represent the ranges of stress states likely to be developed beneath flexible pavements subjected to moving wheel loads. This test procedure has been adapted from the standard test methods given in the VESYS user manual, NCHRP1-28A Draft Report (unpublished), and AASHTO Designations T294-92, TP46, and T292-91.

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

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

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

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

1.6 This standard may involve hazardous materials, operations, and equipment. This standard does not purport to address all of the safety problems associated with its use. It is the responsibility of the user of this standard to consult and establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to use.

2. Referenced Documents

2.1 AASHTO Standards:

T88 Particle Size Analysis of Soils

T89 Determining the Liquid Limit of Soils

T90 Determining the Plastic Limit and the Plasticity Index of Soils

T100 Specific Gravity of Soils

T180 Moisture-Density Relations of Soils using a 454 kg (10 lb) Rammer and 457 mm (18-inch) Drop

T233 Density of Soil-in-Place by Block, Chunk or Core Sampling

T292-91 Resilient Modulus of Subgrade Soils and Untreated Base/Subbase Materials

T296 Strength Parameters of Soils by Triaxial Compression

T265 Laboratory Determination of Moisture Content of Soils

3. Terminology

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

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

3.3 Material Type 1 – This includes all unbound granular base and subbase materials and all untreated subgrade soils with maximum particle sizes greater than 9.5 mm (3/8-inch). All material greater than 25.4 mm (1.0-inch) shall be scraped off prior to testing. Materials classified as Type 1 shall be molded in either a 152 mm (6-inch) diameter mold or a 102 mm (4-inch) diameter mold. Materials classified as Type 1 shall be compacted by impact or vibratory compaction.

3.4 Material Type 2 – This includes all unbound granular base and subbase materials and all untreated subgrade soils that have a maximum particle size less than 9.5 mm (3/8-inch) and that meet the criteria of less than 10 percent passing the 75 μm (No. 200) sieve. Materials classified as Type 2 shall be molded in a 102 mm (4-inch) diameter mold and compacted by vibratory compaction.

3.5 Material Type 3 – This includes all untreated subgrade soils that have a maximum particle size less than 9.5 mm (3/8-inch) and that meet the criteria of more than 10 percent passing the 75 μm (No. 200) sieve. Materials classified as Type 3 shall be molded in a 102 mm (4 inch) diameter mold and compacted by impact compaction.

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

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

3.8 Loading Wave Form – Test specimens are loaded using a haversine load pulse with 0.1-second loading and 0.9-second rest period.

3.9 Maximum Applied Axial Load (P_{max}) – This is the load applied to the sample consisting of the contact load and cyclic load (confining pressure is not included), as follows:

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

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

3.11 Cyclic Axial Load – This is the repetitive load applied to a test specimen, as follows:

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

3.12 Maximum Applied Axial Stress (S_{max}) – This is the axial stress applied to the sample consisting of the contact stress and the cyclic stress (the confining stress is not included), as follows:

$$S_{max} = P_{max}/A$$

where: A = cross-sectional area of the sample.

3.13 Cyclic Axial Stress – Cyclic (resilient) applied axial stress is as follows:

$S_{cyclic} = P_{cyclic}/A$

3.14 Contact Stress ($S_{contact}$) – This is axial stress applied to a test specimen to maintain a positive contact between the specimen cap and the specimen, as follows:

$S_{contact} = P_{contact}/A$

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

$(S_{contact} + S_3)/S_3 = 1.2$

where: S_3 is the confining pressure.

3.15 S_3 is the applied confining pressure in the triaxial chamber (i.e., the minor principal stress σ_3).

3.16 e_r is the resilient (recoverable) axial deformation due to S_{cyclic}.

3.17 ε_r is the resilient (recoverable) axial strain due to S_{cyclic}, as follows:

$\varepsilon_r = e_r/L$

where: L = distance between measurement points for resilient axial deformation, e_r.

3.18 e_p is the permanent (unrecoverable) axial deformation due to S_{cyclic}.

3.19 ε_p is the permanent (unrecoverable) axial strain due to S_{cyclic}, as follows:

$\varepsilon_p = e_p/L$

where: L = distance between measurement points for permanent axial deformation, e_p.

3.20 Resilient modulus (M_r) is defined as:

$M_r = S_{cyclic}/\varepsilon_r$

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

3.22 Cycle duration is the time interval between the successive applications of a cyclic stress (usually 1.0 sec.).

4. Summary of Method

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

5. Significance and Use

5.1 The resilient modulus test results provide a basic constitutive relationship between stiffness and stress state of pavement materials for use in the structural analysis of layered pavement systems. Furthermore, initially repeated load tests can determine permanent deformation properties of pavement materials. The information is critical for pavement rutting performance prediction. The permanent deformation and resilient modulus tests simulate the conditions in a pavement with the application of moving wheel loadings.

6. Permanent Deformation and Resilient Modulus Test Apparatus

6.1 Triaxial Pressure Chamber – The pressure chamber contains the test specimen and the confining fluid during the test. Figure A1 shows a typical triaxial chamber suitable for use in resilient modulus testing of soils. The axial deformation is measured internally, directly on the specimen using normal gauges with rubber bands (Figure A2), an optical extensometer, non-contact sensors, or clamps. For soft and very soft subgrade specimens (i.e., $S_u < 36$ kPa or 750 psf, where S_u is the undrained shear strength of the soil), rubber bands or clamps should not be used since they may damage the specimen. However, a pair of linear variable differential transformers (LVDTs) extending between the top and bottom platens can be used to measure axial deformation of these weak soils.

6.1.1 Use air in the triaxial chamber as the confining fluid for all testing.

6.1.2 Make the chamber out of suitable translucent material (such as polycarbonate).

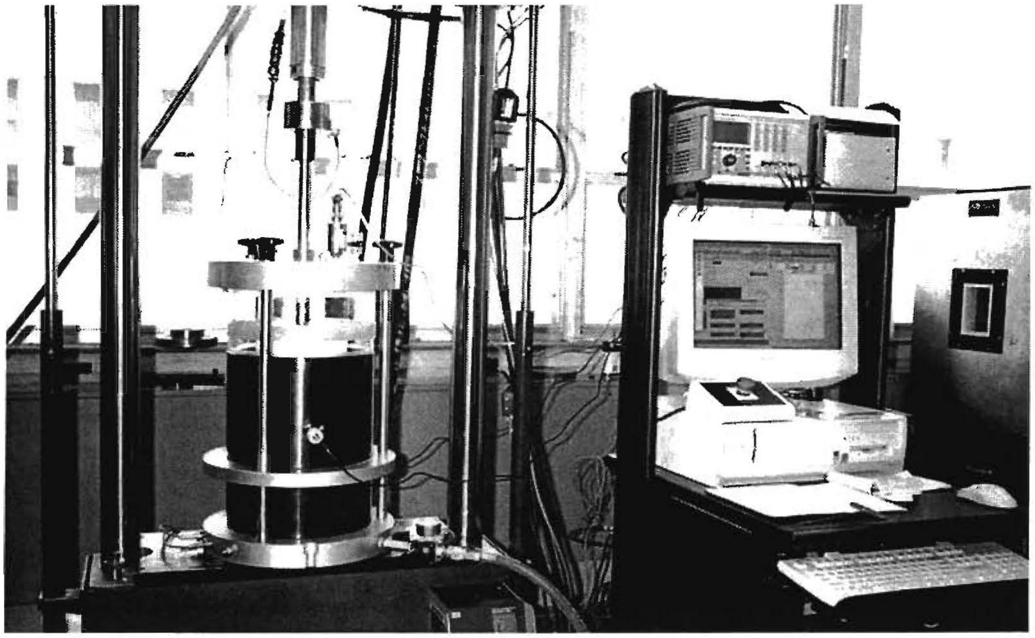


Figure A1. Triaxial Cell and Test System.

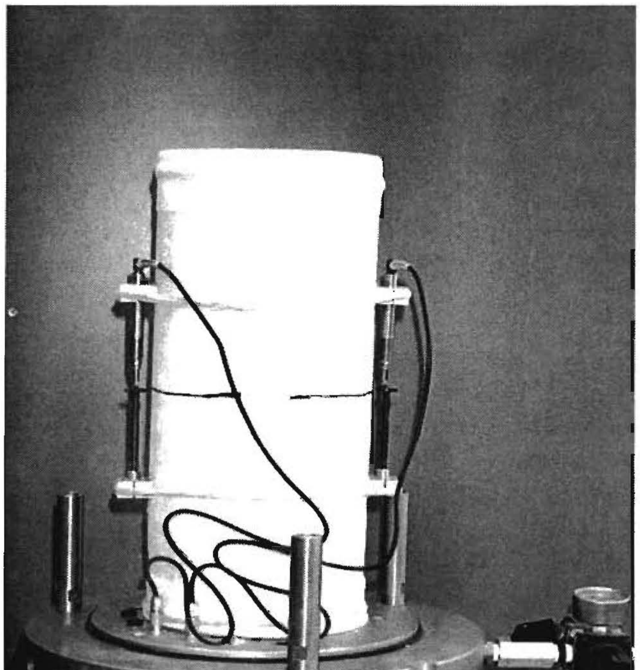


Figure A2. Sample with Instruments.

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

6.2.1 All conditioning and testing shall be conducted using a haversine-shaped load pulse. The electro-hydraulic system generated haversine waveform and the response waveform shall be displayed to allow the operator to adjust the gains to ensure they coincide during conditioning and testing.

6.3 Load and Specimen Response Measuring Equipment:

6.3.1 The axial load measuring device should be an electronic load cell, which is preferred to be located inside the triaxial cell. The load cell should have the capacities presented in Table A1.

Table A1. Load Cell Capacity.

Sample diameter mm (inch)	Max. Load Capacity kN (lb)	Required Accuracy N (lb)
102 (4.0)	8.9 (2000)	±17.8 (±4)
152 (6.0)	22.24 (5000)	±22.24 (±5)

Note 1 – During periods of permanent deformation and resilient modulus testing, the load cell shall be monitored and checked once every two weeks or after every 50 permanent deformation and resilient modulus tests with a calibrated proving ring to assure that the load cell is operating properly. An alternative to using a proving ring is to insert an additional calibrated load cell and independently measure the load applied by the original cell. Additionally, the load cell shall be checked at any time there is a suspicion of a load cell problem. The testing shall not be conducted if the testing system is found to be out of calibration.

6.3.2 The chamber pressures shall be monitored with conventional pressure gauges, manometers, or pressure transducers accurate to 0.69 kPa (0.1 psi).

6.3.3 Axial Deformation: Measured axial deformation with displacement transducers referenced to gauge points contacting the specimen with a rubber band as shown in Figure A2. Measure deformation over approximately the middle one-half of the specimen. Axial deformations shall be measured at a minimum of two locations 180° apart (in plan view) and a pair of spring-loaded LVDTs are placed on the specimen at one-quarter point. Spring-loaded LVDTs shall be used to maintain a positive contact between the LVDTs and the surface on which the tips of the transducers rest.

Note 2– Table A2 summarizes the specifications for spring-loaded LVDTs.

Table A2. Specifications for Axial LVDTs.

Material/specimen size		Min. range (inch)	Approximate resilient specimen displacement (inch)
Aggregate base	6-inch diameter specimen	±0.25	0.001
	4-inch diameter specimen	±0.10	0.00065
Subgrade soil (sand and cohesive)	4-inch diameter specimen	±0.25	0.0014

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

Note 3 – Misalignment or dirt on the shaft of the transducer can cause the LVDT shafts to stick. The laboratory technician shall depress and release each LVDT back and forth a number of times prior to each test to assure that they move freely and are not sticking. A cleaner/lubricant specified by the manufacturer shall be applied to the transducer shafts on a regular basis.

6.3.4 Data Acquisition: An analog-to-digital (A/D) data acquisition system is required. The overall system should include automatic data reduction to minimize production. Suitable signal excitation, conditioning, and recording equipment are required for simultaneous recording of axial load and deformations. The system should meet or exceed the following additional requirements: (1) 25 μs A/D conversion time; (2) 12-bit resolution; (3) single- or multiple-channel throughput (gain = 1), 30 kHz; (4) software selectable gains; (5) measurement accuracy of full scale (gain = 1) of ±0.02 percent; and (6) non-linearity (LSBS) of ±0.5 percent. The signal shall be clean and free of noise. Filtering the output signal during or after data acquisition is discouraged. If a filter is used, it should have a frequency higher than 10 to 20 Hz. A supplemental study should be made to ensure correct peak readings are obtained from filtered data compared to unfiltered data. A minimum of 200 data points from each LVDT shall be recorded per load cycle.

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

6.5 Miscellaneous Apparatus: This includes calipers, micrometer gauge, steel rule (calibrated to 0.5 mm [0.02-inch]), rubber membranes from 0.25 to 0.79 mm (0.02- to 0.031-inch) thickness, rubber O-rings, vacuum source with bubble chamber and regulator, membrane expander, porous stones (subgrade), 6.4 mm (0.25-inch) thick porous stones or bronze discs (base/subbase), scales, moisture content cans, and data sheets.

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

7. Preparation of Test Specimens

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

7.1.1 Use 152 mm (6.0-inch) diameter and 305 mm (12-inch) high specimens for all materials with maximum particle sizes greater than 19 mm (0.75-inch). All material greater than 25.4 mm (1.0-inch) shall be scalped off prior to testing.

7.1.2 Use 102 mm (4.0-inch) diameter and 204 mm (8.0-inch) high specimens for all materials with maximum particle sizes less than 19 mm (0.75-inch).

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

7.2.1 Moisture Content: For in situ materials, the moisture content of the laboratory compacted specimen shall be the in situ moisture content for that layer obtained in the field using T238. If data are not available on in situ moisture content, refer to section 7.2.3.

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

7.2.2 Compacted Density: The density of a compacted specimen shall be the in-place dry density obtained in the field for that layer using T239 or other suitable methods. If these data are not available on in situ density, then refer to section 7.2.3.

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

7.2.3 If either the in situ moisture content or the in-place dry density is not available, then use the optimum moisture content and 95 percent of the maximum dry density by using T180 for the base/subbase and 95 percent of T99 for the subgrade.

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

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

7.2.4 Sample Reconstitution – Appendix A gives provisions for the reconstitution of specimens for all materials. The target moisture content and density to use in determining needed material qualities are given in section 7.2. Appendix A also provides guidelines to obtain a sufficient amount of material to prepare the appropriate specimen type at the designated moisture content and density. After completing this step, specimen compaction can begin.

7.3 Compaction Methods and Equipment for Reconstituting Specimens:

7.3.1 Specimens of Type 1 materials shall be compacted by vibratory or impact compaction. T292-91 gives the general method of vibratory compaction. T292 gives the general method of impact compaction.

7.3.2 Specimens of Type 2 materials shall be compacted by vibratory compaction. The general method of vibratory compaction also is presented in T292-92.

7.3.3 Specimens of Type 3 materials shall be compacted by impact compaction. The general method of impact compaction is given in T292-91.

8. Test Procedure

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

8.1 Base/Subbase Materials: The procedure described in this section applies to all unbound granular base and subbase materials.

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

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

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

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

8.1.5 Apply the specified conditioning confining pressure of 103.5 kPa (15.0 psi) to the test specimen. Apply a contact stress equal to 20 percent of the confining pressure to the specimen so that the load piston stays in contact with the top platen at all times.

8.1.6 Preconditioning: Apply 100 repetitions of a load equivalent to a maximum axial stress of 41.4 kPa (6 psi) and a corresponding cyclic stress of 20.7 kPa (3 psi) using a haversine-shaped, 0.1-second load pulse followed by a 0.9-second rest period.

Permanent Deformation Test

8.1.7 Apply the haversine loading (P_{cyclic}) equivalent to a maximum axial stress of 227.7 kPa (33 psi) and a corresponding cyclic stress of 207 kPa (30 psi) using a haversine shaped, 0.1-second load pulse followed by a 0.9-second rest period, and continue until 10,000 cycles (2.8 hours) or until the specimen fails and the vertical permanent strain reaches 5 percent during the testing, whichever comes first. The total number of cycles or the testing time will depend on the stress levels applied.

8.1.8 During the load applications, record the load applied and the axial deformation measured from two LVDTs through the data acquisition system. Signal-to-noise ratio should be at least 10. All data should be collected in real time and collected/processed so as to minimize phase errors due to sequential channel sampling. In order to save storage space during data acquisition for 10,000 cycles, we recommend using the data acquisition of the cycles shown in Table A3.

Table A3. Suggested Data Collection for Triaxial Repeated Load Permanent Deformation Test.

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

Resilient Modulus Test

8.1.9 Specimen Testing: If the vertical permanent strain has not reached 5 percent or failed during permanent deformation test, use the same specimen to perform the resilient modulus test following the load sequence shown in Table A4. Begin by decreasing the maximum axial stress to 14.5 kPa (2.1 psi) (Sequence No. 1, Table A4) and set the confining pressure to 20.7 kPa (3 psi). If the vertical permanent strain has reached 5 percent or failed during the permanent deformation test, mold a new specimen, then go back to section 8.1.1. In addition, reduce the load repetitions from 10,000 to 5000 during repeated load permanent deformation testing. If the sample again reaches 5 percent total vertical permanent strain during the repeated load test, then terminate the test. No further testing of this material is necessary. If not, perform the resilient modulus test following the load sequence shown in Table A4. Begin by decreasing the maximum axial stress to 14.5 kPa (2.1 psi) (Sequence No. 1, Table A4) and set the confining pressure to 20.7 kPa (3 psi).

Table A4. Permanent Deformation and Resilient Modulus Test Sequence for Granular Base and Subbase.

Sequence	Confining Pressure		Contact Stress		Cyclic Stress		Maximum Stress		$N_{rep.}$
	KPa	psi	kPa	Psi	kPa	psi	kPa	psi	
Preconditioning	103.5	15.0	20.7	3.0	20.7	3.0	41.4	6.0	100
Permanent Deformation	103.5	15.0	20.7	3.0	207.0	30.0	227.7	33.0	10,000
1	20.7	3.0	4.1	0.6	10.4	1.5	14.5	2.1	100
2	41.4	6.0	8.3	1.2	20.7	3.0	29.0	4.2	100
3	69.0	10.0	13.8	2.0	34.5	5.0	48.3	7.0	100
4	103.5	15.0	20.7	3.0	51.8	7.5	72.5	10.5	100
5	138.0	20.0	27.6	4.0	69.0	10.0	96.6	14.0	100
6	20.7	3.0	4.1	0.6	20.7	3.0	24.8	3.6	100
7	41.4	6.0	8.3	1.2	41.4	6.0	49.7	7.2	100
8	69.0	10.0	13.8	2.0	69.0	10.0	82.8	12.0	100
9	103.5	15.0	20.7	3.0	103.5	15.0	124.2	18.0	100
10	138.0	20.0	27.6	4.0	138.0	20.0	165.6	24.0	100
11	20.7	3.0	4.1	0.6	41.4	6.0	45.5	6.6	100
12	41.4	6.0	8.3	1.2	82.8	12.0	91.1	13.2	100
13	69.0	10.0	13.8	2.0	138.0	20.0	151.8	22.0	100
14	103.5	15.0	20.7	3.0	207.0	30.0	227.7	33.0	100
15	138.0	20.0	27.6	4.0	276.0	40.0	303.6	44.0	100
16	20.7	3.0	4.1	0.6	62.1	9.0	66.2	9.6	100
17	41.4	6.0	8.3	1.2	124.2	18.0	132.5	19.2	100
18	69.0	10.0	13.8	2.0	207.0	30.0	220.8	32.0	100
19	103.5	15.0	20.7	3.0	310.5	45.0	331.2	48.0	100
20	138.0	20.0	27.6	4.0	414.0	60.0	441.6	64.0	100
21	20.7	3.0	4.1	0.6	103.5	15.0	107.6	15.6	100
22	41.4	6.0	8.3	1.2	207.0	30.0	215.3	31.2	100
23	69.0	10.0	13.8	2.0	345.0	50.0	358.8	52.0	100
24	103.5	15.0	20.7	3.0	517.5	75.0	538.2	78.0	100
25	138.0	20.0	27.6	4.0	690.0	100.0	717.6	104.0	100
26	20.7	3.0	4.1	0.6	144.9	21.0	149.0	21.6	100
27	41.4	6.0	8.3	1.2	289.8	42.0	298.1	43.2	100
28	69.0	10.0	13.8	2.0	483.0	70.0	496.8	72.0	100
29	103.5	15.0	20.7	3.0	724.5	105.0	745.2	108.0	100
30	138.0	20.0	27.6	4.0	966.0	140.0	993.6	144.0	100

8.1.10 Apply 100 repetitions of the corresponding cyclic axial stress using a haversine-shaped load pulse consisting of a 0.1-second load followed by a 0.9 second rest period. Record the average recovered deformations from each LVDT separately for the last five cycles.

8.1.11 Increase the maximum axial stress to 30 kPa (4.2 psi) and the confining pressure to 41.4 kPa (6 psi) (Sequence No.2 , table A4) and repeat the previous step at this new stress level.

8.1.12 Continue the test for the remaining stress sequences in Table A4 (3 to 30) recording the vertical recovered deformation. If at any time the total permanent strain of the sample exceeds 5 percent, stop the test and report the result on the appropriate worksheet.

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

8.1.14 Remove the membrane from the specimen and use the entire specimen to determine moisture content in accordance with T265.

8.2 Coarse-Grained Subgrade Soils: This procedure is used for all laboratory compacted specimens of subgrade soils for which the percent passing 75 µm (No. 200) sieve is less than 35 percent. Reconstructed specimens will usually be compacted directly on the pedestal of the triaxial cell.

8.2.1 Assembly of the triaxial cell: refer to section 8.1.1.

8.2.2 Set up the axial displacement measurement system and verify it is working properly.

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

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

8.2.5 Apply the specified conditioning confining pressure of 27.6 kPa (4.0 psi) to the test specimen. Apply contact stress equal to 20 percent of the confining pressure to the specimen so that the load piston stays in contact with the top platen at all times.

8.2.6 Preconditioning: Apply 100 repetitions of a load equivalent to a maximum axial stress of 12.4 kPa (1.8 psi) and a corresponding cyclic stress of 6.9 kPa (1 psi) using a haversine-shaped, 0.2-second load pulse followed by a 0.8-second rest period.

Permanent Deformation Test

8.2.7 Apply the haversine loading (P_{cyclic}) equivalent to a maximum axial stress of 60.7 kPa (8.8 psi) and a corresponding cyclic stress of 55.2 kPa (8 psi) using a haversine-shaped, 0.2-second load pulse followed by a 0.8-second rest period, and continue until 10,000 cycles (2.8 hours) or until the specimen fails and/or the vertical permanent strain reaches 5 percent during the testing, whichever comes first. The total number of cycles or the testing time will depend on the stress levels applied.

8.2.8 During the load applications, record the load applied and the axial deformation measured from two LVDTs through the data acquisition system. Collect all data in real time and collect/process so as to minimize phase errors due to sequential channel sampling. In order to save storage space during data acquisition for 10,000 cycles, we recommend using the data acquisition of the cycles shown in Table A5.

Resilient Modulus Test

8.2.9 Specimen Testing: If the vertical permanent strain has not reached 5 percent or failed during permanent deformation test, use the same specimen to perform the resilient modulus test following the load sequence shown in Table A6. Begin by decreasing the maximum axial stress to 9.66 kPa (1.4 psi) (Sequence No. 1, Table A6) and set the confining pressure to 13.8 kPa (2 psi). If the vertical permanent strain has reached 5 percent or failed during permanent deformation test, mold a new specimen, then go back to section 8.2.1. In addition, reduce the load repetitions from 10,000 to 5000 during repeated load permanent deformation test. If the sample again reaches 5 percent total vertical permanent strain during repeated load test, then terminate the test. No further testing of this material is necessary. If not, perform the resilient modulus test following the load sequence shown in Table A6. Begin by decreasing the maximum axial stress to 9.66 kPa (1.4 psi) (Sequence No. 1, Table A6) and set the confining pressure to 13.8 kPa (2 psi).

Table A5. Suggested Data Collection for Triaxial Repeated Load Permanent Deformation Test.

Data Collection During Cycles	Data Collection During Cycles	Data Collection During Cycles	Data Collection During Cycles
1-15	450	1300	4000
20	500	1400	4500
30	550	1500	5000
40	600	1600	5500
60	650	1700	6000
80	700	1800	6500
100	750	1900	7000
130	800	2000	7500
160	850	2200	8000
200	900	2400	8500
250	950	2600	9000
300	1000	2800	9500
350	1100	3000	10,000
400	1200	3500	

8.2.10 Apply 100 repetitions of the corresponding cyclic axial stress using a haversine-shaped load pulse consisting of a 0.2-second load followed by a 0.8-second rest period. Record the average recovered deformations from each LVDT separately for the last five cycles.

8.2.11 Increase the maximum axial stress to 19.32 kPa (2.8 psi) and set the confining pressure to 27.6 kPa (4 psi) (Sequence No. 2, Table A6) and repeat the previous step at this new stress level.

8.2.12 Continue the test for the remaining stress sequences in Table A6 (3 to 20) recording the vertical recovered deformation. If at any time the total permanent strain of the sample exceeds 5 percent, stop the test and report the result on the appropriate worksheet.

Table A6. Permanent Deformation and Resilient Modulus Test Sequence for Granular Subgrades.

Sequence	Confining Pressure		Contact Stress		Cyclic Stress		Maximum Stress		N_{rep}
	KPa	psi	kPa	psi	kPa	Psi	kPa	psi	
Preconditioning	27.6	4.0	5.5	0.8	6.9	1.0	12.4	1.8	100
Permanent Deformation	27.6	4.0	5.5	0.8	55.2	8.0	60.7	8.8	10,000
1	13.8	2.0	2.8	0.4	6.9	1.0	9.7	1.4	100
2	27.6	4.0	5.5	0.8	13.8	2.0	19.3	2.8	100
3	41.4	6.0	8.3	1.2	20.7	3.0	29.0	4.2	100
4	55.2	8.0	11.0	1.6	27.6	4.0	38.6	5.6	100
5	82.8	12.0	16.6	2.4	41.4	6.0	58.0	8.4	100
6	13.8	2.0	2.8	0.4	13.8	2.0	16.6	2.4	100
7	27.6	4.0	5.5	0.8	27.6	4.0	33.1	4.8	100
8	41.4	6.0	8.3	1.2	41.4	6.0	49.7	7.2	100
9	55.2	8.0	11.0	1.6	55.2	8.0	66.2	9.6	100
10	82.8	12.0	16.6	2.4	82.8	12.0	99.4	14.4	100
11	13.8	2.0	2.8	0.4	27.6	4.0	30.4	4.4	100
12	27.6	4.0	5.5	0.8	55.2	8.0	60.7	8.8	100
13	41.4	6.0	8.3	1.2	82.8	12.0	91.1	13.2	100
14	55.2	8.0	11.0	1.6	110.4	16.0	121.4	17.6	100
15	82.8	12.0	16.6	2.4	165.6	24.0	182.2	26.4	100
16	13.8	2.0	2.8	0.4	41.4	6.0	44.2	6.4	100
17	27.6	4.0	5.5	0.8	82.8	12.0	88.3	12.8	100
18	41.4	6.0	8.3	1.2	124.2	18.0	132.5	19.2	100
19	55.2	8.0	11.0	1.6	165.6	24.0	176.6	25.6	100
20	82.8	12.0	16.6	2.4	248.4	36.0	265.0	38.4	100

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

8.2.14 Remove the membrane from the specimen and use the entire specimen to determine moisture content in accordance with T265.

8.3 Cohesive Subgrade Soils: This procedure is used for all laboratory compacted specimens of subgrade soils for which the percent passing 75 μm (No. 200) sieve is greater than 35 percent. Reconstructed specimens will usually be compacted directly on the pedestal of the triaxial cell.

8.3.1 Assembly of the triaxial cell: refer to section 8.1.1.

8.3.2 Stiff to Very Stiff Specimens: For stiff and very stiff cohesive specimens ($S_u >$ 36 kPa [750 psf], here S_u designates the undrained shear strength of the soil), measured preferably axial deformation either directly on the specimen or else between the solid end platens using grouted specimen ends.

8.3.3 Soft Specimens: The axial deformation of soft subgrade soils ($S_u <$ 36 kPa [750 psf]) should not be measured using rubber bands around on the specimen. If the measured resilient modulus is less than 69,000 kPa (10,000 psi), axial deformation can be measured between top and bottom platens. An empirical correction is not required for irregular specimen end contacts for these low modulus soils. If the resilient modulus is greater than 69,000 kPa (10,000 psi), follow the procedure in section 8.3.2.

8.3.4 Install Axial Displacement Device: Carefully install the axial displacement instrumentation selected under section 8.3.2 or 8.3.3. For top-to-bottom displacement measurement, attach the LVDTs or proximity gauges on steel or aluminum bars extending between the top and bottom platens. If using rubber bands or clamps, place rubber band or clamps at the one-quarter points of the specimen using two height gauges to ensure that clamps are positioned horizontally at correct height. Each height gauge can consist of two circular aluminum rods machined to the correct length. Place these rods on each side of the clamp to ensure proper location. Then ensure the displacement instrumentations are working properly by displacing each device and observing the resulting voltage output as shown by the data acquisition system.

8.3.5 Assembly of the triaxial cell: Refer to section 8.1.1.

8.3.6 Set up the axial displacement measurement system and verify it is working properly.

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

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

8.3.9 Apply the specified conditioning confining pressure of 27.6 kPa (4.0 psi) to the test specimen. Apply a contact stress equal to 20 percent of the confining pressure to the specimen so that the load piston stays in contact with the top platen at all times.

8.3.10 Preconditioning: Apply 100 repetitions of a load equivalent to a maximum axial stress of 12.4 kPa (1.8 psi) and a corresponding cyclic stress of 6.9 kPa (1 psi) using a haversine-shaped, 0.2-second load pulse followed by a 0.8-second rest period.

Permanent Deformation Test

8.3.11 Apply the haversine loading (P_{cyclic}) equivalent to a maximum axial stress of 53.8 kPa (7.8 psi) and a corresponding cyclic stress of 48.3 kPa (7 psi) using a haversine-shaped, 0.2-second load pulse followed by a 0.8-second rest period and continue until 10,000 cycles (2.8 hours) or until the specimen fails and the vertical permanent strain reaches 5 percent during the testing, whichever comes first. The total number of cycles or the testing time will depend on the stress levels applied.

8.3.12 During the load applications, record the load applied and the axial deformation measured from all LVDTs through the data acquisition system. Signal-to-noise ratio should be at least 10. Collect all data in real time and collect/process so as to minimize phase errors due to sequential channel sampling. In order to save storage space during data acquisition for 10,000 cycles, we recommend using the data acquisition of the cycles shown in Table A7.

Resilient Modulus Test

8.3.13 Specimen Testing: If the vertical permanent strain has not reached 5 percent or failed during permanent deformation test, use the same specimen to perform the resilient modulus test following the load sequence shown in Table A6.

Table A7. Suggested Data Collection for Triaxial Repeated Load Permanent Deformation Test.

Data Collection During Cycles	**Data Collection During Cycles**	**Data Collection During Cycles**	**Data Collection During Cycles**
1-15	450	1300	4000
20	500	1400	4500
30	550	1500	5000
40	600	1600	5500
60	650	1700	6000
80	700	1800	6500
100	750	1900	7000
130	800	2000	7500
160	850	2200	8000
200	900	2400	8500
250	950	2600	9000
300	1000	2800	9500
350	1100	3000	10,000
400	1200	3500	

Begin by decreasing the maximum axial stress to 38.6 kPa (5.6 psi) (Sequence No. 1, Table A8) and set the confining pressure to 55.2 kPa (8 psi).

If the vertical permanent strain has reached 5 percent or failed during permanent deformation test, mold a new specimen, then go back to section 8.3.1. In addition, reduce the load repetitions from 10,000 to 5000 during repeated load permanent deformation test. If the sample again reaches 5 pecent total vertical permanent strain during repeated load test, then terminate the test. No further testing of this material is necessary. If not, perform the resilient modulus test following the load sequence shown in Table A4. Begin by decreasing the maximum axial stress to 38.6 kPa (5.6 psi) (Sequence No. 1, Table A8) and set the confining pressure to 55.2 kPa (8 psi).

8.3.14 Apply 100 repetitions of the corresponding cyclic axial stress using a haversine-shaped load pulse consisting of a 0.2-second load followed by a 0.8-

Table A8. Permanent Deformation and Resilient Modulus Test Sequence for Fine-Grained Subgrades.

Sequence	Confining Pressure		Contact Stress		Cyclic Stress		Maximum Stress		$N_{rep.}$
	kPa	psi	kPa	psi	kPa	psi	kPa	psi	
Preconditioning	27.6	4.0	5.5	0.8	6.9	1.0	12.4	1.8	100
Permanent Deformation	27.6	4.0	5.5	0.8	48.3	7.0	53.8	7.8	10,000
1	55.2	8.0	11.0	1.6	27.6	4.0	38.6	5.6	100
2	41.4	6.0	8.3	1.2	27.6	4.0	35.9	5.2	100
3	27.6	4.0	5.5	0.8	27.6	4.0	33.1	4.8	100
4	13.8	2.0	2.8	0.4	27.6	4.0	30.4	4.4	100
5	55.2	8.0	11.0	1.6	48.3	7.0	59.3	8.6	100
6	41.4	6.0	8.3	1.2	48.3	7.0	56.6	8.2	100
7	27.6	4.0	5.5	0.8	48.3	7.0	53.8	7.8	100
8	13.8	2.0	2.8	0.4	48.3	7.0	51.1	7.4	100
9	55.2	8.0	11.0	1.6	69.0	10.0	80.0	11.6	100
10	41.4	6.0	8.3	1.2	69.0	10.0	77.3	11.2	100
11	27.6	4.0	5.5	0.8	69.0	10.0	74.5	10.8	100
12	13.8	2.0	2.8	0.4	69.0	10.0	71.8	10.4	100
13	55.2	8.0	11.0	1.6	96.0	14.0	107.6	15.6	100
14	41.4	6.0	8.3	1.2	96.0	14.0	104.9	15.2	100
15	27.6	4.0	5.5	0.8	96.0	14.0	102.1	14.8	100
16	13.8	2.0	2.8	0.4	96.0	14.0	99.4	14.4	100

second rest period. Record the average recovered deformations from each LVDT separately for the last five cycles.

8.3.15 Decrease the maximum axial stress to 35.9 kPa (5.2 psi) and set the confining pressure to 41.4 kPa (6 psi) (Sequence No. 2, Table A8) and repeat the previous step at this new stress level.

8.3.16 Continue the test for the remaining stress sequences in Table A8 (3 to 16) recording the vertical recovered deformation. If at any time the total permanent strain of the sample exceeds 5 percent, stop the test and report the result on the appropriate worksheet.

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

8.3.18 Remove the membrane from the specimen and use the entire specimen to determine moisture content in accordance with T265.

9. Calculations

Calculation of Permanent Strain

9.1 Calculate the average axial deformation for each specimen by averaging the readings from the two axial LVDTs. Convert the average deformation values to total axial strain by dividing by the gauge length, L (152 mm [6-inch]) for 152 mm (4-inch) diameter sample; 102 mm (4-inch) for 102 mm (4-inch) diameter sample. Figure A3 shows typical total axial strain versus time.

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

9.3 Plot the cumulative axial permanent strain versus the number of loading cycles in log space (Figure A4). Determine the permanent deformation parameters, intercept (a) and slope (b), from the linear portion of the permanent strain curve (log-log scale), which Figure A4 also demonstrates.

9.4 Compute the rutting parameters: ALPHA, GNU.

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

$$\alpha = 1 - b$$

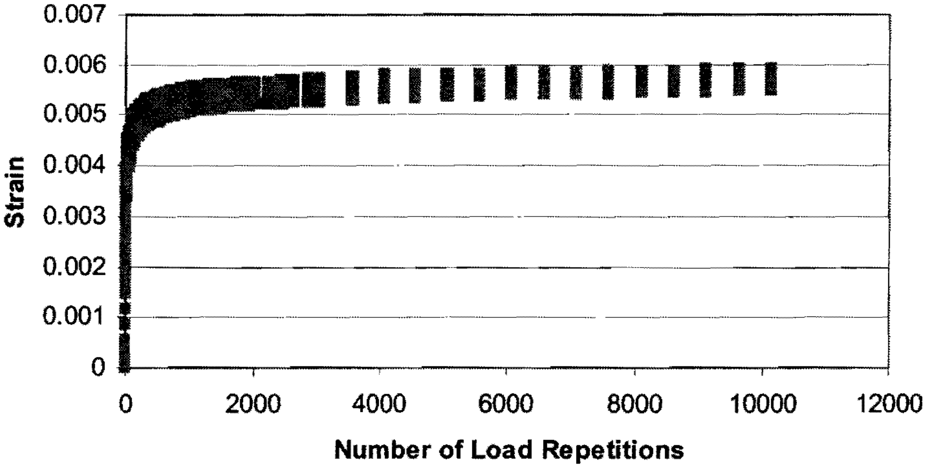


Figure A3. Triaxial Repeated Load Test Results: Strain vs. Number of Load Repetitions.

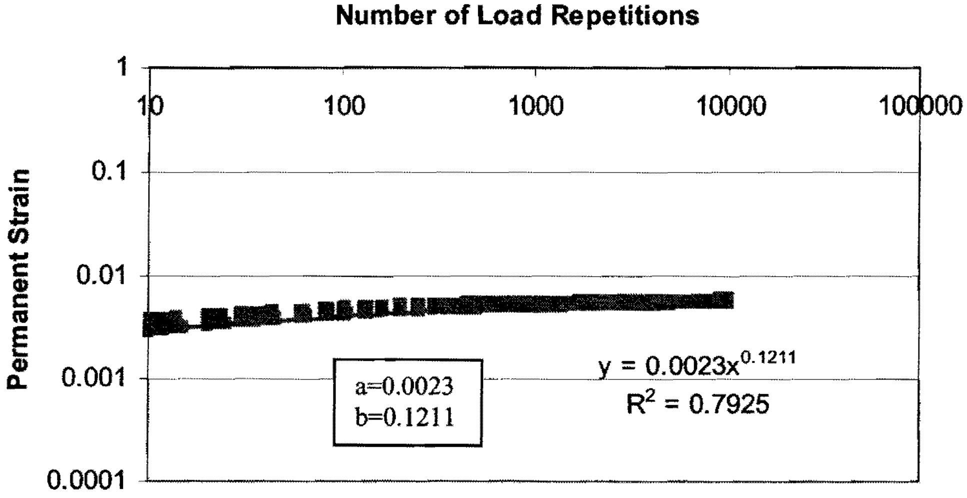


Figure A4. Permanent Strain vs. Number of Load Repetitions.

Calculation of Resilient Modulus

9.5 Perform the calculations to obtain resilient modulus values. The resilient modulus is computed from each of the last five cycles of each load sequence and then averaged. The data reduction processes should be fully automated to minimize the chance for human error.

9.6 Fit using nonlinear regression techniques from the following resilient modulus model to the data obtained from the applied procedure. Equation for normalized log-log k_1, k_2, k_3, k_6, k_7 model is as follows:

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

$k_1, k_2 \geq 0$

$k_3, k_6 \leq 0$

$k_7 \geq 1$

where:

M_R = Resilient Modulus

θ = Bulk Stress, $\theta = \sigma_1 + \sigma_2 + \sigma_3$

τ_{oct} = Octahedral Shear Stress,

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

$\sigma_1, \sigma_2, \sigma_3$ = Principal Stresses

k_i = Regression Constants

p_a = Atmospheric Pressure (14.7 psi)

Assign initial values of $k_6 = 0$ and $k_7 = 1$ restrain all regression constants according to the model. Report the constants k_1, k_2, k_3, k_6, and k_7, the ratio of the standard error of estimate to the standard deviation, and the square of the correlation coefficient.

10. Report

10.1 Permanent Deformation Test:

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

10.2 Resilient Modulus Test:

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

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

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

10.2.4 Report nonlinear resilient modulus model and the model parameters: k_1, k_2, k_3, k_6, and k_7.

APPENDIX B

VESYS TEST PROTOCOL FOR ASPHALT MIXES

1. **Test Samples**

   1.1 Size

   Perform testing on 100 mm (4-inch) diameter by 150 mm (6-inch) or more high test samples from laboratory or cores from the field.

   1.2 Aging

   For laboratory compacted samples, age mixture in accordance with the short-term oven aging procedure in AASHTO PP2.

   1.3 Gyratory Specimens

   For laboratory compacted samples, prepare 150 mm (6-inch) high samples to the required air void content in accordance with AASHTO TP-4. Figure B1 shows gyratory compactor.

   1.4 End Preparation

   The ends of all test samples shall be smooth and perpendicular to the axis of the specimen. Prepare the ends of the samples by milling with a single- or double-bladed saw. To ensure that the sawed samples have parallel ends, the sample ends shall have a cut surface waviness height within a tolerance of ±0.05 mm (0.02-inch) across any diameter.

   1.5 Air Void Content

   Determine the air void content of the final test sample in accordance with AASHTO T269. Reject samples with air voids that differ by more than 0.5 percent from the target air voids.

   1.6 Replicates

   The number of test samples required depends on the number of axial strain measurements made per sample and the desired accuracy of the average permanent deformation. Normally, two replicates are acceptable for each sample with two LVDTs.

2. **Test Sample Instrumentation**

   2.1 Attach mounting studs for the axial LVDTs to both sides of the sample with 180° intervals (in plan view) using epoxy cement (Figure B2). Make sure the studs are in the alignment.

Figure B1. Superpave Gyratory Compactor.

Figure B2. Samples with Studs.

2.2 The gauge length for measuring axial deformations shall be 100 mm ± 1 mm (4-inch ± 0.04-inch). The gauge length is normally measured between the stud centers.

3. Test Procedures

3.1 The recommended test protocol for ALPHA and GNU used in the VESYS program consists of testing the asphalt mix at two temperatures with a specified stress level. Table B1 shows the recommended test temperatures and associated stress level.

Table B1. Recommended Test Temperatures and Associated Stress Level.

Test Temperature (°F)	Test Stress Level (psi)
77	30
104	20

3.2 Place the test sample in the environmental chamber and allow it to equilibrate to the specified testing temperature. A dummy specimen with a temperature sensor mounted at the center can be monitored to determine when the specimen reaches the specified test temperature. In the absence of the dummy specimen, Table B2 provides simple recommended temperature equilibrium times for samples starting from room temperature (77 °F).

Table B2. Recommended Equilibrium Times.

Test Temperature (°F)	Time (min.)
77	10
104	30

3.3 After reaching temperature equilibrium, place one of the friction-reducing end treatments on top of the platen at the bottom of the loading frame. Place the sample on top of the lower end treatment, and mount the axial LVDTs to the studs glued to the sample. Adjust the LVDT to near the end of its linear range to allow the full range to be available for the accumulation of compressive permanent deformation.

3.4 Place the upper friction-reducing end treatment and platen on top of the sample. Center the specimen with the load actuator visually in order to avoid eccentric loading.

3.5 Apply a contact load equal to 5 percent of the total load level that will be applied to the specimen.

3.6 Close the environmental chamber and allow sufficient time (normally 10 to 15 minutes) for the temperature to stabilize within the specimen and the chamber.

3.7 After the time required for the sample to reach the testing temperature, apply the haversine load which yields the desired stress on the specimen. The procedure uses a loading cycle of 1.0 Hz frequency, and consists of applying a 0.1-second haversine load followed by a 0.9-second rest period. The maximum applied load (P_{max}) is the maximum total load applied to the sample, including the contact and cyclic load: $P_{max} = P_{contact} + P_{cyclic}$.

3.8 The contact load ($P_{contact}$) is the vertical load placed on the sample to maintain a positive contact between loading strip and the sample: $P_{contact} = 0.05 \times P_{max}$.

3.9 The cyclic load (P_{cyclic}) is the load applied to the test sample which is used to calculate the permanent deformation parameters: $P_{cyclic} = P_{max} + P_{contact}$.

3.10 Apply the haversine loading (P_{cyclic}) and continue until 5000 cycles or until the sample fails and results in excessive tertiary deformation to the sample, whichever comes first.

3.11 During the load applications, record the load applied and the axial deflection measured from all LVDTs through the data acquisition system. Collect all data in real time and collect so as to minimize phase errors due to sequential channel sampling. Table B3 shows the recommended data acquisition of the cycles.

Table B3. Suggested Data Collection for VESYS Rutting Test.

Data Collected during Cycles	Data Collected during Cycles	Data Collected during Cycles
1 through 10	598 through 600	2723 through 2725
18 through 20	698 through 700	2998 through 3000
28 through 30	798 through 800	3248 through 3250
48 through 50	898 through 900	3498 through 3500
78 through 80	998 through 1000	3723 through 3725
98 through 100	1248 through 1250	3998 through 4000
148 through 150	1498 through 1500	4248 through 4250
198 through 200	1723 through 1725	4498 through 4500
298 through 300	1998 through 2000	4723 through 4725
398 through 400	2248 through 2250	4998 through 5000
498 through 500	2498 through 2500	

4. Calculations

4.1 Calculate the average axial deformation for each specimen by averaging the readings from the two axial LVDTs. Convert the average deformation values to total axial strain by dividing by the gauge length (100 mm [4-inch]).

4.2 Compute the cumulative axial permanent strain and resilient strain (ε_r) at 100th load repetition.

4.3 Plot the cumulative axial permanent strain versus number of loading cycles in log-log space. Determine the permanent deformation parameters, intercept (a) and slope (b), from the linear portion of the permanent strain curve.

4.4 Compute the rutting parameters: ALPHA, GNU.

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

$$\alpha = 1 - b$$

5. Report

Report all sample information including mix identification, dates of manufacturing (or coring) and testing, sample diameter and length, volumetric properties, stress levels used, and axial permanent deformation parameters: α, μ (or ε_r, a, b).

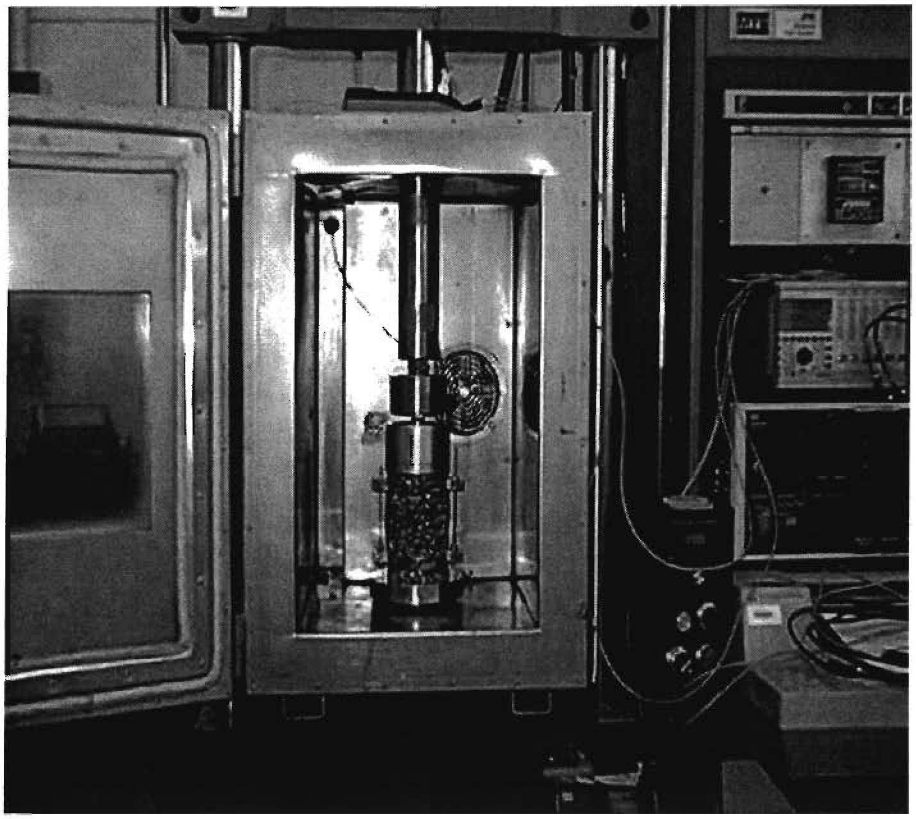


Figure B3. Schematic of Repeated Load Permanent Deformation Test.

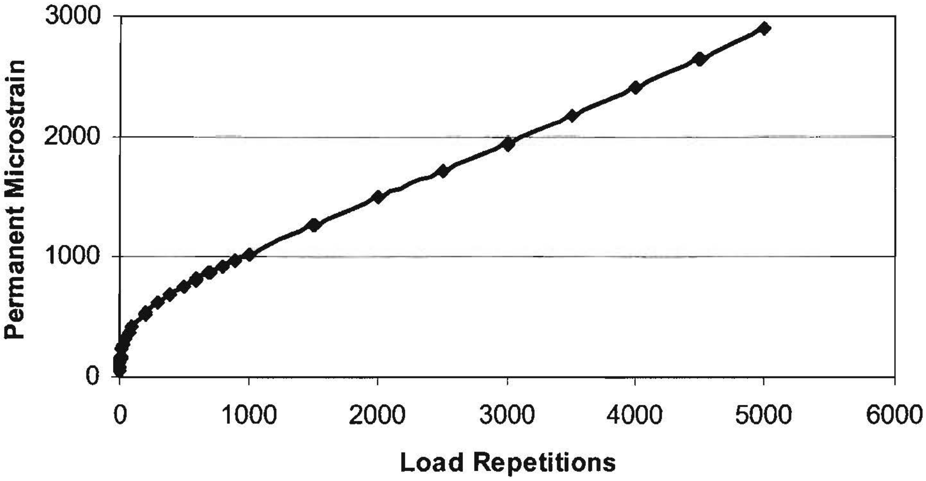


Figure B4. Cumulative Permanent Strain vs. Loading Cycles from a Repeated Load Permanent Deformation Test.

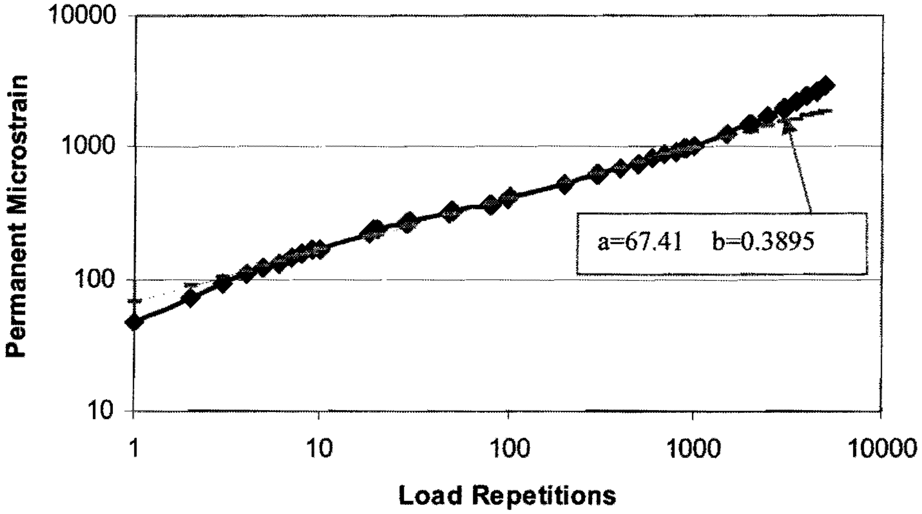


Figure B5. Plot of Regression Constants “a” and “b” from Log Permanent Strain – Log Number of Loading Cycles.

Example: ALPHA and GNU Calculation

$\varepsilon_r = 88.1250$

a = 67.4100

b = 0.3895

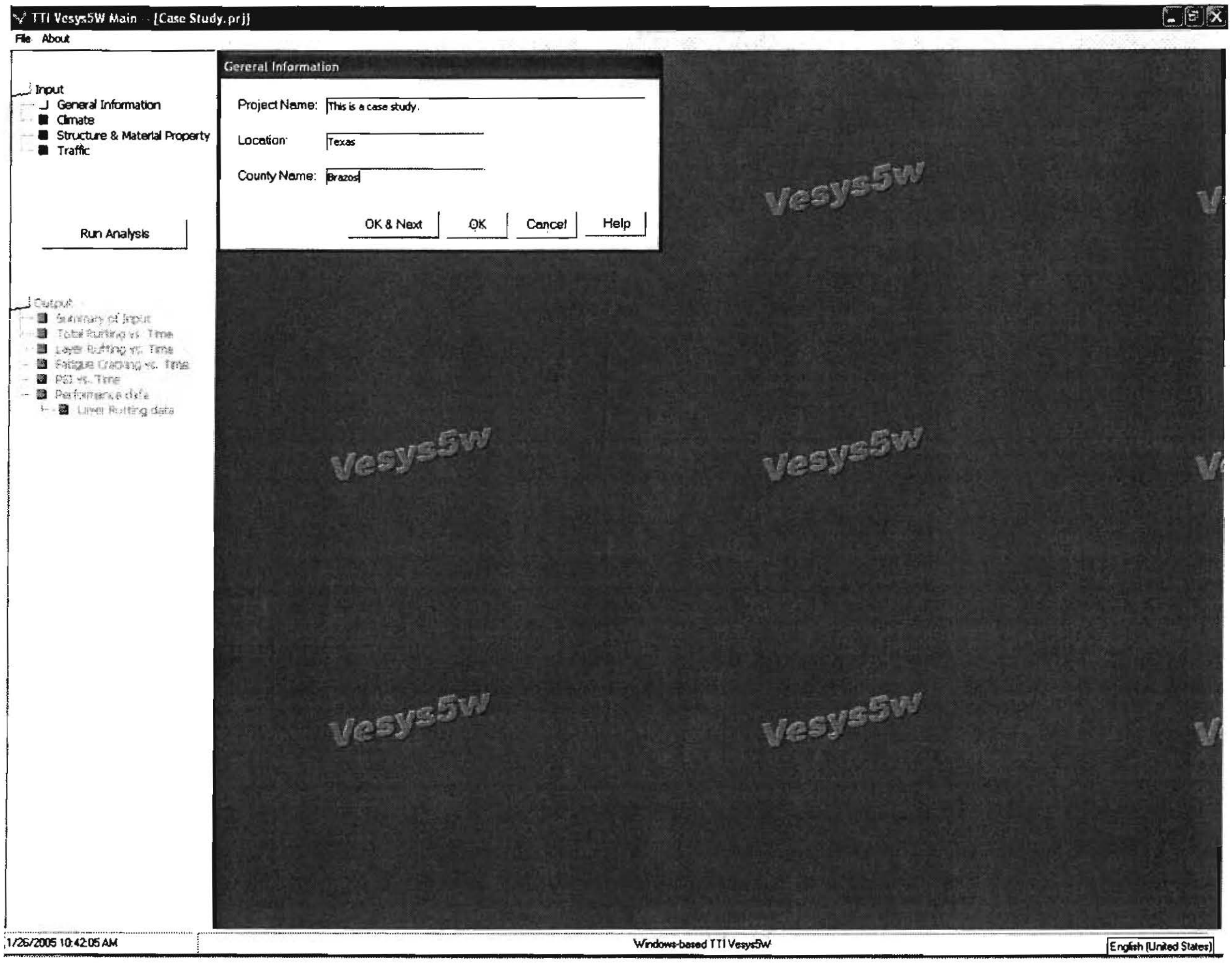
$\mu = a \times b/\varepsilon_r = 67.41 \times 0.3895/88.125 = 0.2979$

$\alpha = 1 - b = 1 - 0.3895 = 0.6105$

APPENDIX C

A CASE STUDY OF ENHANCED VESYS5

This case study is to demonstrate the input and output of enhanced VESYS5 program. Figure C1 shows interface of **"General Input"** and associated input parameters. Figure C2 presents interface of **"Climate"** and input example. Input of **"Structure & Material Properties"** is shown in Figure C3. Traffic information including **"Axle Load"** and **"Repeated Load"** is illustrated in Figures C4 and C5, respectively. The output of this case study is shown in Figures C6 ("Input Summary"), C7 ("Total Rutting vs. Time"), C8 ("Layer Rutting vs. Time"), C9 ("Fatigue Cracking vs. Time"), C10 ("PSI vs. Time"), C11 (tabulated "Performance Data"), and C12 (tabulated "Layer Rutting Data"), respectively.

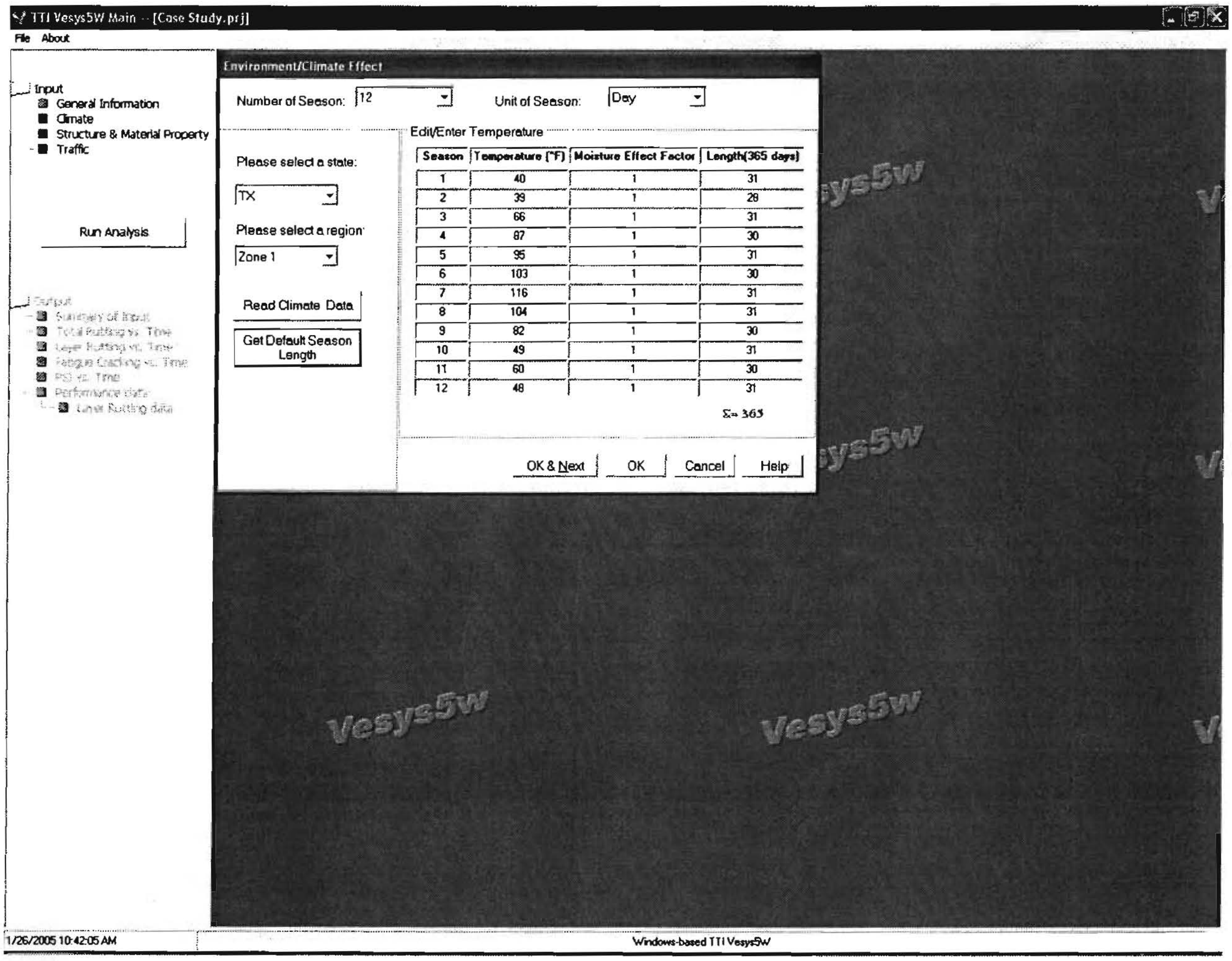


Project Name: This is a case study.

Location: Texas

County Name: Brazos

Figure C1. Input Example of General Input.



Number of Season: 12

Unit of Season: Day

Please select a state: TX

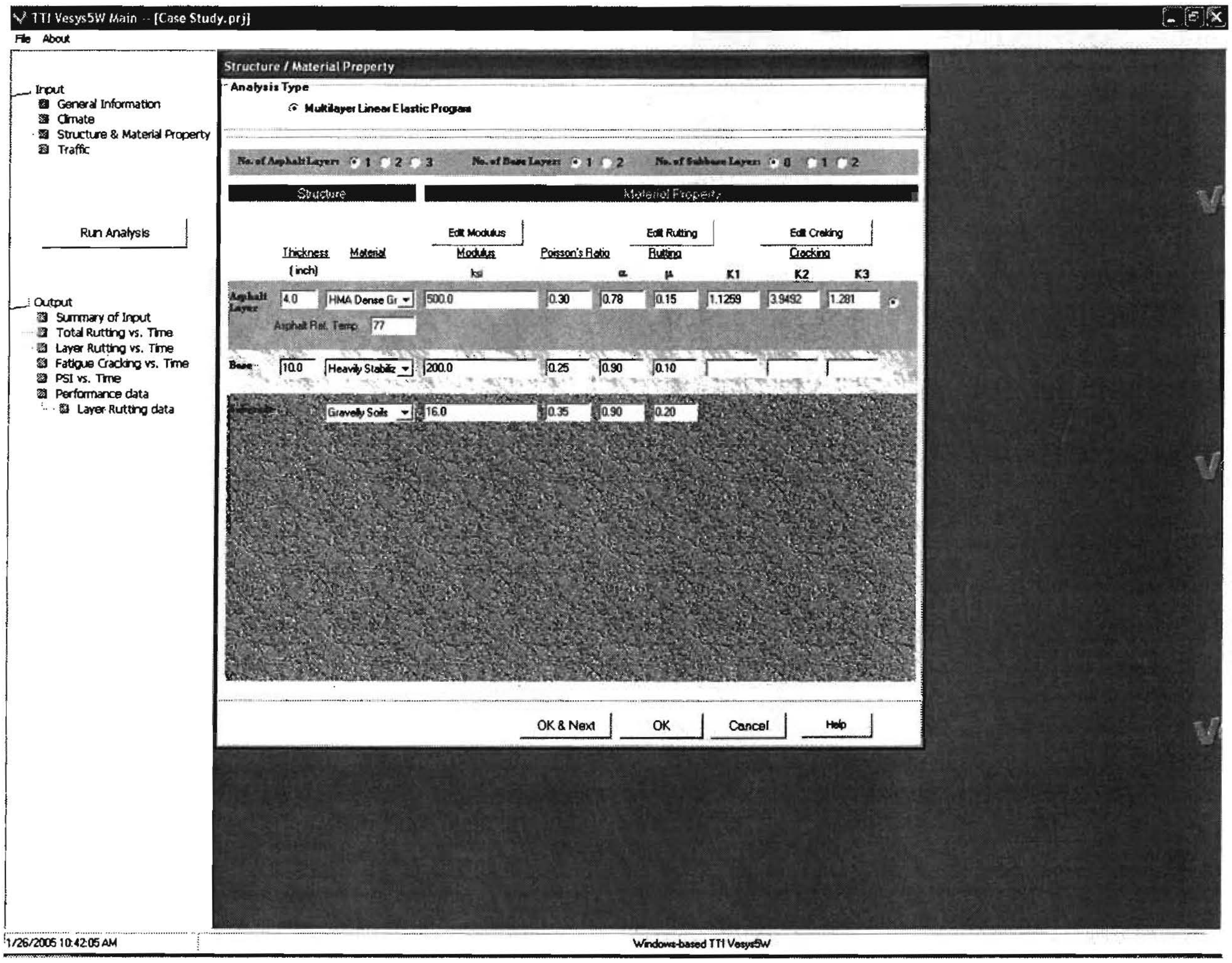
Please select a region: Zone 1

Edit/Enter Temperature

Season	Temperature (°F)	Moisture Effect Factor	Length(365 days)
1	40	1	31
2	39	1	28
3	66	1	31
4	87	1	30
5	95	1	31
6	103	1	30
7	116	1	31
8	104	1	31
9	82	1	30
10	49	1	31
11	60	1	30
12	48	1	31

$\Sigma = 365$

Figure C2. Input Example of Climate.



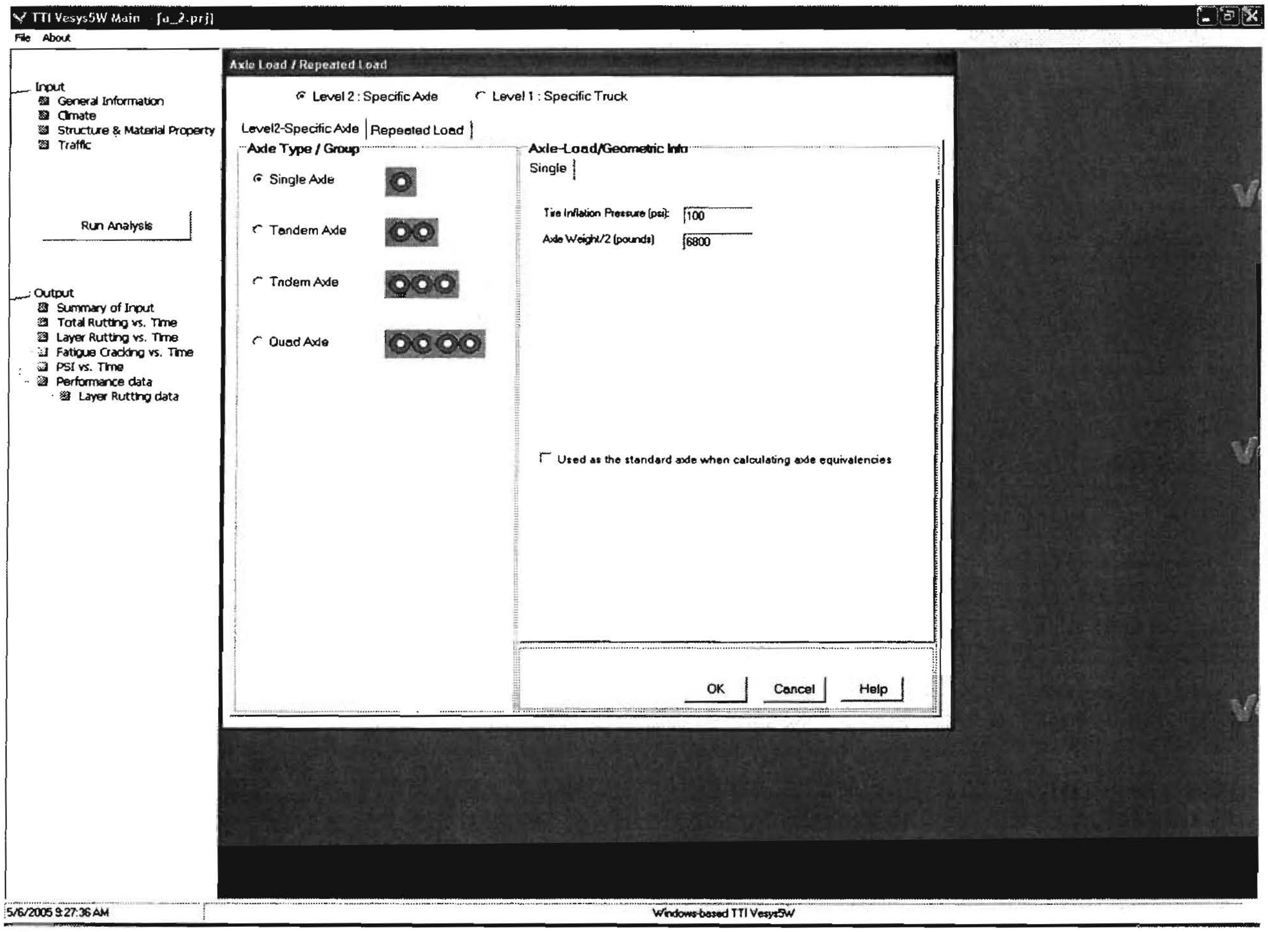
Analysis Type: ● Multilayer Linear Elastic Program

No. of Asphalt Layers: ● 1 ○ 2 ○ 3 No. of Base Layers: ● 1 ○ 2 No. of Subbase Layers: ● 0 ○ 1 ○ 2

	Thickness (inch)	Material	Modulus ksi	Poisson's Ratio	Rutting α	Rutting μ	Cracking K1	Cracking K2	Cracking K3
Asphalt Layer	4.0	HMA Dense Gr	500.0	0.30	0.78	0.15	1.1259	3.9492	1.281
Base	10.0	Heavily Stabiliz	200.0	0.25	0.90	0.10			
Subgrade		Gravelly Soils	16.0	0.35	0.90	0.20			

Asphalt Ref. Temp: 77

Figure C3. Input Example of Structure & Material Properties.



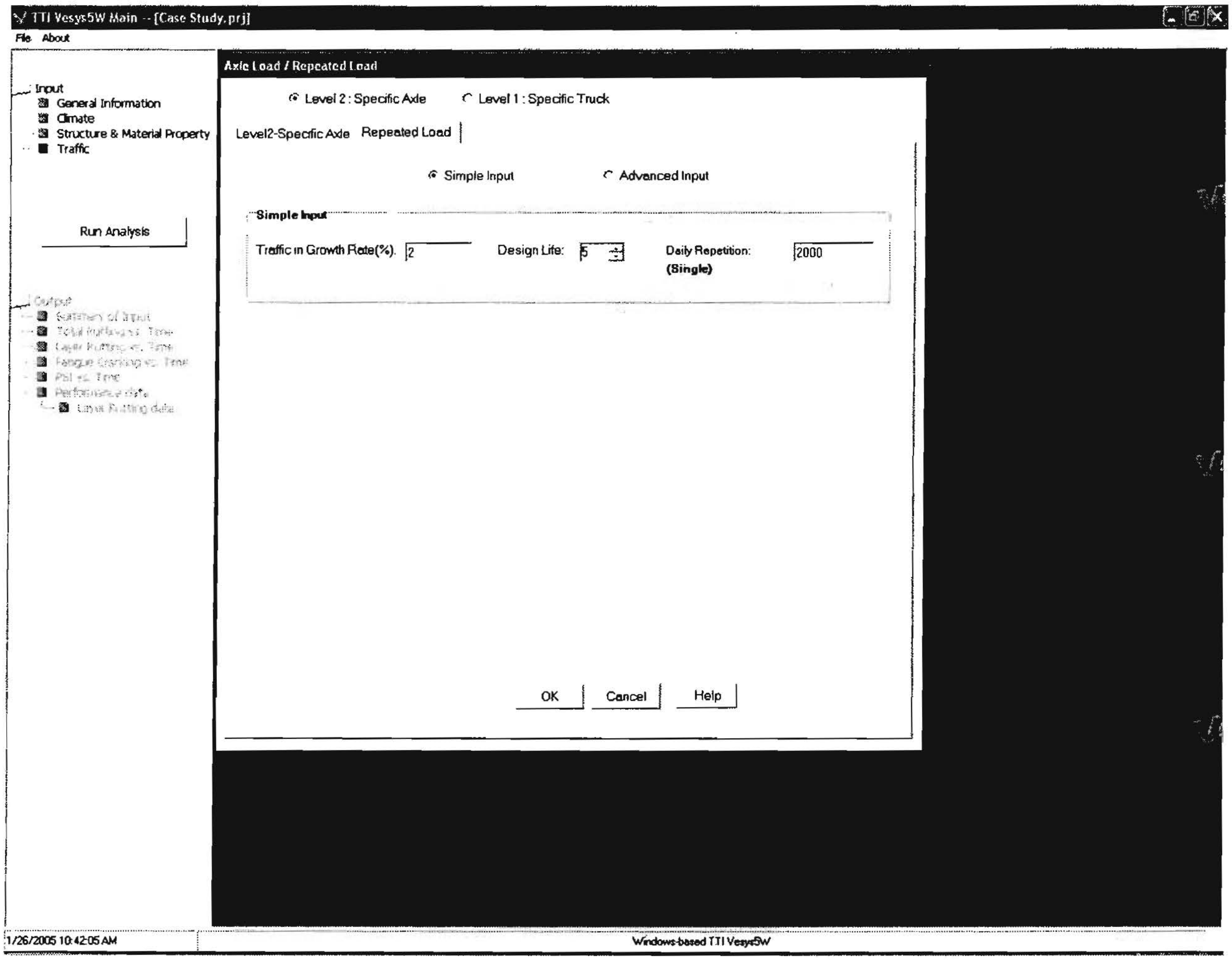
● Level 2 : Specific Axle ○ Level 1 : Specific Truck

● Single Axle
○ Tandem Axle
○ Tridem Axle
○ Quad Axle

Tire Inflation Pressure (psi): 100
Axle Weight/2 (pounds) 6800

☐ Used as the standard axle when calculating axle equivalencies

Figure C4. Input Example of Axle Load.



● Level 2 : Specific Axle ○ Level 1 : Specific Truck

Level2-Specific Axle Repeated Load

● Simple Input ○ Advanced Input

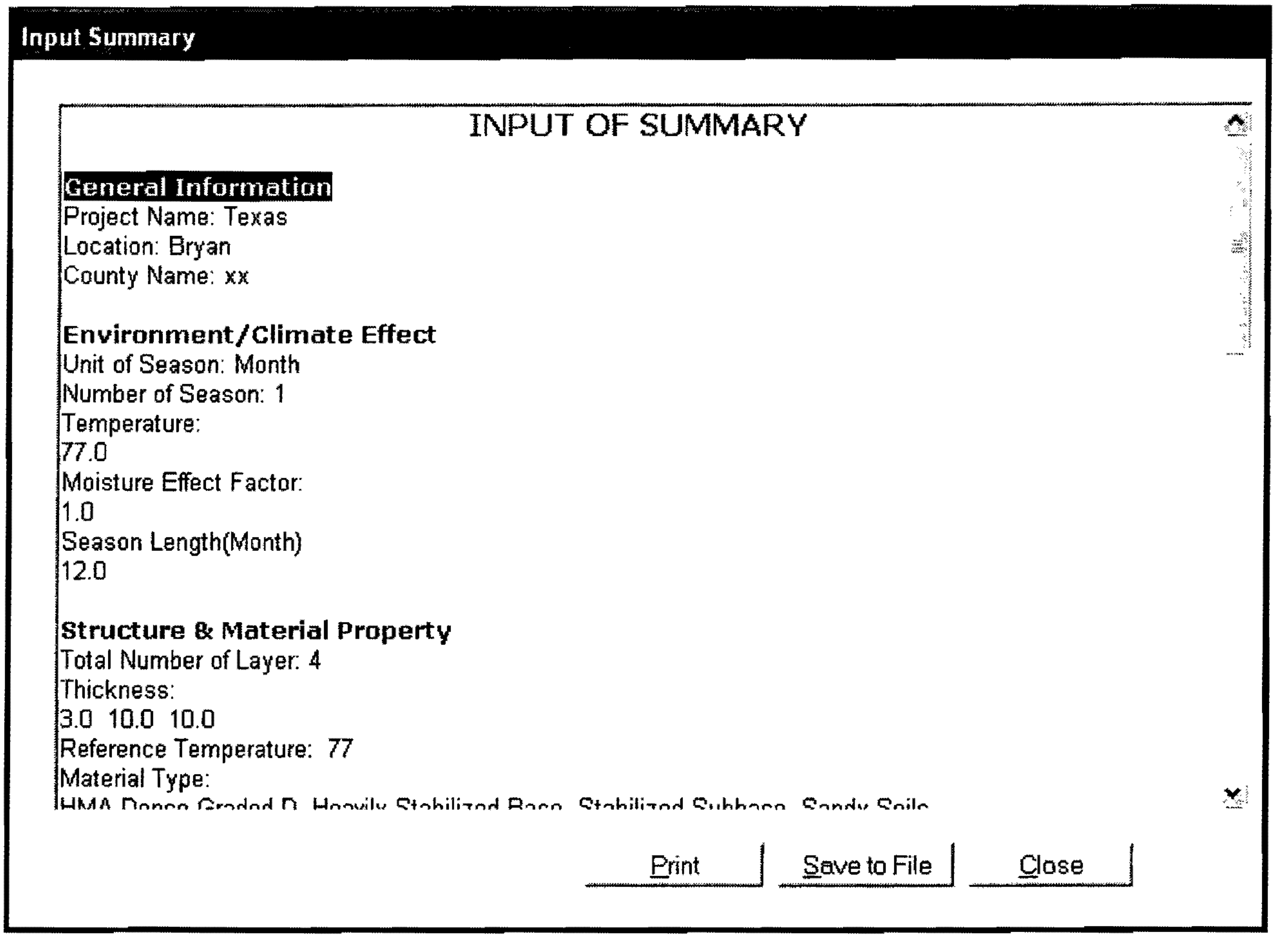
Simple Input

Traffic in Growth Rate(%): 2

Design Life: 5

Daily Repetition: (Single) 2000

Figure C5. Input Example of Repeated Load.



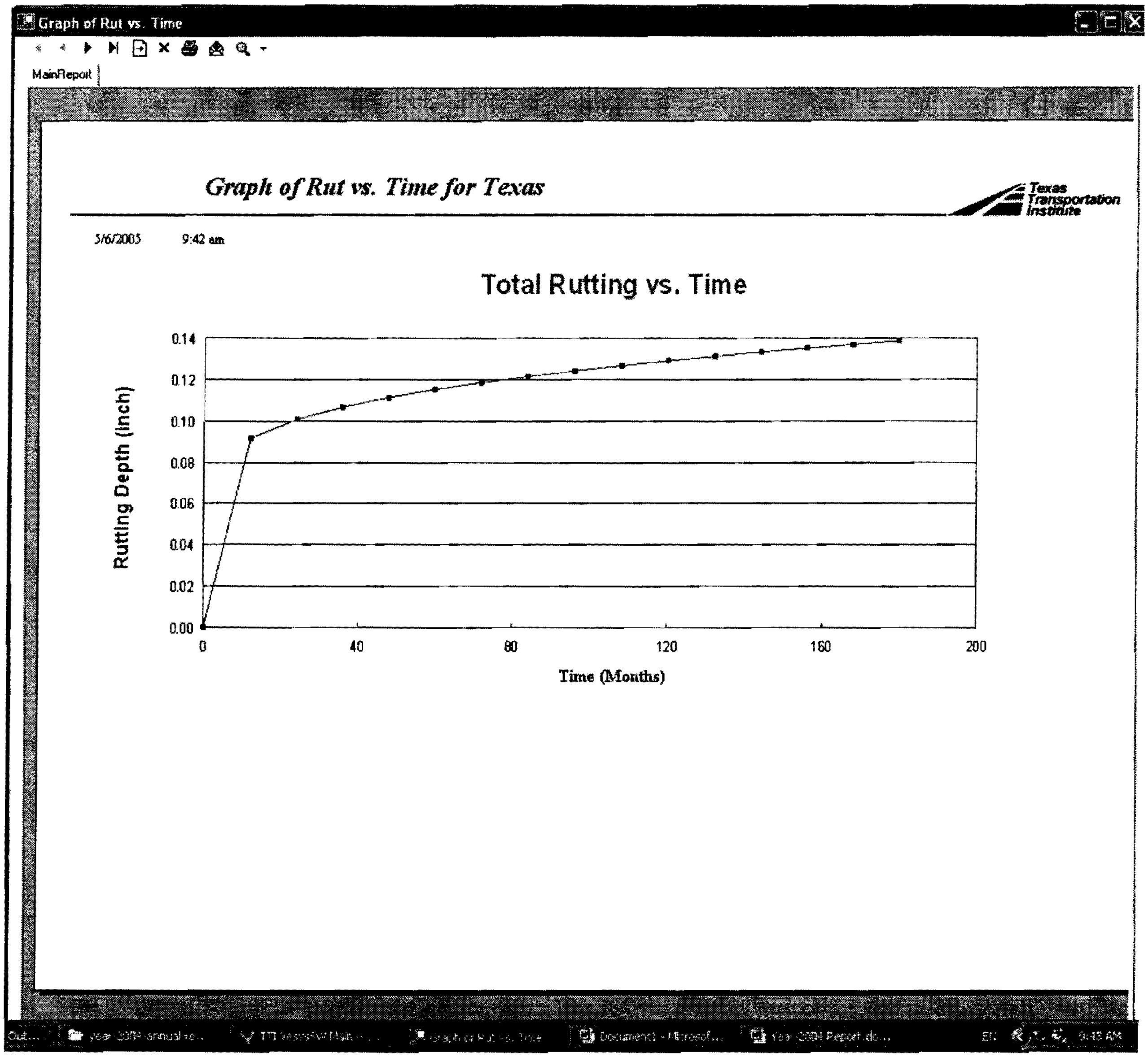
INPUT OF SUMMARY

General Information
Project Name: Texas
Location: Bryan
County Name: xx

Environment/Climate Effect
Unit of Season: Month
Number of Season: 1
Temperature:
77.0
Moisture Effect Factor:
1.0
Season Length(Month)
12.0

Structure & Material Property
Total Number of Layer: 4
Thickness:
3.0 10.0 10.0
Reference Temperature: 77
Material Type:
HMA Dense Graded D Heavily Stabilized Base Stabilized Subbase Sandy Soils

Figure C6. Output Example of “Input Summary.”



Graph of Rut vs. Time for Texas

5/6/2005 9:42 am

Figure C7. Output Example of "Total Rutting vs. Time."

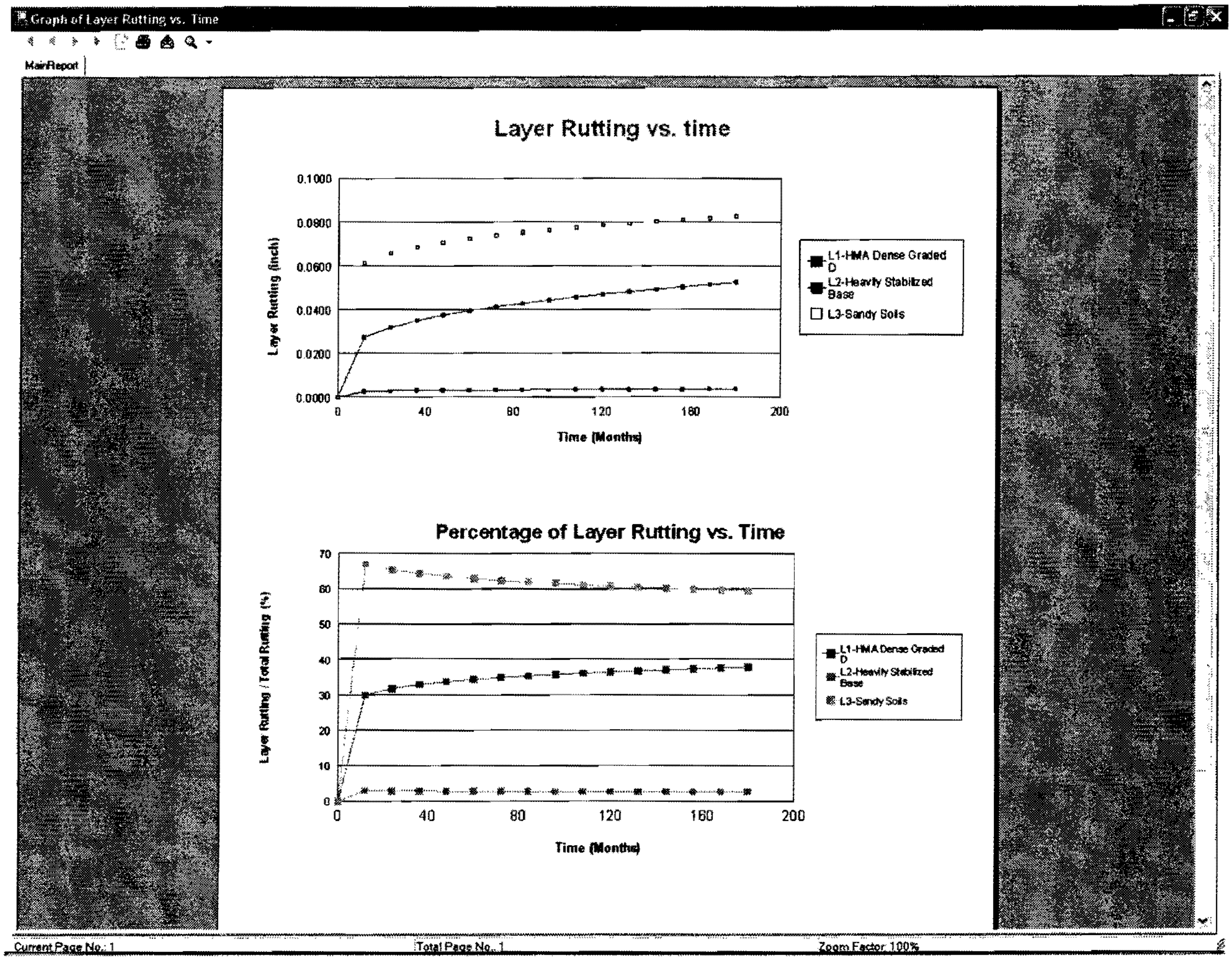
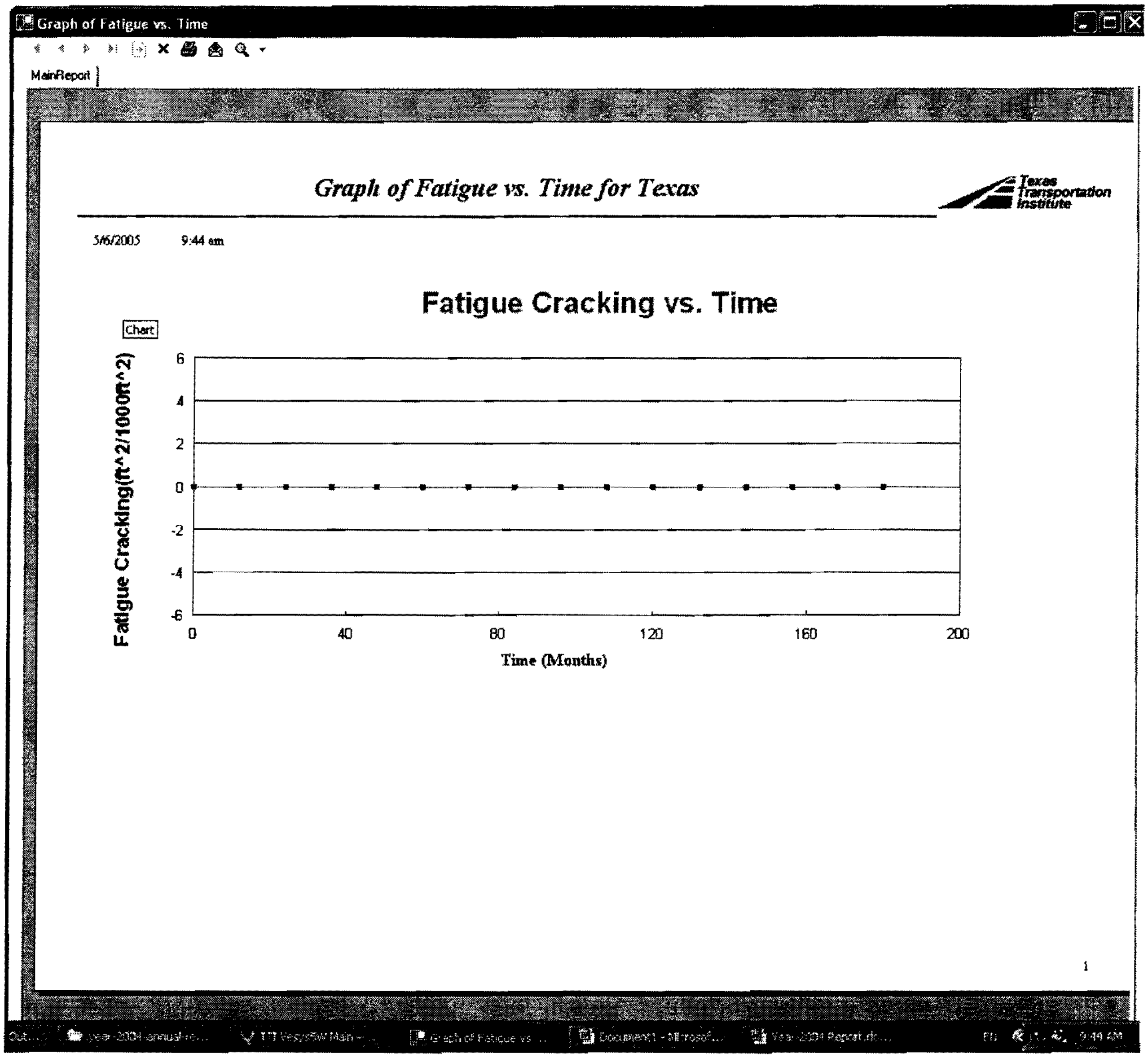


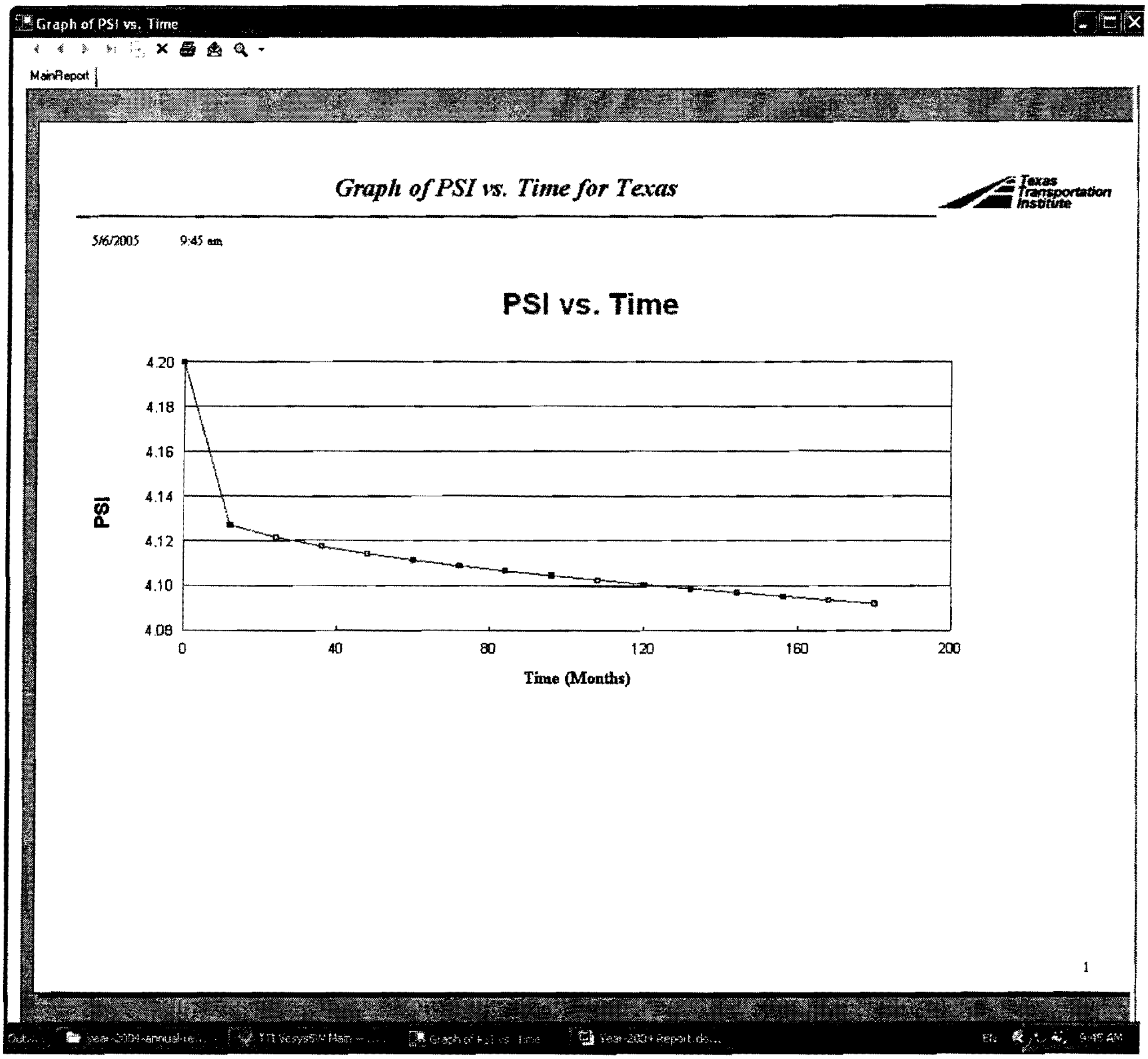
Figure C8. Output Example of "Layer Rutting vs. Time."



Graph of Fatigue vs. Time for Texas

5/6/2005 9:44 am

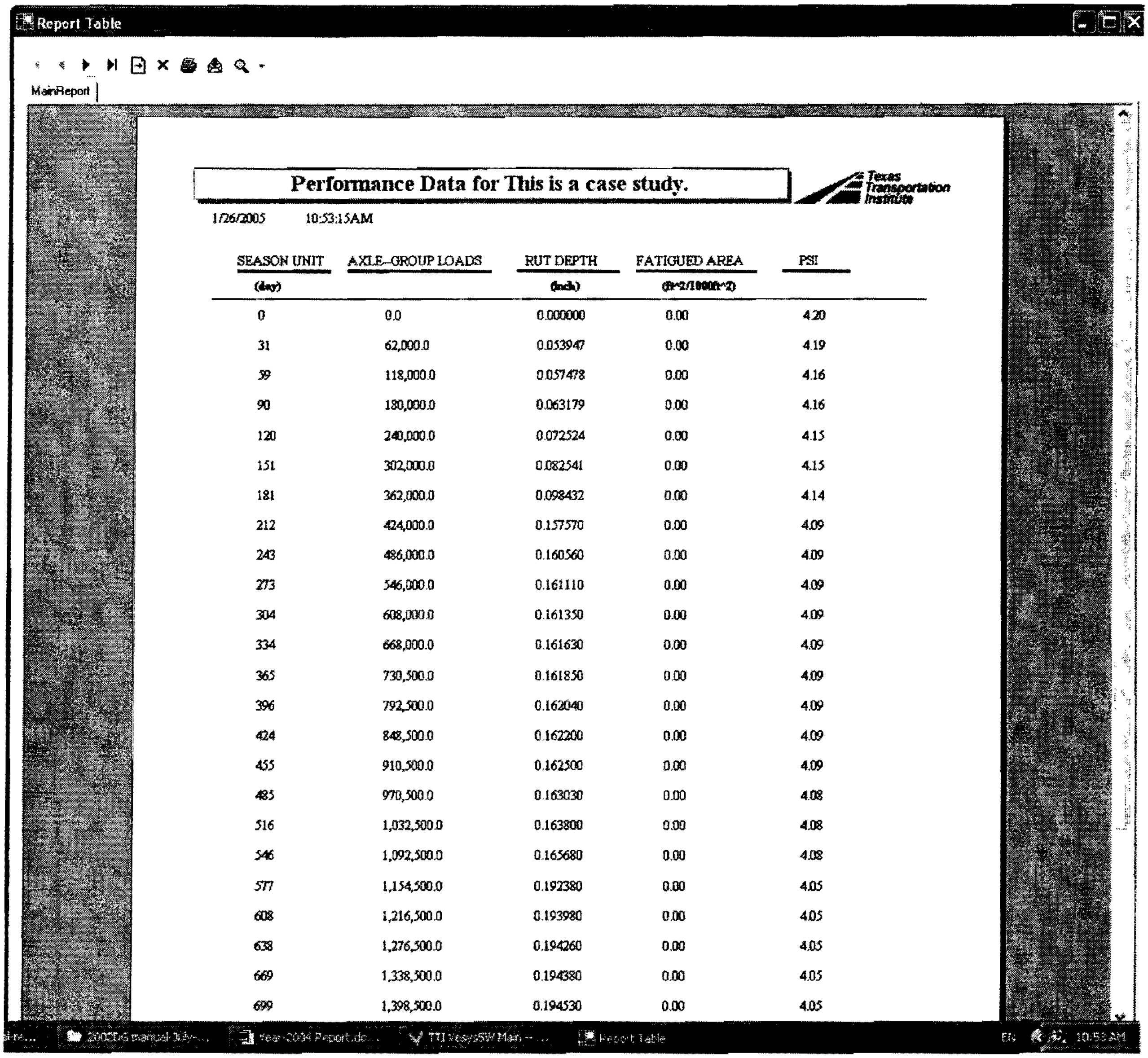
Figure C9. Output Example of "Fatigue Cracking vs. Time."



Graph of PSI vs. Time for Texas

5/6/2005 9:45 am

Figure C10. Output Example of "PSI vs. Time."

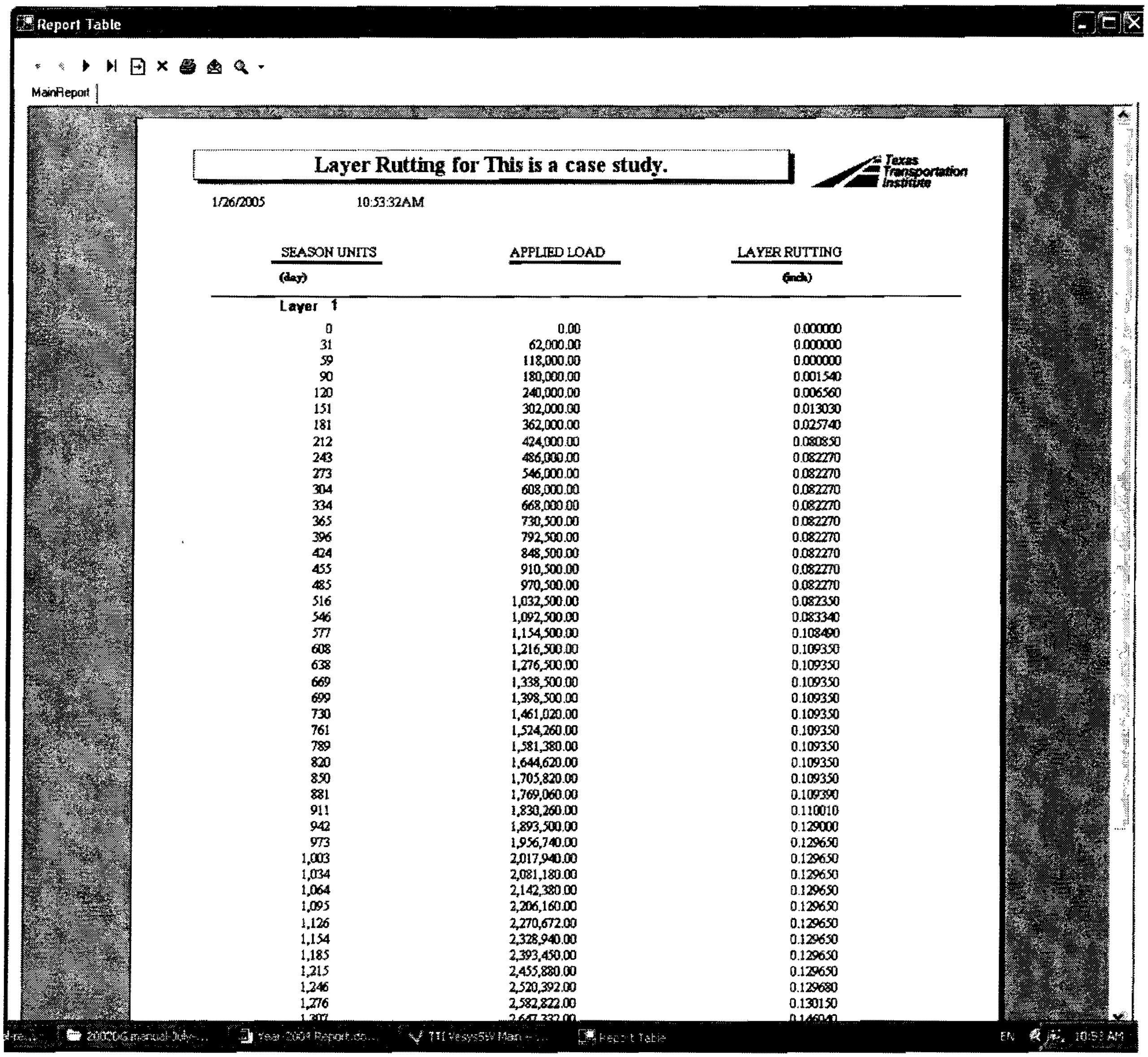


Performance Data for This is a case study.

1/26/2005 10:53:15AM

SEASON UNIT (day)	AXLE-GROUP LOADS	RUT DEPTH (inch)	FATIGUED AREA (ft^2/1000ft^2)	PSI
0	0.0	0.000000	0.00	4.20
31	62,000.0	0.053947	0.00	4.19
59	118,000.0	0.057478	0.00	4.16
90	180,000.0	0.063179	0.00	4.16
120	240,000.0	0.072524	0.00	4.15
151	302,000.0	0.082541	0.00	4.15
181	362,000.0	0.098432	0.00	4.14
212	424,000.0	0.157570	0.00	4.09
243	486,000.0	0.160560	0.00	4.09
273	546,000.0	0.161110	0.00	4.09
304	608,000.0	0.161350	0.00	4.09
334	668,000.0	0.161630	0.00	4.09
365	730,500.0	0.161850	0.00	4.09
396	792,500.0	0.162040	0.00	4.09
424	848,500.0	0.162200	0.00	4.09
455	910,500.0	0.162500	0.00	4.09
485	970,500.0	0.163030	0.00	4.08
516	1,032,500.0	0.163800	0.00	4.08
546	1,092,500.0	0.165680	0.00	4.08
577	1,154,500.0	0.192380	0.00	4.05
608	1,216,500.0	0.193980	0.00	4.05
638	1,276,500.0	0.194260	0.00	4.05
669	1,338,500.0	0.194380	0.00	4.05
699	1,398,500.0	0.194530	0.00	4.05

Figure C11. Output Example of Tabulated "Performance Data."



Layer Rutting for This is a case study.

1/26/2005 10:53:32AM

Layer 1

SEASON UNITS (day)	APPLIED LOAD	LAYER RUTTING (inch)
0	0.00	0.000000
31	62,000.00	0.000000
59	118,000.00	0.000000
90	180,000.00	0.001540
120	240,000.00	0.006560
151	302,000.00	0.013030
181	362,000.00	0.025740
212	424,000.00	0.080850
243	486,000.00	0.082270
273	546,000.00	0.082270
304	608,000.00	0.082270
334	668,000.00	0.082270
365	730,500.00	0.082270
396	792,500.00	0.082270
424	848,500.00	0.082270
455	910,500.00	0.082270
485	970,500.00	0.082270
516	1,032,500.00	0.082350
546	1,092,500.00	0.083340
577	1,154,500.00	0.108490
608	1,216,500.00	0.109350
638	1,276,500.00	0.109350
669	1,338,500.00	0.109350
699	1,398,500.00	0.109350
730	1,461,020.00	0.109350
761	1,524,260.00	0.109350
789	1,581,380.00	0.109350
820	1,644,620.00	0.109350
850	1,705,820.00	0.109350
881	1,769,060.00	0.109390
911	1,830,260.00	0.110010
942	1,893,500.00	0.129000
973	1,956,740.00	0.129650
1,003	2,017,940.00	0.129650
1,034	2,081,180.00	0.129650
1,064	2,142,380.00	0.129650
1,095	2,206,160.00	0.129650
1,126	2,270,672.00	0.129650
1,154	2,328,940.00	0.129650
1,185	2,393,450.00	0.129650
1,215	2,455,880.00	0.129650
1,246	2,520,392.00	0.129680
1,276	2,582,822.00	0.130150

Figure C12. Output Example of Tabulated "Layer Rutting Data."