Consideration of Stress Sensitivity in Backcalculation of Subgrade Moduli

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ABSTRACT

This study examined the effect of subgrade nonlinearity and the presence of a stiff layer at a shallow depth on the backcalculated resilient moduli for eight different highway projects in Kansas. Deflection tests were conducted with a Falling Weight Deflectometer. The subgrade moduli were backcalculated from the surface deflections, using EVERCALC, a backcalculation program developed by the Washington Department of Transportation, and the 1993 AASHTO Design Guide algorithms. On three projects, there were no significant differences in the subgrade resilient moduli values obtained from these two approaches. However, on five other projects differences were significant. Since in most cases the subgrade soils were slightly or negligibly nonlinear, the stress-sensitivity was attributed to the presence of a stiff layer at a shallow depth. It is recommended that during backcalculation of subgrade resilient moduli, the soil nonlinearity coefficients and the depth to the stiff layer always be calculated. If the coefficients indicate significant nonlinearity or the depth to the stiff layer is shallow, then a nonlinear analysis algorithm should be preferred for response calculation.

Key words: Subgrade, backcalculation, FWD, resilient moudlus, stress-sensitivity

INTRODUCTION

The resilient modulus of the subgrade soil is a very important parameter for predicting it's ability to support repeated loads. The elastic modulus based on the recoverable strain under repeated loads is called the resilient modulus, M_R and is defined as (*1*):

$$M_R = \sigma_d / \varepsilon_r \qquad (1)$$

where σ_d is the deviator stress and ε_r is the recoverable strain.

To obtain a reliable backcalculated resilient modulus for the subgrade layer, numerous factors need to be taken into consideration. One such important factor is the stress sensitivity of the subgrade soil. Stress sensitivity can result from material nonlinearity or from the geometry of the pavement, such as, presence of a stiff layer under subgrade (*2*). A simplified power model can be used to define the stress dependent nature of the subgrade resilient modulus (*3*):

$$M_R = K_3 * \sigma_d^{K_4} \qquad (2)$$

where σ_d is the deviator stress and K_3 and K_4 are material constants that are dependant on the physical properties of the soil. For fine-grained soils, K_4 will usually be less than zero indicating a decreasing slope. According to Li and Selig (*4*), K_4 ranges between 0 and -1.0 and K_3 ranges between 0 and 1,378 MPa (200 ksi) for three fine-grained soils collected from San Diego, Illinois, and Maryland. If K_4 is close to zero that would indicate the material is linear.

OBJECTIVE AND RESEARCH APPROACH

The objective of this project was to study the nonlinear structural behavior of asphalt pavements in the field and to quantify the effect of stress-sensitivity on backcalculation of layer moduli. The subgrade resilient moduli for eight asphalt pavement projects with asphalt concrete surface over an aggregate base were backcalculated using the 'EVERCALC' software and the AASHTO design guide algorithms. The backcalculated resilient moduli were compared and the differences (if any) were noted. The effect of stress-sensitivity was taken into consideration by examining the effect of nonlinearity of the subgrade soils and the presence of a stiff layer. EVERCALC can calculate the nonlinear material coefficients K_3 and K_4 for subgrade materials if multiple load levels are used during falling weight deflectometer (FWD) testing. These constants provide a clue to the nonlinear behavior. EVERCALC also computes the depth to the stiff layer. However, the AASHTO design guide algorithms assume that the subgrade material is linear elastic, and the layer is semi-infinite in the vertical direction. Therefore, if the backcalculated moduli by the two methods vary, it could be assumed to be either due to the depth of the stiff layer, or, due, in part, to the nonlinear behavior of the material.

PROJECT SELECTION AND DATA COLLECTION

Project Selection

Eight projects, all flexible (asphalt) pavements, were selected so that the pavement section consists of three layers: surface, granular base and subgrade. Surface deflections were measured at a number of stations by FWD testing. Table 1 lists the details of location of the projects and also the layer thicknesses. The projects are located on the US or state highways.

Data Collection

The FWD test results on the selected projects were collected and analyzed. The layer thicknesses were determined using historical construction and maintenance data. A Dynatest Model 8000 FWD was used to collect the deflection data. Deflections at stations at intervals of 0.16 km (1/10th mile) or 0.032 km (1/50th mile) were taken depending upon the project size. Three drops of multiple target loads at each station were used to get the deflections. For all tests, seven sensors were used. The first sensor was at the center of the load plate. The other sensors were placed at radial distances of 305 mm (12 inches), 610 mm (24 inches), 914 mm (36 inches), 1.2 m (48 inches), 1.5 m (60 inches), 1.8 m (72 inches) from the center of the plate. The tests were conducted on the outer wheel path of the travel lane.

Determination of Soil Properties

Soil properties at each station of the projects were collected from the United States Department of Agriculture (USDA) county soil survey reports. The USDA maps were used to locate the stations in the county. The soil subgrade type, present at each station, was noted based on the USDA symbol. The relevant properties of the soil type were then read from the tables in the USDA soil survey report. Most of the soils are in the CL to ML category. Occasionally some highly plastic soils, such as CH, were also encountered.

BACKCALCULATION OF SUBGRADE RESILIENT MODULI

EVERCALC Program

In this study, a computer program EVERCALC, was used to backcalculate the subgrade layer moduli (*3*). EVERCALC uses WESLEA to compute the deflections. WESLEA was developed by the US Army Corps of Engineers Waterways Experiment Station (WES) in the late 80's. This program can be used to compute the stresses, strains, and deflections in pavements. EVERCALC determines a set of elastic moduli that results in best fit between the measured deflection basins from FWD test analysis and the deflection basin obtained, when an initial set of elastic moduli (seed moduli) is provided (*3*). In this study, the goal was to achieve less than 5% RMS (root mean square) error.

EVERCALC uses a modified augmented Guass-Newton algorithm for optimization (*3*). Optimization is the identification of the set of elastic moduli of the pavement layers that would result in the best fit of the calculated deflections with the measured deflections. EVERCALC also determines the material constants K_3 and K_4. K_3 and K_4 give an estimate of the stress sensitivity of the subgrade materials, and are determined by a linear regression method if deflections at two or more load levels are available at a particular point.

Another important aspect in EVERCALC is the optional algorithm available to calculate the depth of the 'stiff layer'. Depth of the stiff layer is the depth in the pavement system at which the deflection is zero. According to the algorithm in EVERCALC, the depth at which zero deflection occurs is related to the horizontal offset at which zero deflection would happen. WSDOT (*3*) assumes that no surface deflection occurs beyond the horizontal offset from the load plate that corresponds to the intercept of the stress zone and the stiff layer within the pavement system. Usually the stiff layer is encountered within the first 9.15 m (30 ft) from the surface of the layered system.

AASHTO Design Guide Algorithms

The backcalculation of the subgrade resilient modulus using the 1993 AASHTO design guide algorithms (*6*) is done using the following procedure: First the deflections from each station corresponding to the lowest root-mean square (RMS) error in EVERCALC computation were taken. The normalized deflections at each of these stations were also calculated. The subgrade resilient modulus for each deflection was found using the formula:

$$M_R = 0.24 * P / (d_r * r) \tag{3}$$

Where P is the load, d_r is the normalized deflection, and r is the radial distance.

Now, the AASHTO Guide suggests that the deflection used to backcalculate the subgrade modulus must be far enough that gives a reliable estimate of the subgrade modulus. At the same time, the deflection should not be too low to measure accurately. The minimum distance to the deflection for calculating the subgrade modulus is given by:

$$r \geq 0.7\, a_e \tag{4}$$

where

$$a_e = [(a^2 + (D(E_p/M_R)^{1/3})^2]^{1/2} \tag{5}$$

a_e = radius of the stress bulb at subgrade -pavement interface in inches;
A = NDT load plate radius;
D = Total thickness of the pavement layers above the subgrade, inches; and
E_p = Effective modulus of all pavement layers above the subgrade, psi.

Effective modulus of the pavement (E_p) can be calculated if the total thickness of the pavement and the subgrade resilient modulus are known. E_p can be calculated from the deflection at the center of the load plate using the formula

$$d_0 = 1.5\, p_a\{1/M_R[1+(D/a(E_p/M_R)^{1/3})^2] + [1- 1/[1+(D/a)^2]^{1/2}]/E_p\} \tag{6}$$

where d_0 is the deflection at the center of the load plate (and adjusted to a standard 68°F), inches
P = NDT load plate pressure, psi
a = NDT load plate radius, inches
D = Total thickness of pavement layers above the subgrade in inches.
M_R = Subgrade resilient modulus, psi, and
E_p = Effective modulus of all pavement layers above subgrade, psi

Before using the backcalculated M_R value in design it must be adjusted to make it consistent with the value used in the AASHTO flexible pavement design equation. Adjustments to account for seasonal variation are also needed (*6*).

For FWD data analysis the load plate radius is 150 mm (5.9 inches). The E_p/M_R values are taken from the 1993 AASHTO design guide. E_p is then determined from the known M_R value. The E_p/M_R values are substituted in the a_e equation and a_e is determined for each deflection. Then the condition $r \geq 0.7a_e$ is verified. The M_R value corresponding to the first sensor, which satisfies the condition r≥0.7ae, is taken as the subgrade resilient modulus (*6*).

ANALYSIS STEPS

The FWD deflections were taken at 0.16 km (1/10th mile) or 0.032 (1/50th mile) kilometer intervals. At least ten stations were selected for each project. The resilient moduli were backcalculated from the AASHTO design algorithms and EVERCALC. The depths to the stiff layer were calculated. Correlation analysis was conducted between these two sets of backcalculated moduli to determine if the moduli values are linealy correlated. The subgrade soil nonlinearity coefficient values, K_3 and K_4, for each station on each project were also calculated. Finally, paired t-tests were performed on the moduli data sets to assess the correlation between the results of the two methods.

RESULTS AND DISCUSSIONS

Project I: US-54

The US-54 project in Allen County, is 4.95 km (3.072 miles) in length. FWD data for eighteen stations were analyzed and Table 3 tabulates the backcalculation results. The average M_R values are 126.6 MPa (18,380 psi) and 124.2 MPa (18,030 psi), respectively, for the AASHTO algorithm and EVERCALC. The average K_3 value is 112.5 MPa (16,324 psi) and K_4 is –0.098. An average negative value of K_4 indicates that the subgrade material is slightly nonlinear. The average depth to the stiff layer is 2.54 m (100 inches).

Figure 1 indicates a good correspondence between the moduli obtained from the two calculation methods. The variation in the individual moduli values at most of the stations is negligible. The t-test results are shown in Table 3. The Pearson correlation coefficient is 0.97, which indicates a strong linear correlation between the moduli backcalculated by the two methods. The t-test results show that the backcalculated moduli from the two methods are not significantly different. The soil properties show that at most of the stations the subgrade soil is silty loam or silty clay. The AASHO classification classifies the soil to be between A-4 and A-7. Since the difference between the mean resilient moduli from AASHTO and EVERCALC is not significant, we can conclude that neither the stiff layer nor the nonlinearity of the subgrade material has much effect on the backcalculated subgrade soil resilient modulus on this project.

PROJECT II: US-56

This project is 6.0 km (3.722 miles) in length. FWD data for 22 stations were analyzed. The average M_R value from AASHTO algorithms is 70 MPa (10,180 psi) and from EVERCALC is 69 MPa (10,030 psi). The average K_3 and K_4 values from EVERCALC are 71 MPa (10,342 psi) and –0.157, respectively. A value of zero for K_4, indicates that the subgrade material at any station would be linear. A negative K_4 value indicates a nonlinear trend in subgrade material behavior. The backcalculated depth to the stiff layer is 4.3 m (171 inches).

An almost perfect correspondence between the resilient modulus from the two methods is indicated in Figure 2. The variation in the moduli at most stations is negligible. The Pearson correlation coefficient is 0.97 implying a strong linear correlation between the moduli backcalculated by the two methods. The t-test results showed that the moduli backcalculated by the two methods are not significantly different. The soil properties listed show that at most of the stations the subgrade soil is silty loam or silty clay. The AASHO classification system classified the soil to be between A-4 and A-7. Neither the stiff layer nor the nonlinearity of the subgrade material seems to affect the resilient modulus of the subgrade on this project since there is no significant difference in the M_R values estimated by the two methods.

PROJECT III: US-59

This project, located on US-59 in Anderson County, is 8.5 km (5.274 miles) long. FWD data for 21 stations were analyzed. The average M_R value from the AASHTO algorithms is 159 MPa (23,110 psi) and from EVERCALC is 136 MPa (19,800 psi). The stress-sensitivity coefficients, K_3 and K_4, from EVERCALC are 127 MPa (18,460 psi) and –0.097, respectively. The K_4 value indicates a nonlinear material. For two stations the K_4 value was found to be zero. This indicates that the materials at those stations are linear. Average depth to the stiff layer is 2.03 m (80 inches).

Figure 3 indicates that there is a noticeable difference in backcalculated modulus values, later confirmed by the computed t-statistic. AASHTO modulus values are higher than the corresponding EVERCALC values for all stations. The soil properties listed show that at most of the stations the subgrade soil is silty loam or silty clay. The AASHO classification classified the soil to be between A-4 and A-7. The significant difference in the resilient moduli values from the two methods may be caused by the presence of the stiff layer. As mentioned earlier, the depth to the stiff layer is only 2.03 m (80 inches).

Project IV: US-77-1

The project length is 6.32 km (3.923 miles). Thirty stations were considered in FWD data analysis. Deflections at the first and third sensors were considered for all stations except one, for calculating M_R values. The average M_R value from the AASHTO algorithms is 116 MPa (16,900 psi) and from EVERCALC is 131 MPa (18,970 psi). The average K_3 and K_4 values are 127 MPa (18,390 psi) and –0.064, respectively. The depth of the stiff layer is 3.05 m (120 inches).

Figure 4 indicates that higher M_R values were obtained from EVERCALC. For some stations the two M_R's coincide but for some, the variation is quite high. The calculated t-statistic showed the moduli predicted by the two methods are significantly different. At most stations the subgrade soil is silty loam or silty clay. The AASHO classification classifies the soil to be between A-4 and A-7. Since the difference between the mean resilient moduli from the two methods is significant, it could be either due to the stiff layer or due to the nonlinearity of the subgrade material. Since the K_4 value is equal to -0.064, the subgrade material is not highly nonlinear. Therefore, the difference in moduli values can be attributed only to the effect of the stiff layer.

Project V: US-77-2

The project is 4.88 km (3.034 miles) in length. Table 3 shows the EVERCALC results and AASHTO moduli values. The average modulus value from the AASHTO algorithms is 97 MPa (14,060 psi) and from EVERCALC is 111 MPa (16,110 psi). Average K_3 value is 106 MPa (15,330 psi) and the average value of K_4 for the project is –0.067. The K_4 value indicates a slightly nonlinear subgrade. The depth to the stiff layer is 2.7 m (108 inches).

The spatial variation in the moduli values computed from the two methods and the AASHTO M_R versus EVERCALC M_R plot are illustrated in Figure 5. The paired t-test results showed that the moduli backcalculated by the two methods are significantly different. At most stations, the subgrade soil is silty loam or silty clay. The AASHO classification classified the soil to be between A-4 and A-7. Again on this project, the difference in M_R values can be attributed to the effect of the stiff layer, since the subgrade soil is not highly nonlinear.

Project VI: K-92

The total length of the project is 23.1 km (14.374 miles). FWD data was analyzed for 14 stations. The average M_R value from the AASHTO algorithms is 77 MPa (11,180 psi) and from EVERCALC is 69.3 MPa (10,060 psi). The average K_3 and K_4 values are 69.4 MPa (10,070 psi) and –0.228, respectively. The subgrade material appears to be nonlinear. The depth of the stiffness layer is 1.85 m (73 inches).

The spatial variation in the moduli values computed from the two methods and the AASHTO M_R versus EVERCALC M_R plot are illustrated in Figure 6. The figure shows that a clear difference between the moduli values, with higher AASHTO M_R values for most of the stations. The paired t-test results indicate that the moduli estimated by two methods are significantly different. At most stations the subgrade soil is silty loam or clay loam. The AASHO classification classified the soils to be between A-4 and A-7. The non-linear soil and shallow depth of the stiff layer 1.85 m (73 inches) could be attributed to the significant difference in moduli from EVERCALC and the AASHTO algorithms.

Project VII: K-116

This project is 9.67 km (6.006 miles) in length. FWD data for 10 stations were analyzed for this study. The average M_R value from the AASHTO algorithms is 119 MPa (17,320 psi) and from EVERCALC is 122 MPa (17,740 psi). Average K_3 value from EVERCALC is 123 MPa (17,890 psi). The average K_4 value is –0.143. The subgrade material is not highly nonlinear. The backcalculated depth to the stiff layer is 2.54 m (100 inches).

Figure 7 indicates a good correspondence between the moduli obtained from the two calculation methods. This conclusion is supported by the t-test results in Table 3. At most stations the subgrade soil is clay loam or silty clay. The AASHO classification classified the soil to be A-6 or A-7. The difference in the resilient moduli of the subgrade layer from the two methods is not significant as the material is not highly nonlinear. The stiff layer, estimated to be at a depth of 2.54 m (100 inches), did not affect the computed resilient modulus.

Project VIII: US-166

The project is 4.95 km (3.073 miles) in length. Ten stations were considered for FWD data analysis. The average M_R value from the AASHTO algorithms is 128 MPa (18,600 psi) and from EVERCALC is 147 MPa (21,400 psi). The average K_3 is 144 MPa (20,890 psi) and average K_4 is –0.064. The K_4 value indicates slight nonlinearity of the subgrade material. One station has been observed to have a K_4 value of 0 indicating a linear subgrade. The backcalculated depth to the stiff layer is 2.9 m (114 inches).

The plot of the resilient modulus values and the station locations is shown in Figure 8. The figure does not indicate a linear relation between the two sets of resilient moduli values as it shows scatter in data. The pairwise t-test indicated that the moduli estimated by the two methods are significantly different. At most stations the subgrade soil is silty loam or silty clay. The AASHO classification classified the soil to be between A-4 and A-7. Since the material is negligibly nonlinear, the stiff layer (estimated at a depth of 2.9 m) could be the only cause for the large variation in modulus values calculated from the two methods.

CONCLUSIONS

This study analyzed the backcalculated resilient moduli from the AASHTO Design Guide algorithms and EVERCALC. The stress-sensitivity factor due to material nonlinearity and/or the presence of a stiff layer within the pavement system was taken into consideration. The correlation between the results from the two procedures was observed. Based on the analysis results, the following conclusions can be drawn:

(1) For projects US-54, US-56 and K-116, there are no significant differences in the resilient moduli values calculated from the AASHTO Design Guide algorithms and those calculated from EVERCALC. The t-test results confirmed this fact. The effect of stiff layer and/or the nonlinearity of the subgrade material on the backcalculated subgrade resilient moduli was negligible.

(2) For other projects, there is a significant difference in the resilient moduli values obtained from the two methods. This could be attributed to the effect of the stiff layer. Subgrade soils of all projects were found to be, in most cases, slightly or negligibly nonlinear. Thus the stress-sensitivity in the subgrade layer could be attributed mainly to the stiff layer.

(3) It was observed that for most of the projects where the depth to the stiff layer is less than 2.54 m (100 inches), there is a significant difference in the resilient moduli from the AASHTO Design Guide algorithms and EVERCALC. This happened because the AASHTO algorithm does not consider the effect of stiff layer. If the stiff layer is at a higher depth then the effect becomes negligible.

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TABLE 1 Project Details

Route	County	Start Milepost	Project Length (miles)	Soil Type (AASHTO)	Layer Thickness (in)	
					AC	Base
US-54	ALLEN	19.208	3.072	A-4 to A-7	8	11
US-56	LYON	10.527	3.722	A-4 to A-7	7.5	4
US-59	ANDERSON	21.807	5.274	A-4 to A-7	10.7	6
US-77-1	MARSHALL	15.066	3.923	A-4 to A-7	11.5	5
US-77-2	MARSHALL	35.248	3.034	A-6 to A-7	6.5	8
K-92	LEAVENWORTH	0.144	14.374	A-4 to A-7	5.5	6
K-116	JACKSON	3.519	6.006	A-6 to A-7	3.0	8
US-166	MONTGOMERY	28.101	3.073	A-4 to A-6	7.0	8

TABLE 2 Results of the Backcalculation using EVERCALC

Route	Subgrade soil constants		Comment on Non-linearity	Backcalculated Resilient Modulus from EVERCALC (psi)
	K3 (psi)	K4		
US-54	16,324	-0.098	Slightly nonlinear	18,030
US-56	10,342	-0.16	Slightly nonlinear	10,030
US-59	18,460	-0.097	Slightly nonlinear	19,800
US-77-1	18,376	-0.06	negligibly nonlinear	18,970
US-77-2	15,332	-0.07	negligibly nonlinear	16,110
K-92	10,073	-0.23	Slightly nonlinear	10,060
K116	17,890	-0.098	Slightly nonlinear	17,740
US-166	20,890	-0.06	negligibly nonlinear	21,400

TABLE 3 Comparison of Backcalculated Subgrade Resilient Modulus Results

Route	EVERCALC MR (psi)	AASHTO MR (psi)	% Difference	t-test results*	Backcalculated Depth to Stiff Layer (inches)
US-54	18,030	18,380	2	not significant	100
US-56	10,030	10,180	1.5	not significant	171
US-59	19,800	23,110	17	significant	80
US-77-1	18,970	16,900	11	significant	120
US-77-2	16,110	14,060	13	significant	102
K-92	10,060	11,180	11	significant	73
K-116	17,740	17,320	2	not significant	100
US-166	21,400	16,400	23	significant	138

* at 5% level of significance

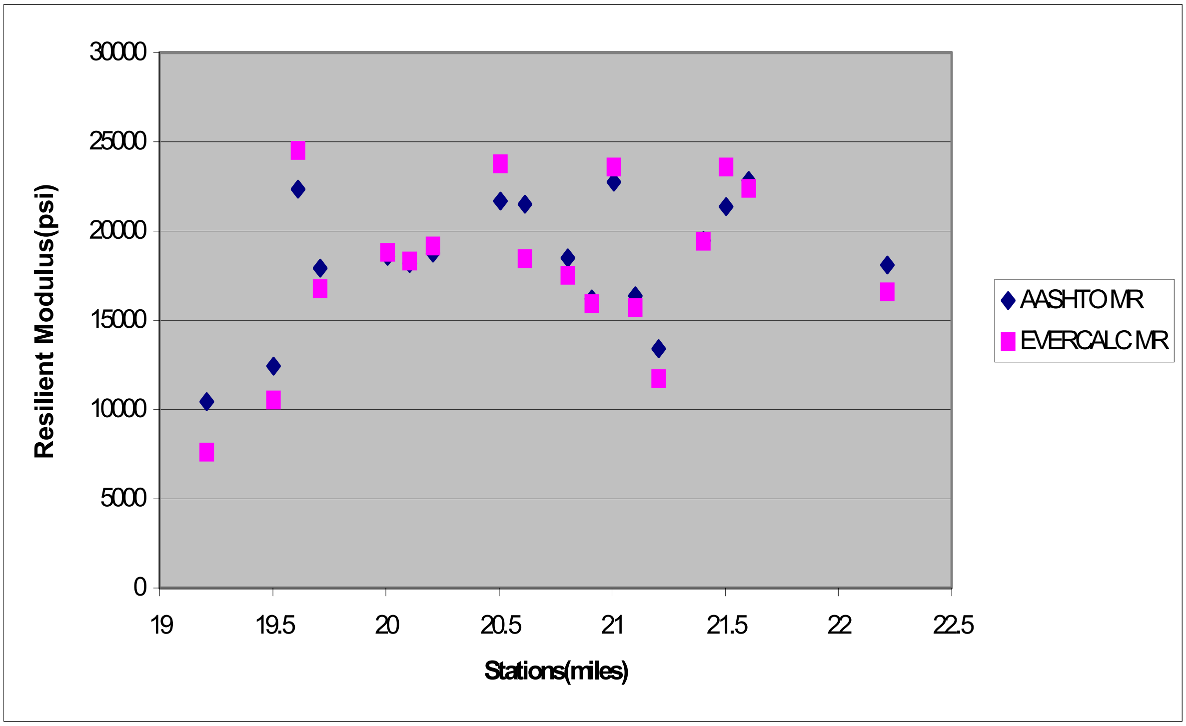

FIGURE 1 Spatial Variation of Subgrade Moduli For US-54

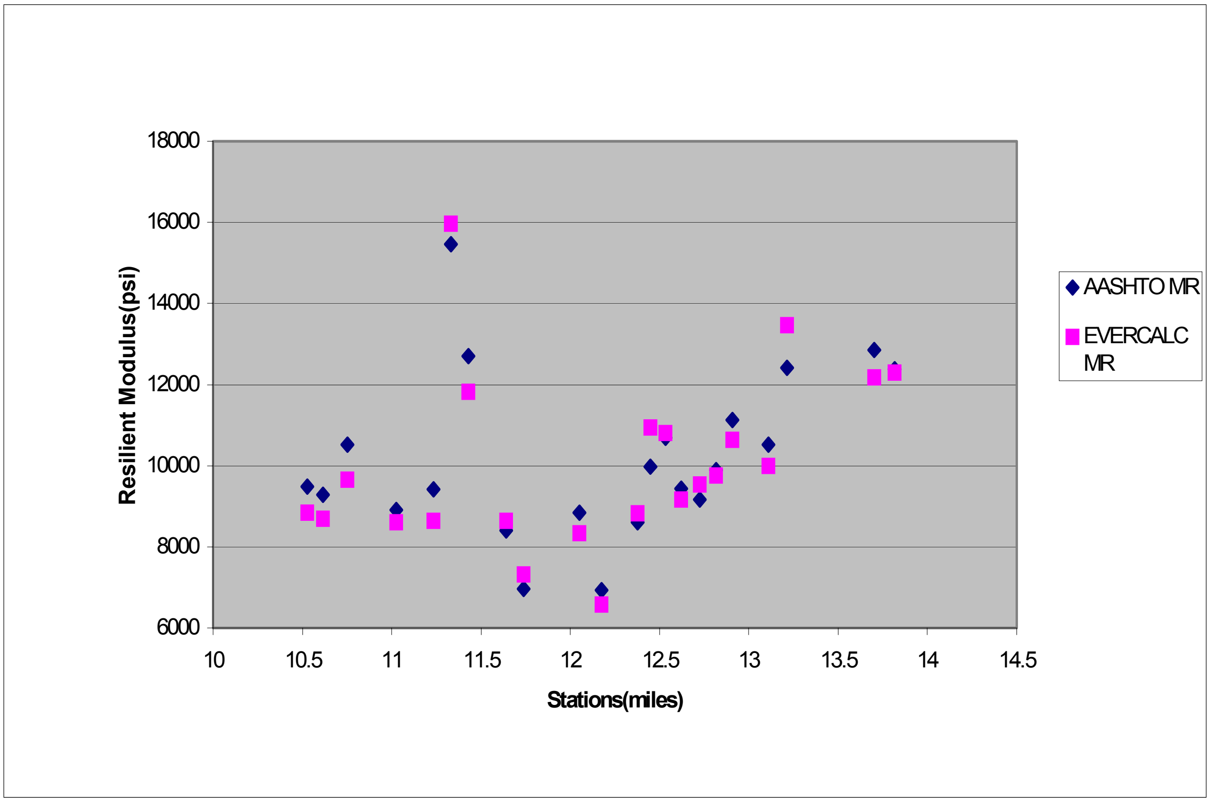

FIGURE 2 Spatial Variation of Subgrade Moduli for US-56

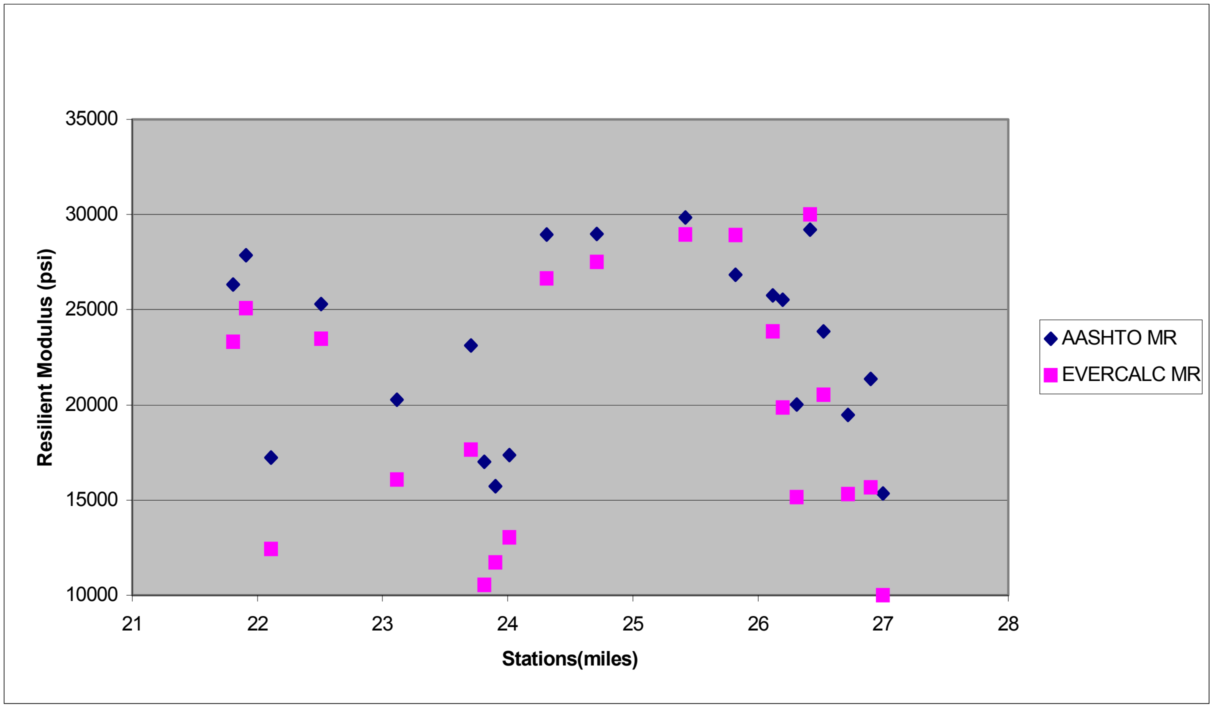

FIGURE 3 Spatial Variation of Subgrade Moduli for US-59

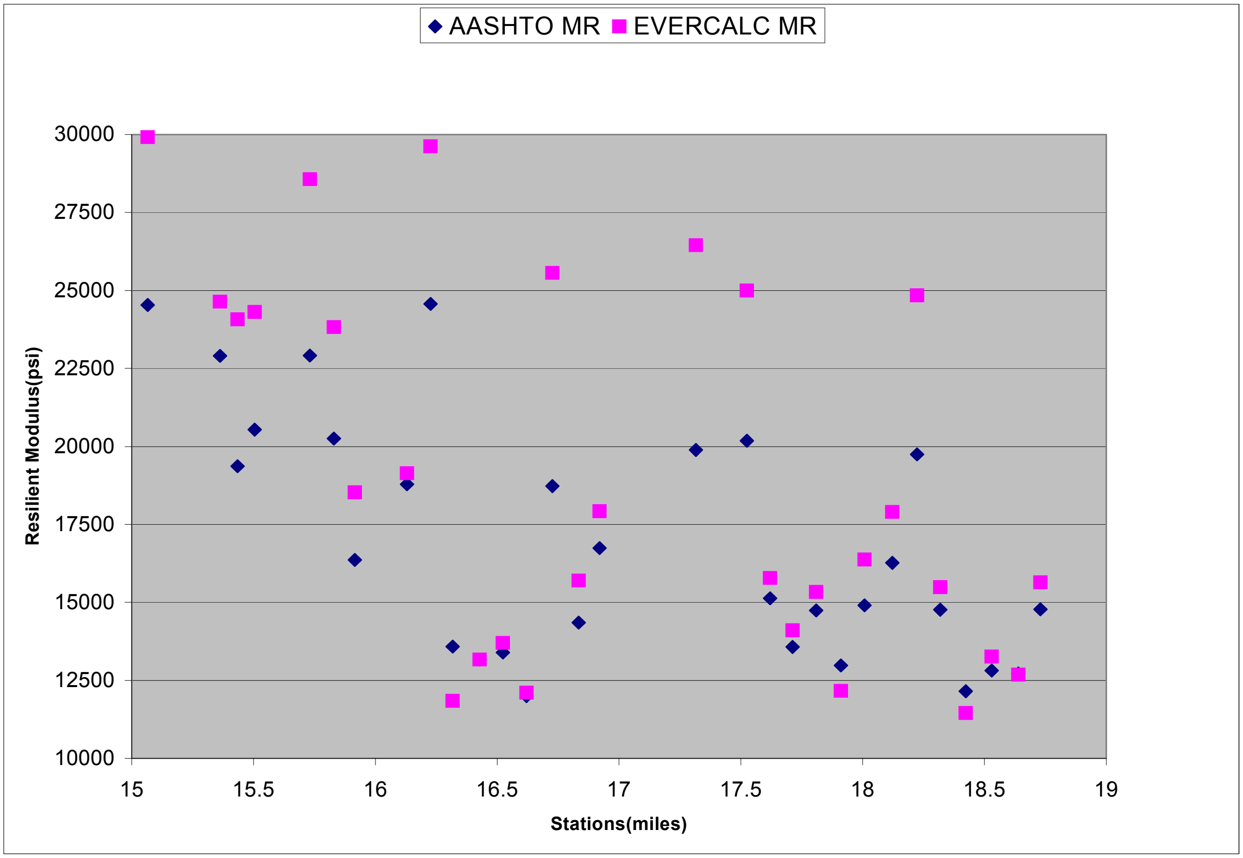

FIGURE 4 **Spatial Variation of Subgrade Moduli for US-77-1**

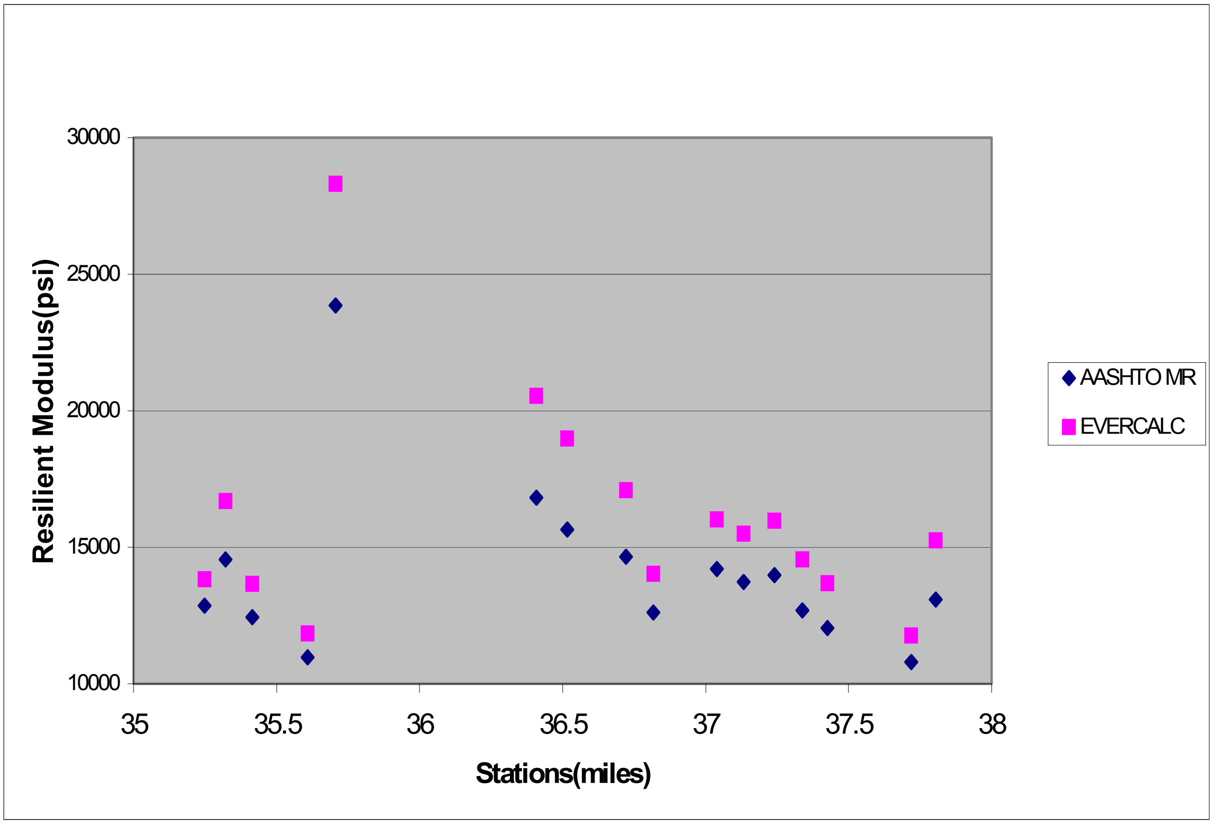

FIGURE 5 **Spatial Variation of Subgrade Moduli for US-77-2**

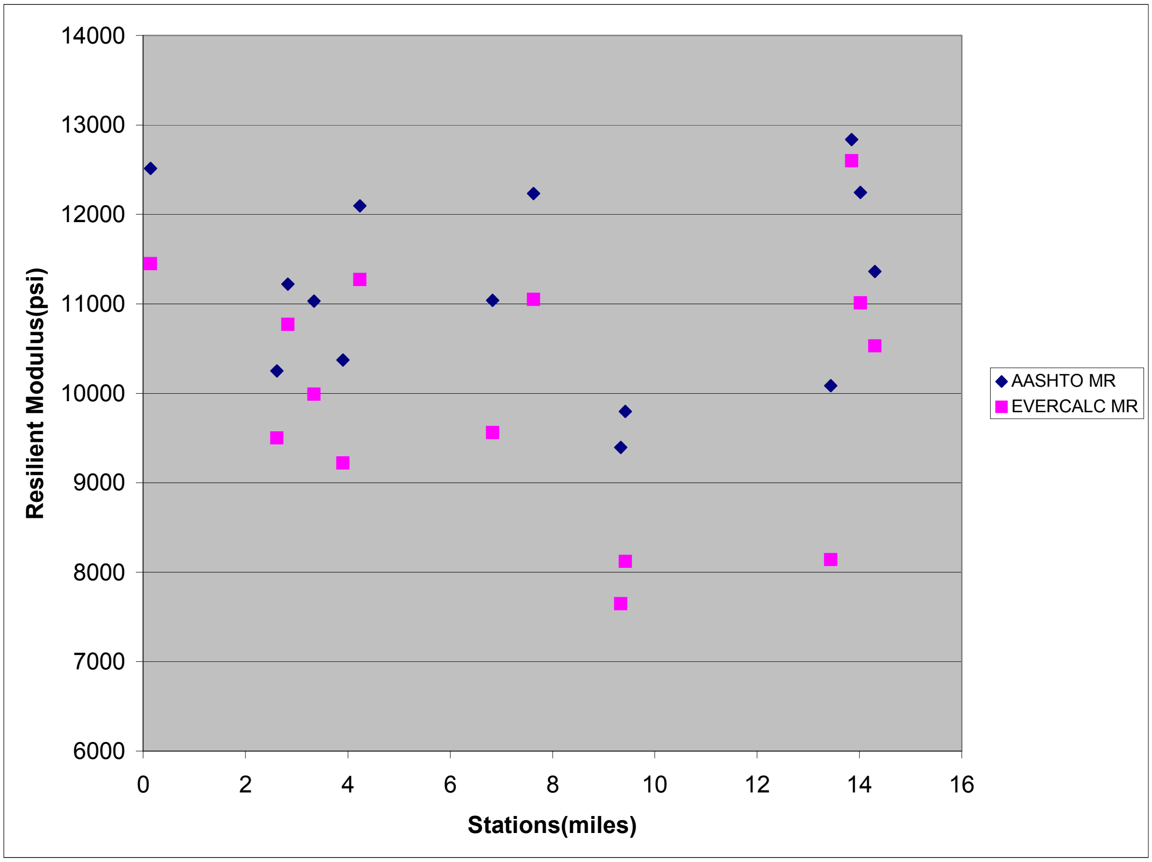

FIGURE 6 Spatial Variation of Subgrade Moduli for K-92

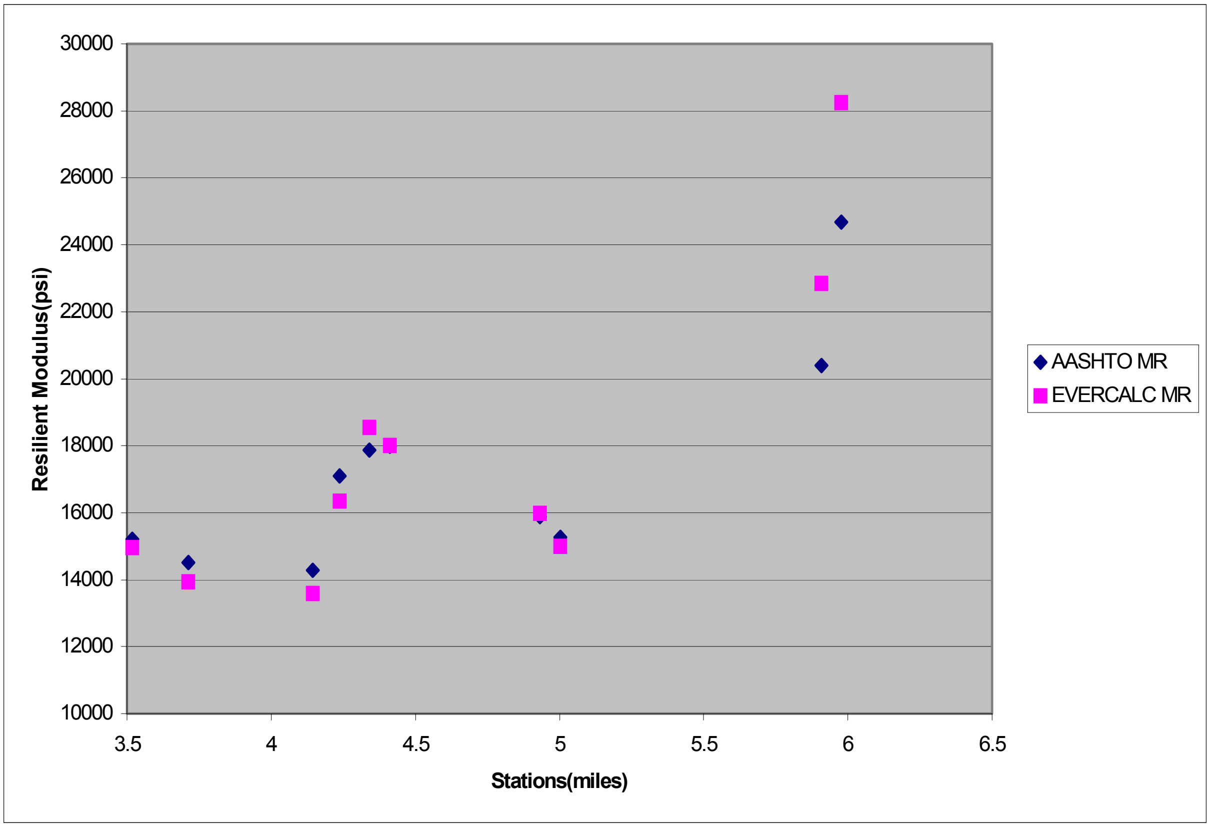

FIGURE 7 Spatial Variation of Subgrade Moduli for K-116

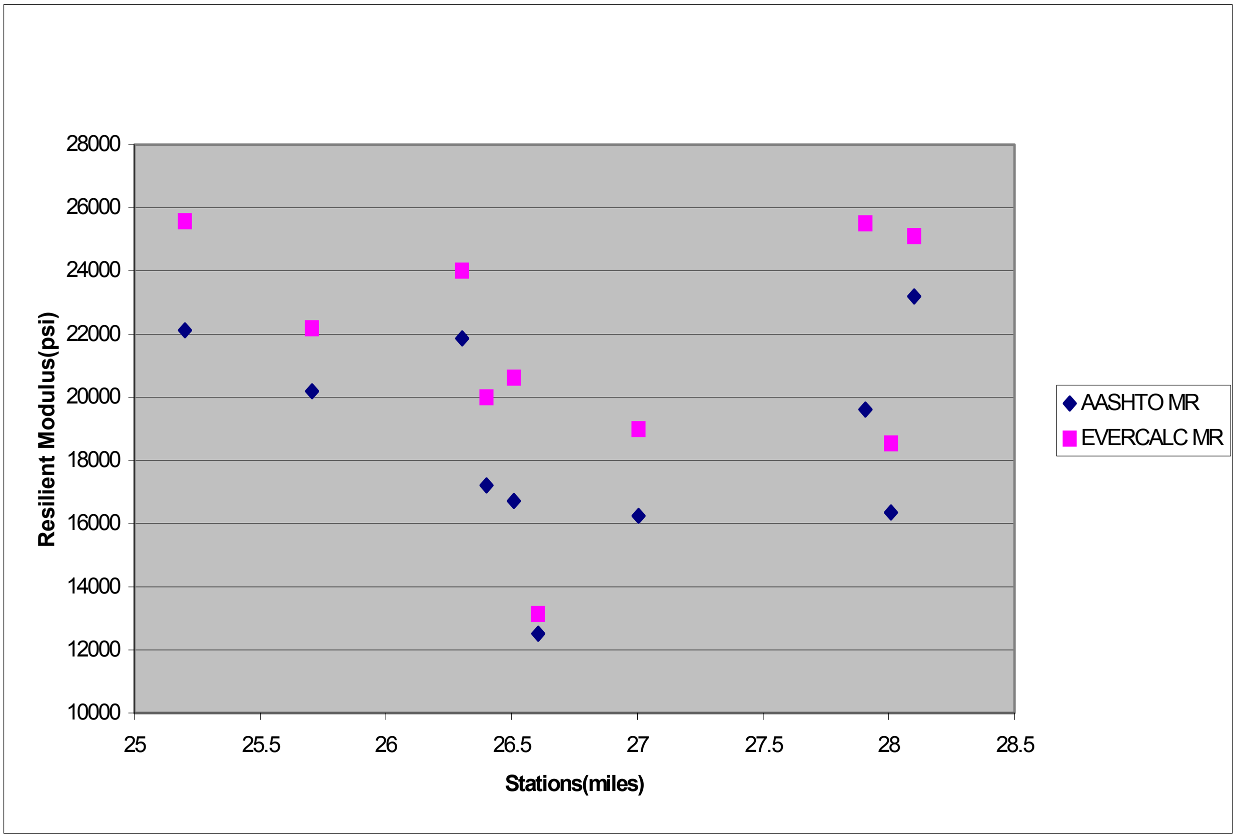

FIGURE 8 Spatial Variation of Subgrade Moduli for US-166