Report No. KS-07-10
FINAL REPORT

EVALUATION OF PROCEDURE TO ESTIMATE SUBGRADE RESILIENT MODULUS FOR USE IN PAVEMENT STRUCTURAL DESIGN

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Applied Research Associates, Inc.

November 2007

KANSAS DEPARTMENT OF TRANSPORTATION

Division of Operations
Bureau of Materials and Research

KANSAS
DEPARTMENT OF TRANSPORTATION

1 Report No.
KS-07-10

2 Government Accession No.

3 Recipient Catalog No.

4 Title and Subtitle
Evaluation of Procedure to Estimate Subgrade Resilient Modulus For Use in Pavement Structural Design

5 Report Date
November 2007

6 Performing Organization Code

7 Author(s)
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8 Performing Organization Report No.

9 Performing Organization Name and Address
Applied Research Associates, Inc.
12511 S. Hagan Lane
Olathe, KS 66062-6075

10 Work Unit No. (TRAIS)

11 Contract or Grant No.
DOA Contract# 10159

12 Sponsoring Agency Name and Address
Kansas Department of Transportation
Bureau of Materials and Research
700 SW Harrison Street
Topeka, Kansas 66603-3745

13 Type of Report and Period Covered
Final Report

14 Sponsoring Agency Code
AD-2302-07

15 Supplementary Notes
For more information write to address in block 9.

16 Abstract

The Kansas Department of Transportation (DOT) uses the 1993 DARWin version of the 1986 AASHTO Guide to design rigid and flexible pavements. One of the inputs needed for the flexible pavement design procedure is the modulus of the subgrade soils, which has an effect on the total pavement thickness. Different procedures can be used to estimate the effective roadbed resilient modulus for flexible pavement design and effective modulus of subgrade reaction for rigid pavement design. As part of the study entitled Determination of the Appropriate Use of Pavement Surface History in the KDOT Life-Cycle Cost Analysis Process an evaluation of the procedure that Kansas DOT uses to estimate the effective subgrade resilient modulus was completed. This report provides the results of that evaluation.

17 Key Words
DARWin, rigid pavement, flexible, pavement design, subgrades

18 Distribution Statement
No restrictions. This document is available to the public through the National Technical Information Service, Springfield, Virginia 22161

19 Security Classification (of this report)
Unclassified

20 Security Classification (of this page)
Unclassified

21 No. of pages
44

22 Price

Form DOT F 1700.7 (8-72)

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Final Report

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A Report on Research Sponsored By

THE KANSAS DEPARTMENT OF TRANSPORTATION
TOPEKA, KANSAS

November 2007

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INTRODUCTION

The Kansas Department of Transportation (DOT) uses the 1993 DARWin version of the 1986 AASHTO Guide to design rigid and flexible pavements. One of the inputs needed for the flexible pavement design procedure is the modulus of the subgrade soils, which has an effect on the total pavement thickness. Different procedures can be used to estimate the effective roadbed resilient modulus for flexible pavement design and effective modulus of subgrade reaction for rigid pavement design. As part of the study entitled *Determination of the Appropriate Use of Pavement Surface History in the KDOT Life-Cycle Cost Analysis Process* an evaluation of the procedure that Kansas DOT uses to estimate the effective subgrade resilient modulus was completed. This memorandum provides the results of that evaluation.

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CHAPTER ONE - IN PLACE RESILIENT MODULUS

Resilient modulus is the primary material property that is used to characterize the roadbed soil and other structural layers for flexible pavement design in the 1986 and 1993 *AASHTO Guide for Design of Pavement Structures*. Resilient modulus was also adopted as the primary material property for characterizing all unbound pavement layers and soils in the new Mechanistic-Empirical Pavement Design Guide (MEPDG) developed under NCHRP Project 1-37A.

Resilient modulus is a measure or estimate of the elastic modulus of the material at a given stress state or temperature (i.e., assumed to be the modulus of elasticity). It is mathematically defined as the applied stress (or deviator stress change for triaxial testing of unbound materials) divided by the recoverable strain that occurs when the cyclic load is removed from the test specimen. Resilient modulus can be measured in the laboratory using repeated load triaxial tests for unbound materials and soils, in accordance with AASHTO T-307.

As part of the Long Term Pavement Performance (LTPP) program, resilient modulus tests were performed on unbound pavement layers and soils recovered from both ends of most test sections in accordance with LTPP Test Protocol P-46 (*Resilient Modulus of Unbound Granular Base/Subbase Materials and Subgrade Soils*). These tests were performed over a range of stress states and confining pressures to evaluate the nonlinear elastic behavior of these materials and soils. In general, 12 to 15 different stress states were used in the test program. Graphical examples of these test results for unbound materials and soils are provided in Attachment A for the LTPP sites located in Kansas.

The following summarizes a procedure that has been used to determine the in place resilient modulus for use in mechanistic-empirical (M-E) based flexible pavement designs. An in place resilient modulus value was determined for each repeated load resilient modulus test that is included in the LTPP database for the sites located in Kansas.

1.1 Procedure for Determining Resilient Modulus

The procedure used to determine the in place resilient modulus is an iterative one that equates the laboratory test results and theoretical computations using elastic layered theory. In other words, the elastic modulus of the elastic layered program is varied until the total stresses computed with elastic layered theory (wheel load and at-rest stresses) will result in the same resilient modulus from the repeated load laboratory test results.

This iterative procedure has been used by pavement engineers for many years. The procedure used was documented by Von Quintus and Killingsworth in 1997 for the Federal Highway Administration (FHWA).[1,2,3] The elastic layered program used for this demonstration is ***EVERSTRS***, which was developed at the University of Washington.

1.2 Assumptions and Factors

In order to determine the in place resilient modulus from laboratory repeated load triaxial tests, the in place lateral and vertical stresses must be calculated from truck loadings and added to the at-rest earth pressures. To determine these values, density and layer thickness of the pavement structure and truck loads must be estimated or assumed. Table 1.1 summarizes the pavement structure and layer properties that were used for this demonstration.

As noted above, the at-rest earth pressures must be superimposed with the wheel-load stresses calculated with ***EVERSTRS***. The depth at which the stresses are computed is 18 inches into the foundation soil. This foundation characterization depth has been used by Von Quintus since 1977.[1,4,5] The at-rest earth pressure coefficient was assumed to be 0.9 for this demonstration.

A standard 18-kip equivalent single axle load was used for computing the wheel load stresses in the foundation soil. The following lists the assumptions used to simulate the truck loads.

- Loads Located at (0, 0) and (12, 0)
- Load Magnitude = 4,500 pounds
- Tire Pressure = 120 psi

Table 1.1: Pavement Layers and Properties Used in Calculations to Determine the In Place Resilient Modulus

Layer & Material Type		Layer Thickness, inches	Equivalent Annual Modulus, ksi	Poisson's Ratio	Density, pcf
1	HMA Surface Mixture	LTPP	500	0.30	LTPP
1	Portland Cement Concrete	LTPP	4,000	0.15	155
2	Asphalt Treated Base Mix	LTPP	350	0.35	LTPP
2	Granular Base	LTPP	Attachment A	0.35	LTPP
3	Foundation Soil	LTPP	Attachment A	0.45	LTPP
4	Apparent Rigid Layer	Boring Logs	1,000	0.15	NA

1.3 Stress State Computations and Resulting In Place Resilient Modulus

Table 1.2 summarizes the overburden stresses, wheel load stresses computed with ***EVERSTRS***, total stress state, and resulting in place resilient modulus for some of the resilient modulus tests for the LTPP sites in Kansas. As noted above, the in place values were determined in accordance with the procedure outlined in the FHWA pamphlet for laboratory repeated load resilient modulus tests.[1,2] Example output from the ***EVERSTRS*** program is provided in Attachment B for one of the full-depth hot mix asphalt (HMA) sections and one of the portland cement concrete (PCC) sections.

The in place values listed in Table 1.2 represent the resilient modulus of a soil sample taken from one location and at one point in time. The in place resilient modulus will vary along a project and with season. Within the LTPP program, there is insufficient data for the Kansas and other sites to determine the resilient modulus variance along the project from the laboratory test results and to estimate seasonal variation, with the exception of the seasonal sites. Other techniques (such as back-calculation of elastic modulus from deflection basins) would have to be used to determine the variance in resilient modulus at a specific site and for different seasons.

1.4 Effective Resilient Modulus For Use in Design

The resulting in place resilient modulus values vary from 4.5 to 18 ksi (refer to Table 1.2). These are the values that can be used with M-E based design procedures, as long as the procedure was calibrated using the same resilient modulus determination procedure. The 1986 and 1993 *AASHTO Guide for Design of Pavement Structures*, however, was not calibrated using this procedure to determine the in place resilient modulus. The effective roadbed resilient modulus value of the foundation soil to be used with the 1993 Design Guide must be adjusted by a factor of about 2.0. As noted in the design manual, “it is emphasized that this effective resilient modulus value should be used only for the design of flexible pavements based on serviceability criteria.”

Table 1.2: Summary of Stress State Calculations to Determine the In Place Resilient Modulus from Repeated Load Resilient Modulus Test Data for the LTPP Sites in Kansas

Parameter	LTPP Site Identification – Kansas Sections							
	0203	**0212**	**1005**	**1006**	**1009**	**1010**	**3013**	**3015**
Type of Material	**Soil**	**Soil**	**Soil**	**Soil**	**Soil**	**Soil**	**Soil**	**Soil**
Overburden Stresses, psi								
Vertical Stress, σ_v	2.83	3.04	2.15	2.25	2.39	1.86	2.65	2.18
Lateral Stress, σ_h	2.54	2.74	1.94	2.03	2.15	1.67	2.38	1.96
Stresses from Wheel Loads, psi								
Vertical Stress, σ_z	0.5	0.2	1.15	1.32	1.29	2.24	0.63	0.69
Lateral Stress, σ_x	0.05	0.0	.14	.27	.26	.35	0.12	0.16
Lateral Stress, σ_y	0.05	0.0	.13	.25	.27	.32	0.12	0.16
Total Stresses, psi								
Vertical Stress, σ_1	3.33	3.24	3.30	3.57	3.68	4.10	3.26	2.87
Horiz. Stress, σ_3	2.59	2.74	2.08	2.30	2.42	2.02	2.50	2.12
Bulk Stress, θ	8.52	8.71	7.44	8.15	8.51	8.02	8.28	7.11
In Place Resilient Modulus, ksi	**14.5**	**10.5**	**13.0**	**6.5**	**6.0**	**9.0**	**13.0**	**11.0**

Table 1.2: Summary of Stress State Calculations to Determine the In Place Resilient Modulus from Repeated Load Resilient Modulus Test Data for the LTPP Sites in Kansas, continued

Parameter	LTPP Site Identification – Kansas Sections							
	3060	**4016**	**4016**	**4052**	**4053**	**4054**	**4063**	**6026**
Type of Material	**Soil**	**Soil**	**Base**	**Soil**	**Soil**	**Soil**	**Soil**	**Soil**
Overburden Stresses, psi								
Vertical Stress, σ_v	2.65	1.99	0.93	2.36	2.78	2.15	2.66	2.50
Lateral Stress, σ_h	2.38	1.79	0.84	2.12	2.50	1.93	2.39	2.25
Stresses from Wheel Loads, psi								
Vertical Stress, σ_z	0.57	0.78	1.3	0.63	0.59	0.80	0.57	1.43
Lateral Stress, σ_x	0.11	0.2	.22	0.16	0.13	0.17	0.11	0.21
Lateral Stress, σ_y	0.10	0.2	.17	0.16	0.13	0.17	0.11	0.23
Total Stresses, psi2.99								
Vertical Stress, σ_1	3.22	2.77	2.23	2.98	3.37	2.95	3.23	3.93
Horiz. Stress, σ_3	2.49	1.99	1.06	2.28	2.80	2.10	2.50	2.48
Bulk Stress, θ	8.19	6.75	4.29	7.55	8.64	7.15	8.23	8.86
In Place Resilient Modulus, ksi	**10.5**	**10.0**	**10.0**	**7.5**	**9.5**	**12.0**	**8.0**	**18.0**

Table 1.2: Summary of Stress State Calculations to Determine the In Place Resilient Modulus from Repeated Load Resilient Modulus Test Data for the LTPP Sites in Kansas, continued

Parameter	LTPP Site Identification – Kansas Sections							
	4067	**4067**	**7073**	**7073**	**7085**	**7085**	**9037**	**9037**
Type of Material	**Soil**	**Base**	**Soil**	**Base**	**Soil**	**Base**	**Soil**	**Base**
Overburden Stresses, psi								
Vertical Stress, σ_v	2.83	1.28	2.71	1.39	2.41	1.23	2.96	1.60
Lateral Stress, σ_h	2.55	1.15	2.44	1.25	2.17	1.11	2.66	1.44
Stresses from Wheel Loads, psi								
Vertical Stress, σ_z	0.20	0.80	0.62	0.69	0.05	0.99	0.20	0.36
Lateral Stress, σ_x	0.01	0.22	0.26	0.09	0.02	0.01	0.10	0.01
Lateral Stress, σ_y	0.02	0.23	0.27	0.11	0.02	0.04	0.10	0.00
Total Stresses, psi								
Vertical Stress, σ_1	3.03	2.08	3.33	1.99	2.46	2.22	3.16	1.96
Horiz. Stress, σ_3	2.57	1.38	2.71	1.36	2.19	1.15	2.76	1.45
Bulk Stress, θ	8.17	4.83	8.74	4.79	6.85	4.49	8.68	4.86
In Place Resilient Modulus, ksi	**7.0**	**4.5**	**6.5**	**7.0**	**8.5**	**13.0**	**7.0**	**10.0**

The reason for this adjustment is that the resilient modulus of the foundation soil at the AASHO Road Test was determined to be 3 ksi for development of the performance equation, which represents the critical condition during spring-thaw. A value of approximately 6 ksi is the value that would be obtained using the equivalent stress state concept, under non-critical conditions. As such, the in place resilient modulus values should be adjusted by a factor to account for the critical loading condition when using the 1986 and 1993 AASHTO Design Guide or similar empirical procedures based on the serviceability concept. For the AASHO Road Test site that factor is about 2.

For this evaluation that same adjustment factor was used for all of the Kansas LTPP test sites. In reality, however, this adjustment factor is climate and soil specific. These values are included in Table 1.3 and identified as adjusted resilient modulus to be consistent with the AASHTO performance equation for flexible pavements. This adjustment is not required for most M-E based design procedures.

The Kansas DOT estimates the subgrade effective roadbed resilient modulus from the liquid limit of the soil using a regression equation that was developed many years ago. The regression equation was derived from the relationship used to estimate the subgrade modulus of reaction, as shown in equation 1.1.

$$K = 19199.6(LL)^{-1.329} \qquad \text{(Equation 1.1)}$$

Where:

K = Subgrade modulus of reaction, pci.

LL = Liquid limit of the soil, %.

Von Quintus developed a similar relationship in the early 1980's for estimating the Texas Triaxial Strength value from the liquid limit of the soil for use in flexible pavement design. The coefficient and exponent of the regression equation, however, were soil type dependent.

Table 1.3: Resilient Modulus Values Determined by Different Procedures for the LTPP Sites Located in Kansas

LTPP Sites and Materials		Method to Determine Resilient Modulus, ksi				
		KDOT Procedure	Illinois Procedure	Laboratory Values		MEPDG Default Values
				With Adjustments	Without Adjustments	
20-0203	A-7-6	2.34	11.1	7.25	14.5	11.5
	A-7-5	1.77	13.0	7.25	14.5	13.0
	A-6	3.04	10.0	7.25	14.5	14.5
20-0212	A-7-6	2.34	11.1	5.25	10.5	11.5
	A-7-5	1.77	13.0	5.25	10.5	13.0
	A-6	3.04	10.0	5.25	10.5	14.5
20-1005	A-7-6	2.20	11.9	6.50	13.0	11.5
	A-7-6	2.20	11.9	6.50	13.0	11.5
20-1006	A-4	5.17	6.06	6.5	13.0	16.5
	A-4	5.17	6.06	3.25	6.5	16.5
20-1009	A-2-4	6.51	6.29	3.0	6.0	21.5
	A-2-4	6.51	6.29	8.5	17.0	21.5
20-1010	A-6	4.44	7.32	4.5	9.0	14.5
	A-4	4.44	7.32	5.0	10.0	16.5
20-3013	A-7-6	2.20	11.12	6.5	13.0	11.5
	A-7-6	2.20	11.12	8.0	16.0	11.5
20-3015	A-6	2.91	9.02	7.5	15.0	14.5
	A-7-6	2.91	9.02	5.5	11.0	11.5
20-3060	A-6	2.96	9.21	5.5	11.0	14.5
	A-7-6	2.96	9.21	5.25	10.5	11.5
20-4016	A-6	2.86	9.14	8.5	17.0	14.5
	A-6	2.86	9.14	5.0	10.0	14.5
	Base	5.94	6.26	5.0	10.0	26.5
	Base	5.94	6.26	5.0	10.0	26.5
20-4052	A-3	16.4	5.68	3.75	7.5	24.5
	A-4	16.4	5.68	4.25	8.5	16.5
20-4053	A-4	3.72	7.37	5.0	10.0	16.5
	A-6	3.72	7.37	4.75	9.5	14.5
20-4054	A-6	2.55	10.7	6.75	13.5	14.5
	A-7-6	2.55	10.7	6.0	12.0	11.5
20-4063	A-4	4.55	7.51	4.75	9.5	16.5
	A-6	4.55	7.51	4.0	8.0	14.5
20-4067	A-7-6	2.11	11.5	10.0	20.0	11.5
	A-7-6	2.11	11.5	3.5	7.0	11.5
	Base	9.35	4.70	3.0	6.0	21.5
	Base	8.63	4.70	2.25	4.5	21.0
20-6026	A-4	4.66	7.76	9.5	19.0	16.5
	A-6	4.66	7.76	9.0	18.0	14.5

Table 1.3: Resilient Modulus Values Determined by Different Procedures for the LTPP Sites Located in Kansas, continued.

LTPP Sites and Materials		Method to Determine Resilient Modulus, ksi				
		KDOT Procedure	Illinois Procedure	Laboratory Values		MEPDG Default Values
20-7073	A-2-4	17.5	5.35	4.0	8.0	21.5
	A-2-4	15.4	5.35	3.23	6.5	21.5
	Base	7.4	5.70	6.0	12.0	20.5
	Base	8.0	5.70	3.5	7.0	21.0
20-7085	A-6	2.63	10.3	6.5	13.0	14.5
	A-7-6	2.63	10.3	4.25	8.5	11.5
	Base	5.77	7.04	6.75	13.5	21.0
	Base	5.77	6.84	6.5	13.0	20.5
20-9037	A-4	4.06	7.63	5.25	10.5	16.5
	A-6	4.06	7.63	3.5	7.0	14.5
	Base	4.78	8.21	9.5	19.0	21.5
	Base	4.78	8.21	5.0	10.0	26.5

For the Kansas resilient modulus estimation procedure, the subgrade modulus of reaction is multiplied by a factor of 19.4 to obtain the effective roadbed resilient modulus for use in flexible pavement design (refer to equation 1.2). Equation 1.3 shows the resulting relationship for estimating the roadbed effective resilient modulus from the liquid limit of the soil.

$$M_r = 19.4(K) \qquad \text{(Equation 1.2)}$$

$$M_r = 372.47(LL)^{-1.329} \qquad \text{(Equation 1.3)}$$

Where:

M_r = Resilient modulus of the soil, ksi.

LL = Liquid limit of the soil, %.

The effective roadbed resilient modulus was calculated for the subgrade soil at each LTPP site using equation 1.3. These values are also listed in Table 1.3. Figure 1.1 shows a comparison of the laboratory adjusted resilient modulus and the values estimated from equation 1.3. As shown, there is extensive dispersion between the two resilient modulus values. This large dispersion, however, is expected when the resilient modulus values, derived from a strength-based property of the soil, are compared to values measured from laboratory repeated load resilient modulus tests. The dispersion in the data might be reduced if the coefficient and exponent in equation 1.3 were related to soil type. The four values in Figure 1.1 that are greater than 15,000 psi have a higher percentage of coarse-grained particles.

Other regression equations have also been developed to estimate the resilient modulus of the subgrade soils. The Illinois DOT uses a regression equation that includes percent clay and the plasticity index of the soil to estimate resilient modulus for their M-E based procedure. The regression equation is shown in equation 1.4 and was derived from repeated load resilient modulus tests. The values estimated from that equation are also included in Table 1.3. Figure 1.2 shows a comparison of the laboratory resilient modulus, with and without the adjustments, to the values estimated from equation 1.4. As shown, the relationship between the two resilient modulus values has a flatter slope than the line of equality.

$$M_r = 4.46 + 0.098(Clay) + 0.119(PI) \qquad \text{(Equation 1.4)}$$

Where:

Clay = Percent clay in the soil.

PI = Plasticity index of the soil, %.

Von Quintus and Yau developed multiple regression equations (material specific) under sponsorship of the FHWA to predict the resilient modulus using a range of physical properties that are included in the LTPP database.[6] The regression equation for fine grained clay soils was used to estimate the in place subgrade resilient modulus at each LTPP site in Kansas. An average bulk stress of 8 psi was used in the computations. Figure 1.3 shows a comparison of the laboratory resilient modulus values to the values estimated from the LTPP regression equation.

As shown, the values resulting from the LTPP regression equation are within the same range as those from the Illinois regression equation. The authors of the LTPP report, however, recommended that laboratory resilient modulus tests be conducted because the standard error of these regression equations is high.

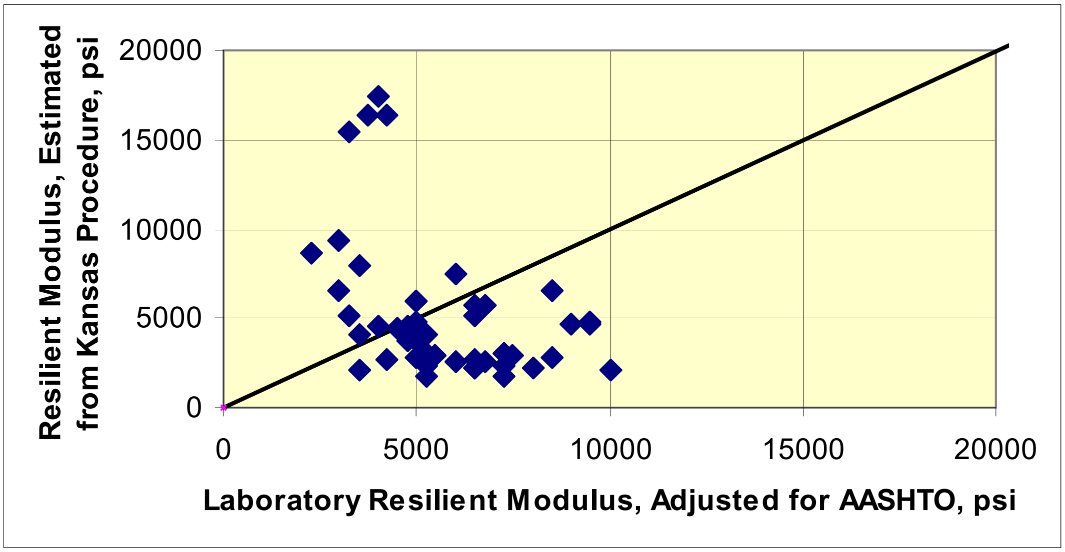

Figure 1.1: Graphical comparison of the laboratory adjusted resilient modulus and the values estimated from the Kansas procedure (equation 1.3).

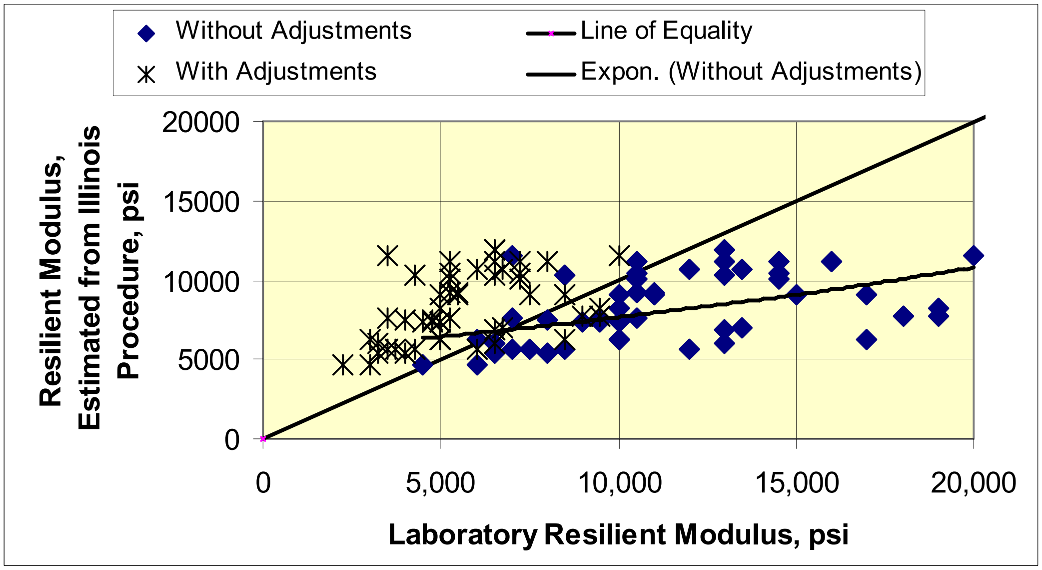

Figure 1.2: Graphical comparison of the laboratory resilient modulus and the values estimated from the Illinois procedure (equation 1.4).

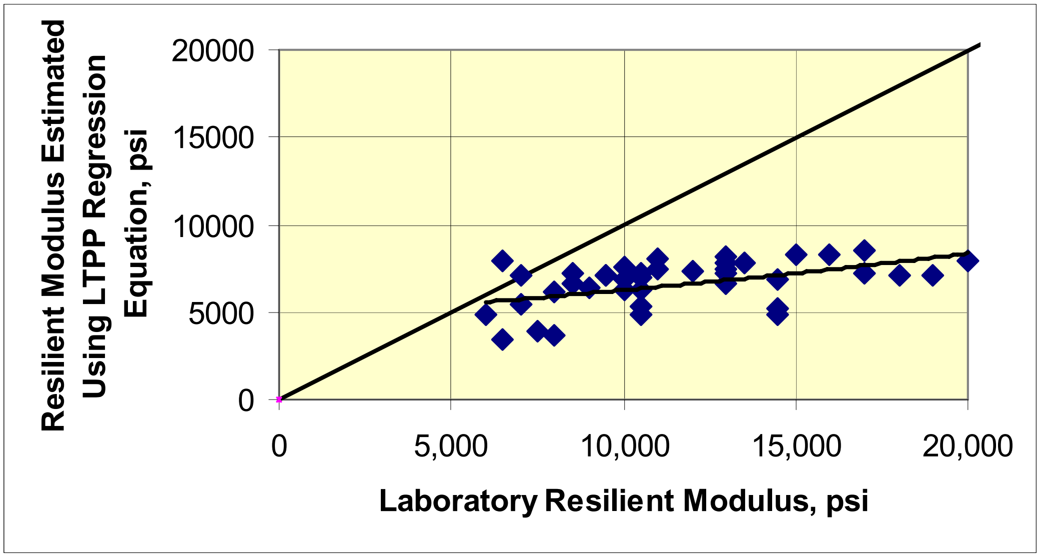

Figure 1.3: Graphical comparison of the laboratory resilient modulus and the values estimated from the LTPP regression equation for fine-grained clay soils.

Figure 1.4 combines all comparisons of the laboratory resilient modulus with those values estimated from regression equations and the default values included in the MEPDG. As shown, there are significant differences between each of the procedures. The following summarizes some of the reasons why these values are so diverse.

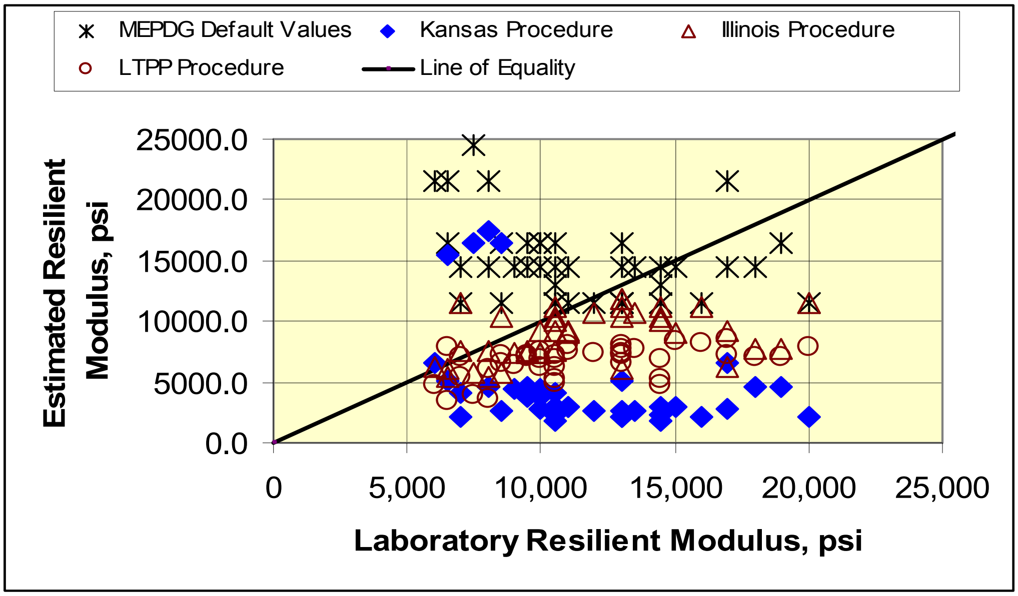

Figure 1.4: Graphical comparison of the laboratory resilient modulus and the values estimated from the different regression equations and default values included in the MEPDG.

- The effective roadbed resilient modulus values estimated from the Kansas regression equation has a negative bias of about 590 psi (the regressed values are lower than the adjusted laboratory values), which is small. Eliminating the four locations where the estimated resilient modulus values exceed 15,000 psi (refer to Figure 1.1), that negative bias increases to 1,711 psi.

  The negative bias is probably related to the condition of the soil samples and stress state that were used to develop the regression equation. The resilient modulus was initially based on the regression equation for subgrade modulus of reaction. It is expected that the condition of the samples that were used to develop the regression equation are more represented of wet conditions—like a soaked CBR test. Values resulting from soaked conditions will generally be lower than the in place values because soaked conditions generally do not exist in place except for short periods of time. The bias is not of a concern, but the scatter in the data around the line of equality is of a concern. The values should parallel the line of equality. This scatter implies that the regression equation may be capturing the strength characteristics of the material, but not the stiffness characteristics.
- The resilient modulus values estimated using the Illinois regression equation are also consistently lower than those determined from the laboratory tests using the equivalent stress state with an average negative bias of 2,994 psi. The Illinois values, however, are generally parallel to the line of equality. Some bias between these values is expected because they are based on different stress

states, and the stress sensitivity of the soil dictates the difference between the two values.

- The resilient modulus values estimated using the LTPP regression equation for fine-grained clay soils are similar in range and comparison to those resulting from the Illinois procedure. Both were derived using M-E based methods and generally follow the line of equality. The Illinois regression equation was based on a deviator stress of 6 psi, while the values calculated from the LTPP regression equation were determined at an average bulk stress of 8 psi.
- The default values included in the MEPDG are consistently higher than those estimated from laboratory resilient modulus tests using the equivalent stress state procedure (a positive bias of about 4,990 psi). The reason for these higher default values is that they represent the resilient modulus measured on specimens compacted to the maximum dry unit weight and optimum moisture content. The resilient modulus values measured on soils recovered from the LTPP sites in Kansas and other states were at the in place dry density and moisture content.

1.5 Summary and Recommendations

The following summarizes the findings and recommendations from this study.

1. The effective roadbed resilient modulus values estimated using the Kansas regression equation are consistently lower than those determined from laboratory resilient modulus tests. Some bias is expected, because the 1986 and 1993 AASHTO Design Guide was based on the serviceability concept and not on M-E based methods. As long as the resilient modulus values resulting from the

regression equation were calibrated to Kansas conditions, that bias need not be eliminated because of the empirical design procedure. The subgrade modulus of reaction is believed to be reasonable for the soils in Kansas.

2. The scatter in the data comparing the effective roadbed resilient modulus determined from the Kansas regression equation to those measured in the laboratory at equivalent (refer to Figure 1.1) stress states should be reduced. It is expected that the regression equation for resilient modulus could be improved by considering the effect of different soil types on the exponent and coefficient of equation 1.3, such that the comparison of data are more consistent with the line of equality—similar to the results from the Illinois and LTPP regression equations. However, it is recommended that more resilient modulus data be collected and obtained prior to making any changes to the regression equation. The comparisons presented within this memorandum are based on a limited study of only the LTPP test sections.
3. It is recommended that the Kansas regression equation not be used to estimate the resilient modulus values when using the MEPDG. The resilient modulus values used within that procedure need to be based on M-E based determination methods. It is recommended that the LTPP regression equations be used as a starting point but the bias within those values needs to be eliminated.

REFERENCES

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2. Von Quintus, Harold, and Brian Killingsworth, *Design Pamphlet for the Determination of Layered Elastic Moduli for Flexible Pavement Design in Support of the AASHTO Guide for the Design of Pavement Structures*, Report No. FHWA-RD-97-077, Federal Highway Administration, Department of Transportation, Washington, DC, September 1997.

3. Von Quintus, Harold, and Brian Killingsworth, *Analyses Relating to Pavement Material Characterizations and Their Effects on Pavement Performance*, Report No. FHWA-RD-97-085, Federal Highway Administration, Department of Transportation, Washington, DC, January 1998.

4. Treybig, Harvey, B.F. McCullough, P.R. Jordahl, Phil Smith, and Harold L. Von Quintus, *Flexible and Rigid Pavement Overlay Design Procedure*, Report No. FHWA-RD-77-133, Federal Highway Administration, Department of Transportation, Washington, DC, October 1977.

5. Von Quintus, Harold L., and Abe Gonzales, *Flexible Pavement Design Guidelines for Street and Roadways, Bexar County, Texas – Volume I: Data Collection and Analyses, Volume II: Pavement Design Procedures*, Final Report No. BC-1, Bexar County Public Works Department, San Antonio, Texas, October 1987.

6. Von Quintus, Harold L., and Amber Yau, *Evaluation of Resilient Modulus Test Data in the LTPP Database*, Publication Number FHWA-RD-01-158, Federal Highway Administration, Office of Infrastructure Research and Development, Turner-Fairbanks Research Station, Washington, DC, 2001.

APPENDIX A

GRAPHICAL PRESENTATION OF REPEATED LOAD RESILIENT MODULUS TEST DATA EXTRACTED FROM THE LTPP DATABASE FOR THE SITES LOCATED IN KANSAS

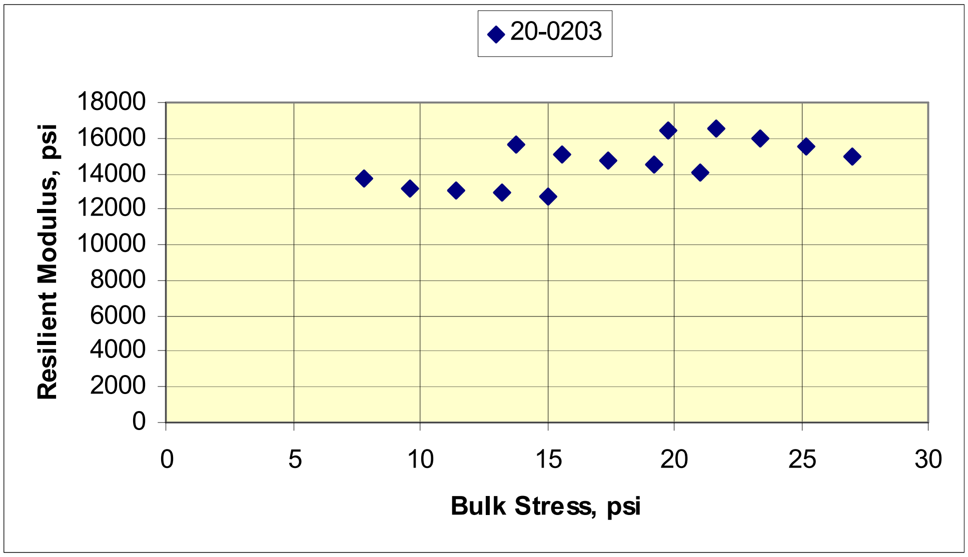

Figure A1: LTPP Site 20-0203; Subgrade Soil

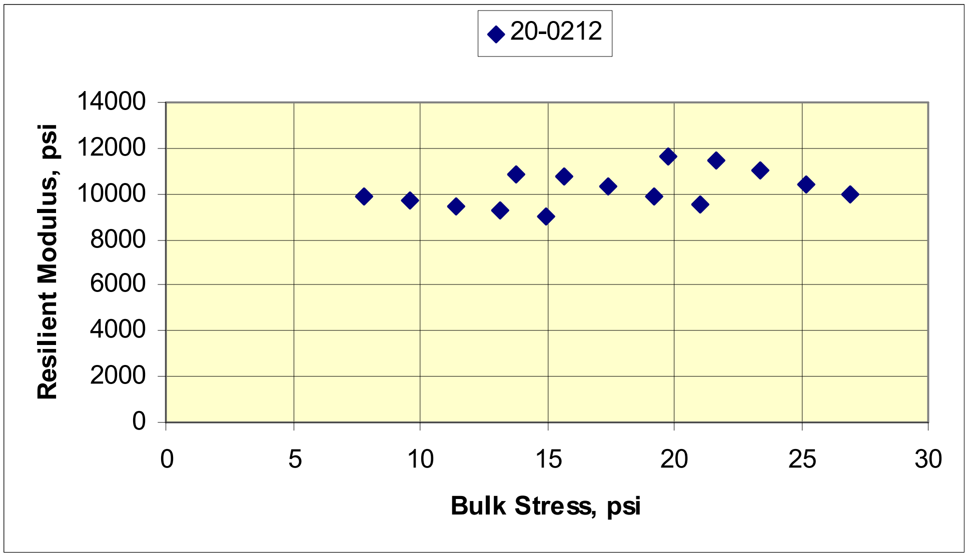

Figure A2: LTPP Site 20-0212; Subgrade Soil

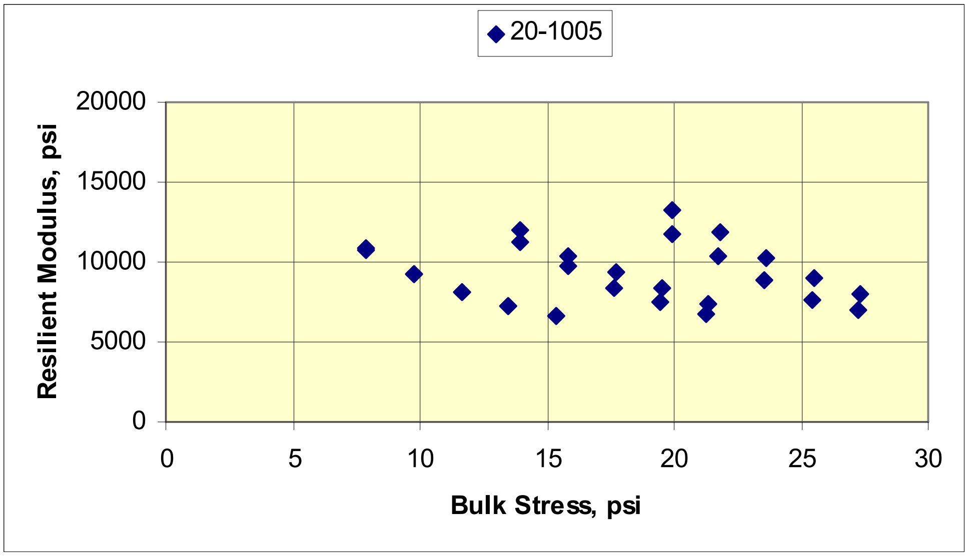

Figure A3: LTPP Site 20-1005; Subgrade Soil

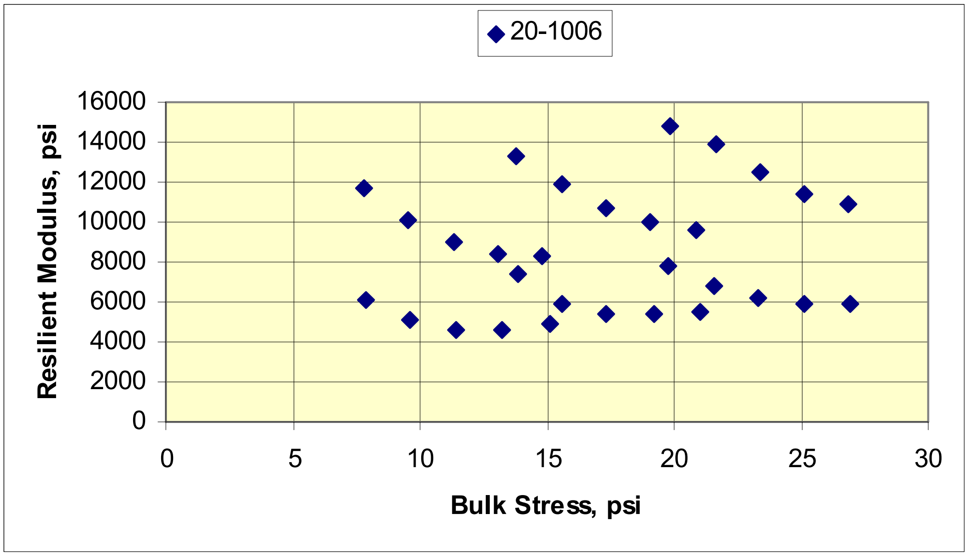

Figure A4 : LTPP Site 20-1006; Subgrade Soil

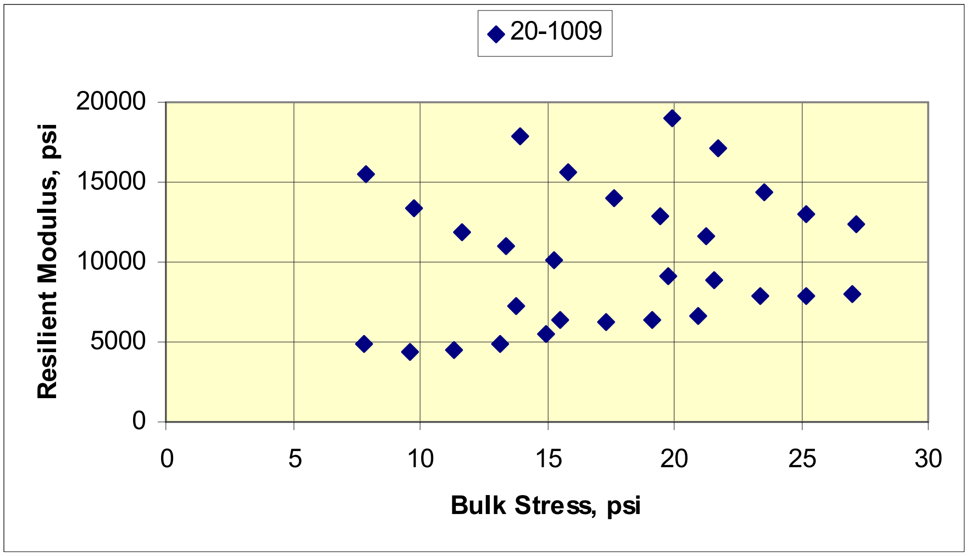

Figure A5 : LTPP Site 20-1009; Subgrade Soil

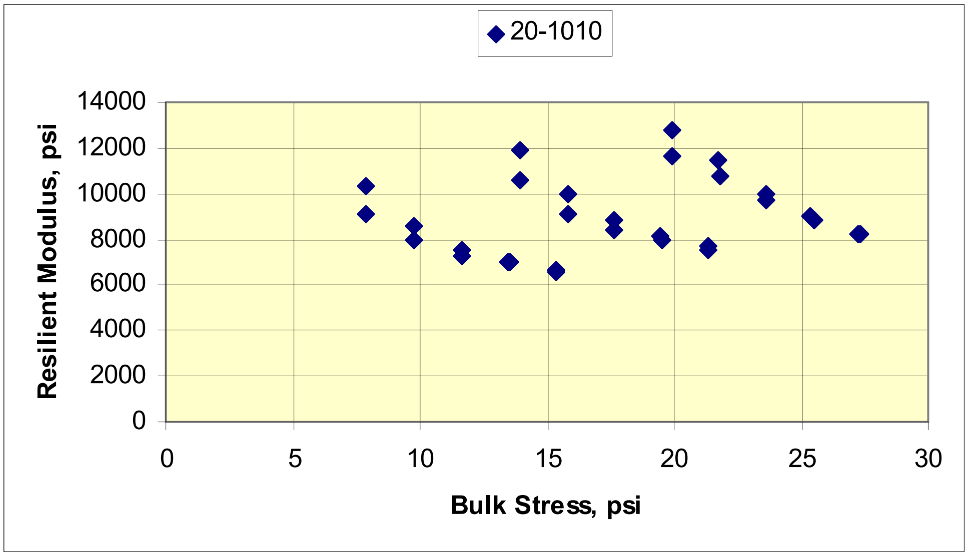

Figure A6 : LTPP Site 20-1010; Subgrade Soil

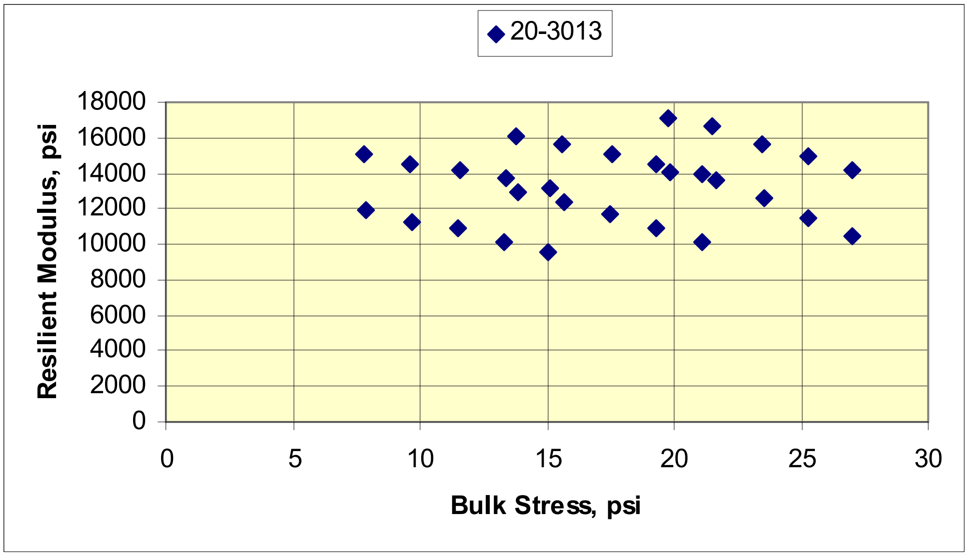

Figure A7 : LTPP Site 20-3013 ; Subgrade Soil

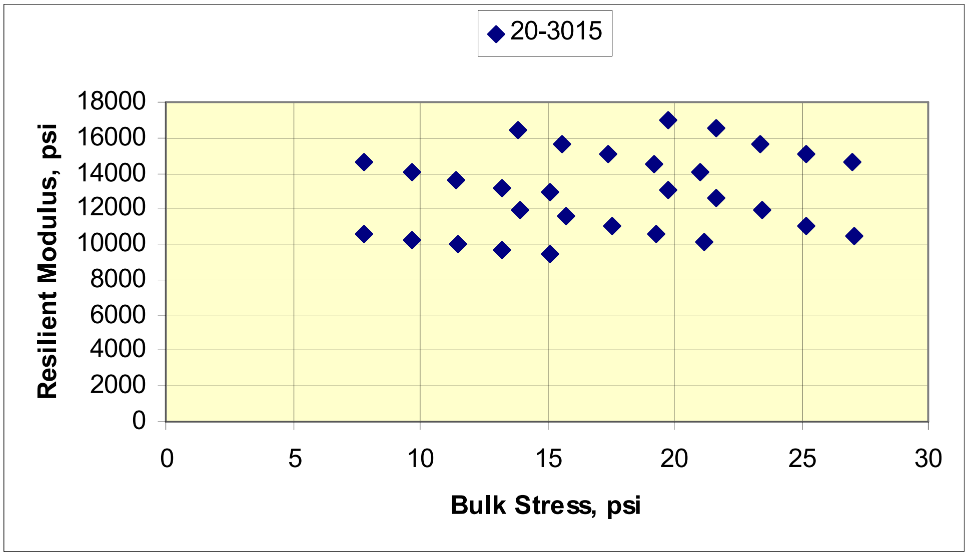

Figure A8 : LTPP Site 20-3015 ; Subgrade Soil

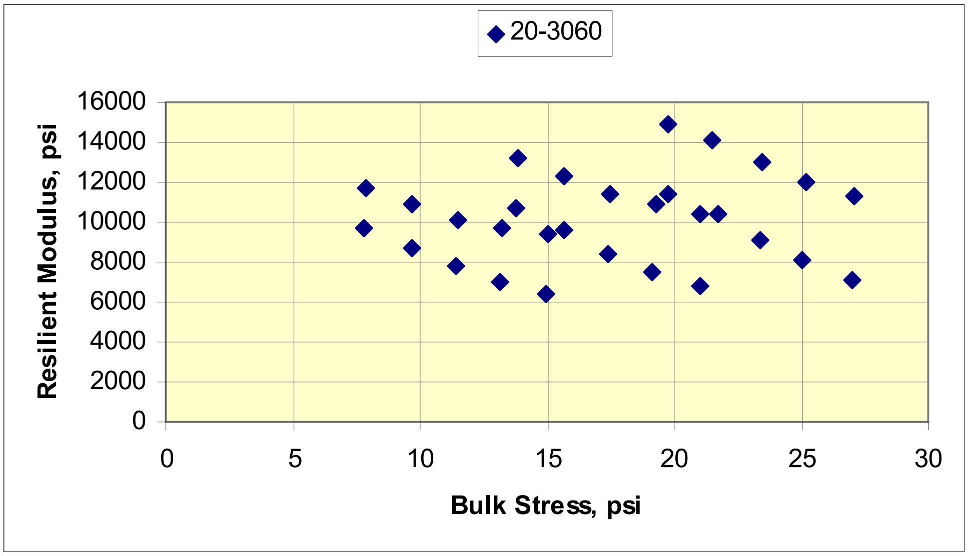

Figure A9 : LTPP Site 20-3060; Subgrade Soil

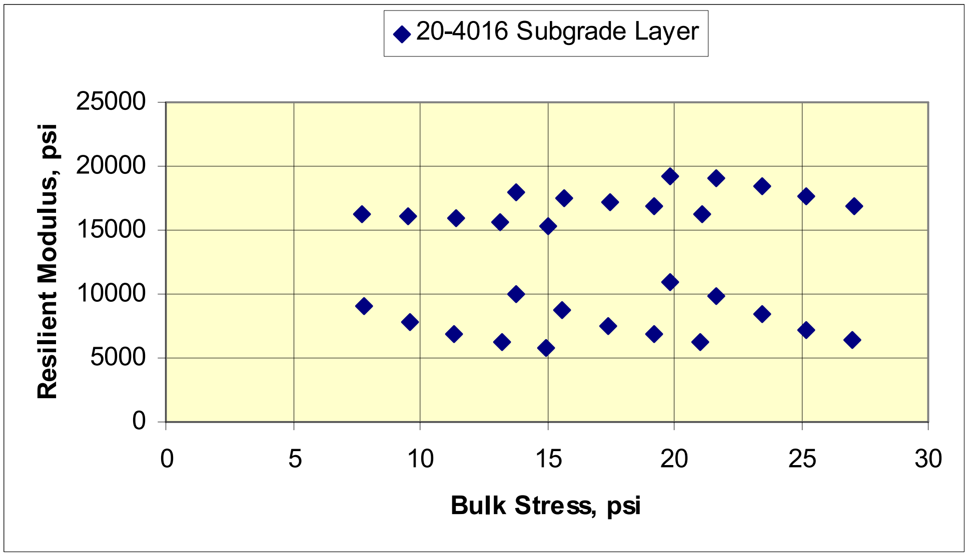

Figure A10 : LTPP Site 20-4016; Subgrade Soil

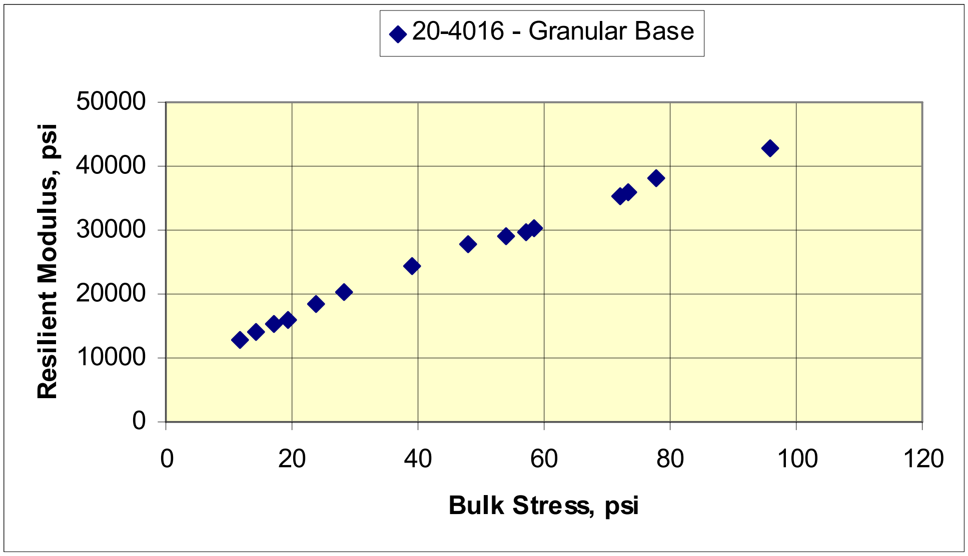

Figure A11: LTPP Site 20-4016; Granular Base Material

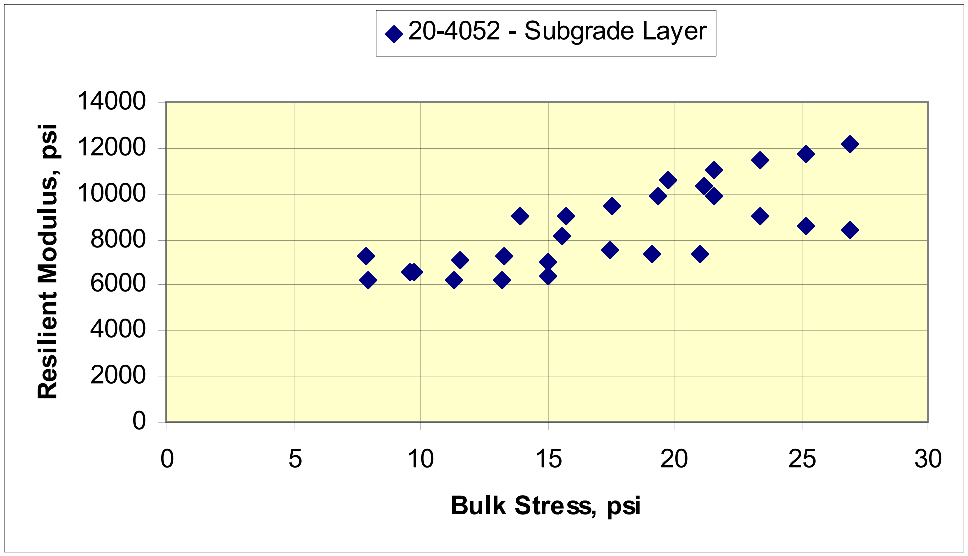

Figure A12: LTPP Site 20-4052; Subgrade Soil

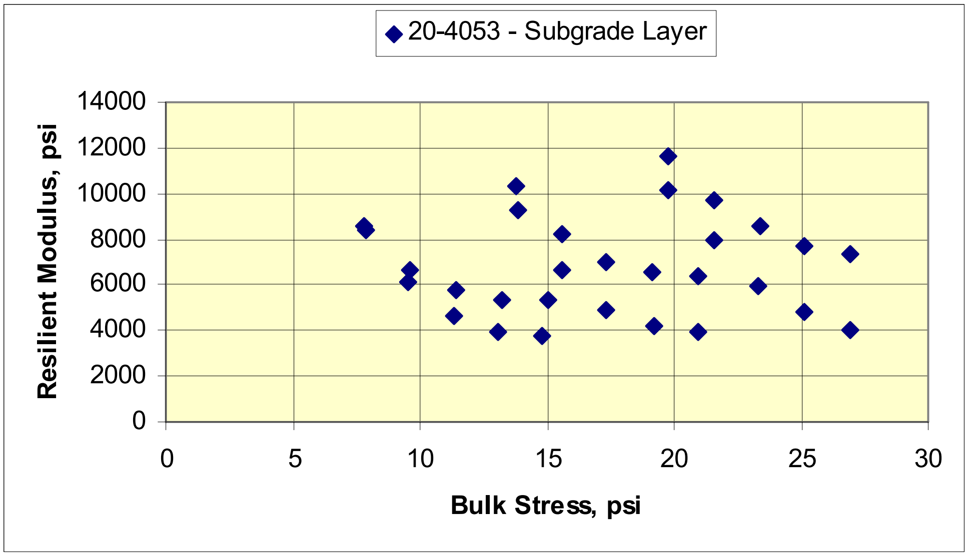

Figure A13: LTPP Site 20-4053; Subgrade Soil

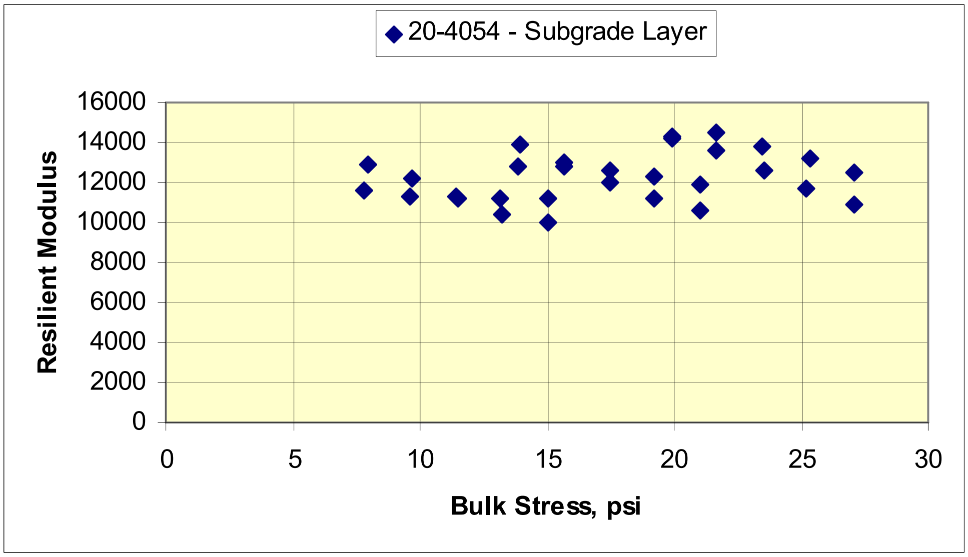

Figure A14 : LTPP Site 20-4054; Subgrade Soil

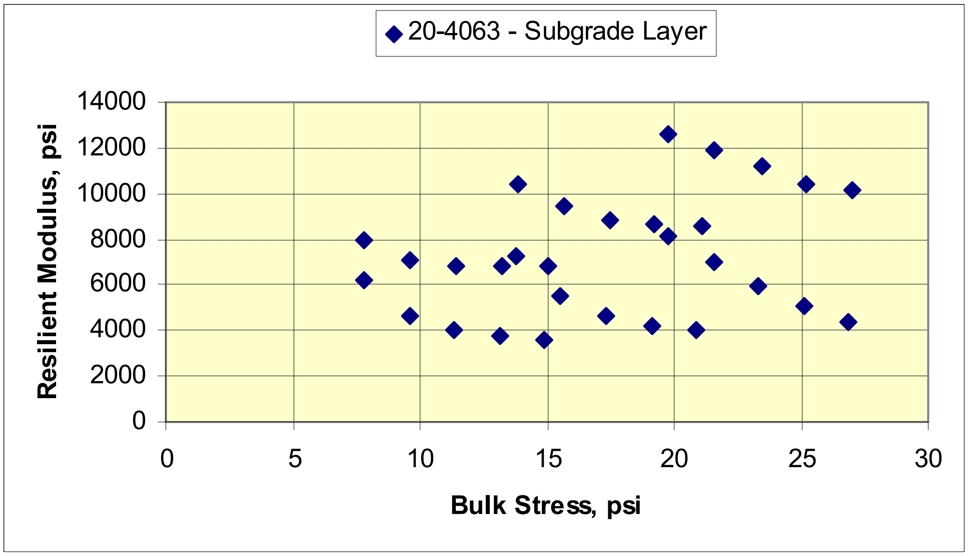

Figure A15 : LTPP Site 20-4063; Subgrade Soil

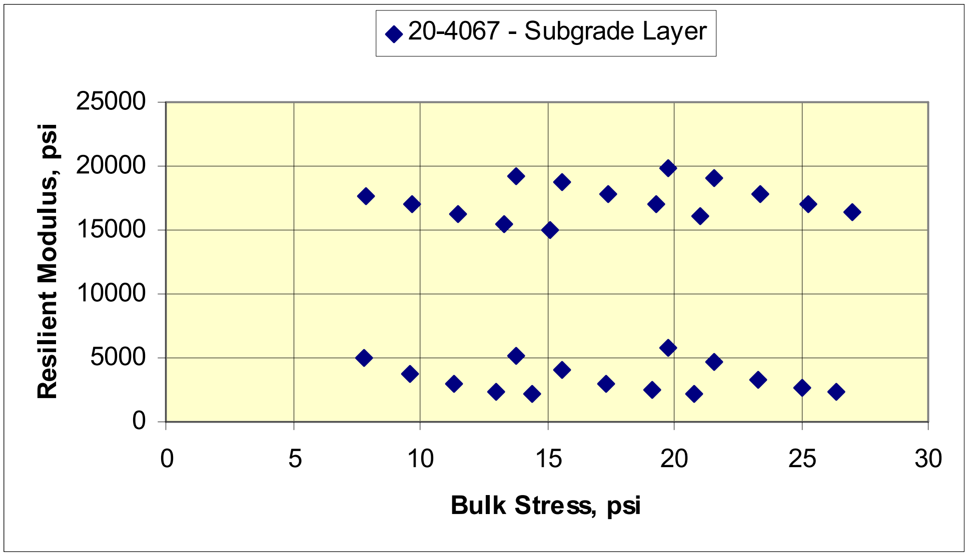

Figure A16 : LTPP Site 20-4067; Subgrade Soil

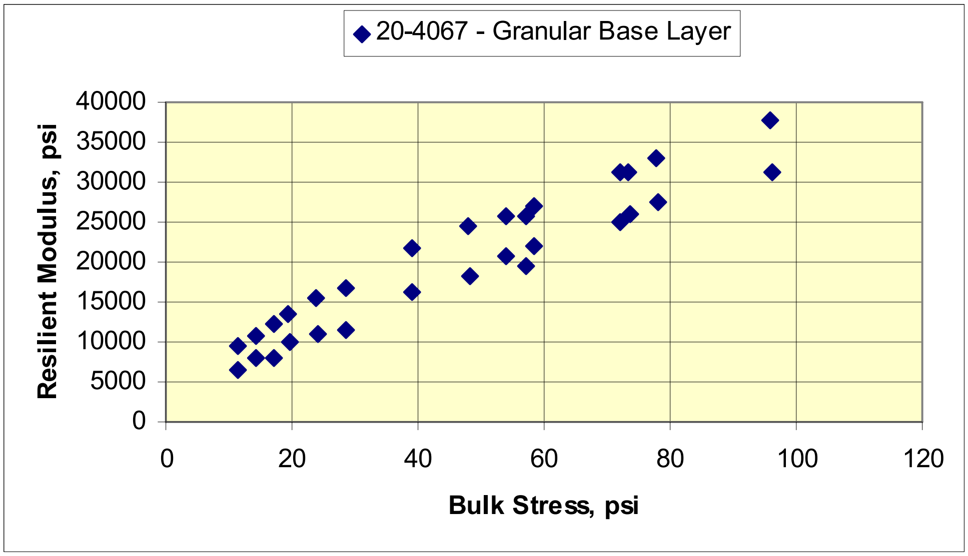

Figure A17 : LTPP Site 20-4067 ; Granular Base Material

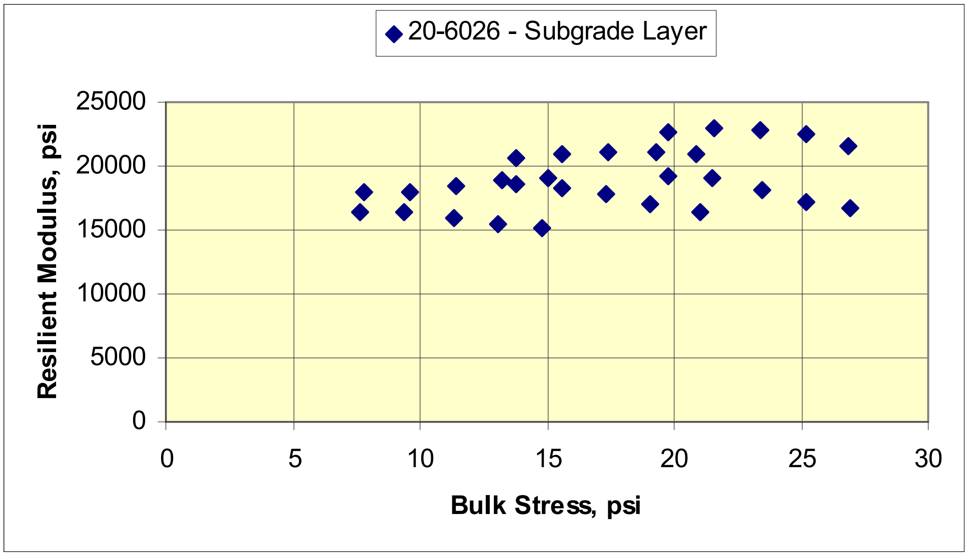

Figure A18 : LTPP Site 20-6026; Subgrade Soil

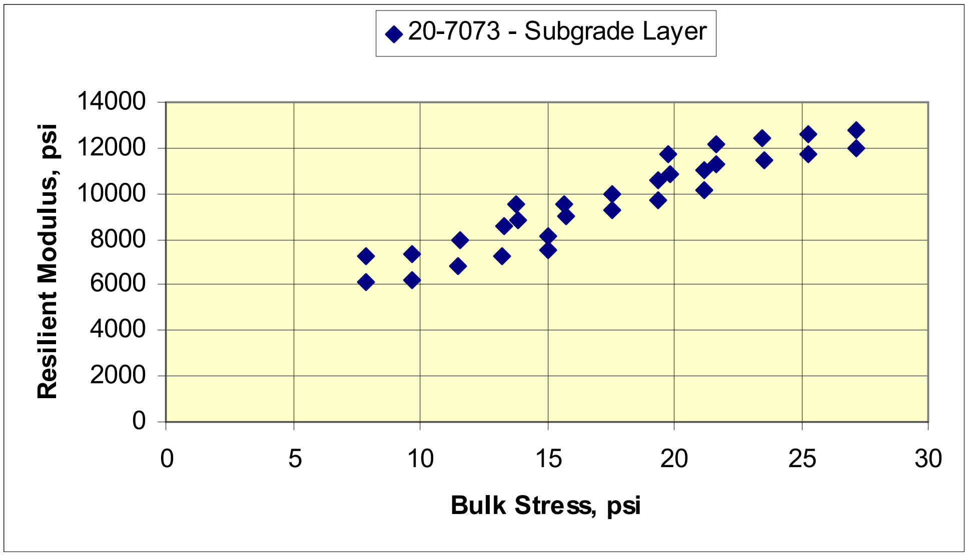

Figure A19 : LTPP Site 20-7073; Subgrade Soil

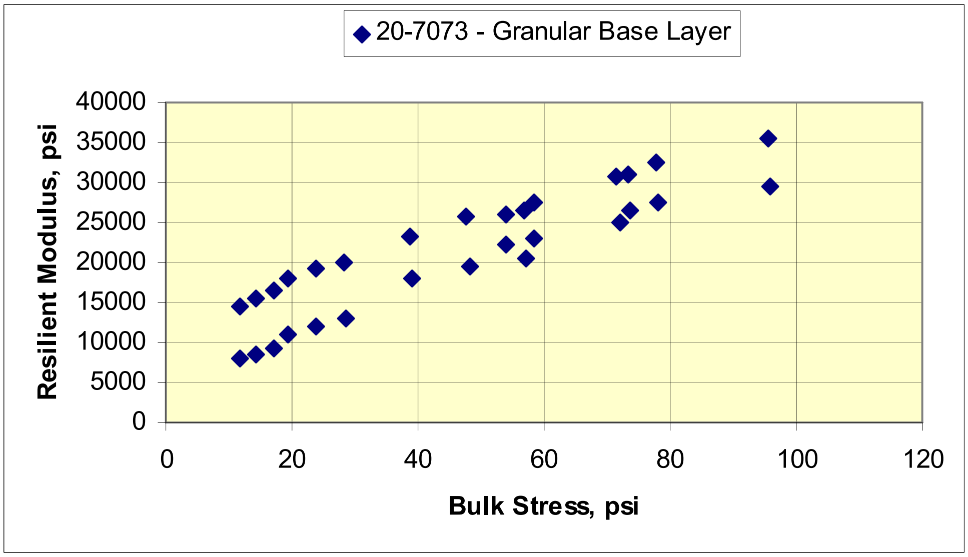

Figure A20 : LTPP Site 20-7073; Granular Base Material

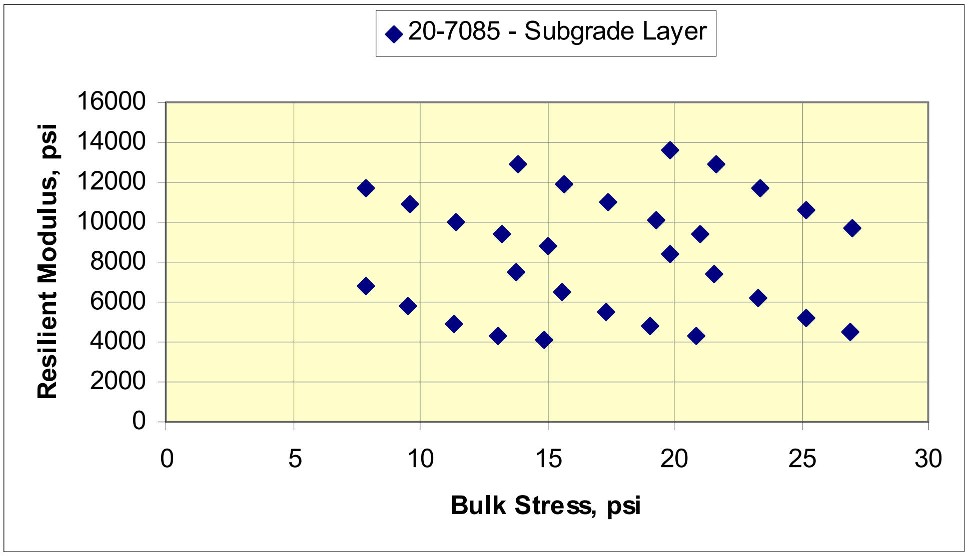

Figure A21 : LTPP Site 20-7085; Subgrade Soil

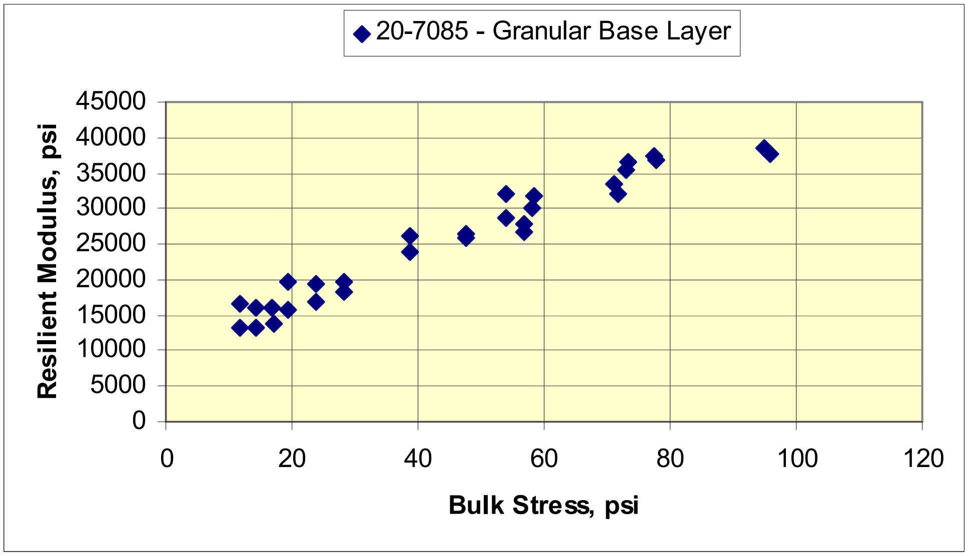

Figure A22 : LTPP Site 20-7085; Granular Base Material

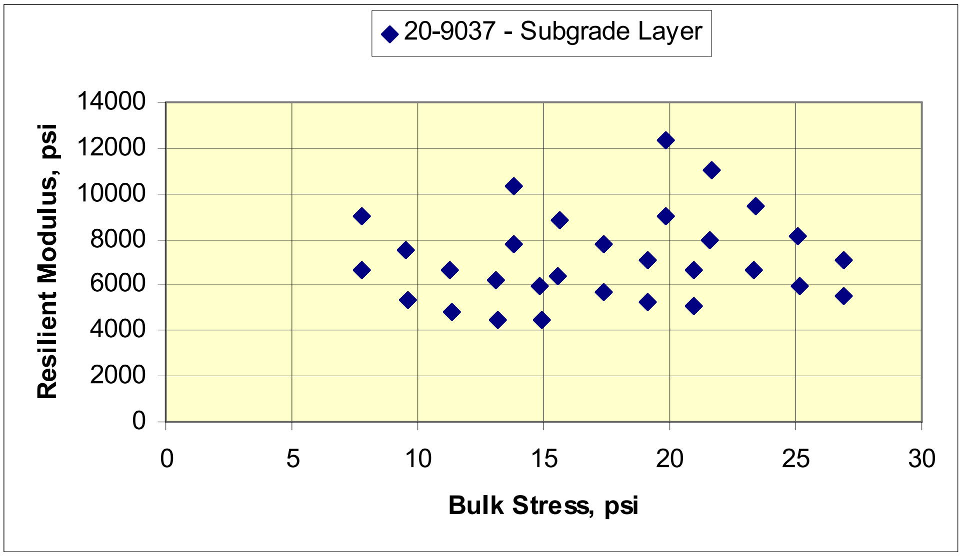

Figure A23: LTPP Site 20-9037; Subgrade Soil

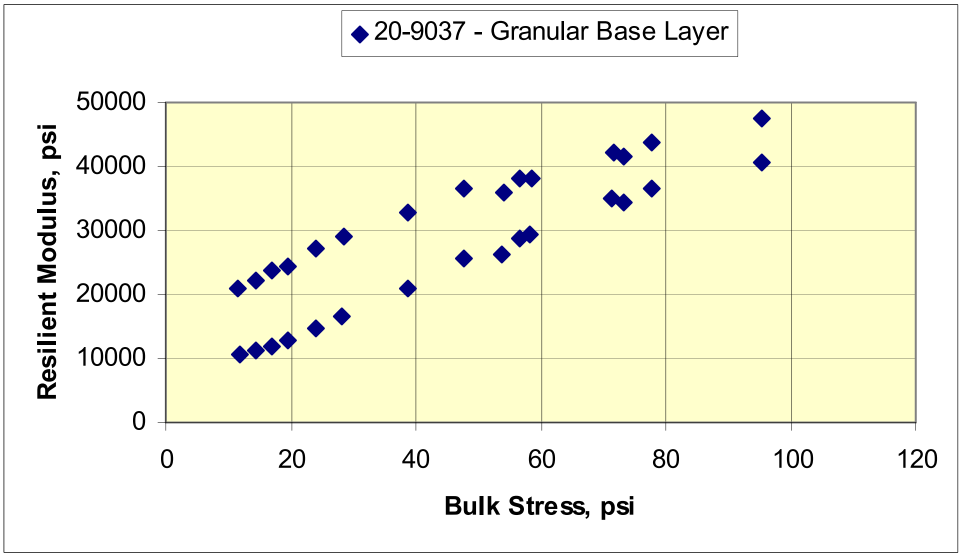

Figure A24: LTPP Site 20-9037; Granular Base Material

APPENDIX B

EXAMPLE OUTPUT FROM THE EVERSTRESS PROGRAM THAT WAS USED TO CALCULATE THE WHEEL LOAD STRESSES AT A DEPTH OF 18 INCHES INTO THE FOUNDATION SOIL

Layered Elastic Analysis by EVERSTRESS for Windows
Title: Kansas DOT Resilient Modulus Study; LTPP Site 20-1009

```
No of Layers:  5      No of Loads:   2      No of X-Y Evaluation Points:   2
Layer  Poisson's      Thickness    Moduli
*      Ratio  (in)    (ksi)
1       .30            11.100        500.00
2       .45            12.000          6.00
3       .45            12.000          6.00
4       .45            12.000          6.00
5       .45            *                        6.00

Load No     X-Position    Y-Position    Load          Pressure      Radius
*           (in)          (in)          (lbf)         (psi)         (in)
 1          0.00          0.00          4500.0              120.00              3.455
 2          12.00         0.00          4500.0              120.00              3.455

Location No:   1     X-Position (in):     .000     Y-Position (in):     .000
Normal Stresses
Z-Position    Layer  Sxx           Syy           Szz           Syz    Sxz    Sxy
(in)                 (psi)         (psi)         (psi)         (psi)  (psi)  (psi)
  .000        1       -143.67      -153.70       -120.00       0.00   0.00   0.00
 12.100       2          -.85      -0.74           -2.28       0.00   0.21   0.00
 29.000       3          -.28      -0.26           -1.31       0.00   0.11   0.00
 42.000       4          -.14      -0.13           -0.94       0.00   0.07   0.00

Normal Strains and Deflections
Z-Position    Layer  Exx           Eyy           Ezz           Ux     Uy     Uz
(in)                 (10^-6)             (10^-6)               (10^-6)              (mils)
        (mils)  (mils)
  .000        1      -123.12       -149.19       -61.58        0.488  0.000  18.246
 12.100       2        84.38         111.07       -259.96      -.0521 0.000  16.979
 29.000       3        70.13          76.05       -177.04      -0.437 0.000  13.374
 42.000       4        56.80          59.53       -136.58      -0.349 0.000  11.349
```

Location No: 2 X-Position (in): 6.000 Y-Position (in): .000

Normal Stresses

Z-Position (in)	Layer	Sxx (psi)	Syy (psi)	Szz (psi)	Syz (psi)	Sxz (psi)	Sxy (psi)
.000	1	-38.55	-75.07	0.00	.00	.00	.00
12.100	2	-0.89	-0.76	-2.36	.00	.00	.00
29.000	3	-0.28	-0.26	-1.34	.00	.00	.00
42.000	4	-0.14	-0.13	-0.96	.00	.00	.00

Normal Strains and Deflections

Z-Position	Layer	Exx	Eyy	Ezz	Ux	Uy	Uz
(in)		(10^-6)	(10^-6)		(10^-6)		(mils)
(mils)	(mils)						
.000	1	-32.05	-127.01	68.17	0.000	0.000	17.711
12.100	2	86.50	116.89	-270.16	0.000	0.000	17.284
29.000	3	74.11	77.56	-183.06	0.000	0.000	13.507
42.000	4	58.75	60.23	-139.46	0.000	0.000	11.427

Layered Elastic Analysis by EVERSTRESS for Windows
Title: Kansas DOT Resilient Modulus Study; LTPP Site 20-4016

```
No of Layers:  5      No of Loads:   2      No of X-Y Evaluation Points:   2
Layer  Poisson's      Thickness      Moduli
*      Ratio          (in)           (ksi)
1      0.15            9.100         4000.00
2      0.30            4.000            17.00
3      0.45           12.000                   10.00
4      0.45           24.000                   10.00
5      0.45           *                 10.00

Load No      X-Position    Y-Position    Load                   Pressure     Radius
*            (in)          (in)          (lbf)                  (psi)        (in)
 1            0.00         0.00          4500.0                 120.00       3.455
 2           12.00         0.00          4500.0                 120.00        3.455

Location No:   1     X-Position (in):     .000     Y-Position (in):     .000
Normal Stresses
Z-Position     Layer  Sxx           Syy           Szz           Syz    Sxz    Sxy
(in)           *      (psi)         (psi)         (psi)         (psi)  (psi)  (psi)
  .000         1       -160.71      -181.50       -120.0        0.00   0.00   0.00
 10.100        2          -0.01         0.07       -10.35       0.00   0.13   0.00
 31.000        4          -0.19        -0.19        -0.77       0.00   0.05   0.00
 42.000        4          -0.12        -0.12        -0.63       0.00   0.03   0.00

Normal Strains and Deflections
Z-Position     Layer  Exx           Eyy           Ezz           Ux     Uy     Uz
(in)     *            (10^-6)       (10^-6)       (10^-6)       (mils) (mils) (mils)
  .000         1        -28.87      -34.85        -17.17         0.125 0.000  7.862
 10.100        2         22.20        27.87       -80.39        -0.134 0.000  7.659
 31.000        4         23.77        25.01       -60.32        -0.146 0.000  6.196
 42.000        4         21.18        21.90       -51.75        -0.129 0.000  5.581
```

Location No: 2 X-Position (in): 6.000 Y-Position (in): .000

Normal Stresses

Z-Position (in) *	Layer	Sxx (psi)	Syy (psi)	Szz (psi)	Syz (psi)	Sxz (psi)	Sxy (psi)
.000	1	-65.15	-132.85	0.00	0.00	0.00	0.00
10.100	2	-0.01	0.08	-1.37	0.00	0.00	0.00
31.000	4	-0.19	- 0.19	-0.79	0.00	0.00	0.00
42.000	4	-.12	-0.12	-0.63	0.00	0.00	0.00

Normal Strains and Deflections

Z-Position (in) *	Layer	Exx (10^-6)	Eyy (10^-6)	Ezz (10^-6)	Ux (mils)	Uy (mils)	Uz (mils)
.000	1	-11.31	-30.77	7.43	0.000	0.000	7.838
10.100	2	21.95	28.96	-81.57	0.000	0.000	7.744
31.000	4	24.64	25.33	-61.62	0.000	0.000	6.233
42.000	4	21.70	22.08	-52.52	0.000	0.000	5.606


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