Final Report 930-418

EVALUATION OF THE ACCURACY OF PAVEMENT SURFACE LAYER THICKNESS MEASURED WITH GROUND PENETRATING RADAR

Sponsored by

Alabama Department of Transportation
Montgomery, Alabama

Prepared by

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DISCLAIMER

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ABSTRACT

This study evaluated ground penetrating radar (GPR) for estimating bound pavement surface layer thickness as a possible alternative to coring. Three pavements in the Montgomery, Alabama area were studied: a flexible pavement with thin (<6") surface, a flexible pavement with thick (>6") surface, and a composite, asphalt concrete (AC) over Portland cement concrete (PCC), pavement. Falling weight deflectometer (FWD) measurements, two sets of GPR thickness estimates, and cores were collected. DARWin and EVERCALC were used to backcalculate pavement moduli with surface layer thicknesses estimated from GPR measurements and cores. Comparisons of GPR estimated thicknesses with core thicknesses and comparisons of backcalculated moduli suggest that GPR estimated thicknesses are comparable to core thicknesses. Also, for pavements with thickness variation comparable to the three sites studied, estimation of surface layer thickness with only one core per site may also be adequate for backcalculation of moduli.

I. INTRODUCTION

1.1 Background

To evaluate the structural capacity or adequacy of a pavement, material properties of the pavement must be measured. Deflection testing is a nondestructive method commonly used to estimate the elastic modulus of pavement materials. Elastic moduli are used in the AASHTO structural design procedure to determine overlay thickness. An underestimate of existing pavement stiffness will result in a conservative overlay design that is more costly than required. An overestimate of existing pavement stiffness will result in a structurally inadequate overlay.

Deflection testing is most often accomplished with a falling weight deflectometer (FWD). Layered elastic backcalculation procedures use FWD data along with other properties, such as layer thicknesses, to estimate the elastic modulus of pavement layers and subgrade soils in existing pavements.

It is important to have an accurate database of pavement layer thicknesses, along with falling weight deflectometer data to provide reliable backcalculated moduli. Conventional pavement layer thickness measurements consist of coring or test pit excavations. These methods are time consuming, expensive, and require diversion of traffic. Construction records may be used to determine layer thicknesses for new pavements but records for older pavements may be unavailable or unreliable. In addition, many older pavements may have had been milled or leveled and/or patched during maintenance and rehabilitation, resulting in considerable longitudinal variability in bound surface layer thickness. Ground penetrating radar (GPR) is a developing technology for estimating layer thicknesses that may offer a practical and economical alternative to coring.

1.2 Objective

This study was conducted to evaluate the accuracy of GPR estimates of bound surface layer thicknesses. A second objective was to evaluate the effects of bound surface thickness estimates on backcalculated paving material and subgrade moduli.

1.3 Scope

To accomplish the study objectives, a limited study was made to compare core thicknesses and GPR estimated thicknesses of the bound surface layers of three pavements. The study included pavements with a thin asphalt bound surface, a thick asphalt bound surface, and a composite pavement consisting of Portland cement concrete (PCC) overlaid with asphalt concrete (AC).

Work included FWD testing, GPR thickness estimates, and core thickness measurements. GPR data was collected by Terracon and thickness estimates were provided by Terracon using the Rodar II software package and INFRASENSE, Inc. using the PAVLAYER software package. Software, EVERCALC and DARWin, were used to backcaclulate pavement moduli from FWD data.

To determine accuracy of GPR estimated bound surface layer thicknesses, GPR and core thicknesses were compared. To evaluate the effects of bound surface thickness, moduli backcalculated using core and GPR estimated thicknesses were compared.

II. CURRENT STATE OF PRACTICE

2.1 Nondestructive Deflection Testing and Moduleus Backcalculation

Deflection measurements are commonly used to evaluate structural capacities of pavements. Deflection testing can be divided into three categories based on the type of loading applied to the pavement. These categories are: static or slowly moving loads, steady state vibration, and impulse loads (1). Falling weight deflectometers and all other devices that deliver a transient force to the pavement surface are included in the impulse load category. The FWD simulates a moving wheel load in both magnitude and duration. This type of testing is performed by dropping a weight from a selected height and measuring the surface deflections. By varying the weight, height of drop, and loading plate properties, impulse forces with desired characteristics can be generated (1).

Deflection measurements may be used to backcalculate moduli of pavement layers and subgrade soils. Most backcalculation procedures are based on either wave theory or an iterative adaptation of elastic layer theory. These procedures estimate a set of moduli that result in a calculated deflection basin that matches the measured deflection basin within set tolerances. Iterative backcalculation programs make repetitive calls to an elastic layer analysis subroutine in order to match measured deflection basins with calculated deflection basins. The process stops when the measured and calculated deflections converge within tolerance levels set by the user.

Backcalculation procedures require input parameters from the user. The most common are layer thickness, Poisson's ratio, number of iterations and allowable deflection match tolerances. Other information the user may be required to supply include a seed modulus to start the iteration process, a range for each unknown layer modulus, test temperature to normalize moduli of asphalt bound layers, and depth to a stiff layer.

It is often necessary to include a stiff layer with a semi infinite depth to achieve reasonable backcalculation results. Deflections are computed by integrating vertical strains over the depth of the pavement layers and the subgrade. In the subgrade, this means integration to infinity and can lead to overestimation of vertical deflections. This is corrected by placing a stiff boundary layer in the subgrade to reduce strains at great depths.

There are several reasons why a stiff boundary layer is needed to accurately model the subgrade. Rock layers can exist relatively near the pavement, but most common is the natural stiffening of soil with depth (2). This stiffening is due to geological soil forming processes and the effect of increasing confinement with depth. Recent work in the state of Washington has identified soil saturation as an additional factor (3,4).

Procedures used to estimate the depth to the apparent stiff layer have been incorporated into backcalculation procedures such as EVERCALC. These procedures are usually based on the assumption that measured pavement surface deflections are a result of deformation of various materials in the applied stress zone. Furthermore, the offset distance from the load to the location at which zero surface deflection takes place is related to the depth at which zero stress, and therefore zero strain and deflection occurs in the subgrade. This situation is shown in figure 2.1, where D_c is the zero surface deflection. An estimate of the depth at which zero deflection occurs can be obtained from a plot of measured surface deflections and the inverse of the corresponding offsets. The offset radius, r, to zero surface deflection is estimated by extrapolating the linear portion of the D versus 1/r plot to D=0, as shown in figure 2.2. The depth to the rigid layer is then computed using the radius of the loaded area and assumed slopes of the stress zone through the pavement layers and subgrade soil.

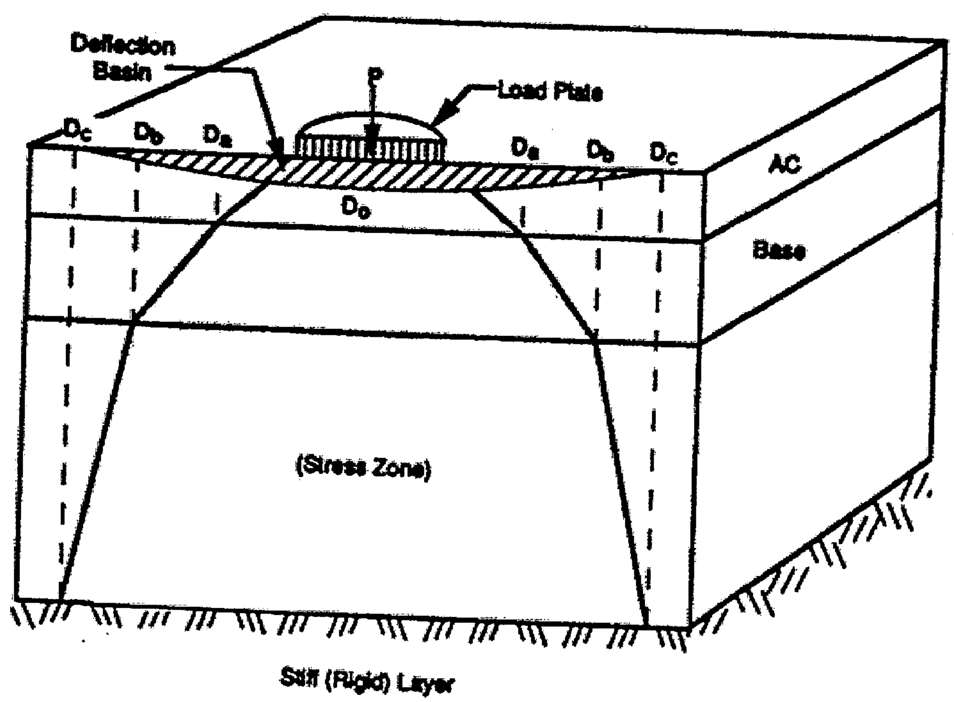

Figure 2.1 Zero Deflection Due to A Stiff Layer (4)

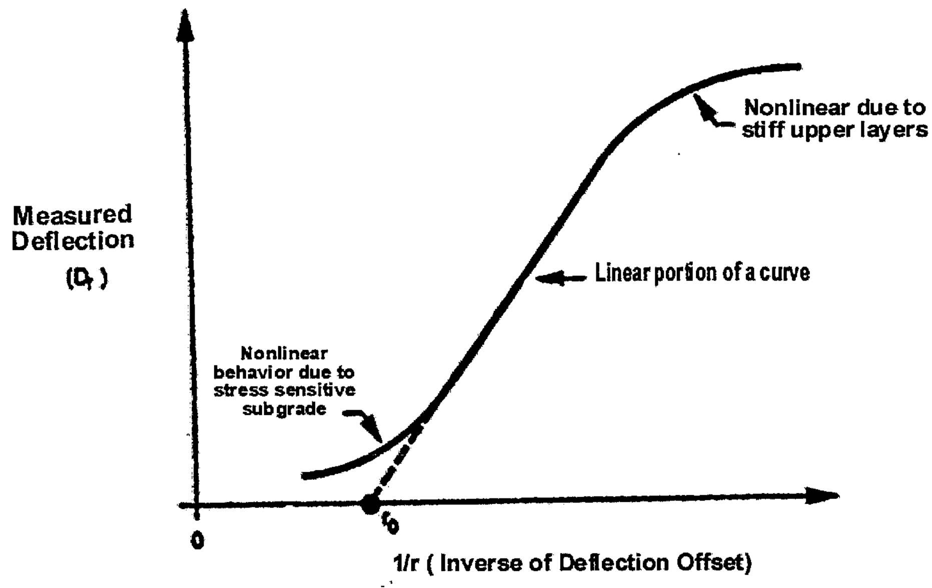

Figure 2.2 Plot of Inverse of Deflection Offset
Versus Measured Deflection (4)

There are several limitations to backcalculation procedures. It is difficult to obtain a reasonable moduli estimate for thin layers. The deflection basin is relatively insensitive to the moduli of thin layers and calculated and measured deflections can be matched within reasonable tolerances with totally unreasonable moduli estimates (1). Composite pavements such as a PCC pavement overlaid with AC present unique problems for backcalculation procedures. There is a tendency to under predict the modulus for the AC and overestimate the modulus for the PCC (5). Finally, perhaps the biggest disadvantage of backcalculation procedures is the non uniqueness of solutions, i.e., there are multiple combinations of moduli and layer thicknesses that can produce calculated deflection basins that match measured deflection basins within reasonable tolerances.

2.2 Effects of Layer Thickness Variability on Backcalculated Modulus

There have been several studies performed to evaluate the effect of layer thicknesses on backcalculated moduli. Some of the studies evaluating the effect of variable layer thickness on backcalculated moduli are summarized below.

Irwin, et al.

Irwin, et al (6) evaluated the importance of obtaining accurate deflection readings from FWD testing and layer thickness. A sensitivity study was conducted in which the pavement layer thicknesses were randomly varied to ascertain the effect on backcalculated moduli. Data from field observations of the variability of pavement layer thicknesses were used to define typical standard deviations of thicknesses for an AC surface course, a granular base course, and a granular subbase course. The simulated pavement was composed of a 3 inch surface course, a 6 inch base course, and a 12 inch subbase course. A layered elastic back calculation procedure known as MODCOMP 2 was used to analyze thirty individual simulations in the study.

The results from the variable layer thickness study are shown in table 2.1. The mean backcalculated moduli were a fairly good estimate of the true moduli, however, there was a substantial range in the results. The surface course moduli ranged from 37 percent greater to 21 percent less than the true moduli while the base course ranged from 19 percent greater to 21 percent less than the true moduli. The modulus of the subgrade was only slightly sensitive.

Table 2.1 - Effect of Layer Thickness Variability on Back Calculated Moduli (6)				
	Surface Course	Base Course	Subbase Course	Subgrade
True Moduli, psi	300000	45000	21000	7500
Mean Back Calculated Moduli, psi	311000	46000	20900	7500
Maximum Back Calculated Moduli, psi	410000	53700	26400	7670
Minimum Back Calculated Moduli, psi	236000	39800	15800	7350
Standard Deviation, psi	38000	3700	2300	70

Rwebangira, et al.

Rwebangira, et al (7) presented evaluations of selected procedures that are currently being used for backcalculation purposes. Layered elastic backcalculation procedures BISDEF, MODCOMP2, and SEARCH were used for the study. The sensitivity of the estimated moduli to various input parameters was also investigated. The evaluated input parameters included all of the user-supplied inputs that could affect the predicted value of the moduli.

For the backcalculation procedures BISDEF and MODCOMP2, a 2.5 inch asphalt surface layer and a 14.5 inch granular base layer were used as the standard pavement structure. An AC surface layer of 3 inches and a granular base layer of 7 inches were used to evaluate the backcalculation procedure SEARCH. The predicted moduli for all three of the procedures was sensitive to variations in surface and base layer thickness. For the BISDEF procedure, one inch of change in the surface layer thickness resulted in a change of over 60 percent in the value of the estimated surface and base modulus. The base layer thickness did not have as much effect on the moduli as the surface layer thickness. An 18 percent change in the base modulus occurred with a two inch change in the base layer thickness. Layer thickness variations had little effect on subgrade modulus. The maximum observed change in the predicted subgrade modulus was approximately seven percent for all of the thickness variations considered. The other back calculation procedures had similar results. For MODCOMP2, the estimated moduli were more sensitive to both surface and base layer thickness inputs than BISDEF. The moduli predicted by SEARCH for the base and subgrade were more sensitive to the surface layer thickness than the base layer thickness.

Texas SHRP Study

Briggs, et al (8) investigated the errors introduced into the backcalculation process by variable pavement layer thicknesses. Deflection data was gathered on four Strategic Highway Research Program (SHRP) General Pavement Sites (GPS). Each test section was1,500 feet long. GPR surveys were conducted and cores taken to estimate pavement layer thicknesses. Asphalt concrete surface layer thicknesses for the four test sites ranged from approximately 1.5 inches to 9 inches.

The MODULUS program was used for backcalculation and a rigid layer was assigned at a depth of 240 inches below the pavement surface. The results of this study indicated that variations found in surface and base layer thicknesses were large enough to cause up to 100 percent difference in the backcalculated surface moduli. Also, up to 80 percent difference in the backcalculated base moduli was observed. Variations in pavement layer thickness did not appreciably affect the backcalculated modulus of the subgrade.

Results from comparisons of GPR and core thicknesses will be summarized later.

Zaniewski and Hossain

Zaniewski and Hossain (9) investigated the effect of layer thickness on structural capacity of pavements. The analysis method included backcalculation of layer moduli from FWD data and computation of structural capacity of the existing pavement, in terms of the allowable number of 18-kip ESAL's, through fatigue analysis using backcalculated moduli. Backcalculation was performed with Arizona deflection analysis method (ADAM) which incorporates the computer program CHEVRON for pavement response analysis.

Three 90 foot sections comprised of 10 test locations each were used in the study. The thickness for the AC layer ranged from 4.3 to 9.0 inches. The base layer thickness ranged from 4.0 to 6.0 inches and the subbase layer thickness ranged from 12.0 to 18.0 inches.

Analysis of variance (ANOVA) was used to study the variation in calculated 18-kip ESALs. Zaniewski and Hossain concluded that the variability in thickness of AC and base layers affects the estimated structural capacity, but their interaction is not significant. Furthermore, for pavements with AC thickness of 6 inches or more, the AC layer input thickness in FWD data analysis should be known within 1.0 inch and the base layer within 2.0 inches. For pavements with AC thickness of 4 to 6 inches, input thickness should not vary from the actual thickness by more than 1.0 inch for all of the layers. Input thickness for pavements with AC thickness of less than 4 inches should be known within 0.5 inches and base layer thickness should be known within less than 1.0 inch.

Summary

All studies concluded variations in layer thickness inputs have some impact on backcalculated moduli. Generally, upper layer thicknesses have the most impact on estimated layer moduli. The surface layer modulus is the most sensitive to layer thickness variation but the base and subbase moduli are also somewhat affected. Backcalculated subgrade moduli are mostly unaffected by variability in upper layer thicknesses.

2.3 Principles of Operation of Ground Penetrating Radar

Ground penetrating radar is a tool used to detect and locate subsurface artifacts and features. Soil, rock, concrete, water and other materials can be characterized by their electromagnetic properties. Essential to the application of GPR is the accurate measurement of wave propagation of electromagnetic energy transmitted and reflected through dielectric material. GPR systems direct short pulses of electromagnetic energy into the ground using an antenna capable of transmitting and receiving signals. When this pulse of energy is transmitted through a structured layer it may encounter an interface between materials of different electromagnetic properties. An example of this type of layered structure would be a pavement system with an air-AC or an AC -base interface.

A portion of the signal is reflected back to the antenna while the rest continues into the next layer. The amount of signal that continues through an interface is a function of the contrasting electromagnetic properties of the interface materials. The greater the contrast in electromagnetic properties of the interface materials the greater the reflection of the radar signal. The reflected energy is used to determine the location and nature of electromagnetic property differences. The reflected energy is stored and represented by a waveform of voltage changes as a function of time. Figure 2.3 shows the principles of operation and a typical waveform (10).

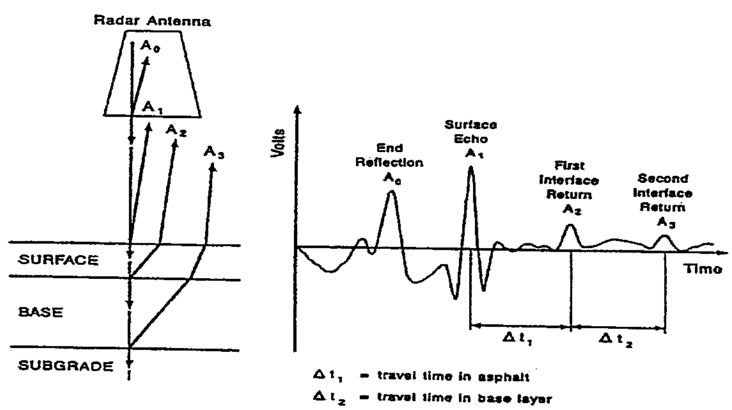

Figure 2.3 Ground Penetrating Radar Principles of Operation and Typical Waveform (10)

Sequential waveforms can be stacked to create a profile of horizontal distance over the pavement surface as a function of radar signal travel time into the ground. Figure 2.4 shows this technique (11). This technique displays a record of the properties and thicknesses of the layers within the pavement.

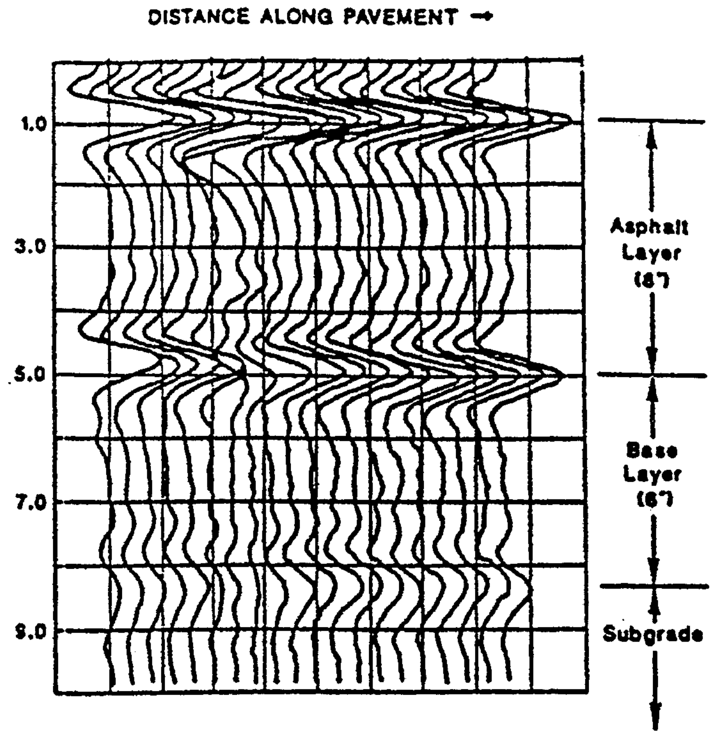

Figure 2.4 Stacked GPR Waveform (11)

Peaks in the waveforms correspond to reflections at interfaces between layers. By using the amplitude and arrival times of the reflected peak waveforms, it is possible to calculate pavement layer thicknesses. The arrival time that is measured is the round trip travel time of the reflected radar pulse. Knowledge of the velocity propagation into the pavement subsurface along with the travel time is used to calculate the thickness of the layer (11).

The range or depth of a GPR system is primarily a function of material properties, signal frequency, and system characteristics including power output, antenna gain and efficiency, and receiver sensitivity. Two material properties, velocity and attenuation, control the propagation of radio waves into a pavement. Attenuation is the measure of energy lost in travel related to the conductivity of the layer. Radar signal attenuation is controlled by the electrical conductivity of the material. This is significant for conductive materials such as PCC, wet bases and clays. Penetration depths have been found limited in fine grained A-4 to A-7 soils and particularly clay soils such as Montmorillonite (12,13).

Resolution is a function of frequency (12). Resolution can be described as the ability of the system to distinguish two signals that are close to each other in time. The radar pulse has a finite width measured in nanoseconds so layers must be thick enough for the reflections to appear without overlap. For a material with a particular dielectric constant, higher operating frequencies are needed to resolve thinner layers (12). However, it is impossible to resolve any layer that does not provide a recognizable reflection from both the top and bottom layer.

Ground penetrating radar systems used in transportation applications are composed of three basic pieces of equipment. This equipment includes a control unit, an antenna that is used for transmitting and receiving the reflected signals, and a recorder to capture and store the reflected signals from the pavement. Once the reflected wave has been captured and stored, another pulse of radar energy is transmitted into the ground.

There are two different approaches to antenna design and fabrication in the application of GPR systems. These are ground-coupled antennas which are operated on the surface of the pavement and air-coupled antennas which are suspended above the surface of the pavement.

The ground-coupled antennas offer a wide range of central frequencies. These frequencies range from 50 MHz to 2.5 GHz and provide a variety of penetration depths and resolutions (13). Ground-coupled antennas can be pulled behind a vehicle at maximum speeds limited to about 5 mph or they can be manually pulled across the surface of the pavement.

Air-coupled antennas operate with frequencies ranging from 1 GHz to 2.5 GHz and are able to penetrate only limited depths. Air-coupled antennas are mounted about 10 inches from the surface of the pavement and can be operated at highway speeds up to 55 mph. For the 1 GHz horn antenna, only asphalt bound layers thicker than 2.5 inches can be individually resolved by radar (10).

Ground penetrating radar equipment typically collects scans, represented by waveforms, of reflected signals at rates of up to 100 scans per second (14). This acquisition rate makes it possible to collect data at highway speeds . Data is continuously collected and recorded to either a digital tape or a hard disk. Data is often displayed graphically to represent pavement layers and thicknesses with arrival times of peak waveforms. Another technique to display data is to present GPR waves in color. Strong positive voltages and strong negative voltages are color coded. Each individual trace will become a single vertical line containing several colors. Figure 2.5 shows this technique (10). The pavement shown in figure 2.5 is a PCC with an AC overlay. The horizontal axis is the distance along the highway and the vertical axis is depth below the surface. The zero depth is at the center of the solid red line, which is the reflection of the pavement surface. The lower, somewhat fainter red line, is the reflection from the PCC surface and intersects the vertical scale at approximately 6 inches. The asphalt layer thickness, represented by these reflections, can be seen to vary from 4 to 8 inches thick.

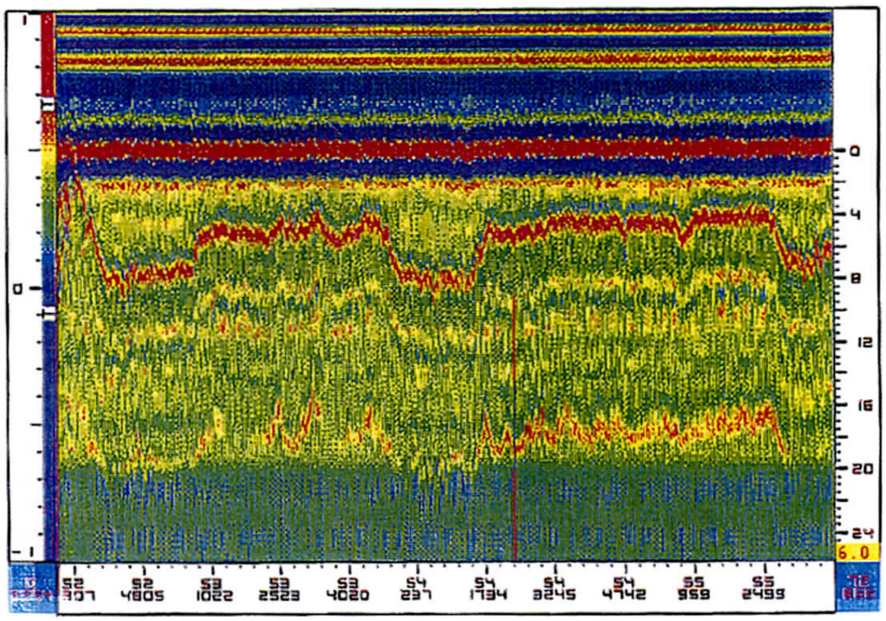

Figure 2.5 Color Coded GPR Display (10)

2.4 Surface Layer Thickness Accuracy Studies

The Transportation Research Board recently published the results of a survey conducted to collect information on ground penetrating radar and it's application to transportation facilities (12). Sixty three questionnaires were sent to the 50 state highway agencies, the District of Columbia, Puerto Rico, and 11 Canadian transportation agencies. Of the 51 responses returned 24 agencies claimed to have experience using GPR to evaluate pavement layer thicknesses. It was reported that layer thicknesses up to of 24 inches can be measured to an accuracy of ± 0.25 inches (12).

In addition, several states have studied the accuracy of GPR. These studies compare thicknesses from measured cores to thicknesses determined from GPR data. Most studies show accurate asphalt bound layer thicknesses can be obtained using ground penetrating radar data. Several studies are summarized below.

Texas SHRP Study

During June of 1990 a GPR survey was performed using an air coupled antenna on four Strategic Highway Research Program (SHRP) General Pavement Sites (GPS) (8). Fifty cores were obtained from four test sites with asphalt surface layer thicknesses ranging from approximately 1.5 inches to 9 inches. It was determined that GPR could predict AC thicknesses with a standard error of ± 0.11 inches with verification and calibration by coring and ± 0.32 inches with radar alone. A linear regression was performed using the core thicknesses and the GPR thicknesses. Excellent relationships between radar predictions and actual thicknesses were noted with $R^{2,}$ the coefficient of determination, of 0.98 and 0.99 for cases with radar alone and with calibration with a core. The study also indicated that there was a tendency to overestimate the AC thickness by approximately 0.25 inches with radar alone. This tendency was reduced to 0.12 inches with the use of calibration cores.

Mn/ROAD Study

In 1994, Mn/ROAD performed a GPR survey to obtain as built pavement layer thickness data on the 40 - Mn/ROAD research pavement sections (15). A total of 74 cores from the transition areas were used for verification. Of these cores, 52 represented AC surfaces and 22 represented PCC surfaces. An air coupled, 1 GHz antenna was used for the AC sections and a combination of an air coupled, 1 GHz antenna and a ground coupled, 500 MHz antenna was used for the PCC sections. The AC surface layer thicknesses for the test sites ranged from approximately 3.5 inches to 11.5 inches. The PCC thicknesses ranged from 6.2 inches to 8.2 inches. A linear regression between radar data and core AC thicknesses had an R^2 of 0.98. The average deviation between radar and core AC thicknesses was 0.24 inches. A linear regression between radar data and core PCC thicknesses had an R^2 of 0.76. The average deviation between radar and core PCC thicknesses was 0.53 inches.

Idaho Transportation Department Study

In 1995 and 1996, the Idaho Transportation Department (IDT) conducted a series of GPR surveys to evaluate the thickness of AC and PCC pavements (16). The study considered network and project level pavement applications. Data was obtained every foot for project level evaluations and every 5 feet for network level evaluations. A 1 GHz, ground coupled antenna and a combination of a 3 GHz, air coupled antenna and a 1 GHz, ground coupled antenna was used in the study. A total of 30 miles of pavement was evaluated. For the project level evaluations, average percent deviations from core thicknesses of 2.5% and 4.7% for the air coupled and combined antennas, respectively, were obtained. Linear regressions were performed using the core thicknesses and the GPR estimated thicknesses and R^2 values of 0.963 and 0.978 were achieved for the air coupled and combined antennas, respectively. For the network level evaluations, average percent deviations from core thicknesses of 4.5% and 9.8% for the air coupled and combined antennas, respectively, were obtained. Linear regressions were performed using the core thicknesses and the GPR estimated thicknesses and R^2 values of 0.655 and 0.950 were achieved for the air coupled and combined antennas, respectively. It was noted that both GPR systems at the network level tended to overestimate the surface layer thickness. The study concluded that reasonably accurate and dependable determination of pavement surface course layer thicknesses can be achieved using a GPR system.

Summary

All of the studies concluded that GPR systems can accurately and dependably predict surface layer thickness. Most of the studies showed a very high correlation between GPR thickness estimates and core data using linear regression. Generally, there is a better relationship between AC thicknesses obtained from coring and GPR data than PCC thicknesses obtained from coring and GPR data. Also, there is a tendency to overestimate layer thickness.

III. EXPERIMENT DESIGN AND DATA COLLECTION

3.1 Test Site Selection

Three sites were selected in the Montgomery, Alabama area for the study. Two of the sites were located north of Montgomery in Elmore County. A site on SR 14 with estimated AC layer thicknesses of 3.7 inches was selected as typical of thin surfaces. A site on US 231 with estimated AC layer thicknesses of 10.7 inches was selected as typical of thick surfaces. The site on SR 14 started approximately at mile marker 170 and measurements were made in the eastbound outer lane. The test located on US 231 started approximately at mile marker 119 and measurements were made in the southbound outer lane. Twenty six test locations for FWD testing, coring and GPR measurements were spaced at about 100 foot intervals resulting in a total site length of approximately 2,500 feet. It should be noted that the surface layers at both sites were comprised of both AC and surface treatment layers and would be accurately characterized as asphalt bound layers. However, AC was the largest constituent and the layers will be so designated.

The third site was located in Montgomery County between Montgomery and Prattville on US 31. This site was selected as a typical composite pavement and had estimated AC layer thicknesses of 6 inches and estimated PCC thickness of 8 inches. The site started approximately at mile marker 183 and measurements were made in the northbound outer lane. Twenty six test locations were spaced at about 160 foot intervals resulting in a total site length of approximately 4,000 feet. All three sites were on four lane roads to minimize traffic control requirements.

3.2 Falling Weight Deflectometer Testing

Falling weight deflectometer testing was performed on May 25, 1999. Test locations for GPR measurements and coring were also marked as FWD testing was performed by the Alabama Department of Transportation using the Dynatest 8000 system. This system uses a 9,000 pound load applied through a 5.9 inch radius plate and seven sensors evenly spaced 12 inches apart to measure surface deflections. Sensor 1 is located at the center of the load plate with sensors 2 - 7 successively farther away. Three drops at each test site were made. The first drop was used to make sure that the load plate was seated correctly. The surface deflections from the second and third drop were averaged for use in the analysis. Figure 3.1 shows the FWD in operation and marking of test locations. Load, temperature of the pavement surface, and resulting deflections for the three sites are tabulated in Appendix A.

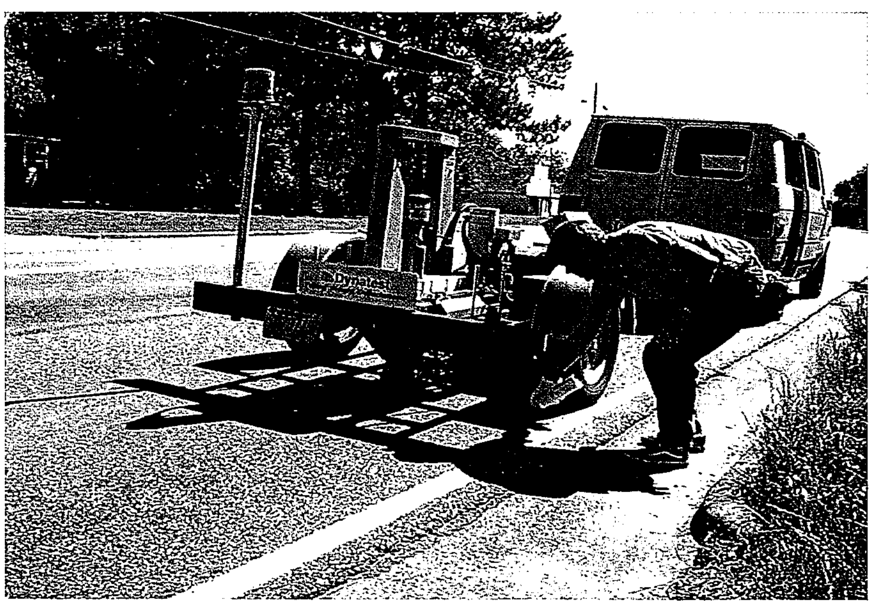

Figure 3.1 FWD Operation and Marking Test Locations

Deflection data for the three sites are plotted in figures 3.2 - 3.4. These plots provide a visual representation of the pavement stiffness throughout each site. The deflection basins at the first test location for each site are plotted in figure 3.5 to show typical basin shapes. The magnitude of the deflections are indications of the relative stiffness of the three pavements: US 31 the stiffest, US 231 intermediate, and SR 14 the least stiff. The relative magnitude of the deflections at the sensors, in figures 3.2 - 3.4, provides an indication of the shape of the deflection basins, in figure 3.5, that is consistent with the pavement stiffness. The relatively large differences between deflections at sensors 1 - 3 and small differences between sensors 3 - 7 for SR 14 indicate a steep slope in the deflection basin near the load which flattens to small deflections rapidly as distance from the load increases. This shape is confirmed in figure 3.5 and is typical of low stiffness pavements with thin asphalt bound surfaces. The relatively uniform difference between deflections for all sensors on US 31 (figure 3.4) indicates a flat deflection basin (figure 3.5) which is typical of high stiffness rigid pavements. The deflections for the US 231 site are intermediate to the extremes represented by SR 14 and US 31 and are typical of pavements with thick asphalt bound surfaces.

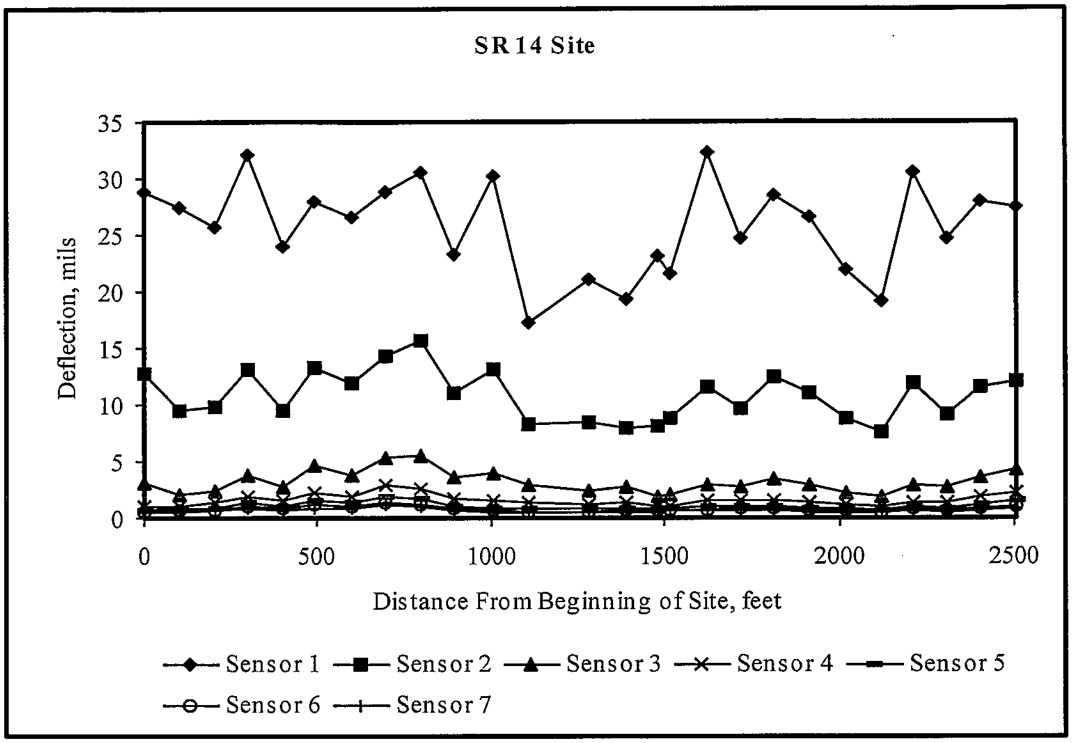

Figure 3.2 Measured Deflections at SR 14 Site

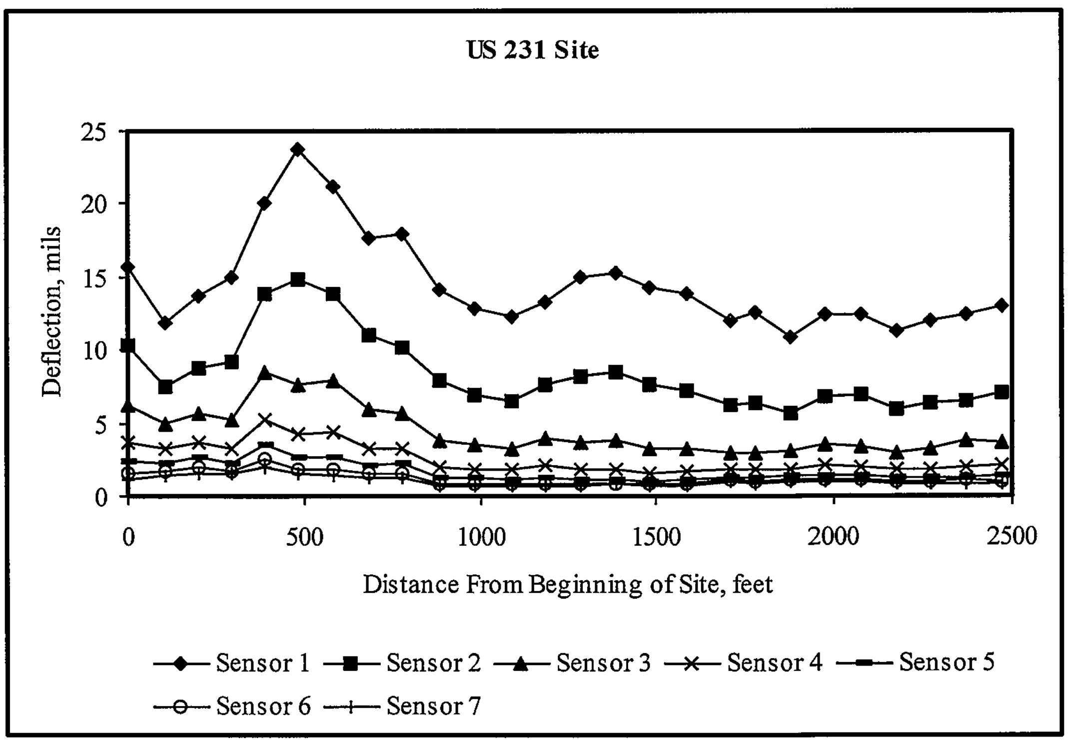

Figure 3.3 Measured Deflections at US 231 Site

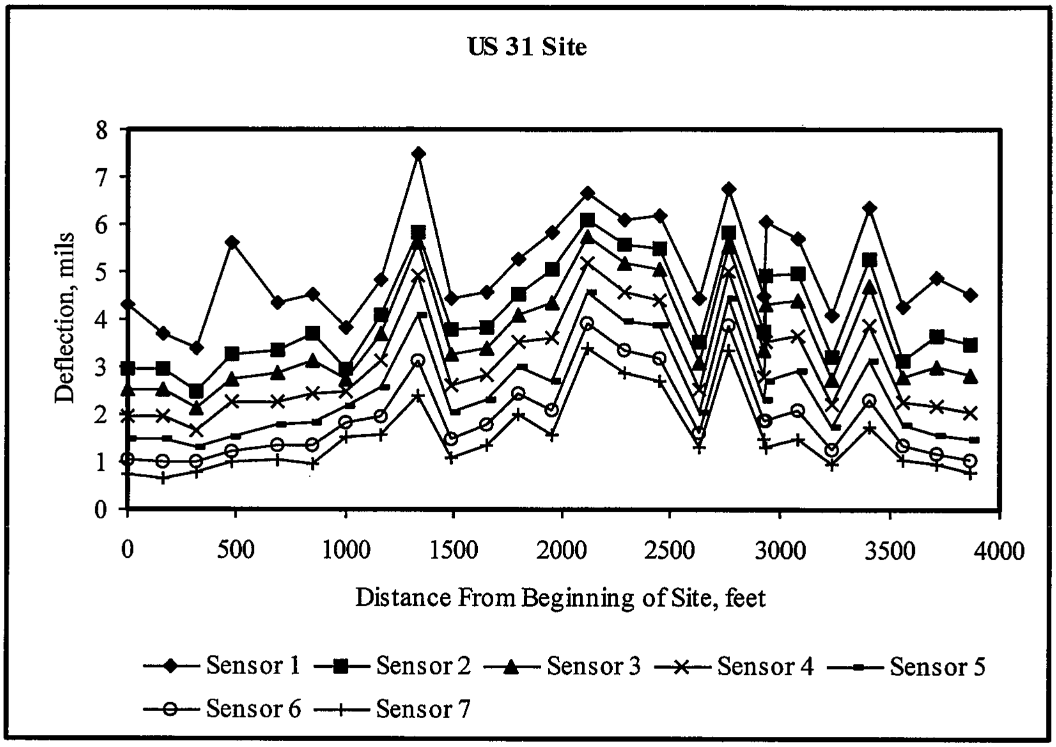

Figure 3.4 Measured Deflections at US 31 Site

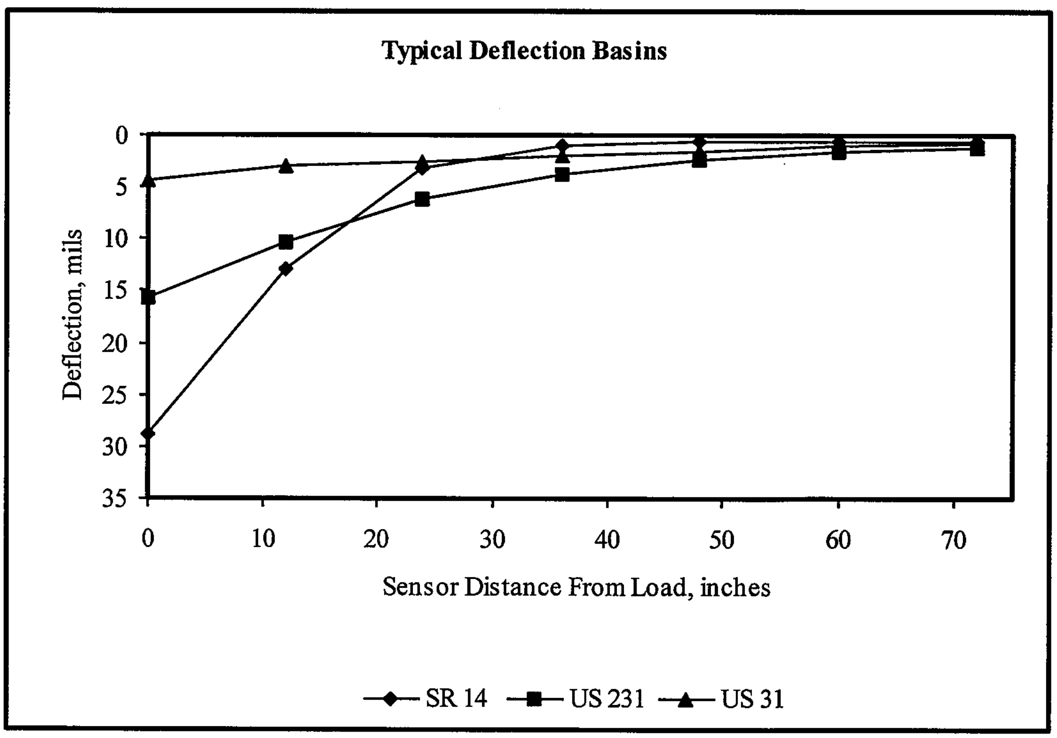

Figure 3.5 Typical Deflection Basins for SR 14, US 231, and US 31 Sites

3.3 Ground Penetrating Radar Testing

The GPR data was collected by Rodar II on June 3, 1999. Rodar II conducted the survey using a 1.0 GHz, air coupled antenna mounted on a van, as shown in figure 3.6.

Figure 3.6 Terracon's GPR System

Several calibration tests were run before the data collection took place. These tests included a metal plate test, a "jump" test, a time delay test, and an antenna end reflection test. The metal plate test was conducted at the beginning and end of the data collection process. This test was performed by placing a metal plate directly under the antenna and measuring the reflection response. The "jump" test was performed to account for the change in height with respect to the ground surface. To perform this test, a metal plate test was conducted at different heights. This results in an amplitude calibration curve for the received signals at different heights. The time delay test was performed to measure the velocity of the radar by measuring the round trip travel time it took for a radar signal to travel a predetermined distance. To account for the reflection that takes place at the end of a horn antenna, an end reflection test was conducted by pointing the antenna toward the sky and measuring the response. These measured reflections can then be subtracted from other radar responses.

The GPR system emitted and captured 50 pulses per second to obtain nearly continuous thickness data for the bound surface layers. The software used to record the data allowed individual test locations to be electronically marked so that they could be found when reviewing the raw data. The van that was used to collect the data traveled between speeds of 20 and 30 miles per hour. Traffic safety measures were provided by a flashing arrow board and a yellow strobe bar mounted on the vehicle.

Analysis of GPR data was conducted by both Rodar II and PAVLAYER, to provide estimates of bound layer thickness at test locations. INFRASENSE, Inc. used it's software, PAVLAYER to analyze the GPR data. This software is self calibrating so cores are not necessary to make thickness calculations, however, cores can be used to identify pavement layer boundaries that are not clear in the GPR data. For SR 14 and US 31, the cores provided asphalt layer identification information, but for US 231, the cores did not supply any useful information.

Terracon used the Rodar II software package from Pusle Radar, Inc. to analyze the GPR data. A dielectric constant of 7.0 was initially used in the analysis and cores supplied were used to calibrate the dielectric constants. Figure 3.7 shows a typical GPR display used by Terracon of the US 31 site. From these displays, thicknesses at each test location were estimated and are tabulated in Appendix B.

GPR SCREEN IMAGE

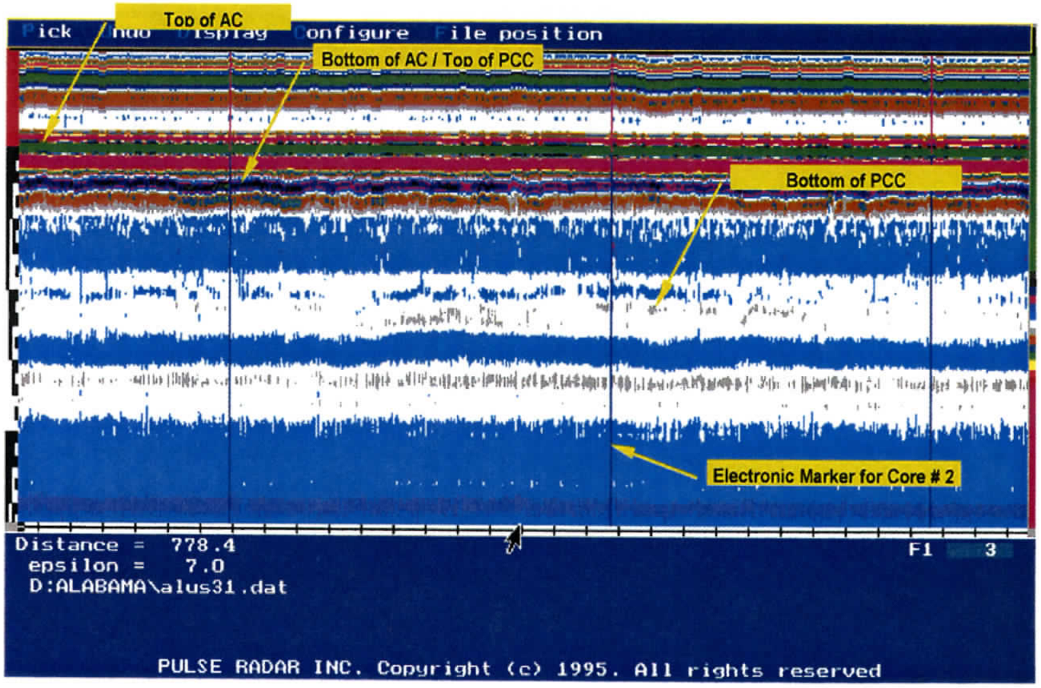

Figure 3.7 Ground Penetrating Radar Display of US 31 (17)

3.4 Coring

Four inch cores were drilled at each test location by the Alabama Department of Transportation on June 16 -17, 1999. Figure 3.8 shows the core rig in operation and figure 3.9 shows typical cores obtained. The cores were taken to Auburn University where their thicknesses were measured. Three individuals made four thickness measurements on each core. Averages from these twelve measurements are tabulated in Appendix B. Stripping in the asphalt bound layers at five test locations on US 231 prevented measurable cores from being obtained.

Figure 3.8 Core Rig in Operation

Figure 3.9 Typical Cores Obtained

One core from each site was sent to Terracon and INFRASENSE, Inc. to be used as a calibration core for the GPR estimations. Cores 5, 26 and 8 from SR 14, US 231, and US 31 sites respectively, were sent to INFRASENSE, Inc.. Cores 4, 25 and 7 from SR 14, US 231, and US 31 sites respectively, were sent to Terracon.

Several of the core holes at each site were augured to determine approximate thicknesses for base/subbase layers. It was determined that the pavement on SR 14 had approximately 10 inches of clay gravel base/subbase and that the subgrade was silty clay. US 231 had approximately 8 inches of clay gravel base/subbase and the subgrade was characterized as silty sand. Finally, US 31 had approximately 6 inches of clay gravel base/subbase and the subgrade was clay.

3.5 Backcalculated Moduli

EVERCALC 5.0 and DARWin 3.01 were used to backcalculate layer and subgrade moduli. To study the effects of bound surface layer thickness on backcalculated moduli, each backcalculation procedure was run for each site with four sets of thicknesses. The first run was with core thicknesses at each test location. The second run was with a constant thickness at each test location equal to the core thickness at the first test location. This was done to see if estimation of surface thickness for a site from one core might be an adequate alternate to coring at each test location or equivalent to a GPR survey. Runs three and four were with PAVLAYER and Rodar II GPR thicknesses at each test location, respectively. Complete sets of input for the backcalculation procedures are presented after each is briefly described.

EVERCALC

EVERCALC was developed at the University of Washington for the Washington State Department of Transportation. It uses an iterative procedure by changing the moduli in a layered elastic solution to match measured and calculated deflections. It is based on the Chevron N-layer elastic analysis computer program and was developed primarily for flexible pavement analysis and FWD data (18).

Moduli estimated using EVERCALC were backcalculated with a goalof achieving an average root mean square (RMS) error of 1 percent or less per sensor when comparing backcalculated verses measured deflections or a 1 percent difference in backcalculated moduli. The majority of the backcalculated deflection basins satisfied the modulus tolerance but not the average RMS error tolerance. Despite not achieving less than 1 percent average RMS error, all of the backcalculations appeared reasonable.

EVERCALC inputs for the three sites are shown in tables 3.1 - 3.3. Thickness, Poisson's ratio and a seed modulus are input for each pavement layer. Poisson's ratio and a seed modulus are input for the subgrade. The modulus and depth to an apparent stiff layer to model natural subgrade stiffening may be varied in EVERCALC. A modulus of 1000 ksi and a depth of 240 inches produced reasonable moduli estimates and minimized RMS error for matching measured and computed deflection basins. These input parameters for an apparent stiff layer are shown in tables 3.1 - 3.3.

Moduli backcalculated with EVERCALC for all three sites are tabulated in Appendix C. An example for the US 31 site with surface layer thickness from cores at each test location is shown in table 3.4. The AC modulus, PCC modulus, subgrade modulus, and average RMS error in matching deflection basins for each test location are tabulated.

Table 3.1 EVERCALC Inputs for SR 14 Site

Layer	Layer Thickness, inches	Poisson's Ratio	Seed Modulus, ksi
AC	1. Core Thickness 2. First Core Thickness (3.1") 3. GPR Estimated Thickness - PAVLAYER 4. GPR Estimated Thickness - Rodar II	0.35	100
Base/Subbase	10	0.35	30
Subgrade	NA	0.45	10
Stiff Layer	240 inches From Surface	0.5	Fixed at 1000

Table 3.2 EVERCALC Inputs for US 231 Site

Layer	Layer Thickness, inches	Poisson's Ratio	Seed Modulus, ksi
AC	1. Core Thickness 2. First Core Thickness (11.3") 3. GPR Estimated Thickness - PAVLAYER 4. GPR Estimated Thickness - Rodar II	0.35	100
Base/Subbase	8	0.35	30
Subgrade	NA	0.45	10
Stiff Layer	240 inches From Surface	0.5	Fixed at 1000

Table 3.3 EVERCALC Inputs for US 31 Site

Layer	Layer Thickness, inches	Poisson's Ratio	Seed Modulus, ksi
AC	1. Core Thickness 2. First Core Thickness (3.4") 3. GPR Estimated Thickness - PAVLAYER 4. GPR Estimated Thickness - Rodar II	0.35	100
PCC	1. Core Thickness 2. First Core Thickness (8.9") 3. GPR Estimated Thickness - PAVLAYER 4. GPR Estimated Thickness - Rodar II	0.15	3000
Subgrade*	NA	0.45	10
Stiff Layer	240 inches From Surface	0.5	Fixed at 1000

* The 6" clay gravel subbase included with subgrade for consistency with DARWin.

Table 3.4 EVERCALC Backcalculation Results Using Core Data - US 31 Site				
Location	AC Moduli, ksi	PCC Moduli, ksi	Subgrade Moduli, ksi	Average RMS Error (%)
1	239	3247	278	2.76
2	729	2619	30	5.00
3	287	6090	29	1.80
4	93	4251	24	4.07
5	276	4602	22	0.90
6	682	1859	22	2.49
7	305	14885	13	1.03
8	489	5261	14	1.63
9	215	4334	9	4.32
10	888	2686	20	2.24
11	581	4921	16	1.66
12	334	6529	11	0.82
13	773	2260	14	1.95
14	723	7161	6	0.94
15	631	77912	7	0.78
16	347	7144	8	0.97
17	260	5710	18	0.88
18	262	9961	5	0.87
19	390	6891	15	0.71
20	493	1677	15	5.09
21	699	1971	14	5.15
22	416	4252	23	1.57
23	457	3101	12	2.66
24	259	6436	22	1.43
25	272	2517	24	3.69
26	412	2067	27	1.83

DARWin

DARWin is a computerized version of the pavement design models found in the 1993 AASHTO Guide for the Design of Pavement Structures. The backcalculation procedure calculates a subgrade modulus and an effective pavement modulus of all pavement layers above the subgrade (19). The following equations are used in the AASHTO Guide for the Design of Pavement Structures (20) for backcalculation:

$M_R = 0.24P/d_r r$

M_R is the backcalculated subgrade resilient modulus in psi, P is the applied load in pounds, d_r is the deflection at a distance r from the center of the load in inches and r is the distance from the center of the load in inches. The deflection used to backcalculate the subgrade modulus must be measured far enough away from the load so it is primarily affected by the subgrade modulus and is independent of the effects of the pavement layers. The minimum distance from the load is computed as follows:

$r \geq 0.7a_e$

where

$$a_e = \sqrt{\left[a^2 + \left(D \sqrt[3]{E_p/M_R} \right)^2 \right]}$$

where a_e is the radius of the stress bulb at the subgrade-pavement interface in inches, a is the load plate radius in inches, D is the thickness of pavement layers above the subgrade in inches, and E_p is the effective modulus of all pavement layers above the subgrade in psi. The backcalculation procedure uses the deflection from the sensor that meets the minimum offset distance requirement. Due to the stiffness of the pavement at some test locations on the US 31 site, no sensor spacing was larger than the minimum offset distance and moduli could not be backcalculated.

The effective pavement modulus can be calculated with the following equation for the deflection at the center of the load:

$$d_0 = 1.5pa\left\{\frac{1}{M_R\sqrt{1+\left(\frac{D}{a}\sqrt[3]{\frac{E_p}{M_R}}\right)^2}} + \frac{\left[1-\frac{1}{\sqrt{1+\left(\frac{D}{a}\right)^2}}\right]}{E_p}\right\}$$

where d_0 is the deflection in inches measured at the center of the load plate and p is the load plate pressure in psi.

The user inputs required by DARWin for backcalculation include the total thickness of pavement layers above the subgrade, the type of base material, and pavement temperature. The pavement temperature is required to adjust the modulus of AC layers to a standard temperature of 68° F. DARWin does not provide a method to calculate the moduli of pavements with AC thicknesses greater than 12 inches or less than 2 inches which precluded backcalculation at several locations on the US 231 and SR 14 sites. Also, DARWin does not provide a way to backcalculate composite pavements. Therefore, for US 31, the PCC was modeled as a cement treated base and the effective pavement moduli was backcalculated accordingly. The 6 inch clay gravel subbase was included with the subgrade. Input parameters for DARWin are illustrated on the pavement models shown in figure 3.10.

Moduli backcalculated with DARWin for all three sites are tabulated in Appendix D. An example for the SR 14 site with surface layer thicknesses from the cores at each site is shown in table 3.5. The effective pavement modulus and subgrade modulus for each test location are tabulated. Surface thicknesses at test locations 23 - 26 were less than 2 inches and moduli could not be backcalculated.

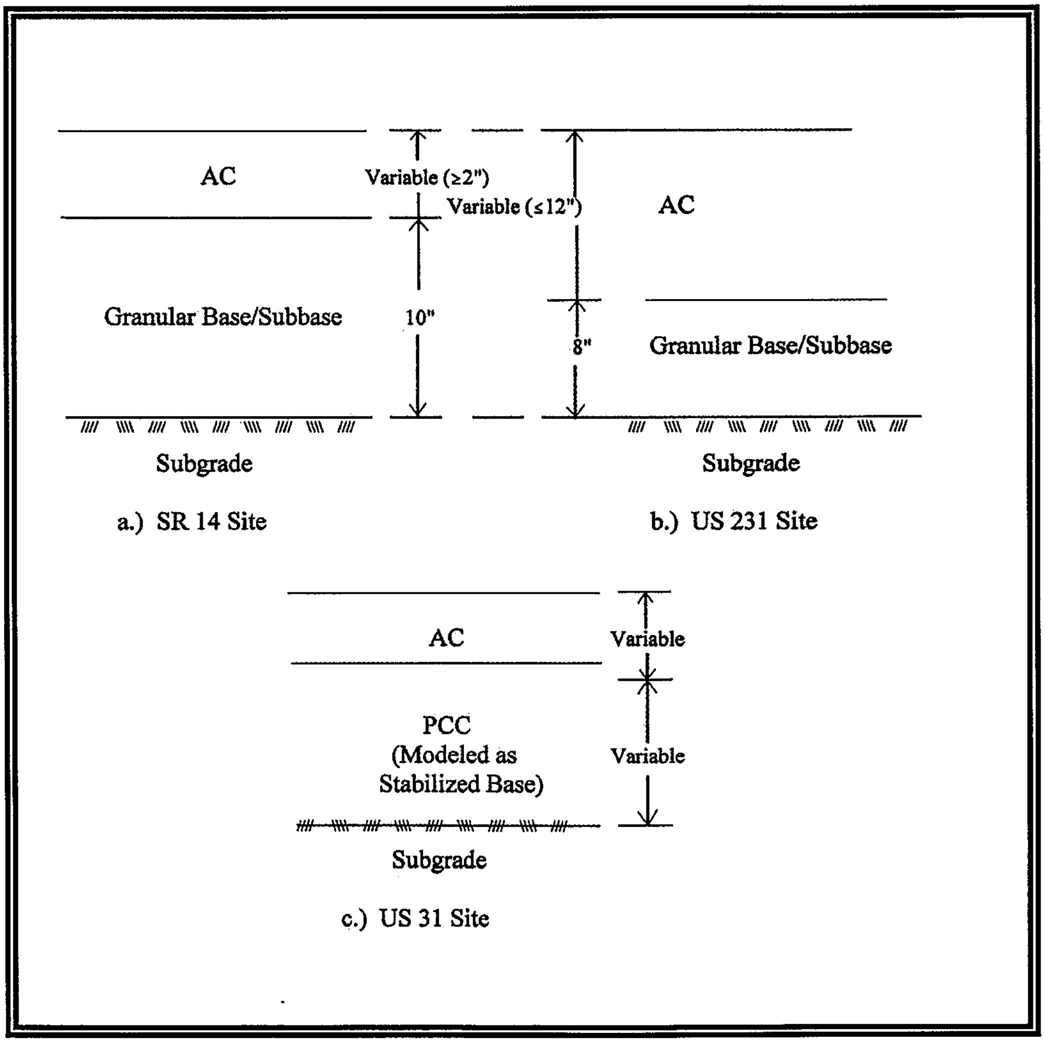

Figure 3.10 Pavement Models for DARWin Input

Table 3.5 DARWin Backcalculation Results Using Core Data - SR 14 Site		
Location	Effective Pavement Moduli, ksi	Subgrade Moduli, ksi
1	29	10
2	35	6
3	36	12
4	26	8
5	35	11
6	37	7
7	36	8
8	38	6
9	35	5
10	44	8
11	32	8
12	63	11
13	39	12
14	49	11
15	47	16
16	42	14
17	30	10
18	34	11
19	31	9
20	32	10
21	41	14
22	47	16
23	NA	NA
24	NA	NA
25	NA	NA
26	NA	NA

IV. DATA ANALYSIS

4.1 Comparison Methods

The analysis of data will consist of comparisons between core and GPR pavement surface layer thicknesses and comparisons of moduli backcalculated with the various estimates of thicknesses. For pavement surface layer thicknesses, the following comparisons will be made:

- Visual comparisons of plots of thicknesses for each site,
- Numerical comparisons of averages of the absolute deviations between core and GPR thicknesses for each site, and
- Statistical comparisons between mean core and GPR thicknesses for each site.

For moduli backcalculated with the various estimates of surface layer thickness, the following comparisons will be made:

- Visual comparisons of plots of moduli backcalculated with core thicknesses, constant surface layer thickness based on only the first core, and GPR thicknesses,
- Numerical comparisons of averages of the absolute deviations between moduli backcalculated with all core thicknesses and moduli backcalculated with first core thickness and GPR thicknesses, and

- Statistical comparisons of the constants for linear regression equations between moduli backcalculated with all core thicknesses and moduli backcalculated with first core thickness and GPR thicknesses.

4.1.1 Statistical Method for Comparing Means of Thickness Estimates

The two sample t-test was used to compare means of core and GPR estimated thicknesses. This test has two basic assumptions. The first assumption is that both populations are random samples from independent, normal distributions. The second assumption is that the values of the population variances are equal. To check the second assumption of equal variances, an F test was performed on variances. When the second assumption was not true, a modified t-test was employed.

4.1.2 Statistical Method for Comparing Linear Regression Equation Coefficients

Linear regression equations were developed between moduli backcalculated with thicknesses from cores at each test location and moduli backcalculated with a constant surface thickness based on the first core and with GPR thicknesses. The parameters of these linear regression equations were tested to determine if they were different from the parameters of a line of equality.

Linear regression analysis is used to define a mathematical relationship between two variables. This linear relationship is of the form:

$$y = \beta_0 + \beta_1 x$$

where β_0 is the y-intercept, β_1 is the slope of a straight line, x is the independent variable and y is the dependent variable. Regression equations were developed with moduli backcalculated with core thicknesses as the independent variable. Moduli backcalculated with first core or GPR thicknesses were the dependent variable.

The test was used to test the β_0 and β_1 coefficients to determine if backcalculated moduli were significantly different. The coefficients were compared to the coefficients for a line of equality, i.e., $\beta_0 = 0$ and $\beta_1 = 1$, to determine if they were statistically different.

All statistical comparisons were made at a 5% ($\propto = 0.5$) significance level or similarly at a 95% ($1-\propto = 0.95$) confidence level.

4.2 Comparisons of Core and GPR Estimated Thicknesses

Core and GPR estimated thicknesses for the AC and PCC layers at the three sites are plotted in figures 4.1-4.3. For the SR 14 site, shown in figure 4.1, PAVLAYER tended to overestimate core thicknesses while Rodar II tended to underestimate core thicknesses. For the US 231 and 31 sites shown in figures 4.2 and 4.3, respectively, both GPR estimated thicknesses were greater than the AC core thicknesses. For the US 31 site, PAVLAYER's estimated PCC thicknesses showed no trend in either over or underestimating the PCC core thicknesses while Rodar II overestimated PCC thickness. The GPR thickness estimates at the five test locations on US 231 where stripping prevented coring did not appear unusual.

The averages and standard deviations of the absolute deviations between GPR and core thicknesses are tabulated in table 4.1. The average absolute deviation from core thickness attained by PAVLAYER ranged from 0.16 inches for the AC on the US 31 site to 0.41 inches for the PCC on the US 31. The average absolute deviation from core thicknesses achieved by Rodar II were greater and ranged from 0.22 inches for the PCC on US 31 site to 0.53 inches for the AC on the US 231 site. PAVLAYER estimates of the

AC thickness were less variable than Rodar II, but Rodar II's estimates of PCC thicknesses were less variable than PAVLAYER

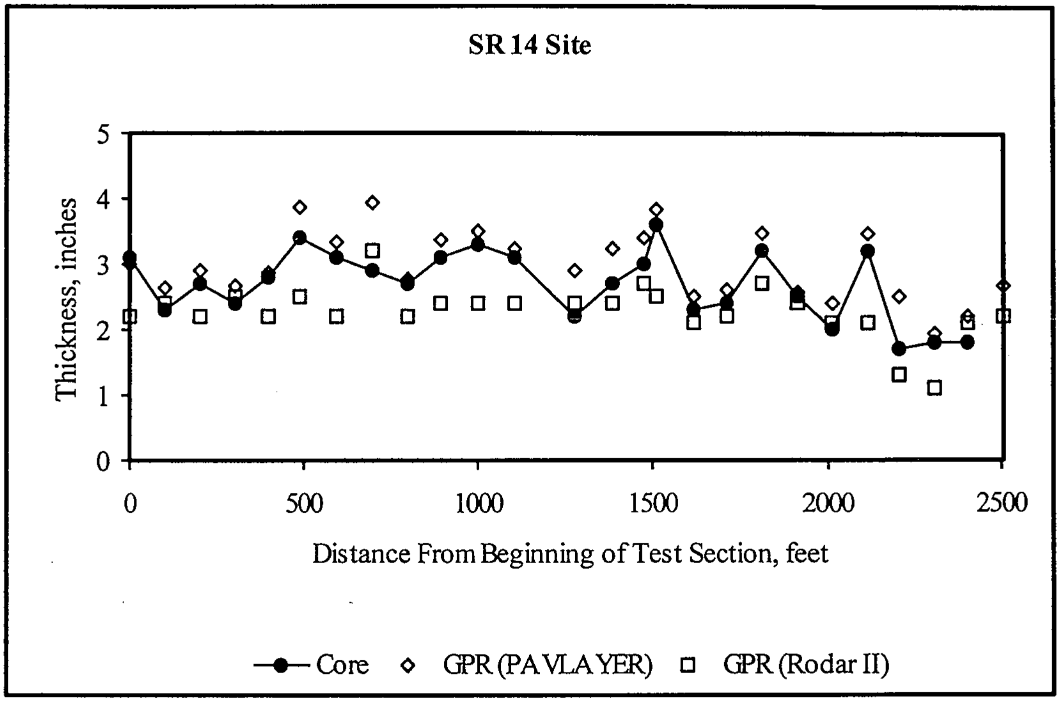

Figure 4.1 Core and GPR Thicknesses for SR 14 Site

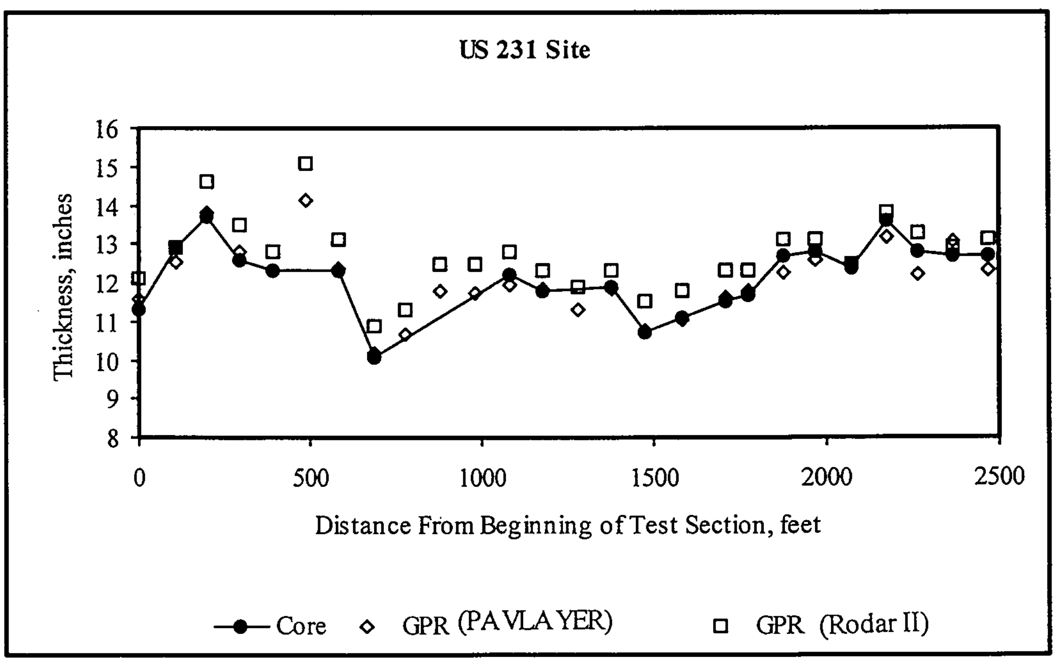

Figure 4.2 Core and GPR Thicknesses for US 231 Site

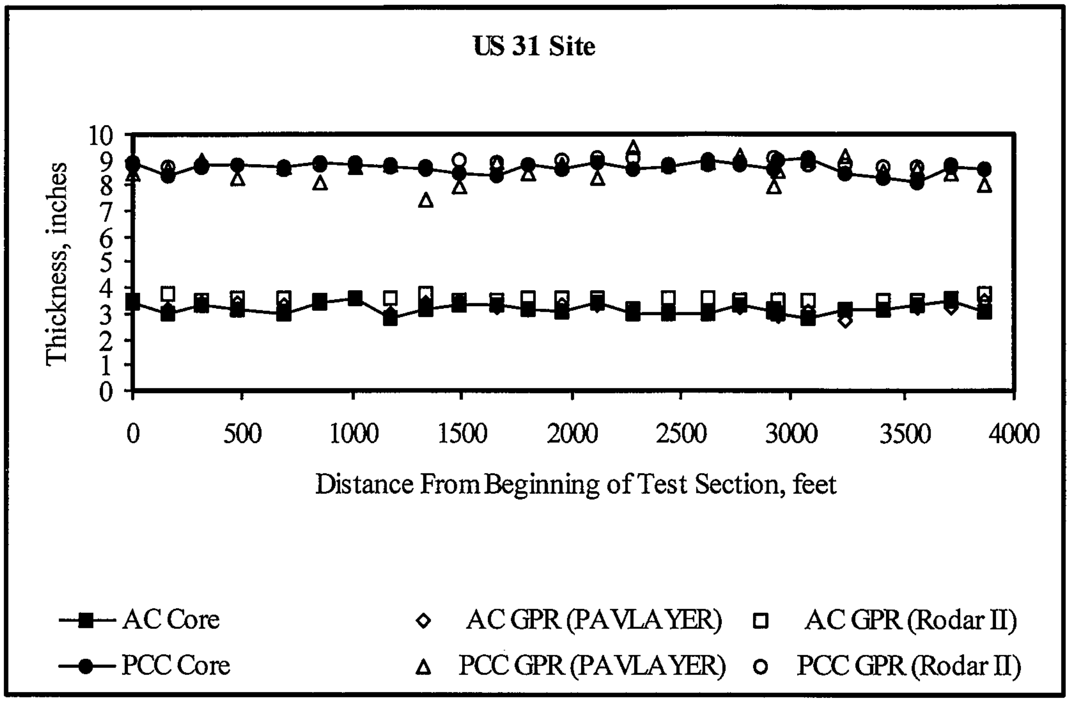

Figure 4.3 Core and GPR Thicknesses for US 31 Site

Table 4.1 Absolute Value of the Differences in Thicknesses

	PAVLAYER				Rodar II			
	SR 14	US 231	US 31 - AC	US 31 - PCC	SR 14	US 231	US 31 - AC	US 31 - PCC
Average, inches	0.32	0.21	0.16	0.41	0.50	0.53	0.36	0.22
Standard Deviation, inches	0.24	0.17	0.13	0.29	0.33	0.27	0.25	0.19

Finally, mean thicknesses for each test site estimated by PAVLAYER and Rodar II were statistically compared to the mean core thicknesses. These comparisons are summarized in tables 4.2 and 4.3. The F test indicated that none of the AC thickness variances were significantly different. However, the PCC thickness variances were significantly different for both PAVLAYER and Rodar II estimations. The mean thicknesses estimated by PAVLAYER were found to be significantly different from the core thicknesses only for the SR 14 site. However, all of the estimated thicknesses by Rodar II were found to be significantly different from the core thicknesses.

Comparisons, particularly for the thin AC surface layer on the SR 14 site, tend to indicate significant differences between GPR and core thicknesses. Comparisons also indicate GPR estimates by PAVLAYER may be more accurate and less variable than estimates by Rodar II. However, from a practical perspective, differences in thicknesses are significant only if their use produces significant differences in structural pavement evaluation. In the following section, moduli backcalculated with the various thickness estimates will be compared.

Table 4.2 Core Thicknesses Versus GPR (PAVLAYER) Thicknesses

	SR 14	US 231	US 31 - AC	US 31 - PCC
Average Thickness	Core = 2.7" GPR = 3.0"	Core = 12.2" GPR = 12.1"	Core = 3.2" GPR = 3.2"	Core = 8.7" GPR = 8.6"
Standard Deviation	Core = 0.534" GPR = 0.536"	Core = 0.896" GPR = 0.826"	Core = 0.200" GPR = 0.217"	Core = 0.231" GPR = 0.453"
F Test H_0: $\sigma_1^2 = \sigma_2^2$ H_1: $\sigma_1^2 \neq \sigma_2^2$	N.S.D.	N.S.D.	N.S.D.	S.D.
t /Mod. t Test H_0: $\mu_1 = \mu_2$ H_1: $\mu_1 \neq \mu_2$	S.D.	N.S.D.	N.S.D.	N.S.D.

Table 4.3 Core Thicknesses Versus GPR (Rodar II) Thicknesses				
	SR 14	US 231	US 31 - AC	US 31 - PCC
Average Thickness	Core = 2.7" GPR = 2.3"	Core = 12.2" GPR = 12.7"	Core = 3.2" GPR = 3.5"	Core = 8.7" GPR = 8.8"
Standard Deviation	Core = 0.534" GPR = 0.406"	Core = 0.896" GPR = 0.809"	Core = 0.200" GPR = 0.155"	Core = 0.231" GPR = 0.144"
F Test $H_0: \sigma_1^2 = \sigma_2^2$ $H_1: \sigma_1^2 \neq \sigma_2^2$	N.S.D.	N.S.D.	N.S.D.	S.D.
t/Mod. t Test $H_0: \mu_1 = \mu_2$ $H_1: \mu_1 \neq \mu_2$	S.D.	S.D.	S.D.	S.D.

4.3 Comparison of Backcalculated Moduli

4.3.1 EVERCALC

Moduli backcalculated using EVERCALC are plotted in figures 4.4 - 4.12. Three plots (AC, base/subbase or PCC, and subgrade) are included for each site. For all sites, backcalculated AC moduli were most affected by surface layer thickness. The base/subbase moduli on US 231 and the PCC moduli on US 31 were somewhat affected by surface layer thickness. Surface layer thicknesses had little effect on backcalculated subgrade moduli.

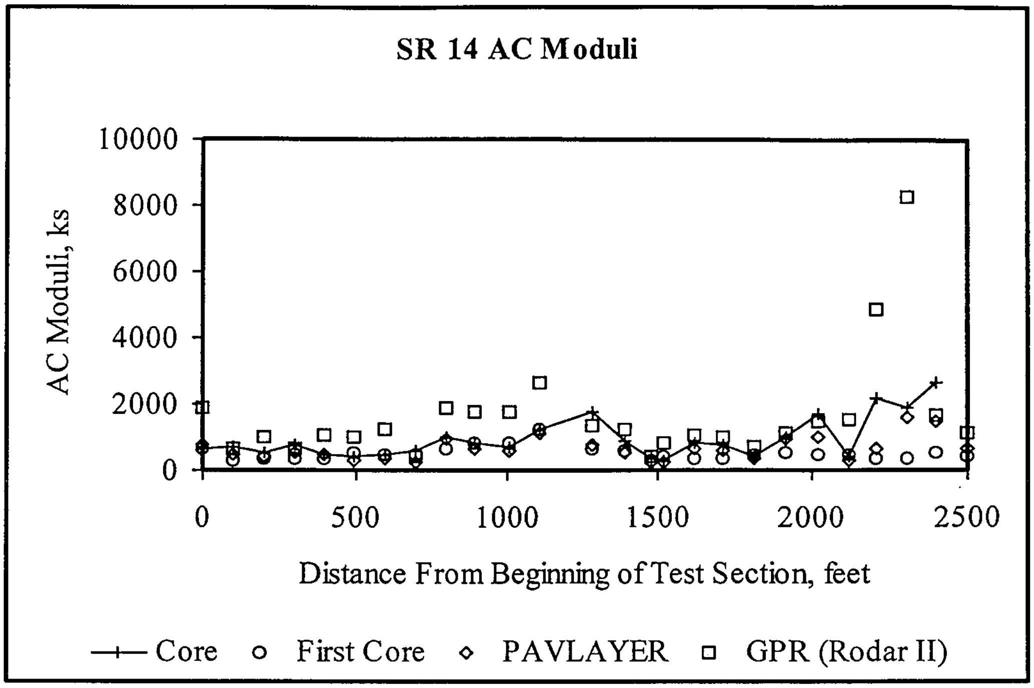

Figure 4.4 Backcalculated AC Moduli for SR 14 Site Using EVERCALC

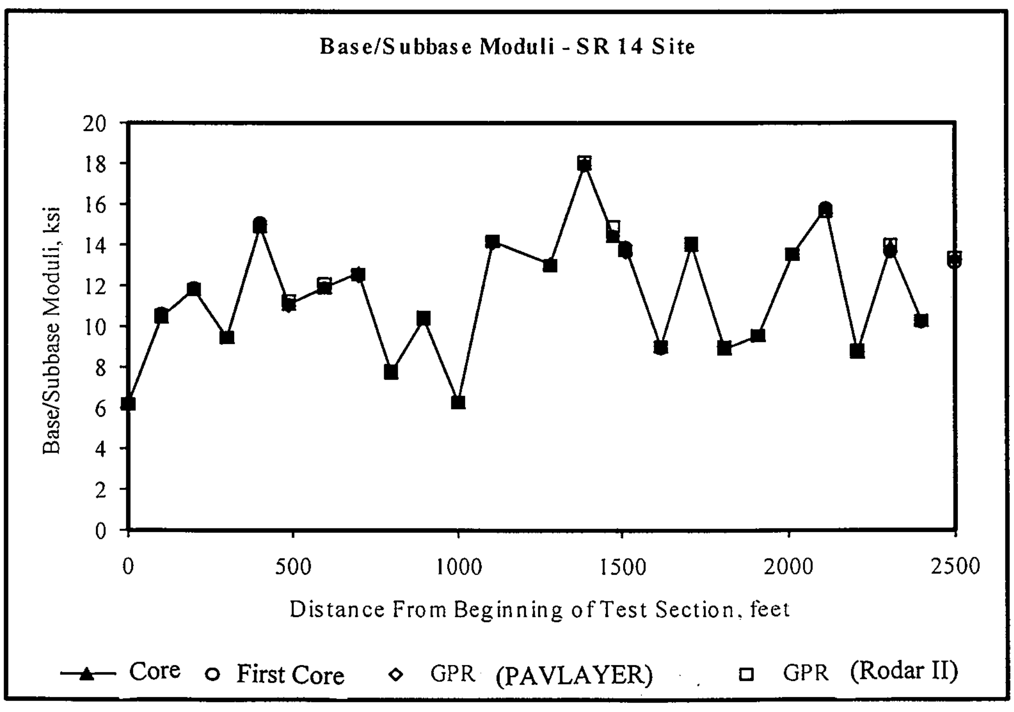

Figure 4.5 Backcalculated Base/Subgrade Moduli for SR 14 Site Using EVERCALC

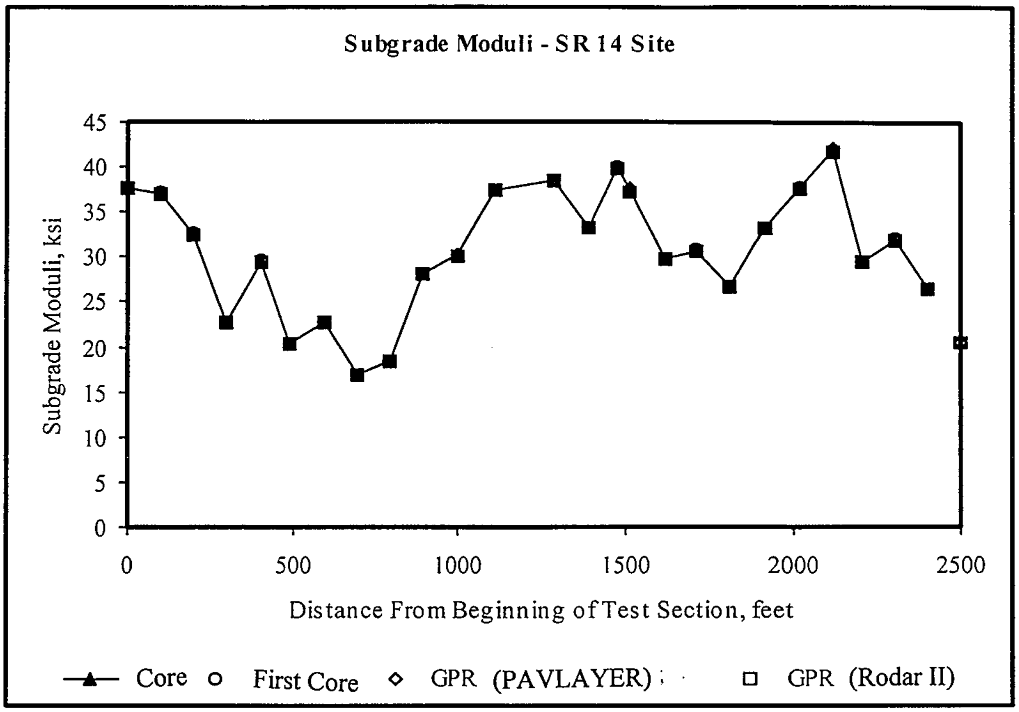

Figure 4.6 Backcalculated Subgrade Moduli for SR 14 Site Using EVERCALC

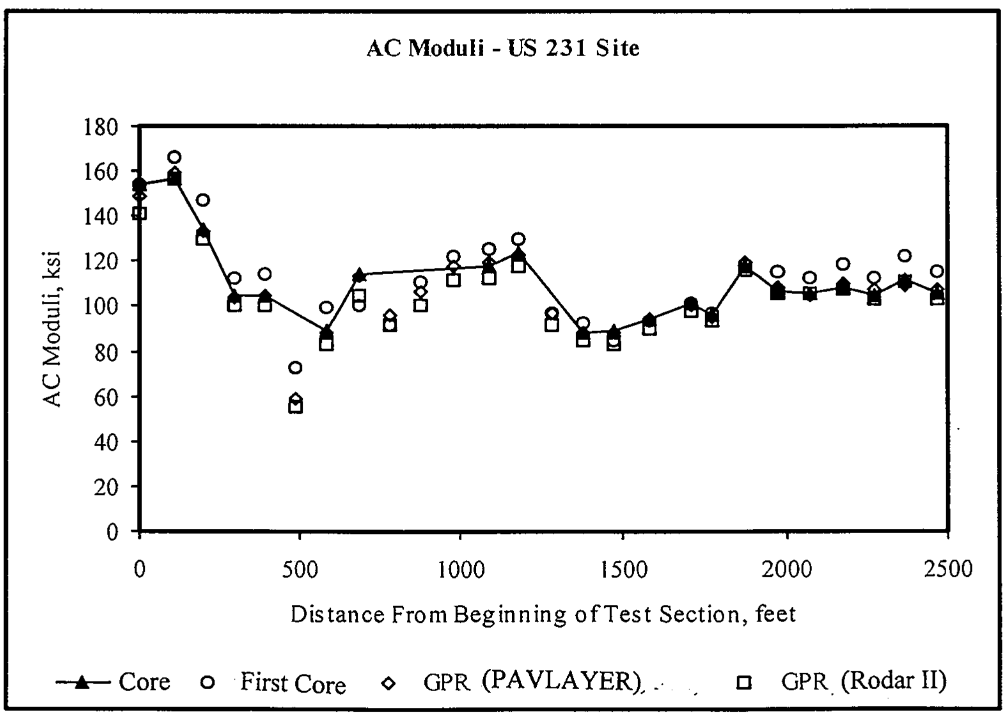

Figure 4.7 Backcalculated AC Moduli for US 231 Site Using EVERCALC

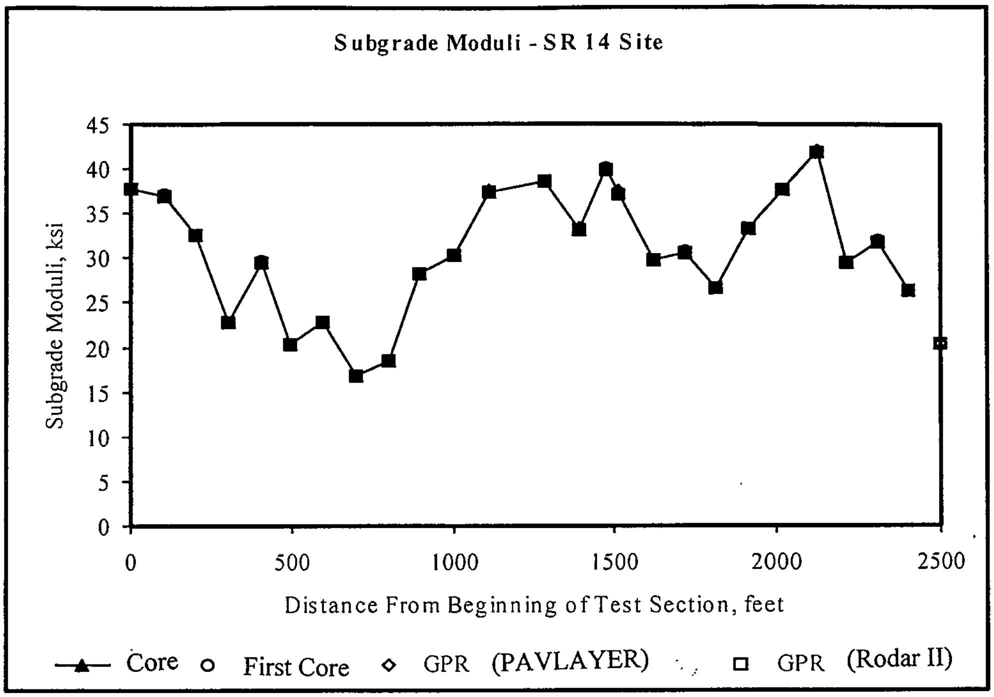

Figure 4.8 Backcalculated Base/Subbase Moduli for US 231 Site Using EVERCALC

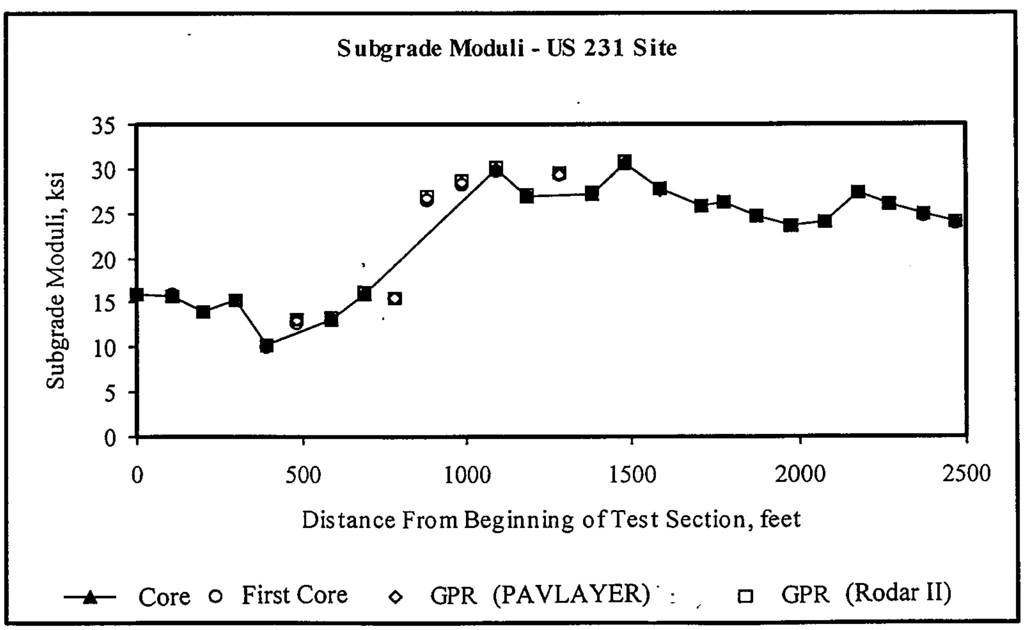

Figure 4.9 Backcalculated Subgrade Moduli for US 231 Site Using EVERCALC

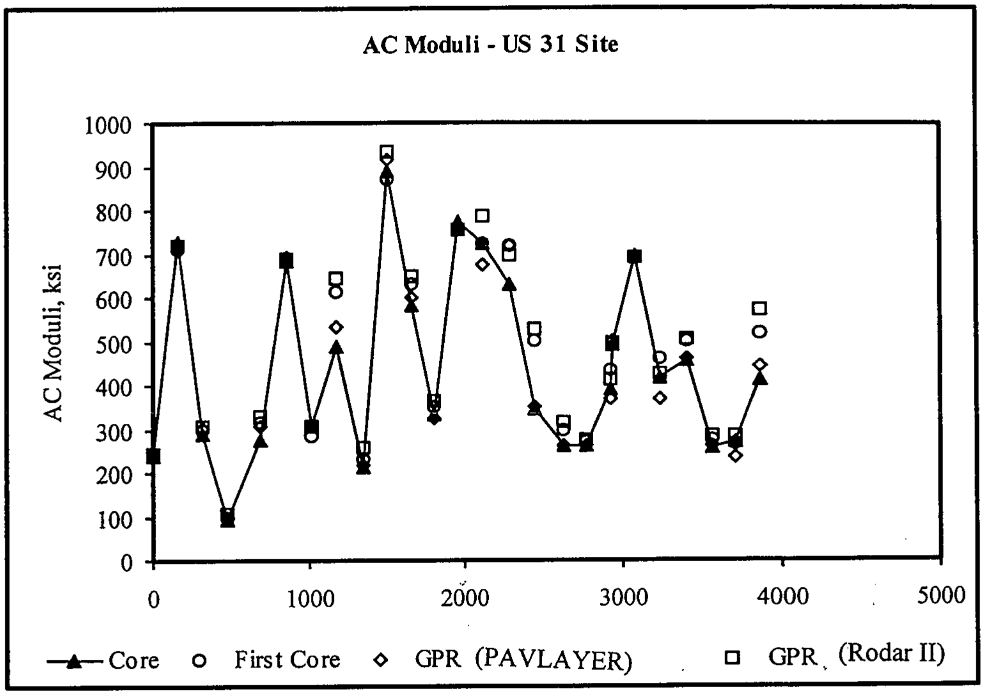

Figure 4.10 Backcalculated AC Moduli for US 31 Site Using EVERCALC

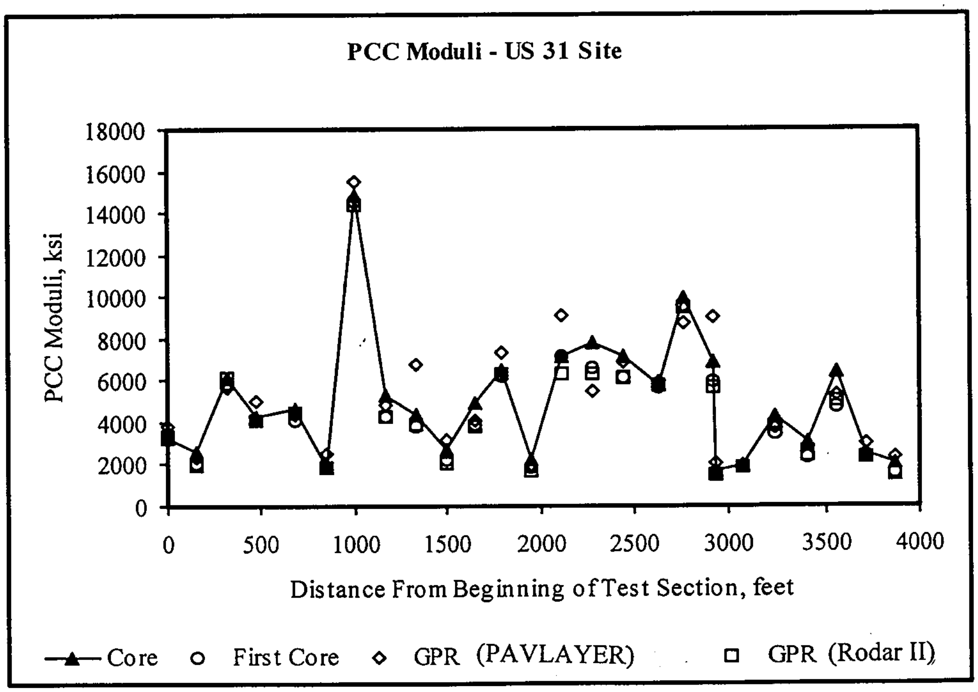

Figure 4.11 Backcalculated PCC Moduli for US 31 Site Using EVERCALC

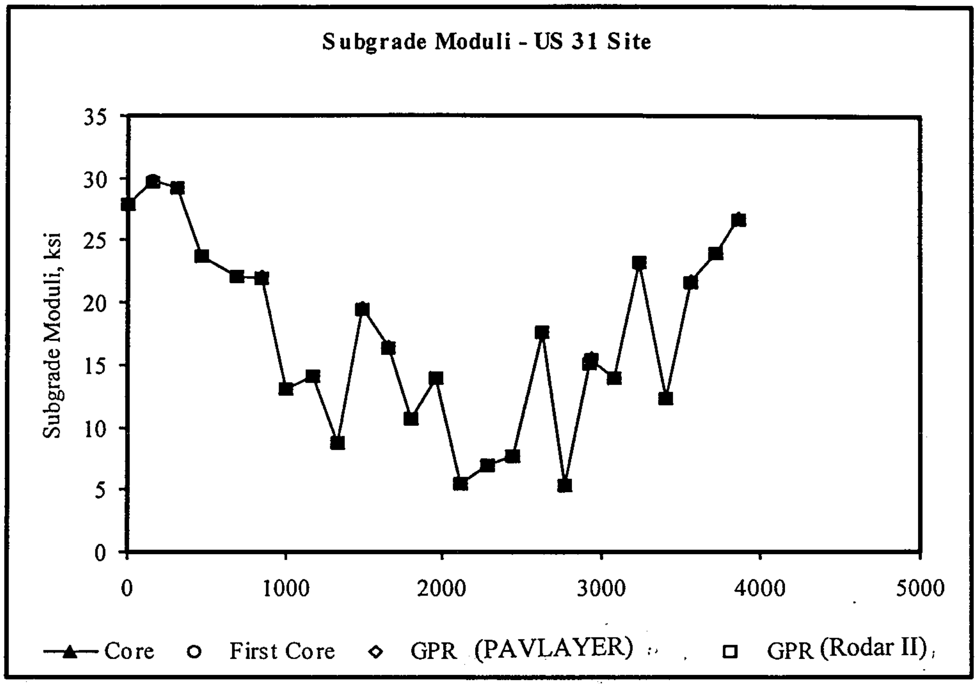

Figure 4.12 Backcalculated Subgrade Moduli for US 31 Site Using EVERCALC

The influence of surface layer thickness may also be examined by studying differences in backcalculated moduli. Tables 4.4 - 4.6 contain averages and standard deviations of absolute differences between moduli backcalculated with core thicknesses and moduli backcalculated with first core and GPR thicknesses. The average absolute differences and corresponding standard deviations confirm visual observations from figures 4.4 - 4.12, i.e.,

- averages and variability for AC modulus on SR 14 and PCC modulus on US 31 were the largest,
- averages and variability for AC modulus on US 231 were intermediate, and

- averages and variability for granular base/subbase and subgrade soils moduli were smallest.

A final observation from tables 4.4 - 4.6 is that averages and standard deviations for PAVLAYER thickness estimates are smaller than corresponding values for first core and Rodar II thickness estimates.

Table 4.4 Absolute Value of the Differences in Moduli for SR 14 Site Using EVERCALC

	Using First Core, ksi	Using PAVLAYER, ksi	Using Rodar II, ksi
AC Average	464.92	299.22	1152.47
AC Standard Deviation	605.44	384.99	1638.96
Base/Subbase Average	0.06	0.06	0.11
Base/Subbase Standard Deviation	0.07	0.08	0.12
Subgrade Average	0.05	0.03	0.06
Subgrade Standard Deviation	0.07	0.04	0.07

Table 4.5 Absolute Value of the Differences in Moduli for US 231 Site Using EVERCALC			
	Using First Core, ksi	Using PAVLAYER, ksi	Using Rodar II, ksi
AC Average	6.80	1.30	3.72
AC Standard Deviation	4.05	1.16	3.18
Base/Subbase Average	4.34	0.66	1.08
Base/Subbase Standard Deviation	6.15	0.89	1.25
Subgrade Average	0.07	0.02	0.06
Subgrade Standard Deviation	0.06	0.02	0.06

Table 4.6 Absolute Value of the Differences in Moduli for US 31 Site Using EVERCALC			
	Using First Core, ksi	Using PAVLAYER, ksi	Using Rodar II, ksi
AC Average	34.48	19.11	43.75
AC Standard Deviation	40.81	20.80	49.89
PCC Average	521.83	772.01	554.93
PCC Standard Deviation	439.02	691.40	444.48
Subgrade Average	0.03	0.03	0.04
Subgrade Standard Deviation	0.03	0.02	0.04

A complete set of linear regression equations with moduli backcalculated with core thicknesses as the independent variable and moduli backcalculated with first core and GPR thicknesses as dependent variables were generated and are contained in Appendix E. Typical regressions illustrating a poor, good and excellent fit are shown in figures 4.13 - 4.15. The linear regressions confirm the effects of surface layer thicknesses on backcalculated moduli visually observed in the plots and numerically demonstrated by comparisons of averages and variability of absolute differences. Hypotheses testing will determine the statistical significance of the influence of surface layer thickness on backcalculated moduli by comparing the coefficients for the linear regression equations with the coefficients for a line of equality.

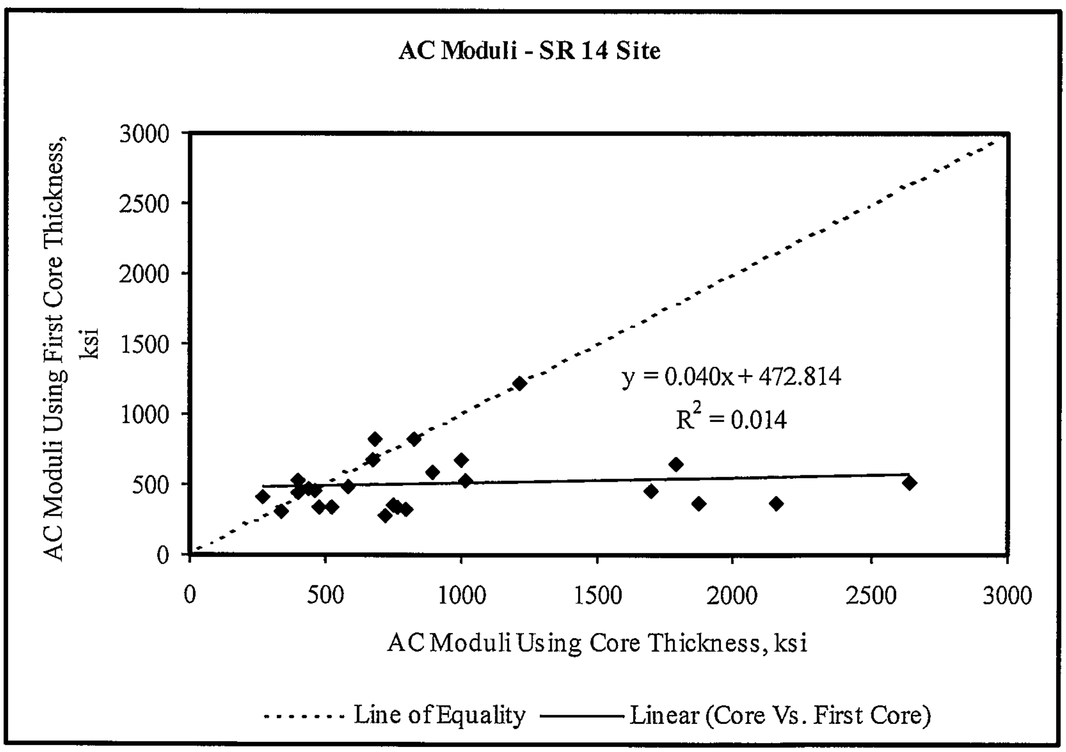

Figure 4.13 AC Moduli of SR 14 Site -Core vs. First core Thickness (EVERCALC)

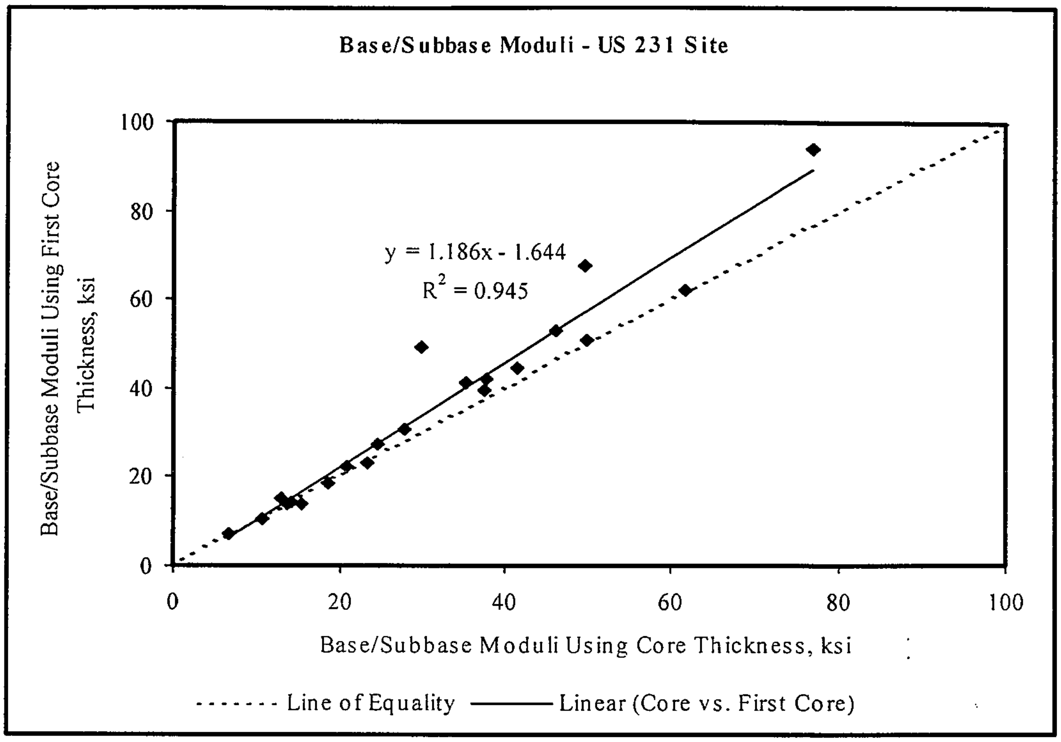

Figure 4.14 Base/Subbase Moduli of US 231 Site - Core vs. First Core Thickness (EVERCALAC)

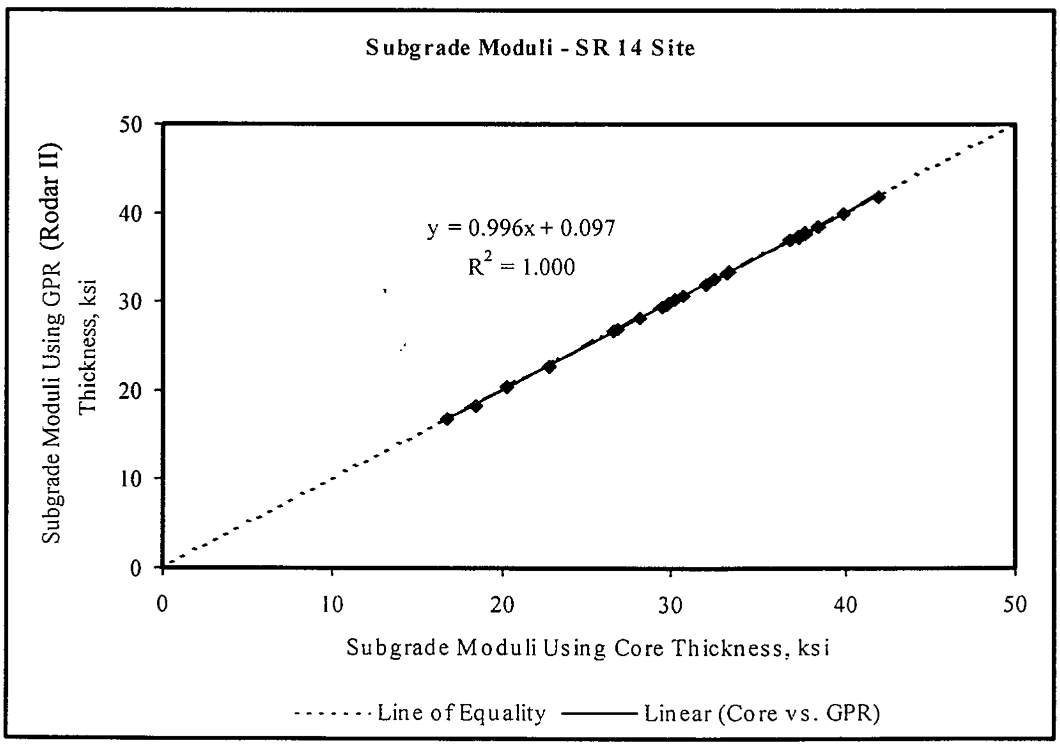

Figure 4.15 Subgrade Moduli of SR 14 Site - Core vs. Rodar II Thickness (EVERCALC)

Tables 4.7 - 4.9 contain the results from hypotheses testing of coefficients for AC modulus regression equations. Significant differences are noted only for the SR 14 site and only for first core (Figure 4.13) and PAVLAYER GPR thickness estimates. This implies thicknesses estimated with one core and GPR for thin surfaces do not result in accurate backcalculation of AC moduli. However, the large differences in moduli are thought due primarily to the inability of the EVERCALC backcalculation procedure to accurately model pavements with relatively thin surface layers.

Tables 4.10 and 4.11 contain results from hypotheses testing of coefficients for granular base/subbase modulus regression equations. Significant differences are noted only for the US 231 site and only for the slope coefficient (β_1) with first core (Figure 4.14), and PAVLAYER thicknesses. However, from the practical perspective of determining pavement structure, the differences between the computed slopes (β_1) of 1.186 and 1.031 and a slope of one for the line of equality may be acceptable.

Tables 4.12 - 4.14 contain results from hypotheses testing of coefficients for subgrade modulus regression equations. Significant differences are noted only for the SR 14 site and only for the slope coefficients (β_1) with GPR thicknesses. However, the magnitude of the slopes (1.003 and 0.996) and a visual examination of Figure 4.15 leads to the conclusions that surface layer thicknesses do not, from a practical perspective, affect EVERCALC backcalculated subgrade moduli.

Results from the hypotheses testing of coefficients for PCC modulus regression equations are shown in Table 4.15. Only the intercept coefficient (β_0 = -356.903 ksi) for the first core thicknesses is significantly different from zero. However, considering estimated moduli are greater than 2000 ksi, the effect of surface layer thickness is not considered practically significant.

Table 4.7 Linear Regression Statistics for AC Moduli Using EVERCALC for SR 14 Site

	First Core	PAVLAYER	Rodar II
β_0, ksi	472.814	200.204	263.376
β_1	0.040	0.472	1.492
R^2	0.0140	0.670	0.321
t Test H_0: $\beta_0 = 0$ H_1: $\beta_0 \neq 0$	S.D.	S.D.	N.S.D.
t Test H_0: $\beta_1 = 1$ H_1: $\beta_1 \neq 1$	S.D.	S.D.	N.S.D.

Table 4.8 Linear Regression Statistics for AC Moduli Using EVERCALC for US 231 Site

	First Core	PAVLAYER	Rodar II
β_0, ksi	0.681	2.265	0.959
β_1	1.039	0.980	0.848
R^2	0.909	0.991	0.972
t Test H_0: $\beta_0 = 0$ H_1: $\beta_0 \neq 0$	N.S.D.	N.S.D.	N.S.D.
t Test H_0: $\beta_1 = 1$ H_1: $\beta_1 \neq 1$	N.S.D.	N.S.D.	N.S.D.

Table 4.9 Linear Regression Statistics for AC Moduli Using EVERCALC for US 31 Site

	First Core	PAVLAYER	Rodar II
β_0, ksi	42.631	0.506	47.083
β_1	0.968	1.010	0.988
R^2	0.953	0.983	0.941
t Test H_0: $\beta_0 = 0$ H_1: $\beta_0 \neq 0$	N.S.D.	N.S.D.	N.S.D.
t Test H_0: $\beta_1 = 1$ H_1: $\beta_1 \neq 1$	N.S.D.	N.S.D.	N.S.D.

Table 4.10 Linear Regression Statistics for Base/Subbase Moduli Using EVERCALC for SR 14 Site

	First Core	PAVLAYER	Rodar II
β_0, ksi	-0.012	0.050	-0.004
β_1	1.000	0.993	1.003
R^2	0.999	0.999	0.998
t Test H_0: $\beta_0 = 0$ H_1: $\beta_0 \neq 0$	N.S.D.	N.S.D.	N.S.D.
t Test H_0: $\beta_1 = 1$ H_1: $\beta_1 \neq 1$	N.S.D.	N.S.D.	N.S.D.

Table 4.11 Linear Regression Statistics for Base/Subbase Moduli Using EVERCALC for US 231 Site

	First Core	PAVLAYER	Rodar II
β_0, ksi	-1.644	-0.663	-0.598
β_1	1.186	1.031	0.985
R^2	0.945	0.998	0.995
t Test H_0: $\beta_0 = 0$ H_1: $\beta_0 \neq 0$	N.S.D.	N.S.D.	N.S.D.
t Test H_0: $\beta_1 = 1$ H_1: $\beta_1 \neq 1$	S.D.	S.D.	N.S.D.

Table 4.12 Linear Regression Statistics for Subgrade Moduli Using EVERCALC for SR 14 Site

	First Core	PAVLAYER	Rodar II
β_0, ksi	0.026	-0.057	0.097
β_1	1.000	1.003	0.996
R^2	1.000	1.000	1.000
t Test H_0: $\beta_0 = 0$ H_1: $\beta_0 \neq 0$	N.S.D.	N.S.D.	N.S.D.
t Test H_0: $\beta_1 = 1$ H_1: $\beta_1 \neq 1$	N.S.D.	S.D.	S.D.

Table 4.13 Linear Regression Statistics for Subgrade Moduli Using EVERCALC for US 231 Site			
	First Core	PAVLAYER	Rodar II
β_0, ksi	0.003	0.031	0.054
β_1	0.998	0.999	1.000
R^2	1.000	1.000	1.000
t Test H_0: $\beta_0 = 0$ H_1: $\beta_0 \neq 0$	N.S.D.	N.S.D.	N.S.D.
t Test H_0: $\beta_1 = 1$ H_1: $\beta_1 \neq 1$	N.S.D.	N.S.D.	N.S.D.

Table 4.14 Linear Regression Statistics for Subgrade Moduli Using EVERCALC for US 31 Site			
	First Core	PAVLAYER	Rodar II
β_0, ksi	-0.006	0.006	-0.016
β_1	0.999	1.000	0.999
R^2	1.000	1.000	1.000
t Test H_0: $\beta_0 = 0$ H_1: $\beta_0 \neq 0$	N.S.D.	N.S.D.	N.S.D.
t Test H_0: $\beta_1 = 1$ H_1: $\beta_1 \neq 1$	N.S.D.	N.S.D.	N.S.D.

Table 4.15 Linear Regression Statistics for PCC Moduli Using EVERCALC for US 31 Site			
	First Core	PAVLAYER	Rodar II
β_0, ksi	-356.903	265.843	-308.019
β_1	0.967	0.972	0.953
R^2	0.978	0.886	0.976
t Test H_0: $\beta_0 = 0$ H_1: $\beta_0 \neq 0$	S.D.	N.S.D.	N.S.D.
t Test H_0: $\beta_1 = 1$ H_1: $\beta_1 \neq 1$	N.S.D.	N.S.D.	N.S.D.

4.3.2 DARWin

Moduli backcalculated using DARWin are plotted in Figures 4.16 - 4.21. Two plots (effective pavement and subgrade moduli) are included for each site. Moduli at some test locations for some thickness estimates are missing. This is because surface thicknesses were less than 2 inches for the SR 14 site and greater than 12 inches for the US 231 site. The moduli missing for the US 31 site are because the pavement was so stiff that FWD deflection sensor spacing did not allow calculation of an offset from the load with zero deflection.

The plots indicate that backcalculated effective pavement and subgrade moduli were not appreciably affected by surface layer thickness. However, for the US 231 site the test locations where moduli were backcalculated with all four thicknesses was limited.

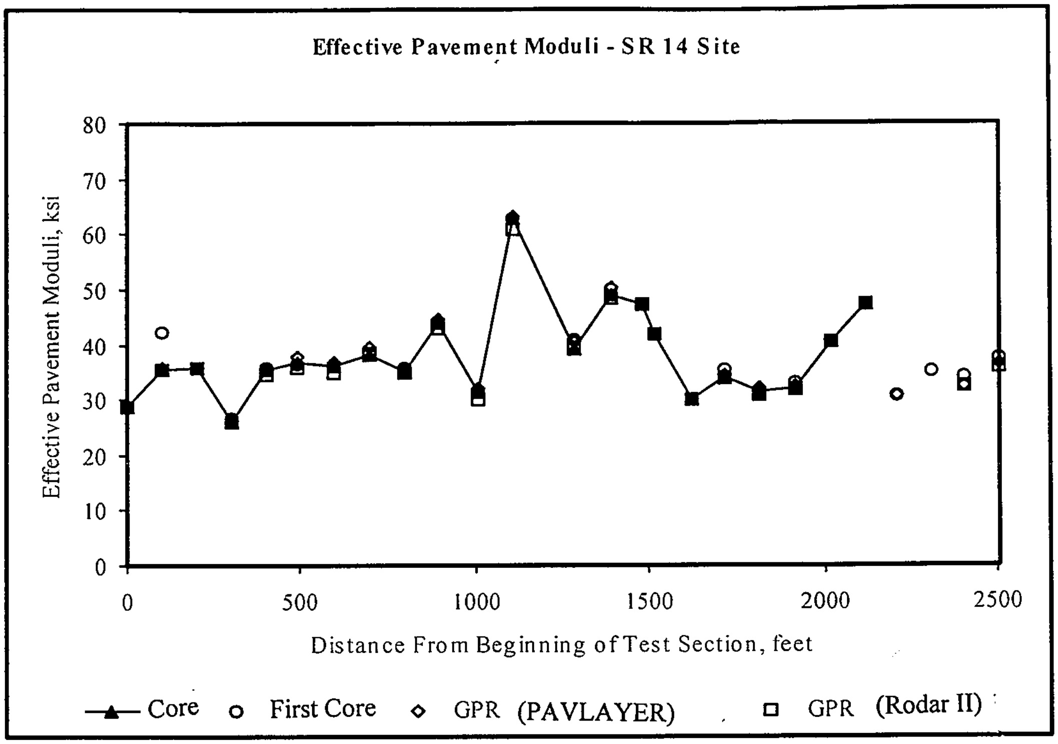

Figure 4.16 Backcalculated Effective Pavement Moduli for SR 14 Site Using DARWin

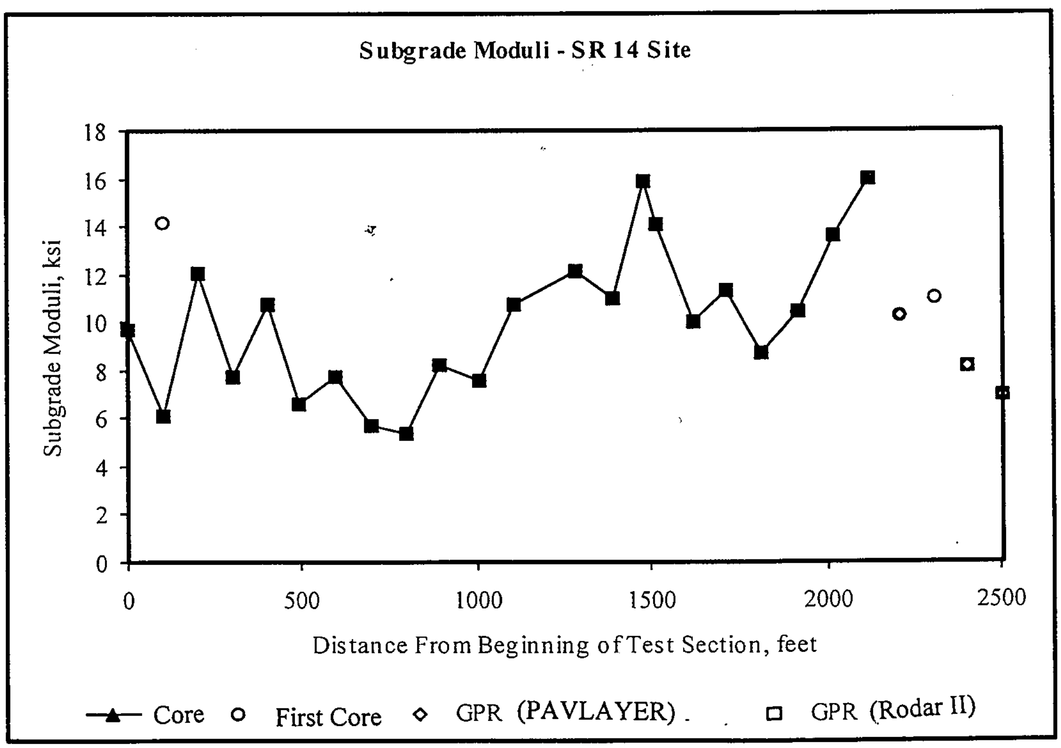

Figure 4.17 Backcalculated Subgrade Moduli for SR 14 Site Using DARWin

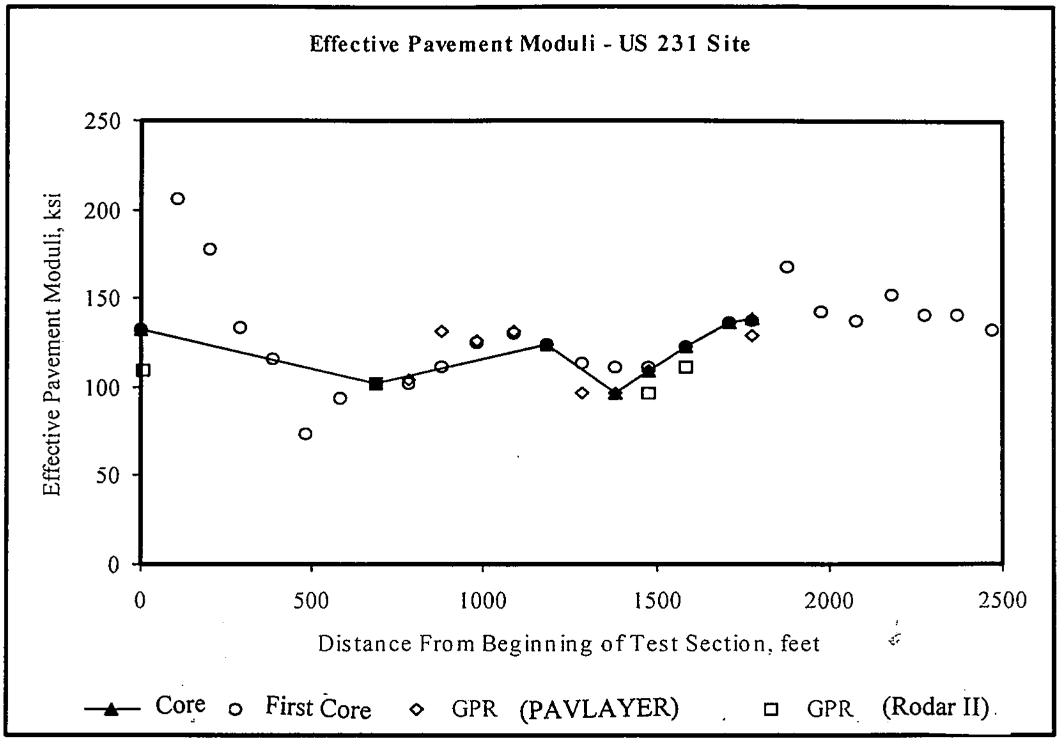

Figure 4.18 Backcalculated Effective Pavement Moduli for US 231 Site Using DARWin

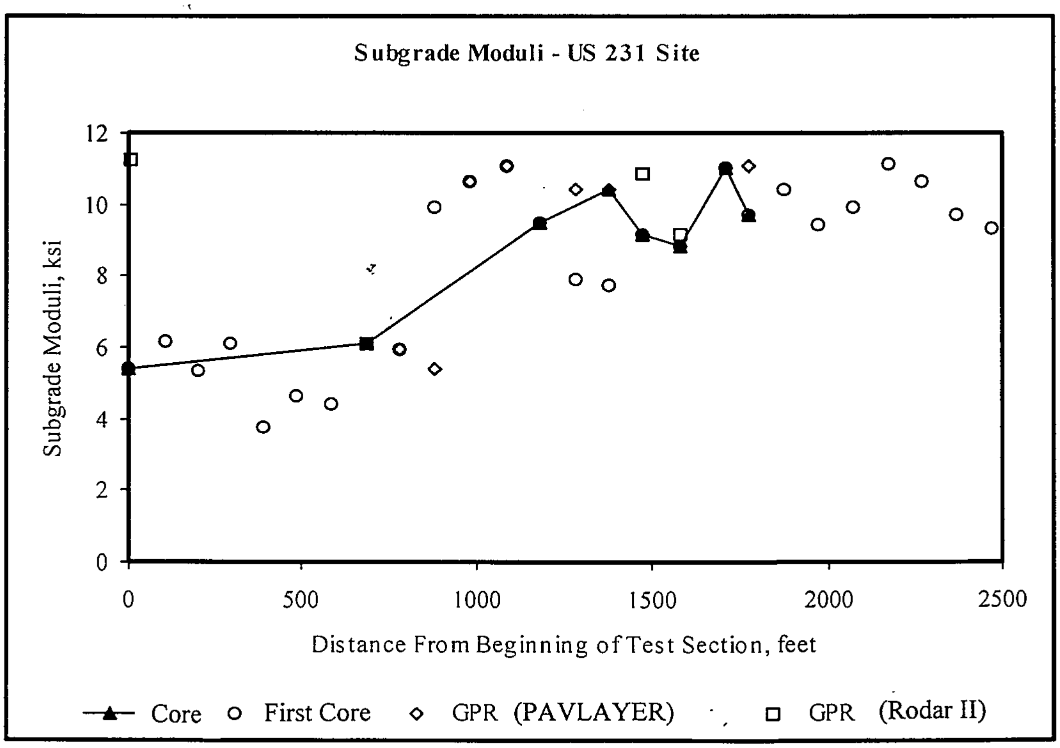

Figure 4.19 Backcalculated Subgrade Moduli for US 231 Site Using DARWin

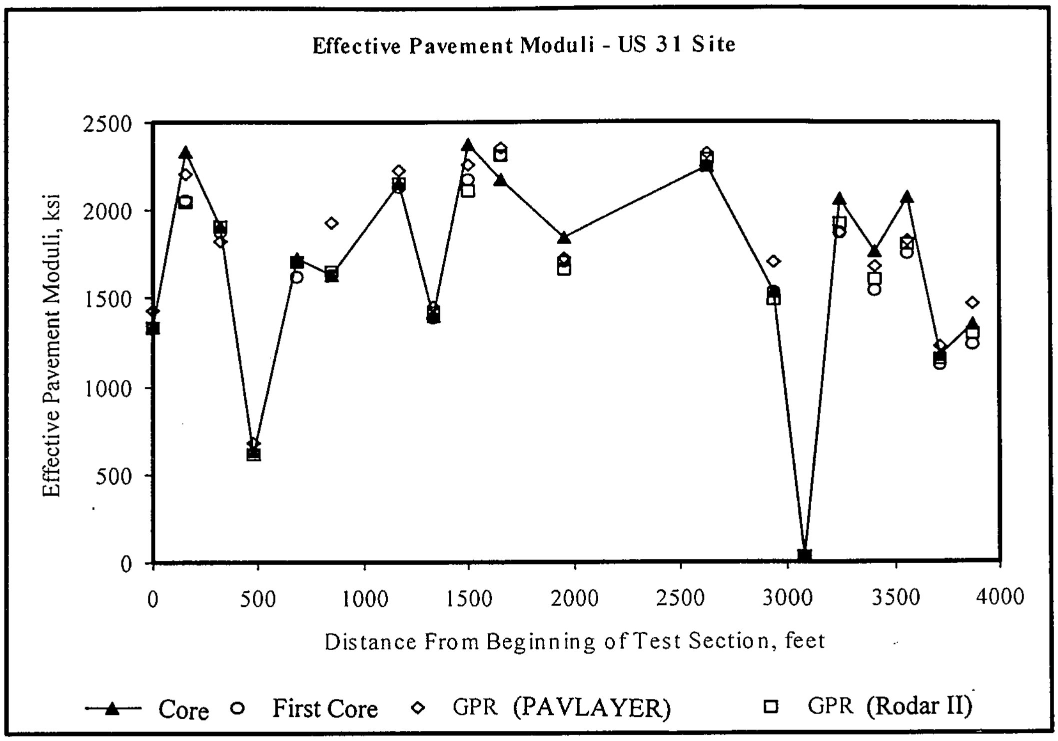

Figure 4.20 Backcalculated Effective Pavement Moduli for US 31 Site Using DARWin

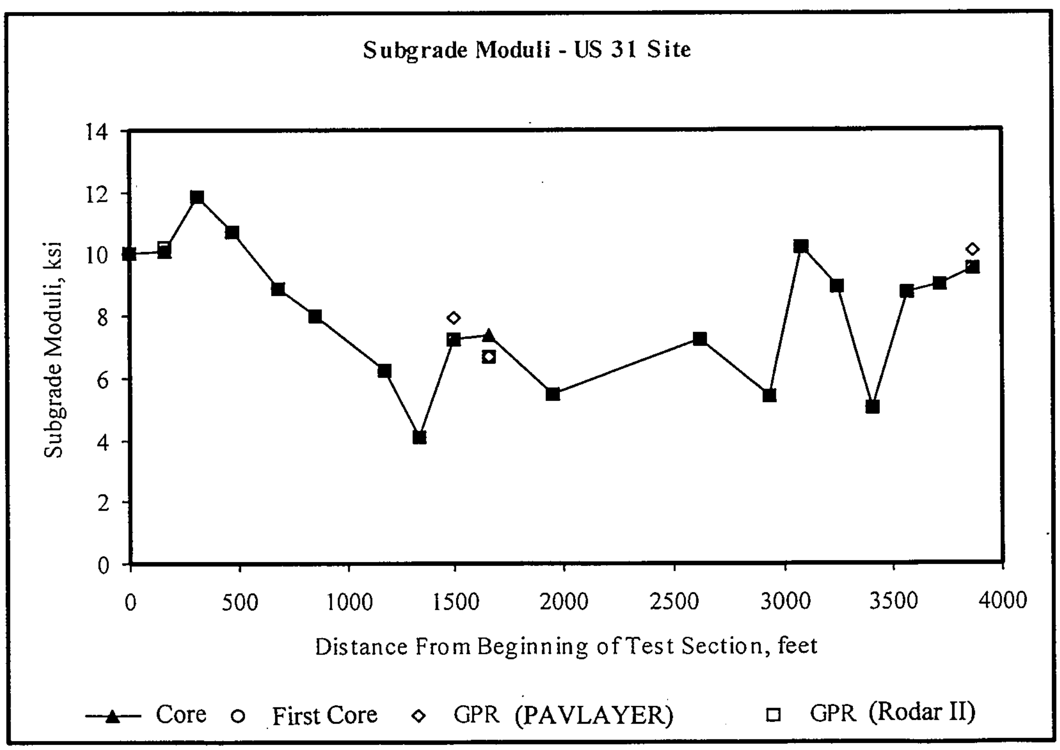

Figure 4.21 Backcalculated Subgrade Moduli for US 31 Site Using DARWin

Averages and standard deviations of absolute differences between moduli backcalculated with core thicknesses and moduli backcalculated with first core and GPR thicknesses are tabulated in Tables 4.16 - 4.18. These statistics, particularly for subgrade modulus, confirm visual observations that backcalculated moduli are relatively unaffected by surface layer thickness.

Table 4.16 Absolute Value of the Differences in Moduli for SR 14 Site Using DARWin

	Using First Core, ksi	Using PAVLAYER, ksi	Using Rodar II, ksi
Effective Pavement Average	0.68	0.39	0.52
Effective Pavement Standard Deviation	1.48	0.46	0.57
Subgrade Average	0.37	0	0
Subgrade Standard Deviation	1.72	0	0

Table 4.17 Absolute Value of the Differences in Moduli for US 231 Site Using DARWin

	Using First Core, ksi	Using PAVLAYER, ksi	Using Rodar II, ksi
Effective Pavement Average	2.37	1.23	5.14
Effective Pavement Standard Deviation	5.33	3.28	7.51
Subgrade Average	0.34	0.17	0.80
Subgrade Standard Deviation	0.95	0.48	1.39

Table 4.18 Absolute Value of the Difference in Moduli for US 31 Site Using DARWin			
	Using First Core, ksi	Using PAVLAYER, ksi	Using Rodar II, ksi
Effective Pavement Average	96.48	112.56	89.04
Effective Pavement Standard Deviation	104.53	73.43	99.42
Subgrade Average	0.04	0.10	0.04
Subgrade Standard Deviation	0.16	0.24	0.16

A complete set of linear regression equations for moduli backcalculated with core thickness as the independent variable and moduli backcalculated with first core and GPR thicknesses as the dependent variables were generated and are included in Appendix F. Tables 4.19 - 4.24 contain results from hypothesis testing of the coefficients from these equations to determine if they were significantly different from a line of equality. This testing indicated no significant difference for any case, confirming the acceptability of estimating surface layer thicknesses with GPR.

The comparisons also indicate estimates of surface layer thickness with a limited number of cores may also be acceptable. This conclusion, however, must be qualified based on thickness variability being less than or equal to that at the sites studied. Variability at the three sites are quantified by the statistics for core thicknesses in table 4.25. Differences between maximum and minimum thicknesses ranged from 3.6 in. for the AC on US 231 to 0.81 in. For the AC on US 31. Those differences as a percentage of the mean thickness ranged from 11.5% for the PCC on US 31 to 70.4% for the AC on SR 14. Coefficients of variation ranged from 3 to 20%.

Table 4.19 Linear Regression Statistics for Effective Pavement Moduli Using DARWin for SR 14 Site

	First Core	PAVLAYER	Rodar II
β_0, ksi	1.321	0.113	0.544
β_1	0.981	1.007	0.974
R^2	0.967	0.997	0.994
t Test H_0: $\beta_0 = 0$ H_1: $\beta_0 \neq 0$	N.S.D.	N.S.D.	N.S.D.
t Test H_0: $\beta_1 = 1$ H_1: $\beta_1 \neq 1$	N.S.D.	N.S.D.	N.S.D.

Table 4.20 Linear Regression Statistics for Effective Pavement Moduli Using DARWin for US 231 Site

	First Core	PAVLAYER	Rodar II
β_0, ksi	29.353	10.062	75.287
β_1	0.773	0.907	0.288
R^2	0.900	0.960	0.415
t Test H_0: $\beta_0 = 0$ H_1: $\beta_0 \neq 0$	N.S.D.	N.S.D.	N.S.D.
t Test H_0: $\beta_0 = 0$ H_1: $\beta_0 \neq 0$	N.S.D.	N.S.D.	N.S.D.

Table 4.21 Linear Regression Statistics for Effective Pavement Moduli Using DARWin for US 31 Site			
	First Core	PAVLAYER	Rodar II
β_0, ksi	35.679	118.209	51.765
β_1	0.930	0.935	0.931
R^2	0.963	0.948	0.963
t Test H_0: $\beta_0 = 0$ H_1: $\beta_0 \neq 0$	N.S.D.	N.S.D.	N.S.D.
t Test H_0: $\beta_1 = 1$ H_1: $\beta_1 \neq 1$	N.S.D.	N.S.D.	N.S.D.

Table 4.22 Linear Regression Statistics for Subgrade Moduli Using DARWin for SR 14 Site			
	First Core	PAVLAYER	Rodar II
β_0, ksi	1.969	0	0
β_1	0.841	1	1
R^2	0.713	1	1
t Test H_0: $\beta_0 = 0$ H_1: $\beta_0 \neq 0$	N.S.D.	N.S.D.	N.S.D.
t Test H_0: $\beta_1 = 1$ H_1: $\beta_1 \neq 1$	N.S.D.	N.S.D.	N.S.D.

Table 4.23 Linear Regression Statistics for Subgrade Moduli Using DARWin for US 231 Site

	First Core	PAVLAYER	Rodar II
β_0, ksi	1.053	0.225	-1.935
β_1	0.842	1.045	1.341
R^2	0.780	0.952	0.761
t Test H_0: $\beta_0 = 0$ H_1: $\beta_0 \neq 0$	N.S.D.	N.S.D.	N.S.D.
t Test H_0: $\beta_1 = 1$ H_1: $\beta_1 \neq 1$	N.S.D.	N.S.D.	N.S.D.

Table 4.24 Linear Regression Statistics for Subgrade Moduli Using DARWin for US 31 Site

	First Core	PAVLAYER	Rodar II
β_0, ksi	-0.086	-0.034	-0.105
β_1	1.006	1.008	1.009
R^2	0.995	0.986	0.994
t Test H_0: $\beta_0 = 0$ H_1: $\beta_0 \neq 0$	N.S.D.	N.S.D.	N.S.D.
t Test H_0: $\beta_1 = 1$ H_1: $\beta_1 \neq 1$	N.S.D.	N.S.D.	N.S.D.

Table 4.25 Statistics for Core Thicknesses				
	SR 14	US 231	US 31	
	AC	AC	AC	PCC
Mean Thickness, in.	2.7	12.2	3.2	8.1
Standard Deviation, in.	0.53	0.90	0.20	0.23
Coefficient of Variation, %	20	7	6	3
t_{max} - t_{min}, in.	1.9	3.6	0.80	1.0
(t_{max} - t_{min})/t_{mean}, %	70.4	29.5	25.0	11.5

V. CONCLUSIONS AND RECOMMENDATIONS

The accuracy of GPR estimated bound surface layer thicknesses was determined by comparing the average deviation from core thicknesses and means testing. The smallest average deviation obtained was 0.16 inches for the AC surface of the composite pavement on the US 31 site. The largest average deviation was 0.53 inches for the US 231 site. The PAVLAYER estimated thicknesses had smaller deviations from core thicknesses for three out of the four bound surface layers measured.

Means testing was performed at a 95% confidence level. Three of four mean bound surface layer thicknesses estimated by PAVLAYER were determined not significantly different from mean core thicknesses. All means of bound surface layer thicknesses estimated by Rodar II were significantly different from mean core thicknesses.

Asphalt concrete, granular base/subbase or PCC and subgrade moduli were backcalculated with EVERCALC. Average absolute differences from backcalculated moduli using the core thicknesses were used as a measure of accuracy. Asphalt concrete layer moduli consistently had larger differences than granular base/subbase, PCC or subgrade moduli. The largest differences were for AC layer moduli for the SR 14 site. The average differences for base/subbase and, particularly, subgrade moduli were small.

Effective pavement and subgrade moduli were backcalculated with DARWin. These moduli were relatively insensitive to input surface layer thicknesses.

Moduli backcalculated with EVERCALC were more sensitive to input surface thicknesses than moduli with DARWin. However, some comparisons were limited due to limitations in the backcalculation procedure.

Hypothesis testing of linear regression coefficients at a confidence level of 95% indicated all moduli backcalculated with DARWin using first core measurement or GPR estimated thicknesses were not significantly different from moduli backcalculated using core thicknesses. This insensitivity to moderate thickness variations is thought to be due to the backcalculation method used by DARWin.

Moduli backcalculated with EVERCALC were more sensitive to input surface layer thicknesses. However, only seven of twenty seven moduli comparisons were found to be significantly different. Four of these seven were from the SR 14 site and are thought due primarily to the EVERCALC backcalculation procedure's insensitivity to thin layers.

Based on the results of this study, GPR may be used to estimate bound surface layer thicknesses for use in FWD analysis. For pavements with similar longitudinal thickness variations, thickness estimates from one core may also be adequate.

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APPENDIX A

FWD MEASUREMENTS

Table A.1 FWD Measurements for SR 14 Site									
Test	Load (lb)	Temp (°F)	D1 (mils)	D2 (mils)	D3 (mils)	D4 (mils)	D5 (mils)	D6 (mils)	D7 (mils)
1	9057	86	28.85	12.83	3.110	1.063	0.669	0.591	0.551
2	8724	88	27.40	9.488	2.047	1.102	0.787	0.630	0.551
3	8850	90	25.66	9.764	2.441	1.299	0.906	0.748	0.630
4	8946	90	32.00	13.15	3.858	1.969	1.339	0.984	0.827
5	9057	90	23.89	9.488	2.795	1.496	1.102	0.827	0.669
6	9136	90	27.99	13.26	4.606	2.283	1.575	1.142	0.945
7	9009	91	26.53	11.96	3.858	1.890	1.378	1.063	0.906
8	9025	91	28.74	14.25	5.276	2.874	1.890	1.339	1.181
9	8993	91	30.51	15.66	5.551	2.598	1.654	1.181	0.984
10	9136	91	23.22	11.02	3.701	1.732	1.102	0.787	0.630
11	9104	93	30.15	13.11	4.016	1.614	0.945	0.669	0.591
12	9263	93	17.20	8.228	2.874	1.378	0.866	0.591	0.472
13	9057	90	20.98	8.386	2.480	1.142	0.787	0.591	0.512
14	9073	93	19.33	7.953	2.756	1.417	0.906	0.709	0.591
15	9025	93	23.11	8.031	1.890	1.102	0.787	0.630	0.551
16	9009	93	21.61	8.780	2.126	1.102	0.866	0.669	0.630
17	8914	93	32.16	11.53	2.953	1.496	0.984	0.709	0.630
18	9104	95	24.64	9.646	2.677	1.496	1.024	0.787	0.630
19	8961	93	28.38	12.44	3.425	1.614	1.102	0.866	0.709
20	9136	95	26.49	10.98	2.913	1.378	0.906	0.669	0.551
21	9025	95	21.92	8.740	2.205	1.181	0.787	0.630	0.551
22	8850	95	19.05	7.638	1.850	0.984	0.748	0.591	0.512
23	8882	95	30.59	11.89	2.874	1.417	0.984	0.787	0.630
24	8961	95	24.72	9.094	2.717	1.417	0.945	0.709	0.591
25	9088	95	27.91	11.57	3.701	1.850	1.181	0.827	0.630
26	8898	95	27.40	12.04	4.291	2.323	1.535	1.063	0.866

Table A.2 FWD Measurements for US 231 Site									
Test	Load (lb)	Temp (°F)	D1 (mils)	D2 (mils)	D3 (mils)	D4 (mils)	D5 (mils)	D6 (mils)	D7 (mils)
1	9041	97	15.63	10.27	6.260	3.701	2.402	1.575	1.181
2	9073	99	11.81	7.480	4.921	3.228	2.323	1.693	1.417
3	9073	99	13.74	8.740	5.591	3.740	2.677	1.929	1.496
4	8961	99	15.00	9.134	5.236	3.228	2.283	1.732	1.496
5	8961	99	20.11	13.81	8.504	5.236	3.543	2.520	2.008
6	8819	99	23.70	14.88	7.598	4.173	2.638	1.850	1.535
7	8898	99	21.18	13.81	7.953	4.449	2.717	1.811	1.457
8	8930	99	17.63	10.98	5.906	3.228	2.126	1.496	1.260
9	8961	99	17.87	10.19	5.669	3.307	2.244	1.614	1.339
10	9041	99	14.09	7.953	3.858	2.008	1.260	0.906	0.748
11	9136	99	12.87	6.929	3.543	1.890	1.220	0.866	0.709
12	9120	99	12.32	6.496	3.307	1.811	1.142	0.827	0.669
13	8993	99	13.30	7.559	3.937	2.087	1.299	0.866	0.709
14	8946	99	15.00	8.189	3.740	1.811	1.102	0.787	0.669
15	8946	99	15.23	8.425	3.819	1.890	1.181	0.866	0.787
16	8850	99	14.33	7.559	3.189	1.535	1.024	0.787	0.748
17	8850	100	13.89	7.244	3.307	1.732	1.181	0.906	0.748
18	8882	100	12.04	6.181	2.992	1.772	1.339	1.063	0.945
19	8898	100	12.55	6.339	3.031	1.772	1.299	1.024	0.906
20	8961	100	10.86	5.709	3.150	1.890	1.417	1.142	0.945
21	8961	100	12.48	6.772	3.504	2.087	1.457	1.102	0.945
22	8898	100	12.48	6.969	3.425	1.969	1.417	1.102	0.945
23	8946	100	11.29	5.866	2.992	1.772	1.260	0.984	0.827
24	8961	100	12.04	6.378	3.189	1.850	1.299	1.024	0.906
25	8866	100	12.36	6.457	3.819	2.008	1.260	1.102	0.866
26	8835	100	12.99	7.126	3.701	2.087	1.417	1.024	0.866

Table A.3 FWD Measurements for US 31 Site									
Test	Load (lb)	Temp (°F)	D1 (mils)	D2 (mils)	D3 (mils)	D4 (mils)	D5 (mils)	D6 (mils)	D7 (mils)
1	8993	100	4.291	2.953	2.520	1.969	1.496	1.063	0.748
2	9041	102	3.701	2.953	2.520	1.969	1.457	0.984	0.669
3	8930	100	3.386	2.480	2.126	1.654	1.299	0.984	0.787
4	8946	100	5.591	3.268	2.756	2.244	1.535	1.220	0.984
5	9088	100	4.331	3.346	2.874	2.244	1.772	1.339	1.024
6	8914	100	4.528	3.701	3.150	2.441	1.811	1.339	0.945
7	8993	100	3.819	2.953	2.756	2.480	2.165	1.811	1.535
8	8977	100	4.843	4.094	3.701	3.110	2.559	1.969	1.575
9	8914	102	7.480	5.827	5.630	4.921	4.094	3.150	2.402
10	8977	102	4.449	3.780	3.268	2.598	2.047	1.496	1.102
11	8993	102	4.567	3.819	3.386	2.835	2.283	1.772	1.339
12	8850	102	5.276	4.528	4.094	3.504	2.992	2.441	2.008
13	9009	102	5.827	5.039	4.331	3.622	2.717	2.087	1.575
14	8898	102	6.654	6.102	5.748	5.157	4.567	3.898	3.386
15	8961	104	6.102	5.551	5.157	4.567	3.976	3.346	2.874
16	8914	104	6.181	5.472	5.039	4.409	3.858	3.189	2.677
17	9025	104	4.449	3.504	3.071	2.520	2.047	1.614	1.299
18	8961	104	6.732	5.827	5.512	5.000	4.449	3.858	3.346
19	9073	102	4.488	3.740	3.346	2.795	2.323	1.850	1.496
20	8898	102	6.024	4.921	4.291	3.504	2.717	1.890	1.299
21	8850	102	5.709	4.961	4.370	3.661	2.913	2.087	1.457
22	8993	102	4.094	3.228	2.756	2.205	1.732	1.260	0.945
23	8882	104	6.339	5.276	4.685	3.858	3.150	2.323	1.732
24	8961	102	4.252	3.150	2.795	2.244	1.772	1.339	1.024
25	8898	102	4.882	3.661	2.992	2.165	1.575	1.181	0.945
26	8882	102	4.528	3.465	2.835	2.047	1.457	1.063	0.787

APPENDIX B

LAYER THICKNESS MEASUREMENTS

GPR AND CORES

Table B.1 GPR Estimated Thicknesses (PAVLAYER)				
	Thickness in Inches			
Site	SR 14	US 231	US 31	
Location	AC	AC	AC	PCC
1	3.01	11.58	3.59	8.43
2	2.64	12.55	3.14	8.63
3	2.90	13.83	3.41	8.98
4	2.67	12.81	3.39	8.33
5	2.86	12.32	3.36	8.70
6	3.88	14.16	3.39	8.09
7	3.35	12.38	3.63	8.68
8	3.94	10.19	3.01	8.82
9	2.77	10.69	3.39	7.40
10	3.36	11.77	3.48	7.95
11	3.49	11.71	3.25	8.89
12	3.22	11.97	3.16	8.47
13	2.90	11.86	3.36	8.82
14	3.23	11.32	3.33	8.31
15	3.39	11.85	3.16	9.49
16	3.82	10.76	3.04	8.80
17	2.49	11.06	3.04	8.86
18	2.60	11.63	3.26	9.18
19	3.47	11.77	3.03	7.92
20	2.56	12.26	2.90	8.52
21	2.40	12.57	3.08	9.00
22	3.48	12.49	2.71	9.11
23	2.51	13.17	3.16	8.54
24	1.92	12.19	3.27	8.64
25	2.19	13.08	3.22	8.50
26	2.66	12.32	3.53	8.03

Table B.2 GPR Estimated Thicknesses (Rodar II)				
	Thickness in Inches			
Site	SR 14	US 231	US 31	
Location	AC	AC	AC	PCC
1	2.2	12.1	3.5	8.8
2	2.4	12.9	3.8	8.7
3	2.2	14.6	3.5	8.7
4	2.5	13.5	3.6	8.8
5	2.2	12.8	3.6	8.6
6	2.5	15.1	3.5	8.8
7	2.2	13.1	3.6	8.9
8	3.2	10.9	3.6	8.8
9	2.2	11.3	3.8	8.7
10	2.4	12.5	3.5	9.0
11	2.4	12.5	3.5	8.9
12	2.4	12.8	3.6	8.8
13	2.4	12.3	3.6	9.0
14	2.4	11.9	3.6	9.1
15	2.7	12.3	3.2	9.1
16	2.5	11.5	3.6	8.8
17	2.1	11.8	3.6	8.8
18	2.2	12.3	3.5	8.9
19	2.7	12.3	3.2	9.1
20	2.4	13.1	3.5	9.0
21	2.1	13.1	3.5	8.8
22	2.1	12.5	3.2	8.8
23	1.3	13.8	3.5	8.7
24	1.1	13.3	3.5	8.7
25	2.1	12.9	3.6	8.8
26	2.2	13.1	3.8	8.6

Table B.3 Average Core Thicknesses

	Thickness in Inches			
Site	SR 14	US 231	US 31	
Location	AC	AC	AC	PCC
1	3.1	11.3	3.4	8.9
2	2.3	12.9	3.0	8.4
3	2.7	13.7	3.3	8.8
4	2.4	12.6	3.2	8.8
5	2.8	12.3	3.0	8.7
6	3.4	Damaged Core	3.4	8.9
7	3.1	12.3	3.6	8.8
8	2.9	10.1	2.8	8.7
9	2.7	Damaged Core	3.2	8.6
10	3.1	Damaged Core	3.3	8.5
11	3.3	Damaged Core	3.3	8.4
12	3.1	12.2	3.2	8.8
13	2.2	11.8	3.1	8.6
14	2.7	Damaged Core	3.4	8.9
15	3.0	11.9	3.0	8.6
16	3.6	10.7	3.0	8.7
17	2.3	11.1	3.0	9.0
18	2.4	11.5	3.3	8.8
19	3.2	11.7	3.1	8.6
20	2.5	12.7	3.0	9.0
21	2.0	12.8	2.8	9.1
22	3.2	12.4	3.2	8.5
23	1.7	13.6	3.2	8.3
24	1.8	12.8	3.3	8.1
25	1.8	12.7	3.5	8.7
26	NA	12.7	3.1	8.6

APPENDIX C

MODULI BACKCALCULATED WITH EVERCALC 5.0

Table C.1 EVERCALC Backcalculation Results Using Core Data - SR 14 Site				
Location	AC Moduli, ksi	Base/ Subbase Moduli, ksi	Subgrade Moduli, ksi	Average RMS Error (%)
1	673.45	6.16	37.71	7.31
2	719.07	10.49	36.95	7.53
3	516.70	11.83	32.53	7.87
4	752.16	9.47	22.77	4.24
5	476.15	14.93	29.52	5.85
6	399.75	11.06	20.32	4.24
7	461.22	11.87	22.79	7.83
8	580.06	12.64	16.80	5.72
9	1004.40	7.76	18.42	3.11
10	828.00	10.40	28.19	2.83
11	678.13	6.29	30.19	7.17
12	1216.98	14.16	37.43	4.10
13	1791.31	13.07	38.51	5.53
14	894.77	17.98	33.26	5.68
15	339.65	14.50	39.97	8.72
16	267.11	13.93	37.42	11.43
17	798.57	8.97	29.91	6.41
18	762.37	14.00	30.73	4.61
19	435.05	8.95	26.83	4.53
20	1019.81	9.53	33.32	4.14
21	1702.66	13.56	37.76	7.12
22	398.97	15.85	42.01	9.35
23	2156.00	8.77	29.71	4.52
24	1878.16	13.91	32.01	4.89
25	2642.60	10.29	26.58	5.06
26	NA	NA	NA	NA

Table C.2 EVERCALC Backcalculation Results Using Core Data - US 231 Site				
Location	AC Moduli, ksi	Base/ Subbase Moduli, ksi	Subgrade Moduli, ksi	Average RMS Error (%)
1	154.08	10.61	15.86	2.97
2	156.81	49.98	15.80	5.93
3	133.97	29.99	14.01	4.10
4	104.67	35.49	15.27	9.32
5	104.47	12.89	10.22	5.85
6	NA	NA	NA	NA
7	89.14	6.66	13.19	6.20
8	114.03	15.54	16.03	7.18
9	NA	NA	NA	NA
10	NA	NA	NA	NA
11	NA	NA	NA	NA
12	117.20	21.06	29.97	6.38
13	123.25	13.71	26.91	5.57
14	NA	NA	NA	NA
15	87.82	14.27	27.12	10.77
16	88.76	18.70	30.65	12.70
17	94.20	23.40	27.63	9.69
18	100.78	62.22	25.81	13.73
19	95.70	50.20	26.25	12.86
20	117.39	77.41	24.65	10.99
21	106.68	37.92	23.64	9.75
22	105.56	37.70	24.03	11.71
23	107.90	46.38	27.22	10.44
24	104.68	41.61	25.97	11.91
25	111.69	28.01	24.80	10.91
26	105.32	24.77	24.01	8.34

Table C.3 EVERCALC Backcalculation Results Using Core Data - US 31 Site				
Location	AC Moduli, ksi	PCC Moduli, ksi	Subgrade Moduli, ksi	Average RMS Error (%)
1	238.67	3246.80	27.88	2.76
2	728.84	2618.57	29.87	5.00
3	286.68	6090.09	29.29	1.80
4	92.54	4251.37	23.68	4.07
5	275.86	4601.53	22.17	0.90
6	682.45	1858.91	21.97	2.49
7	304.69	14885.25	13.05	1.03
8	488.73	5261.20	14.14	1.63
9	215.02	4334.20	8.70	4.32
10	887.74	2685.68	19.56	2.24
11	581.10	4920.86	16.43	1.66
12	334.15	6528.60	10.68	0.82
13	773.36	2260.06	13.98	1.95
14	723.30	7161.11	5.53	0.94
15	631.02	7791.74	7.00	0.78
16	346.54	7144.15	7.66	0.97
17	260.42	5710.13	17.63	0.88
18	261.63	9960.72	5.37	0.87
19	390.09	6891.42	15.13	0.71
20	493.37	1676.77	15.47	5.09
21	698.99	1970.88	13.94	5.15
22	415.67	4252.13	23.26	1.57
23	456.97	3100.87	12.36	2.66
24	258.95	6436.49	21.78	1.43
25	271.61	2517.24	24.04	3.69
26	411.84	2067.03	26.77	1.83

Table C.4 EVERCALC Backcalculation Results Using First Core - SR 14 Site				
Location	AC Moduli, ksi	Base/ Subbase Moduli, ksi	Subgrade Moduli, ksi	Average RMS Error (%)
1	673.45	6.16	37.71	7.31
2	282.04	10.63	37.17	7.41
3	334.00	11.91	32.63	7.85
4	350.21	9.43	22.78	4.24
5	342.80	15.11	29.65	5.79
6	522.29	11.11	20.31	4.16
7	461.22	11.87	22.79	7.83
8	478.81	12.57	16.80	5.77
9	669.60	7.72	18.44	3.08
10	828.00	10.40	28.19	2.83
11	816.84	6.29	30.18	7.29
12	1216.98	14.16	37.43	4.10
13	644.53	12.98	38.52	5.32
14	586.74	17.95	33.28	5.62
15	309.25	14.49	39.99	8.76
16	411.40	13.94	37.21	11.46
17	325.02	8.95	29.93	6.07
18	341.15	14.10	30.90	4.62
19	476.21	8.96	26.83	4.52
20	536.56	9.52	33.31	3.89
21	455.35	13.55	37.80	7.27
22	444.88	15.82	41.96	9.35
23	360.90	8.71	29.66	4.48
24	369.47	13.61	32.13	4.49
25	517.59	10.18	26.59	4.43
26	413.76	13.05	20.61	2.84

Table C.5 EVERCALC Backcalculation Results Using First Core - US 231 Site				
Location	AC Moduli, ksi	Base/ Subbase Moduli, ksi	Subgrade Moduli, ksi	Average RMS Error (%)
1	154.20	10.57	15.88	2.95
2	165.94	67.84	15.86	5.95
3	146.78	49.20	14.01	3.93
4	112.17	41.15	15.30	9.29
5	113.81	15.27	10.17	5.51
6	73.05	8.82	12.71	7.48
7	99.57	7.29	13.04	5.50
8	100.54	13.93	16.18	7.75
9	91.97	21.80	15.50	6.87
10	110.72	15.63	26.57	7.31
11	122.09	20.29	28.30	6.20
12	125.42	22.16	29.84	5.82
13	129.59	14.04	26.82	5.17
14	97.00	12.47	29.27	7.91
15	92.58	14.38	27.05	10.29
16	84.69	18.54	30.82	13.05
17	93.03	23.13	27.70	9.75
18	101.55	62.26	25.87	13.71
19	97.18	50.64	26.31	12.81
20	118.59	94.31	24.75	11.24
21	114.93	42.11	23.63	9.59
22	112.21	39.64	24.04	11.55
23	118.27	53.10	27.24	10.33
24	112.29	44.73	25.99	11.76
25	122.03	30.88	24.70	10.59
26	114.94	27.35	23.90	7.84

Table C.6 EVERCALC Backcalculation Results Using First Core - US 31 Site				
Location	AC Moduli, ksi	PCC Moduli, ksi	Subgrade Moduli, ksi	Average RMS Error (%)
1	238.67	3246.80	27.88	2.76
2	711.72	2001.80	29.76	5.34
3	297.93	5803.88	29.28	1.80
4	99.42	4043.92	23.67	4.07
5	313.84	4058.82	22.15	0.93
6	682.45	1858.91	21.97	2.49
7	285.82	14549.15	13.04	1.04
8	611.84	4307.73	14.10	1.64
9	232.13	3797.47	8.69	4.32
10	870.98	2264.92	19.50	2.41
11	629.74	3905.85	16.38	1.70
12	350.63	6188.51	10.67	0.87
13	760.93	1872.56	13.92	2.12
14	723.30	7161.11	5.53	0.94
15	720.27	6553.74	6.98	0.88
16	501.75	6092.98	7.65	0.79
17	298.13	5663.33	17.63	0.89
18	270.02	9555.96	5.37	0.87
19	437.29	5931.41	15.11	0.71
20	498.80	1583.18	15.44	5.16
21	692.20	1836.81	13.90	5.27
22	462.47	3463.41	23.20	1.61
23	500.94	2292.42	12.31	2.74
24	276.76	4708.39	21.71	1.46
25	267.36	2376.81	24.03	3.67
26	518.78	1536.29	26.70	1.84

Table C.7 EVERCALC Backcalculation Results Using GPR Data (PAVLAYER Estimates) - SR 14 Site

Location	AC Moduli, ksi	Base/ Subbase Moduli, ksi	Subgrade Moduli, ksi	Average RMS Error (%)
1	737.41	6.15	37.71	7.31
2	463.30	10.59	36.98	7.55
3	413.42	11.86	32.57	7.87
4	547.88	9.44	22.77	4.24
5	446.66	15.02	29.54	5.85
6	272.70	11.03	20.34	4.36
7	360.68	11.92	22.80	7.90
8	238.44	12.42	16.83	5.95
9	931.66	7.75	18.42	3.10
10	654.22	10.37	28.20	2.72
11	572.99	6.29	30.19	7.05
12	1091.87	14.12	37.44	4.05
13	783.24	13.00	38.51	5.37
14	523.23	17.88	33.31	5.59
15	240.40	14.48	40.06	8.87
16	241.11	13.63	37.54	11.50
17	635.74	8.93	29.86	6.35
18	598.82	14.07	30.72	4.64
19	342.04	8.96	26.84	4.59
20	948.48	9.53	33.32	4.12
21	982.59	13.52	37.76	7.19
22	316.14	15.85	42.17	9.32
23	667.69	8.73	29.72	4.48
24	1570.84	13.69	32.03	4.87
25	1459.00	10.26	26.60	4.92
26	641.05	13.25	20.60	2.87

Table C.8 EVERCALC Backcalculation Results Using GPR Data (PAVLAYER Estimates) - US 231 Site

Location	AC Moduli, ksi	Base/ Subbase Moduli, ksi	Subgrade Moduli, ksi	Average RMS Error (%)
1	149.21	10.18	15.94	3.12
2	158.85	53.24	15.82	5.91
3	133.39	29.05	14.03	4.10
4	103.67	34.49	15.29	9.31
5	104.33	12.81	10.23	5.85
6	58.42	7.21	13.06	9.32
7	88.46	6.60	13.22	6.24
8	113.07	15.32	16.06	7.20
9	96.06	23.28	15.47	6.74
10	106.15	15.30	26.67	7.66
11	118.09	19.78	28.39	6.45
12	119.22	21.23	29.98	6.20
13	122.68	13.59	26.99	5.58
14	96.81	12.46	29.28	7.92
15	88.25	14.22	27.17	10.69
16	88.45	18.60	30.72	12.69
17	94.56	23.31	27.67	9.62
18	100.39	61.54	25.85	13.68
19	95.54	49.77	26.30	12.82
20	119.17	79.43	24.72	11.03
21	107.85	38.35	23.67	9.70
22	105.12	37.34	24.07	11.68
23	109.61	47.32	27.26	10.38
24	107.64	42.61	26.01	11.82
25	109.44	27.14	24.88	10.96
26	107.68	25.34	24.01	8.17

Table C.9 EVERCALC Backcalculation Results Using GPR Data (PAVLAYER Estimates) - US 31 Site

Location	AC Moduli, ksi	PCC Moduli, ksi	Subgrade Moduli, ksi	Average RMS Error (%)
1	247.44	3766.41	27.91	2.7
2	721.28	2334.62	29.82	5.13
3	300.02	5632.39	29.27	1.80
4	98.10	4964.74	23.72	4.08
5	307.60	4396.50	22.16	0.92
6	691.22	2547.94	22.06	2.20
7	307.06	15495.55	13.06	1.02
8	533.41	4840.25	14.12	1.63
9	219.86	6814.34	8.75	4.26
10	915.45	3158.00	19.61	2.14
11	600.74	4074.04	16.39	1.70
12	324.94	7366.92	10.72	0.85
13	765.24	1945.46	13.94	2.09
14	675.08	9097.42	5.55	0.88
15	720.61	5469.19	6.96	0.87
16	352.14	6869.31	7.65	0.98
17	262.67	5973.83	17.64	0.89
18	263.74	8742.57	5.36	0.84
19	367.75	9015.84	15.18	0.70
20	501.53	2032.82	15.51	4.96
21	695.17	1915.79	13.92	5.20
22	368.14	3680.88	23.23	1.64
23	461.45	2831.63	12.35	2.69
24	261.68	5264.51	21.73	1.46
25	236.29	2931.85	24.07	3.70
26	444.15	2308.98	26.78	1.82

Table C.10 EVERCALC Backcalculation Results Using GPR Data (Rodar II Estimates) -SR 14 Site				
Location	AC Moduli, ksi	Base/ Subbase Moduli, ksi	Subgrade Moduli, ksi	Average RMS Error (%)
1	1885.48	6.15	37.67	7.51
2	628.88	10.54	36.96	7.54
3	975.92	11.79	32.51	7.79
4	666.77	9.46	22.76	4.24
5	1029.48	14.90	29.47	5.75
6	978.64	11.25	20.30	4.04
7	1264.27	12.07	22.77	7.59
8	437.76	12.52	16.80	5.79
9	1888.55	7.80	18.38	3.19
10	1767.02	10.47	28.16	3.11
11	1791.92	6.29	30.18	7.64
12	2619.21	14.22	37.39	4.37
13	1381.47	13.04	38.52	5.48
14	1262.68	18.12	33.26	5.71
15	422.44	14.92	39.83	8.79
16	809.13	13.76	37.11	11.33
17	1059.06	8.96	29.92	6.49
18	986.46	14.05	30.72	4.55
19	718.41	8.96	26.83	4.45
20	1140.60	9.55	33.30	4.18
21	1458.93	13.58	37.75	7.15
22	1502.20	15.60	41.81	9.08
23	4865.88	8.79	29.67	4.59
24	8287.43	14.03	31.95	5.04
25	1656.27	10.27	26.60	4.96
26	1126.15	13.39	20.60	2.91

Table C.11 EVERCALC Backcalculation Results Using GPR Data (Rodar II Estimates) - US 231 Site

Location	AC Moduli, ksi	Base/ Subbase Moduli, ksi	Subgrade Moduli, ksi	Average RMS Error (%)
1	141.05	9.48	16.06	3.44
2	156.92	49.74	15.82	5.92
3	129.59	24.64	14.07	4.23
4	100.51	31.79	15.29	9.36
5	100.53	11.80	10.26	6.02
6	55.40	6.75	13.20	9.90
7	82.72	6.17	13.36	6.76
8	104.58	14.41	16.13	7.55
9	91.97	21.80	15.50	6.87
10	100.15	14.82	26.85	8.19
11	111.49	18.87	28.57	6.92
12	112.82	20.18	30.18	6.68
13	117.74	13.27	27.11	5.91
14	91.63	12.33	29.44	8.46
15	85.21	14.10	27.27	11.02
16	83.44	18.52	30.86	13.19
17	90.12	22.78	27.77	10.01
18	98.07	60.35	25.80	13.61
19	93.85	48.79	26.28	12.82
20	115.99	74.62	24.67	10.89
21	105.35	36.90	23.69	9.75
22	105.60	37.50	24.07	11.67
23	107.22	45.53	27.27	10.41
24	102.62	40.35	26.03	11.92
25	110.50	27.48	24.86	10.92
26	103.12	23.94	24.10	8.44

Table C.12 EVERCALC Backcalculation Results Using GPR Data (Rodar II Estimates) - US 31 Site				
Location	AC Moduli, ksi	PCC Moduli, ksi	Subgrade Moduli, ksi	Average RMS Error (%)
1	245.09	3316.72	27.88	2.74
2	721.00	1934.36	29.72	5.45
3	305.42	6165.67	29.29	1.81
4	106.08	4114.18	23.67	4.08
5	326.80	4412.79	22.16	0.93
6	688.26	1870.99	21.97	2.49
7	305.16	14379.36	13.04	1.03
8	643.84	4262.25	14.09	1.63
9	258.44	3871.41	8.69	4.29
10	933.58	2029.03	19.47	2.49
11	648.11	3802.37	16.37	1.71
12	362.82	6284.98	10.67	0.94
13	756.38	1710.30	13.89	2.24
14	786.74	6352.61	5.48	0.80
15	699.05	6271.56	6.98	0.84
16	526.84	6137.58	7.65	0.80
17	316.43	5727.81	17.63	0.90
18	276.92	9498.72	5.37	0.88
19	415.55	5673.84	15.10	0.72
20	496.45	1494.74	15.42	5.22
21	695.44	1851.62	13.90	5.27
22	427.52	3773.36	23.23	1.60
23	504.48	2418.65	12.31	2.72
24	283.45	4997.90	21.72	1.44
25	285.91	2347.80	24.02	3.68
26	575.17	1445.56	26.68	1.85

APPENDIX D

MODULI BACKCALCULATED WITH DARwin 3.01

Table D.1 DARWin Backcalculation Results Using Core Data - SR 14 Site		
Location	Effective Pavement Moduli, ksi	Subgrade Moduli, ksi
1	28.83	9.70
2	35.31	6.12
3	35.89	12.07
4	25.97	7.72
5	35.32	10.79
6	36.89	6.61
7	36.20	7.78
8	37.98	5.70
9	35.16	5.40
10	43.94	8.22
11	31.51	7.55
12	62.85	10.73
13	39.08	12.16
14	49.05	10.96
15	47.27	15.90
16	41.95	14.11
17	29.88	10.05
18	34.01	11.33
19	31.40	8.71
20	31.99	10.44
21	40.52	13.63
22	47.36	15.93
23	NA	NA
24	NA	NA
25	NA	NA
26	NA	NA

Table D.2 DARWin Backcalculation Results Using Core Data - US 231 Site		
Location	Effective Pavement Moduli, ksi	Subgrade Moduli, ksi
1	131.91	5.37
2	NA	NA
3	NA	NA
4	NA	NA
5	NA	NA
6	NA	NA
7	NA	NA
8	101.99	6.09
9	NA	NA
10	NA	NA
11	NA	NA
12	NA	NA
13	124.39	9.48
14	NA	NA
15	96.24	10.41
16	109.34	9.16
17	123.10	8.83
18	136.67	11.03
19	138.56	9.69
20	NA	NA
21	NA	NA
22	NA	NA
23	NA	NA
24	NA	NA
25	NA	NA
26	NA	NA

Table D.3 DARWin Backcalculation Results Using Core Data - US 31 Site		
Location	Effective Pavement Moduli, ksi	Subgrade Moduli, ksi
1	1339.74	10.05
2	2326.45	10.10
3	1907.66	11.88
4	616.74	10.71
5	1727.96	8.91
6	1631.13	8.03
7	NA	NA
8	2146.88	6.27
9	1397.84	4.08
10	2368.14	7.24
11	2171.57	7.39
12	NA	NA
13	1840.26	5.47
14	NA	NA
15	NA	NA
16	NA	NA
17	2248.53	7.28
18	NA	NA
19	NA	NA
20	1539.22	5.40
21	30.69	10.23
22	2066.42	8.97
23	1774.11	5.05
24	2076.52	8.79
25	1178.18	9.04
26	1359.56	9.55

Table D.4 DARWin Backcalculation Results Using First Core - SR 14 Site		
Location	Effective Pavement Moduli, ksi	Subgrade Moduli, ksi
1	28.83	9.70
2	42.19	14.19
3	35.89	12.07
4	26.67	7.72
5	35.65	10.79
6	36.50	6.61
7	36.20	7.78
8	38.32	5.70
9	35.64	5.40
10	43.94	8.22
11	31.28	7.55
12	62.85	10.73
13	40.90	12.16
14	50.04	10.96
15	47.27	15.90
16	41.95	14.11
17	29.88	10.05
18	35.37	11.33
19	31.14	8.12
20	33.25	10.44
21	40.52	13.63
22	47.36	15.93
23	30.60	10.29
24	34.96	10.98
25	34.13	8.18
26	37.33	6.91

Table D.5 DARWin Backcalculation Results Using First Core - US 231 Site

Location	Effective Pavement Moduli, ksi	Subgrade Moduli, ksi
1	131.91	5.37
2	206.12	6.18
3	177.90	5.34
4	133.80	6.11
5	115.81	3.77
6	73.40	4.65
7	93.33	4.40
8	101.99	6.09
9	101.70	5.96
10	111.66	9.91
11	125.36	10.63
12	130.60	11.08
13	123.81	9.48
14	113.14	7.89
15	111.74	7.73
16	111.01	9.16
17	123.37	8.83
18	136.34	11.03
19	137.98	9.69
20	167.84	10.43
21	143.12	9.45
22	137.28	9.94
23	151.79	11.11
24	141.12	10.66
25	140.41	9.71
26	132.36	9.31

Table D.6 DARWin Backcalculation Results Using First Core - US 31 Site		
Location	Effective Pavement Moduli, ksi	Subgrade Moduli, ksi
1	1339.74	10.05
2	2050.95	10.10
3	1871.67	11.88
4	616.74	10.71
5	1619.96	8.91
6	1631.13	8.03
7	NA	NA
8	2127.88	6.27
9	1385.47	4.08
10	2170.79	7.24
11	2314.23	6.70
12	NA	NA
13	1707.63	5.47
14	NA	NA
15	NA	NA
16	NA	NA
17	2248.53	7.28
18	NA	NA
19	NA	NA
20	1539.22	5.40
21	30.69	10.23
22	1876.09	8.97
23	1544.70	5.05
24	1757.06	8.79
25	1123.38	9.04
26	1243.86	9.55

Table D.7 DARWin Backcalculation Results Using GPR (PAVLAYEREstimates) Data - SR 14 Site

Location	Effective Pavement Moduli, ksi	Subgrade Moduli, ksi
1	28.83	9.70
2	35.68	6.12
3	35.89	12.07
4	26.20	7.72
5	35.32	10.79
6	37.69	6.61
7	36.66	7.78
8	39.34	5.70
9	35.32	5.40
10	44.43	8.22
11	31.96	7.55
12	63.17	10.73
13	40.54	12.16
14	50.37	10.96
15	47.27	15.90
16	41.95	14.11
17	29.88	10.05
18	34.35	11.33
19	31.92	8.71
20	32.30	10.44
21	40.52	13.63
22	47.36	15.93
23	30.60	10.29
24	NA	NA
25	32.41	8.18
26	36.50	6.91

Table D.8 DARWin Backcalculation Results Using GPR (PAVLAYER Estimates) Data - US 231 Site		
Location	Effective Pavement Moduli, ksi	Subgrade Moduli, ksi
1	131.75	5.37
2	NA	NA
3	NA	NA
4	NA	NA
5	NA	NA
6	NA	NA
7	NA	NA
8	101.99	6.09
9	103.51	5.96
10	131.59	5.37
11	125.68	10.63
12	131.61	11.08
13	124.39	9.48
14	113.14	7.89
15	96.24	10.41
16	109.34	9.16
17	123.10	8.83
18	137.01	11.03
19	129.22	11.05
20	NA	NA
21	NA	NA
22	NA	NA
23	NA	NA
24	NA	NA
25	NA	NA
26	NA	NA

Table D.9 DARWin Backcalculation Results Using GPR (PAVLAYER Estimates) Data - US 31 Site		
Location	Effective Pavement Moduli, ksi	Subgrade Moduli, ksi
1	1431.09	10.05
2	2204.00	10.10
3	1825.67	11.88
4	681.66	10.71
5	1700.96	8.91
6	1923.27	8.03
7	NA	NA
8	2222.88	6.27
9	1447.32	4.08
10	2256.25	7.92
11	2354.83	6.70
12	NA	NA
13	1724.21	5.47
14	NA	NA
15	NA	NA
16	NA	NA
17	2314.67	7.28
18	NA	NA
19	NA	NA
20	1702.97	5.40
21	30.69	10.23
22	1876.09	8.97
23	1682.34	5.05
24	1836.93	8.79
25	1232.98	9.04
26	1475.27	10.06

Table D.10 DARWin Backcalculation Results Using GPR (Rodar II Estimates) Data - SR 14 Site

Location	Effective Pavement Moduli, ksi	Subgrade Moduli, ksi
1	28.83	9.70
2	35.49	6.12
3	35.89	12.07
4	25.97	7.72
5	34.35	10.79
6	35.90	6.61
7	34.79	7.78
8	38.32	5.70
9	34.67	5.40
10	42.71	8.22
11	30.15	7.55
12	60.92	10.73
13	39.44	12.16
14	48.39	10.96
15	47.27	15.90
16	41.95	14.11
17	29.88	10.05
18	33.67	11.33
19	30.61	8.71
20	31.68	10.44
21	40.52	13.63
22	47.36	15.93
23	NA	NA
24	NA	NA
25	32.41	8.18
26	35.67	6.91

Table D.11 DARWin Backcalculation Results Using GPR (Rodar II Estimates) Data - US 231 Site

Location	Effective Pavement Moduli, ksi	Subgrade Moduli, ksi
1	NA	NA
2	NA	NA
3	NA	NA
4	NA	NA
5	NA	NA
6	NA	NA
7	NA	NA
8	101.99	6.09
9	NA	NA
10	NA	NA
11	NA	NA
12	NA	NA
13	NA	NA
14	96.82	10.87
15	NA	NA
16	111.01	9.16
17	109.35	11.24
18	NA	NA
19	NA	NA
20	NA	NA
21	NA	NA
22	NA	NA
23	NA	NA
24	NA	NA
25	NA	NA
26	NA	NA

Table D.12 DARWin Backcalculation Results Using GPR (Rodar II Estimates) Data - US 31 Site

Location	Effective Pavement Moduli, ksi	Subgrade Moduli, ksi
1	1339.74	10.05
2	2047.72	10.24
3	1907.66	11.88
4	616.74	10.71
5	1700.96	8.91
6	1655.48	8.03
7	NA	NA
8	2146.88	6.27
9	1422.58	4.08
10	2105.01	7.24
11	2314.23	6.70
12	NA	NA
13	1657.90	5.47
14	NA	NA
15	NA	NA
16	NA	NA
17	2292.62	7.28
18	NA	NA
19	NA	NA
20	1490.10	5.40
21	30.69	10.23
22	1930.47	8.97
23	1605.87	5.05
24	1810.30	8.79
25	1150.78	9.04
26	1301.71	9.55

APPENDIX E

LINEAR REGRESSION EQUATIONS FOR MODULI BACKCALCULATED WITH EVERCALC 5.0

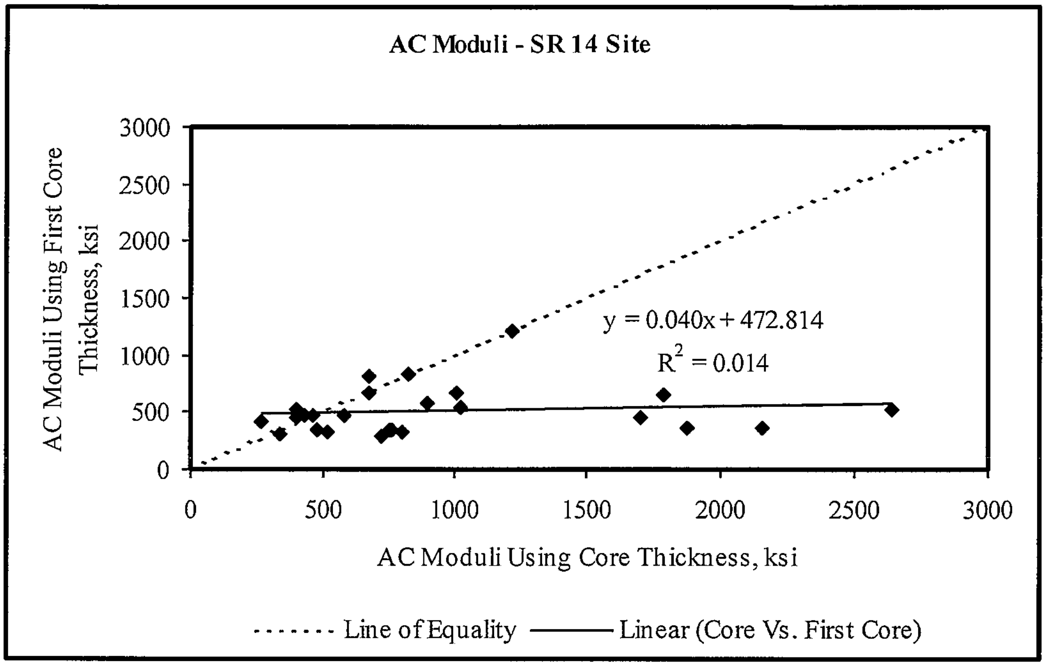

Figure E.1 AC Moduli of SR 14 Site - Core vs. First Core Thickness (EVERCALC)

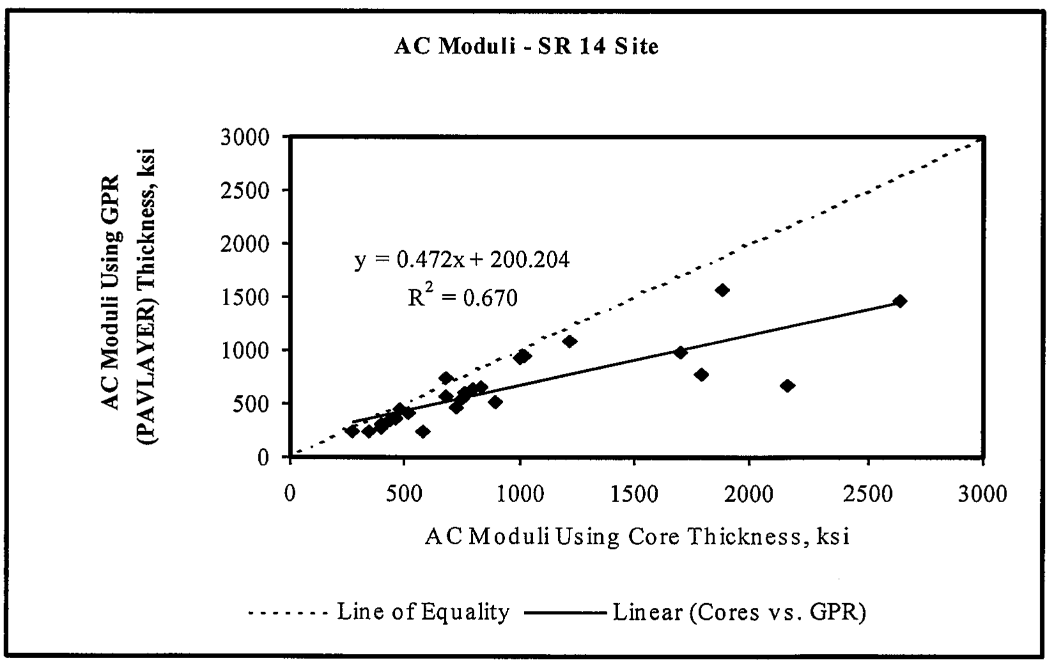

Figure E.2 AC Moduli of SR 14 Site - Core vs. PAVLAYER Thickness (EVERCALC)

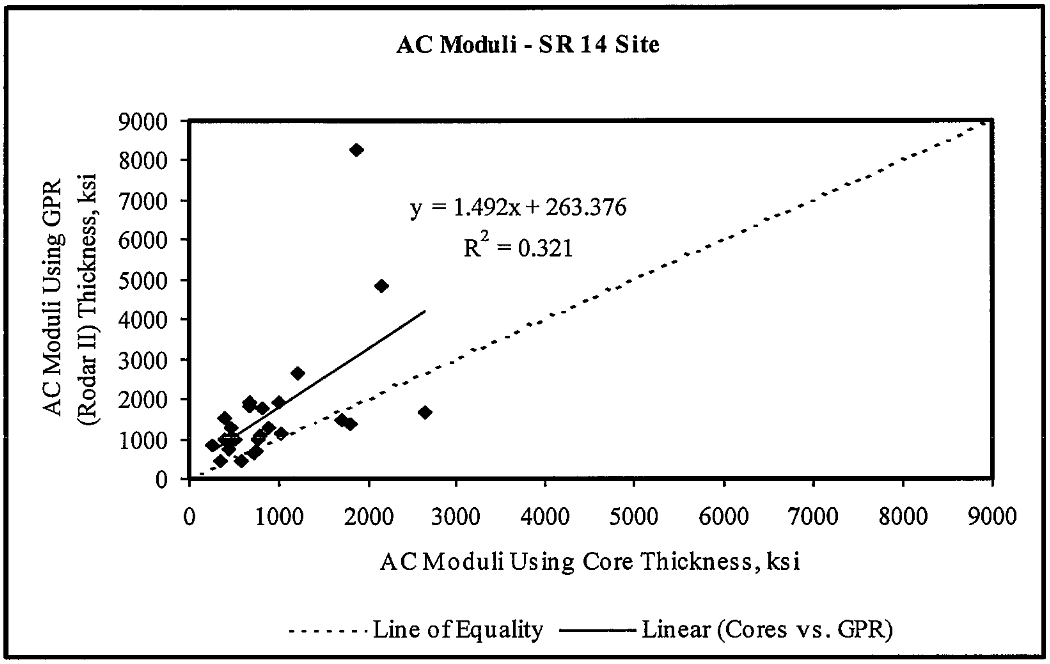

Figure E.3 AC Moduli of SR 14 Site - Core vs. Rodar II Thickness (EVERCALC)

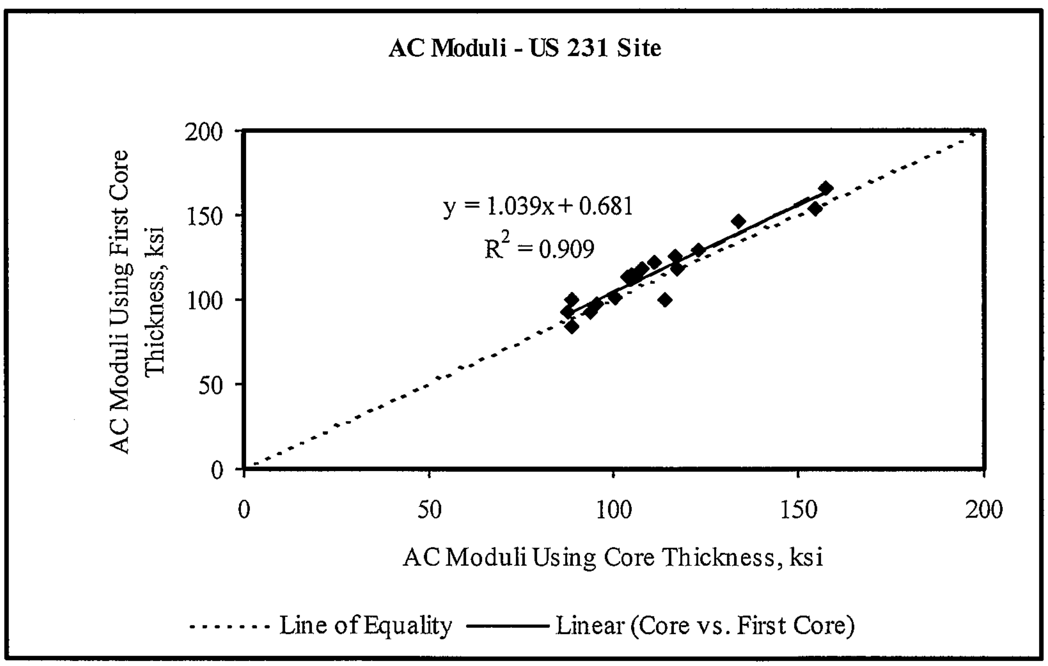

Figure E.4 AC Moduli of US 231 Site - Core vs. First Core Thickness (EVERCALC)

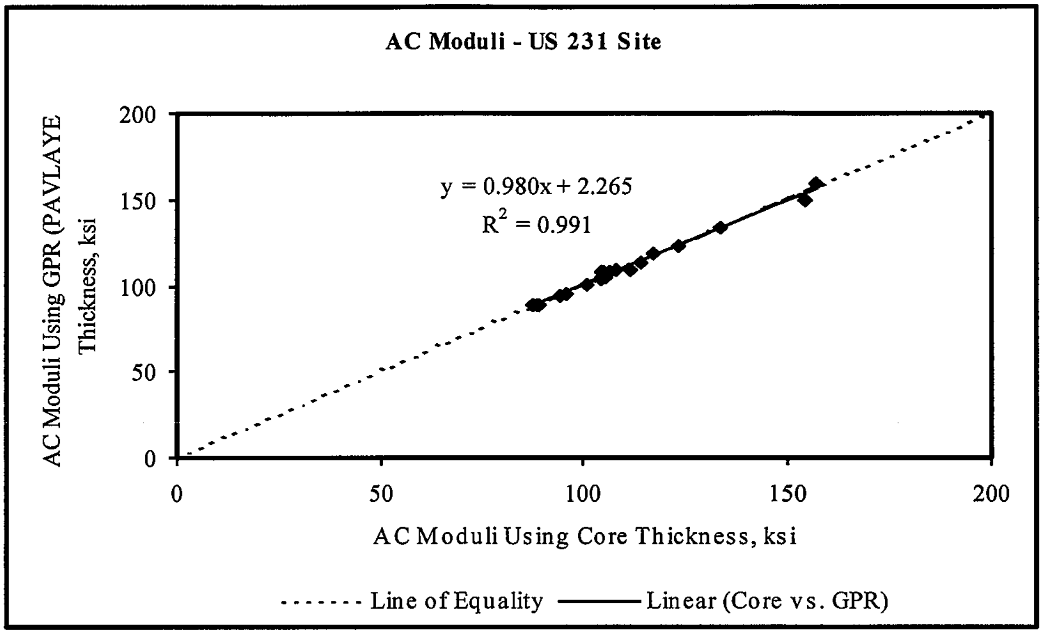

Figure E.5 AC Moduli of US 231 Site - Core vs. PAVLAYER Thickness (EVERCALC)

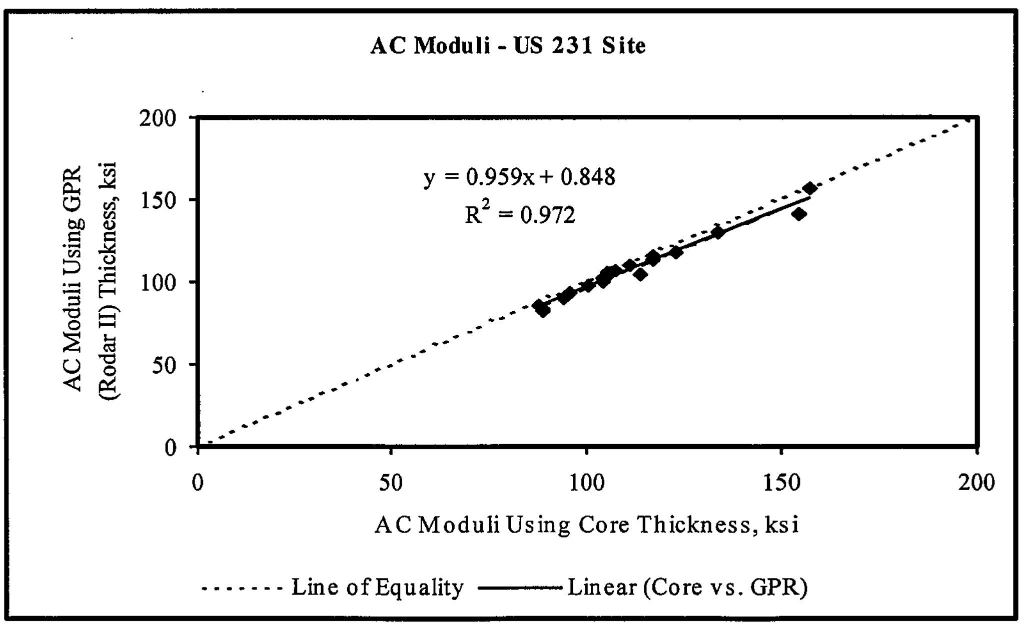

Figure E.6 AC Moduli of US 231 Site - Core vs. Rodar II Thickness (EVERCALC)

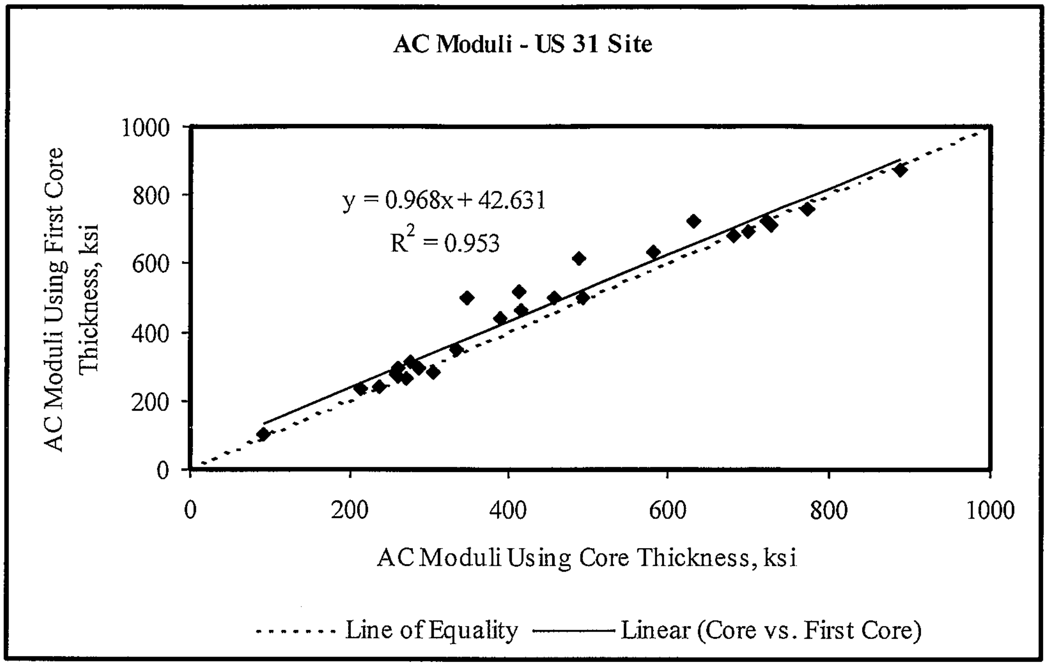

Figure E.7 AC Moduli of US 31 Site - Core vs. First Core Thickness (EVERCALC)

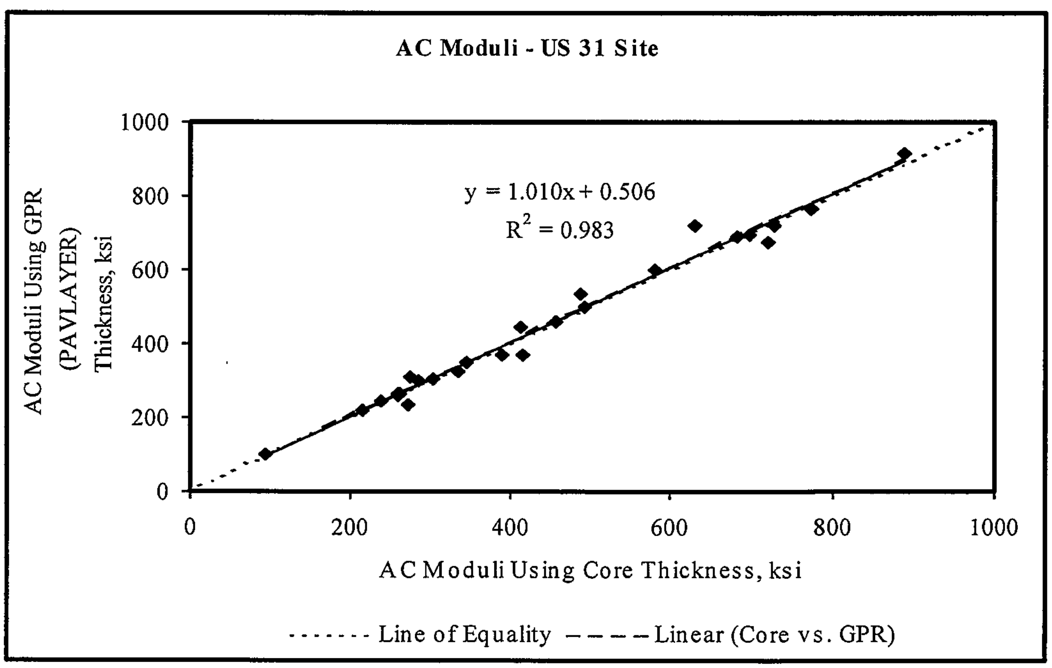

Figure E.8 AC Moduli of US 31 Site - Core vs. PAVLAYER Thickness (EVERCALC)

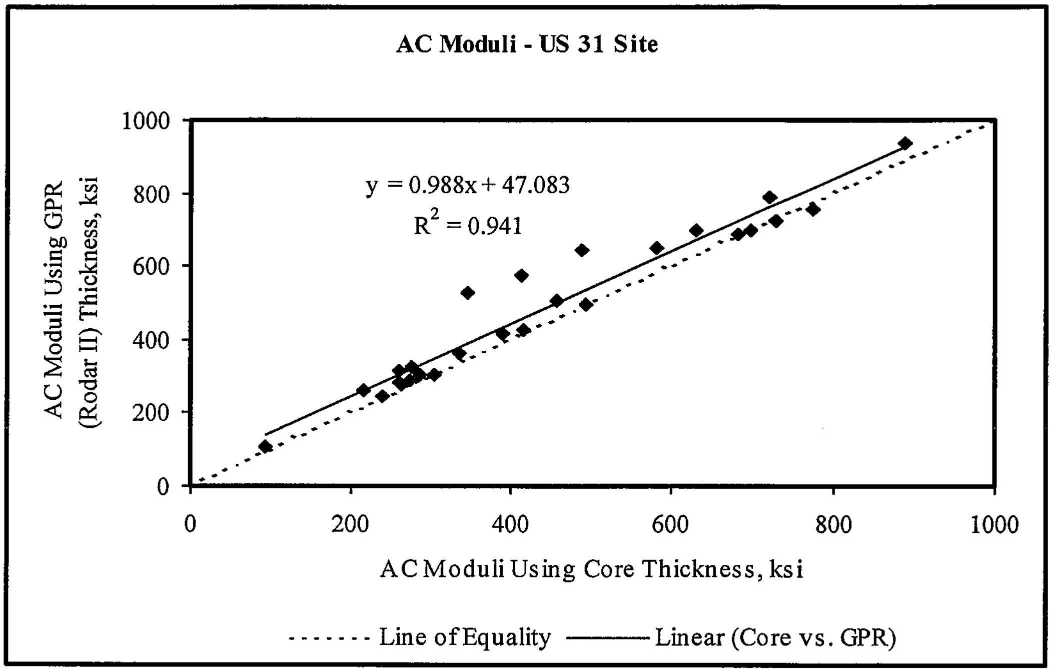

Figure E.9 AC Moduli of US 31 Site - Core vs. Rodar II Thickness (EVERCALC)

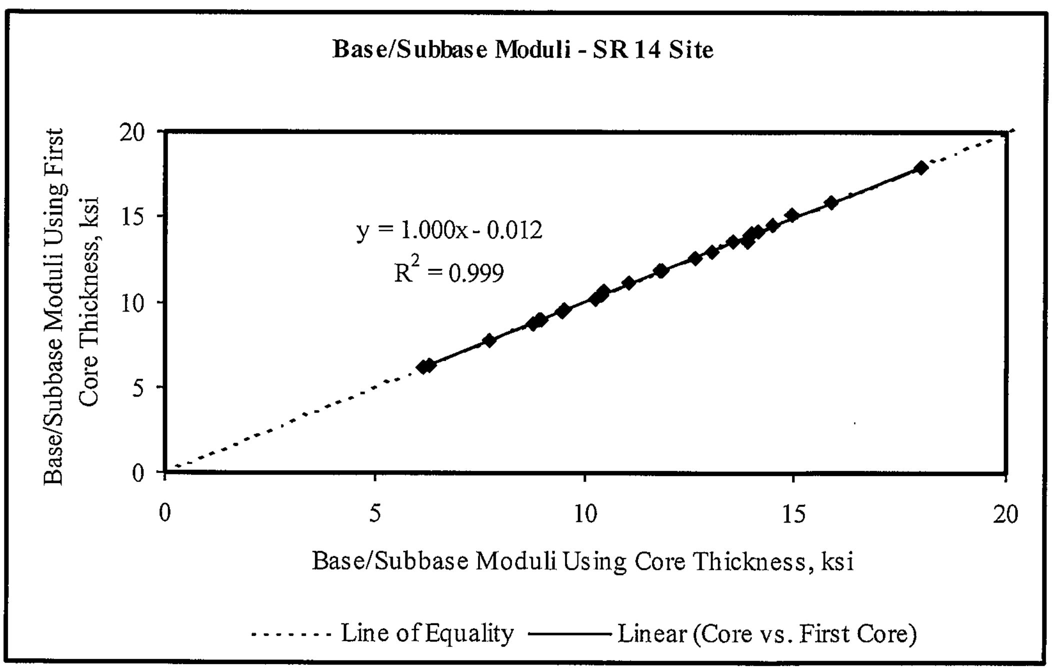

Figure E.10 Base/Subbase Moduli of SR 14 Site - Core vs. First Core Thickness (EVERCALC)

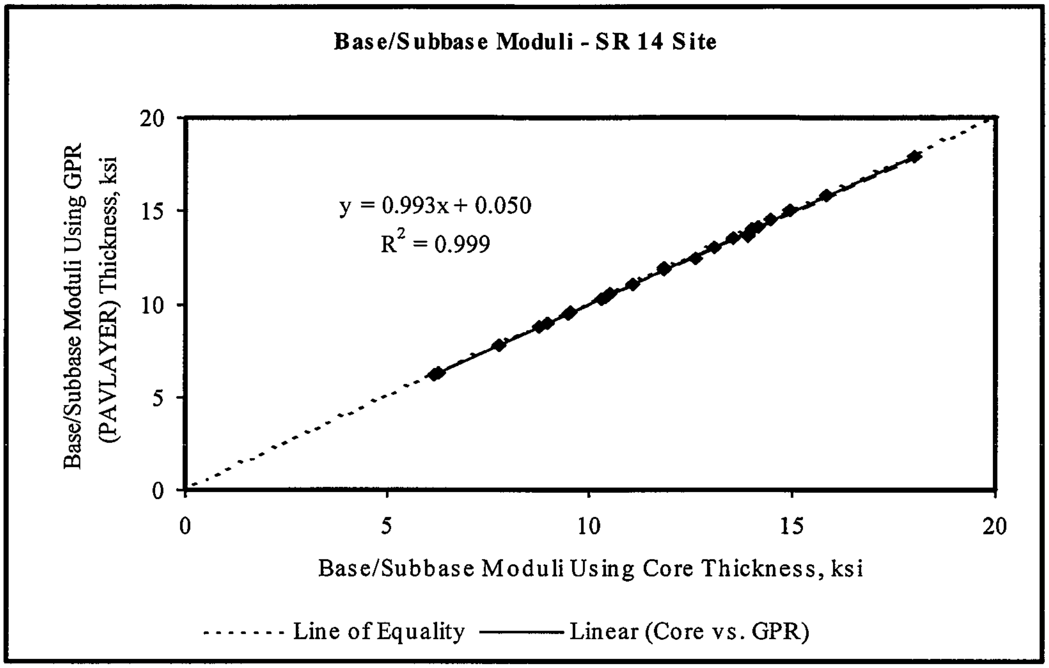

Figure E.11 Base/Subbase Moduli of SR 14 Site - Core vs. PAVLAYER Thickness (EVERCALC)

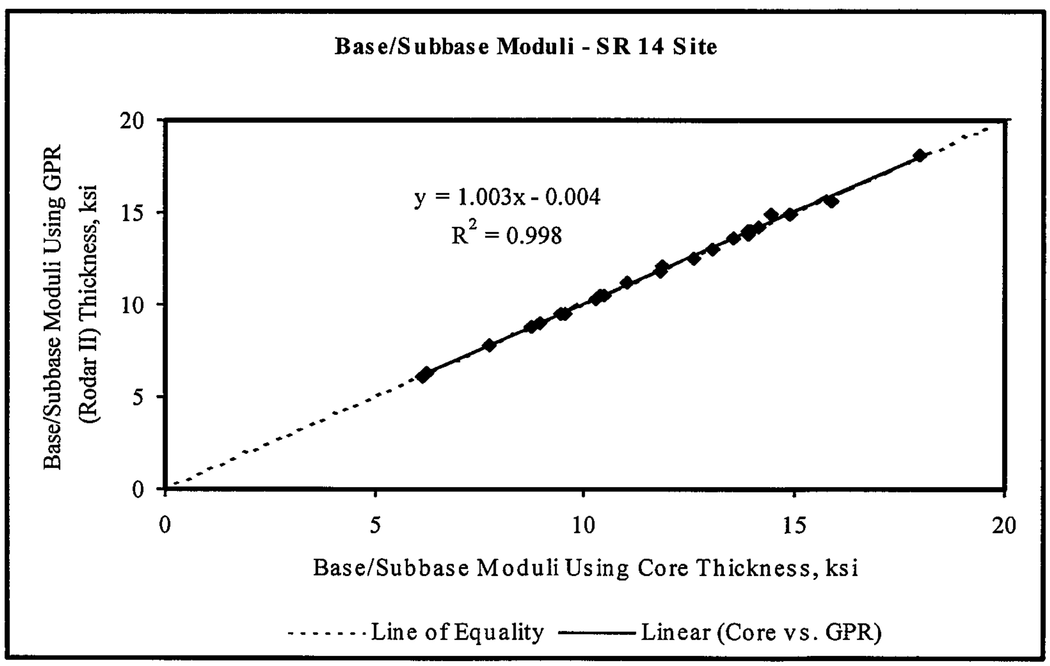

Figure E.12 Base/Subbase Moduli of SR 14 Site - Core vs. Rodar II Thickness (EVERCALC)

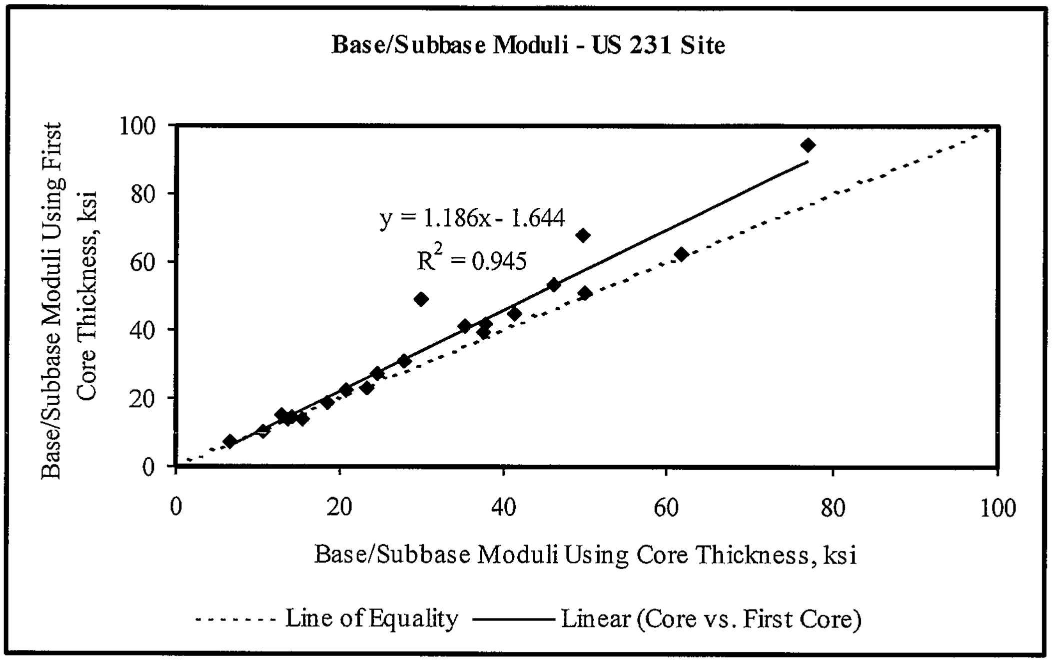

Figure E.13 Base/Subbase Moduli of US 231 Site - Core vs. First Core Thickness (EVERCALC)

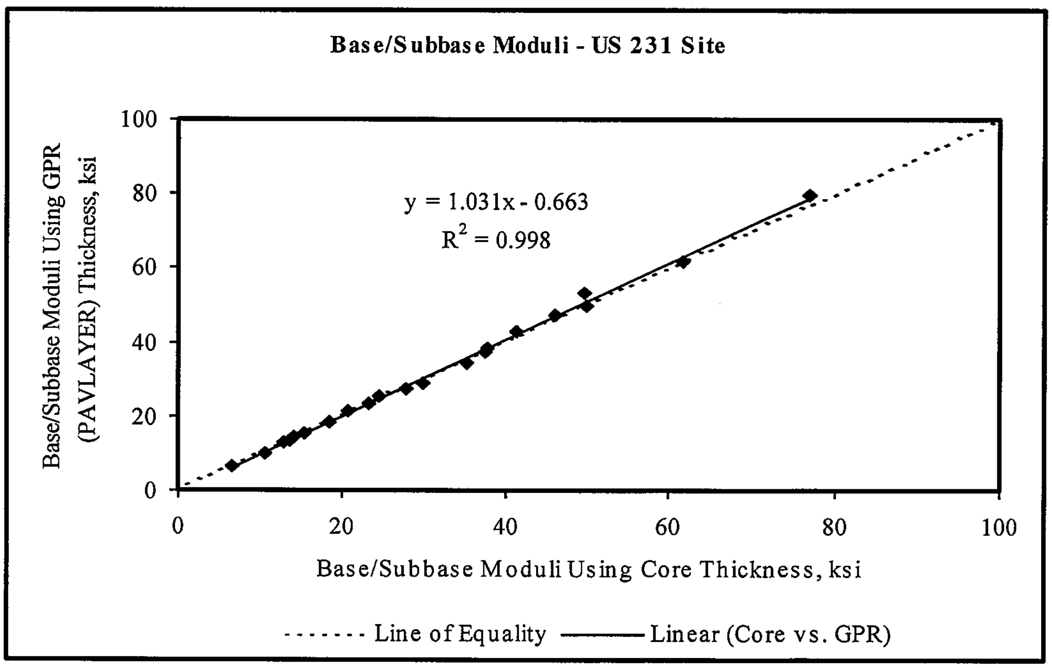

Figure E.14 Base/Subbase Moduli of US 231 Site - Core vs. PAVLAYER Thickness (EVERCALC)

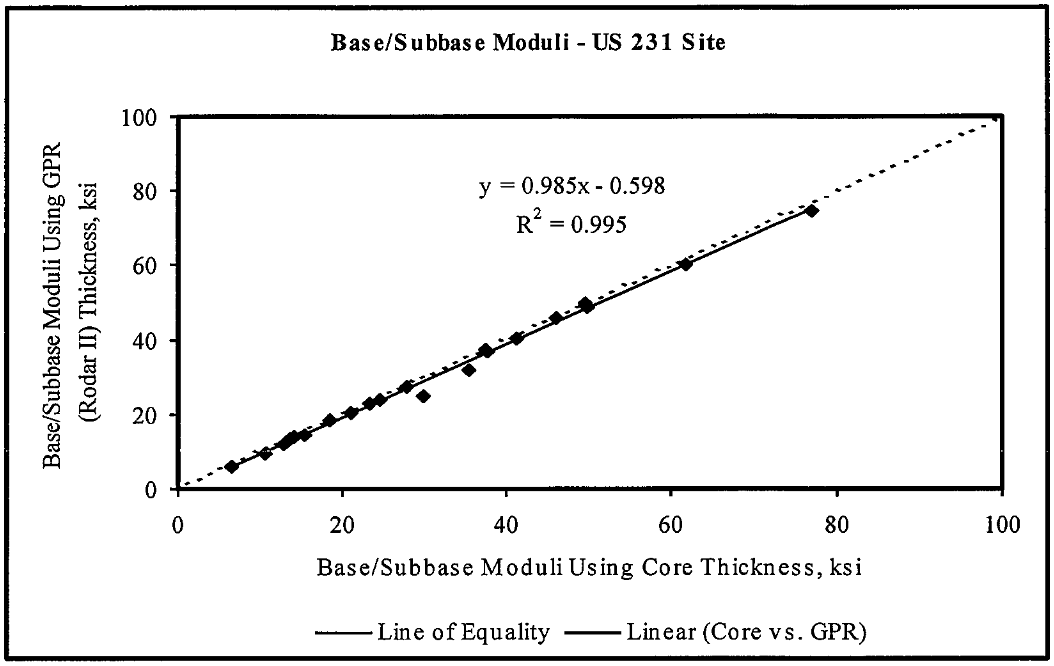

Figure E.15 Base/Subbase Moduli of US 231 Site - Core vs. Rodar II Thickness (EVERCALC)

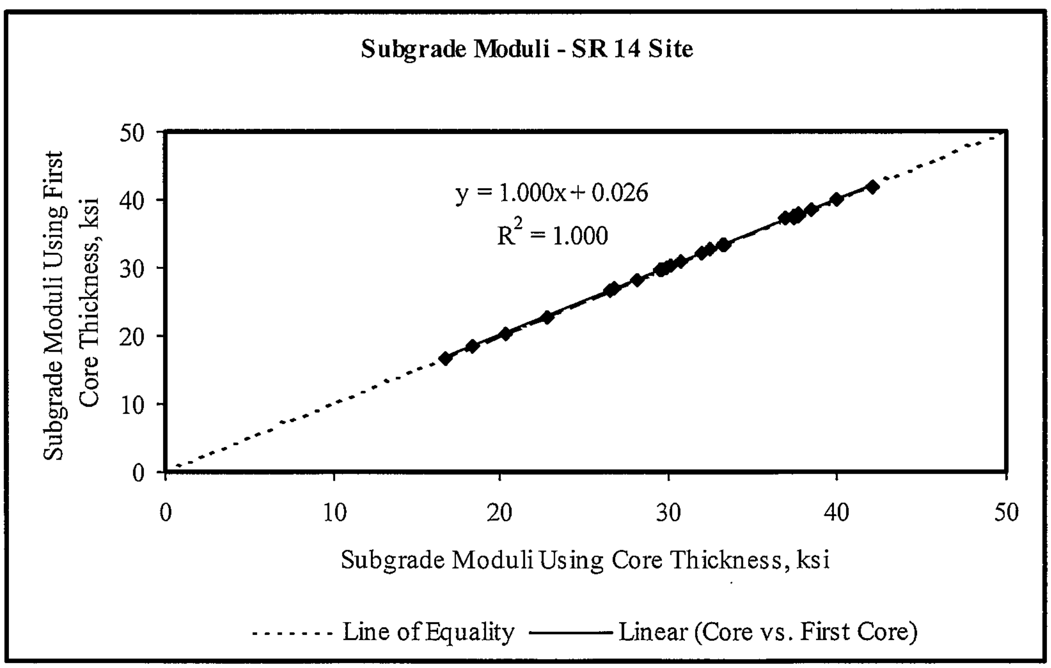

Figure E.16 Subgrade Moduli of SR 14 Site - Core vs. First Core Thickness (EVERCALC)

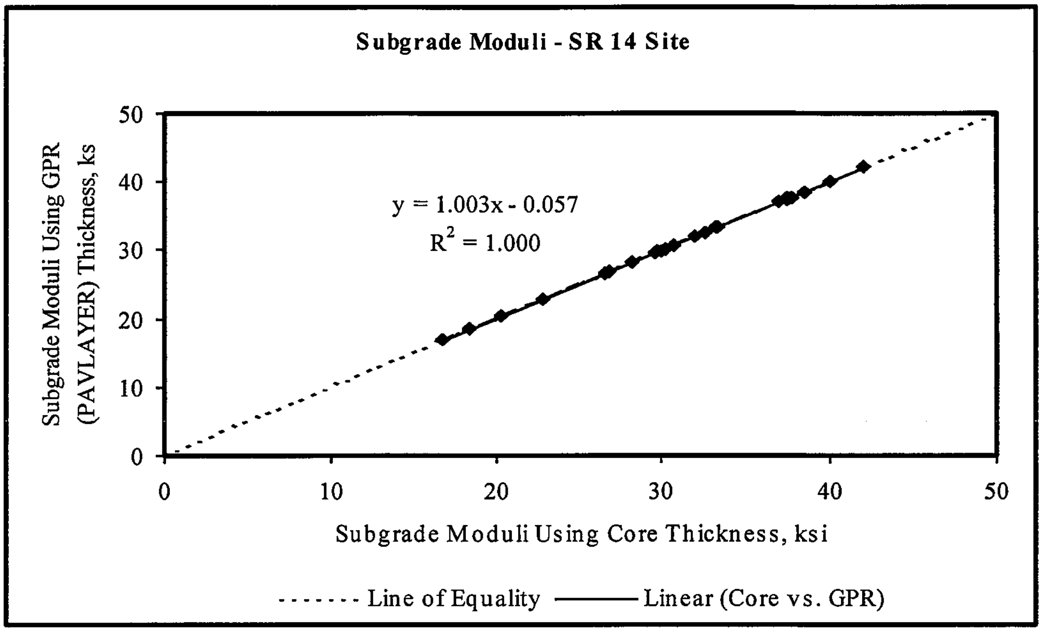

Figure E.17 Subgrade Moduli of SR 14 Site - Core vs. PAVLAYER Thickness (EVERCALC)

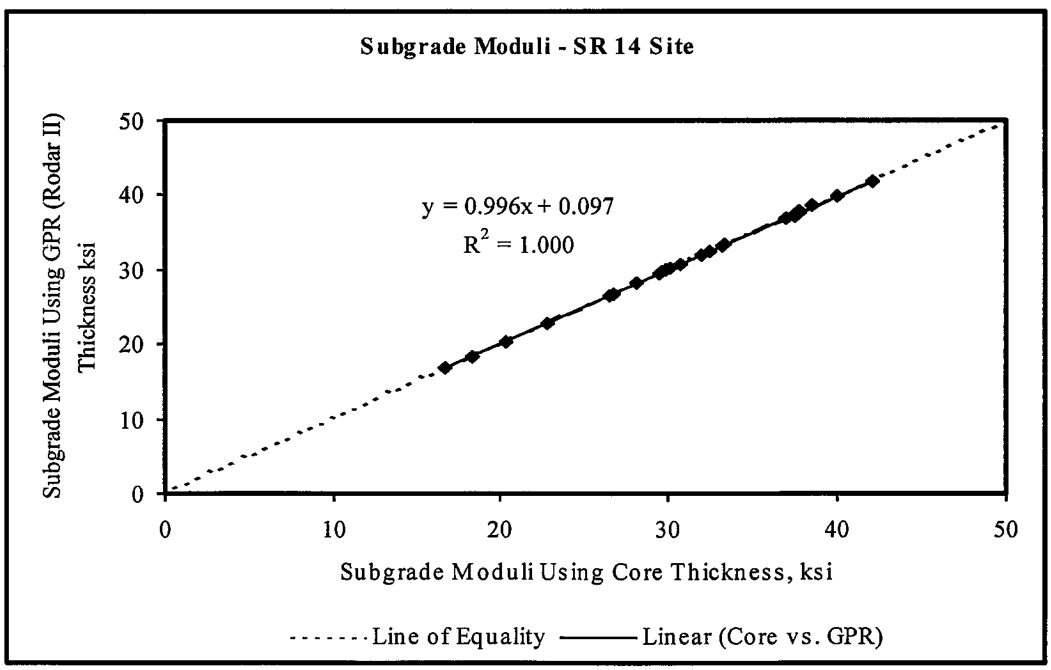

Figure E.18 Subgrade Moduli of SR 14 Site - Core vs. Rodar II Thickness (EVERCALC)

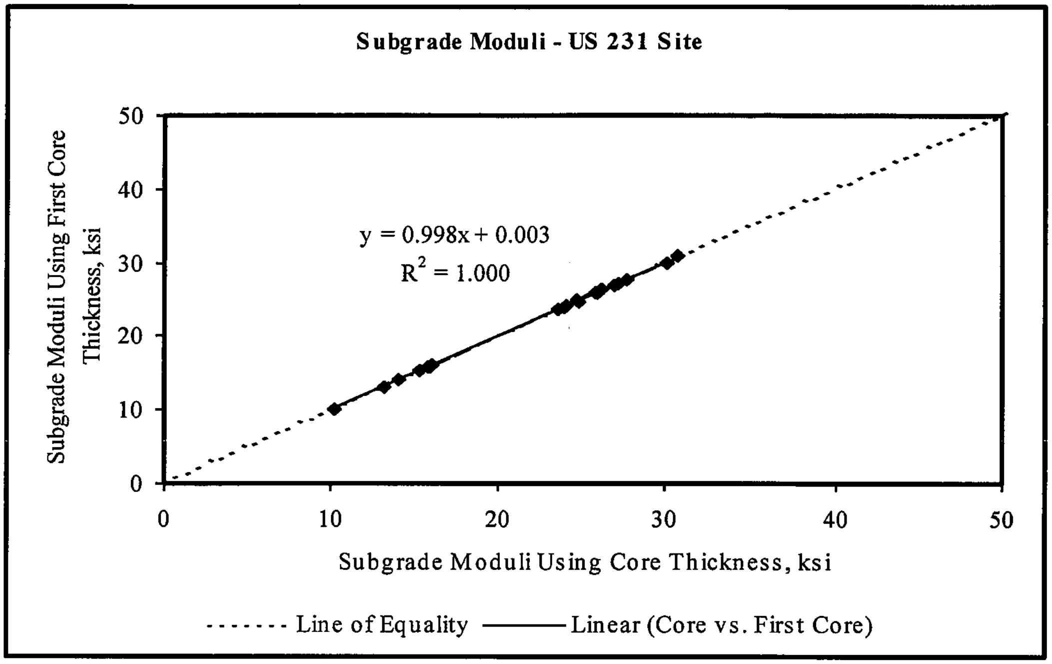

Figure E.19 Subgrade Moduli of US 231 Site - Core vs. First Core Thickness (EVERCALC)

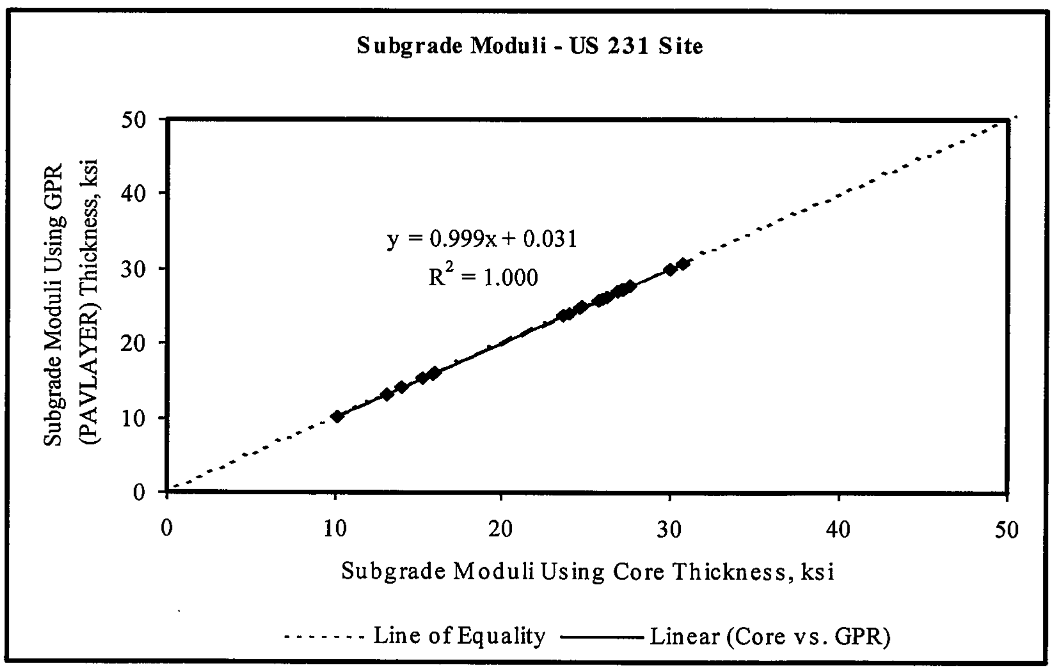

Figure E.20 Subgrade Moduli of US 231 Site - Core vs. PAVLAYER Thickness (EVERCALC)

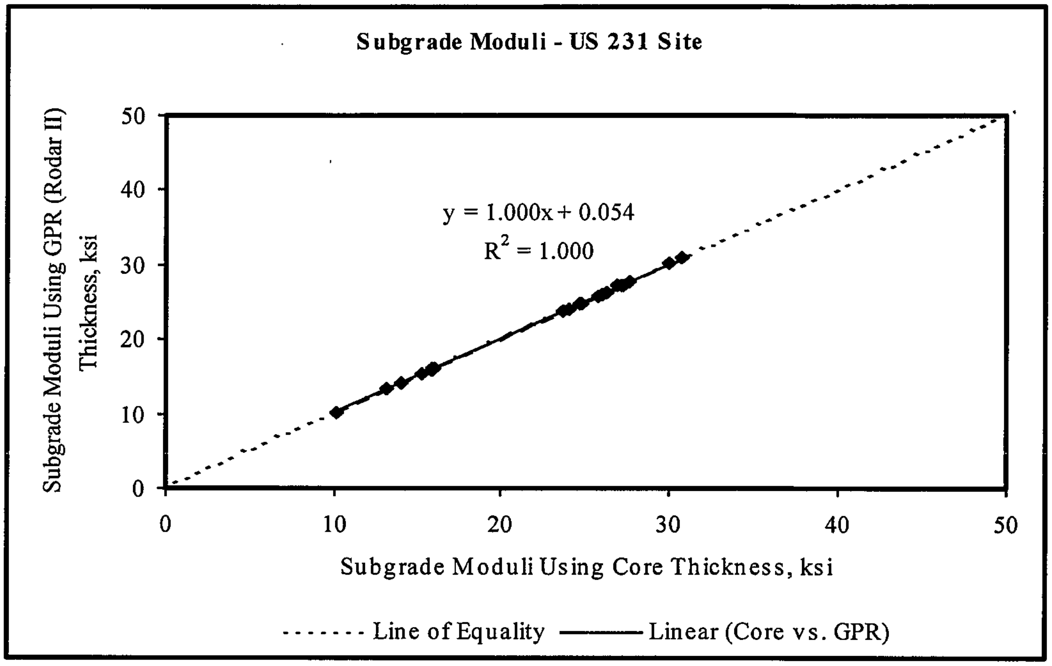

Figure E.21 Subgrade Moduli of US 31 Site - Core vs. Rodar II Thickness (EVERCALC)

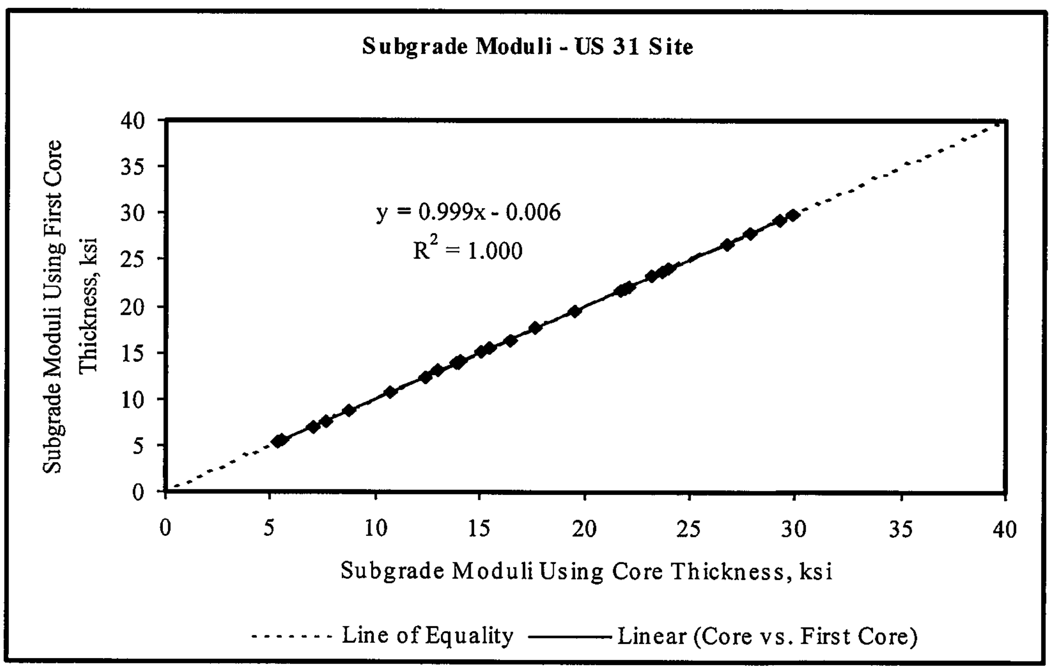

Figure E.22 Subgrade Moduli of US 31 Site - Core vs. First Core Thickness (EVERCALC)

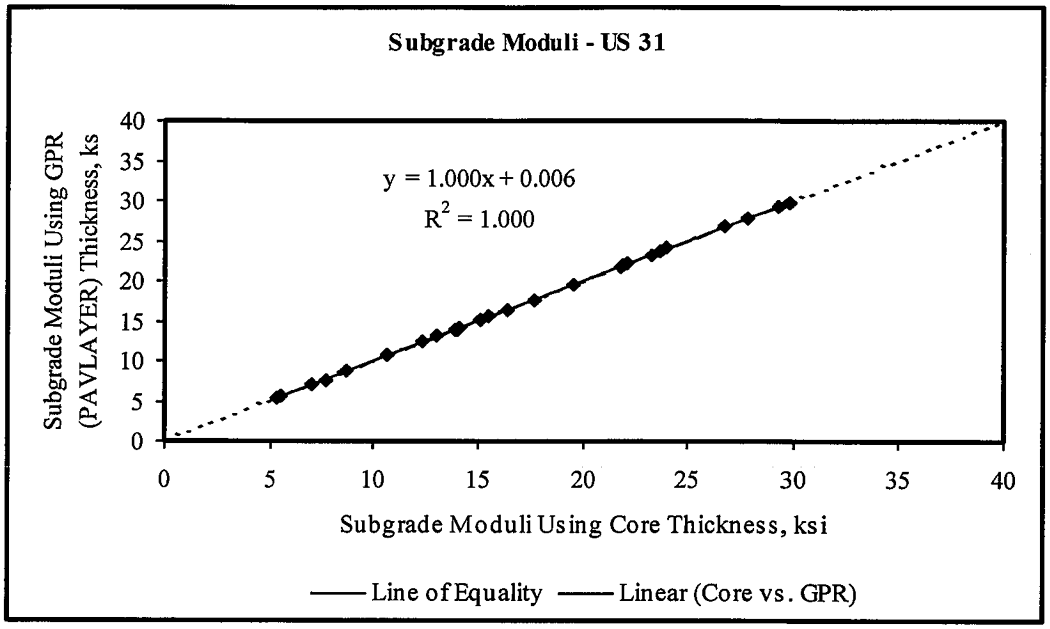

Figure E.23 Subgrade Moduli of US 31 Site - Core vs. PAVLAYER Thickness (EVERCALC

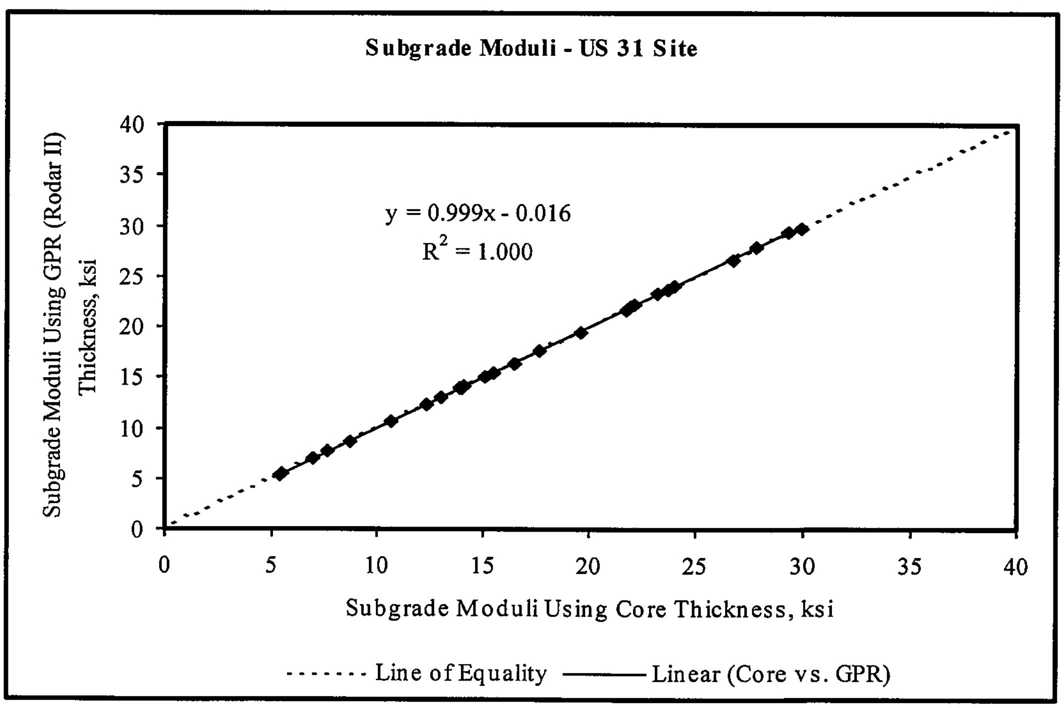

Figure E.24 Subgrade Moduli of US Moduli of US 31 Site - Core vs. Rodar II Thickness (EVERCALC)

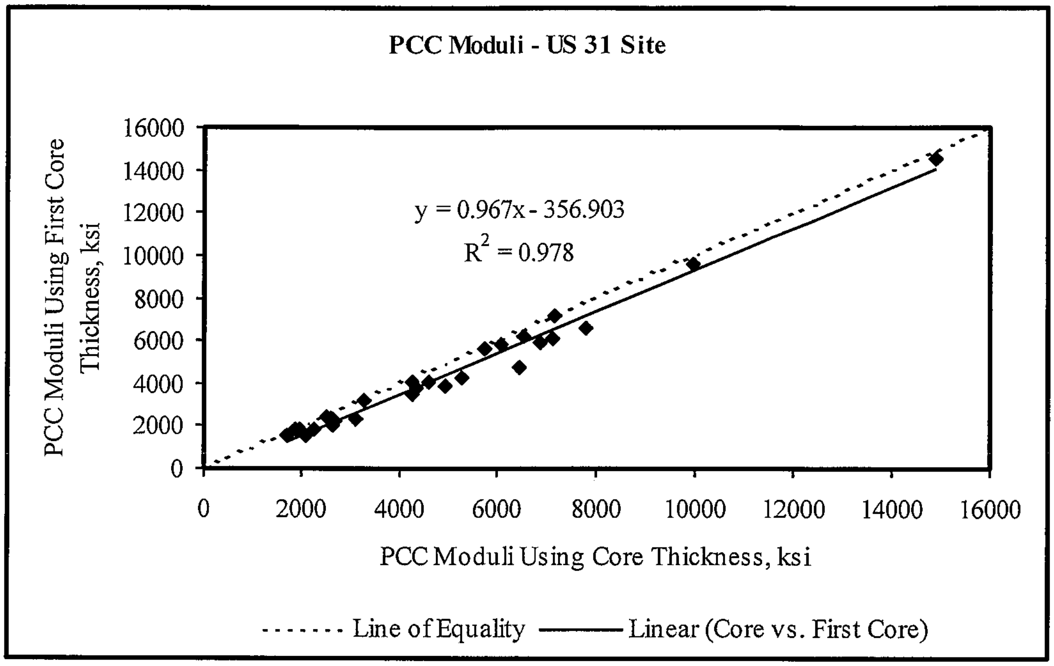

Figure E.25 PCC Moduli of US 31 Site - Core vs. First Core Thickness (EVERCALC)

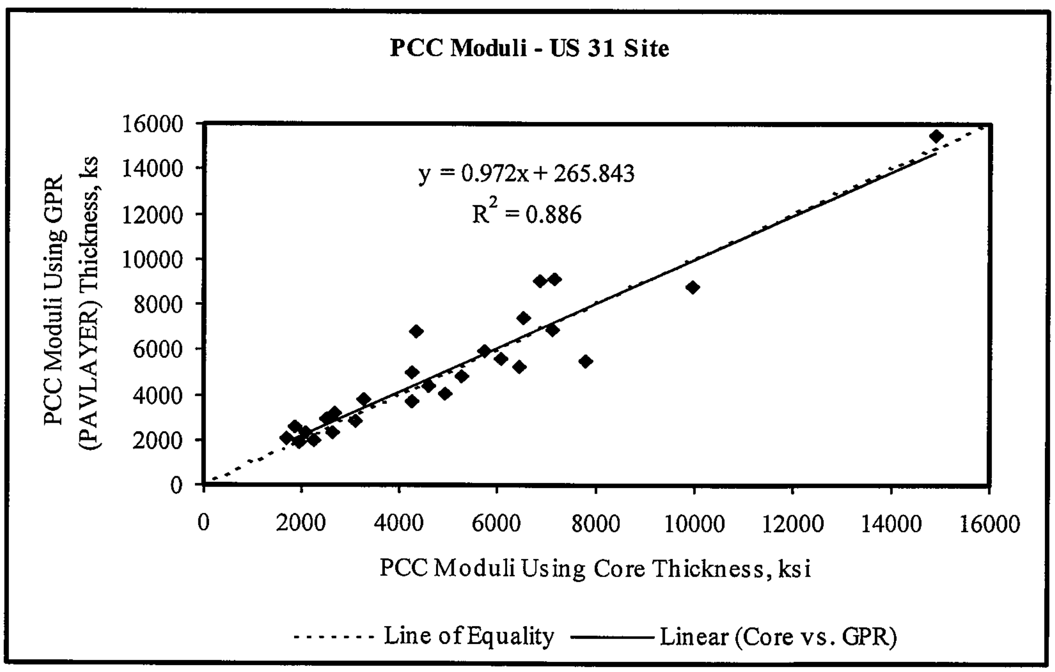

Figure E.26 PCC Moduli of US 31 Site - Core vs. PAVLAYER Thickness (EVERCALC)

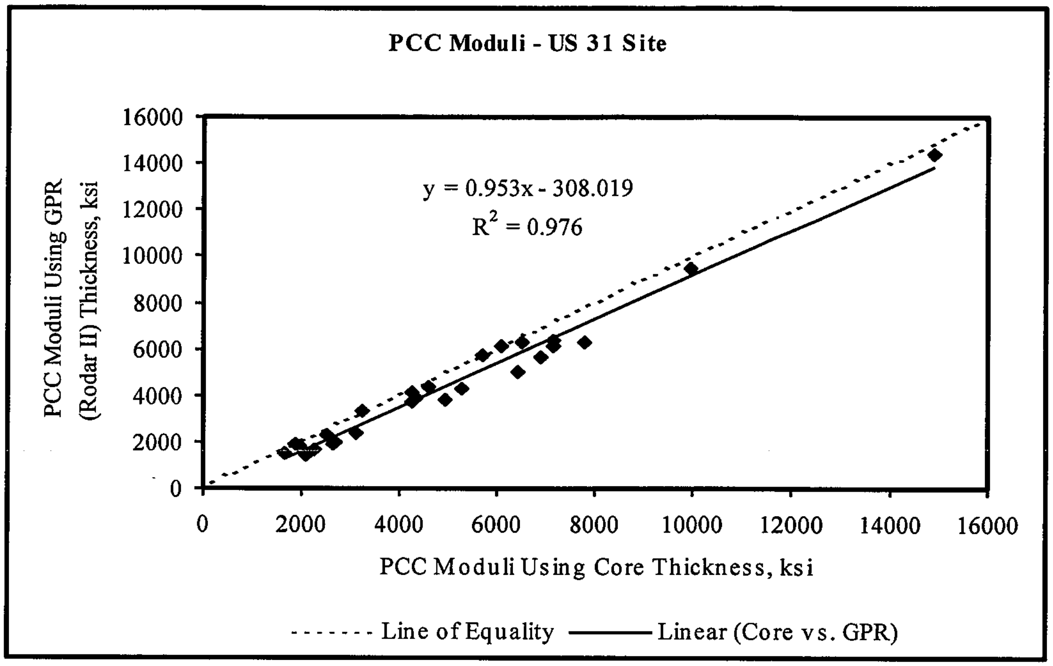

Figure E.27 PCC Moduli of US 31 Site - Core vs. Rodar II Thickness (EVERCALC)

APPENDIX F

LINEAR REGRESSION EQUATIONS FOR MODULI BACKCALCULATED WITH DARWin 3.01

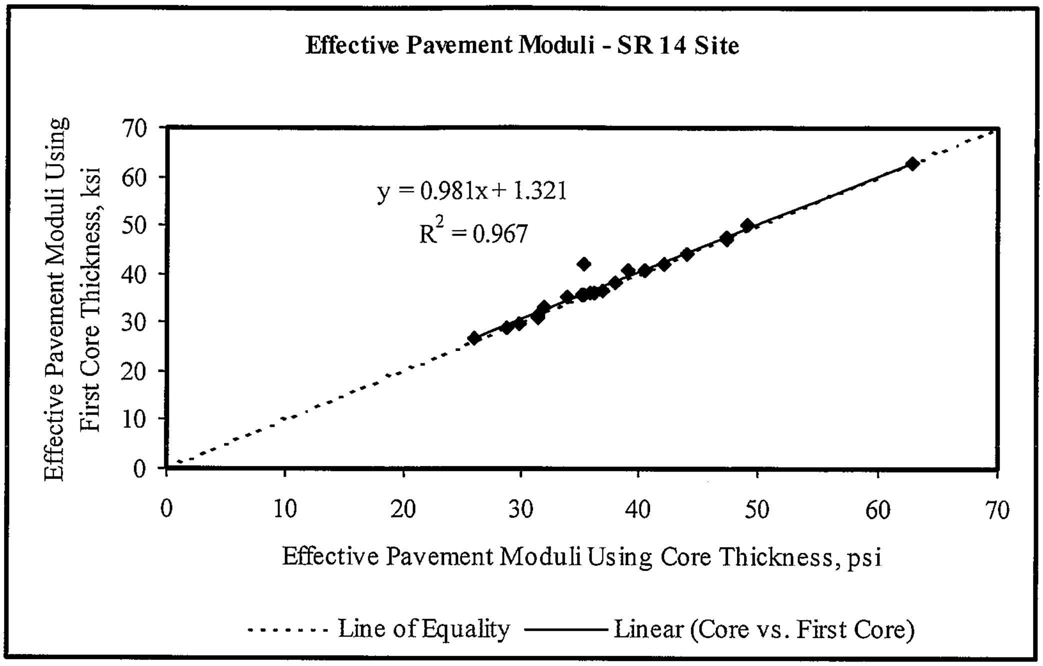

Figure F.1 Effective Pavement Moduli of SR 14 Site - Core vs. First Core Thickness

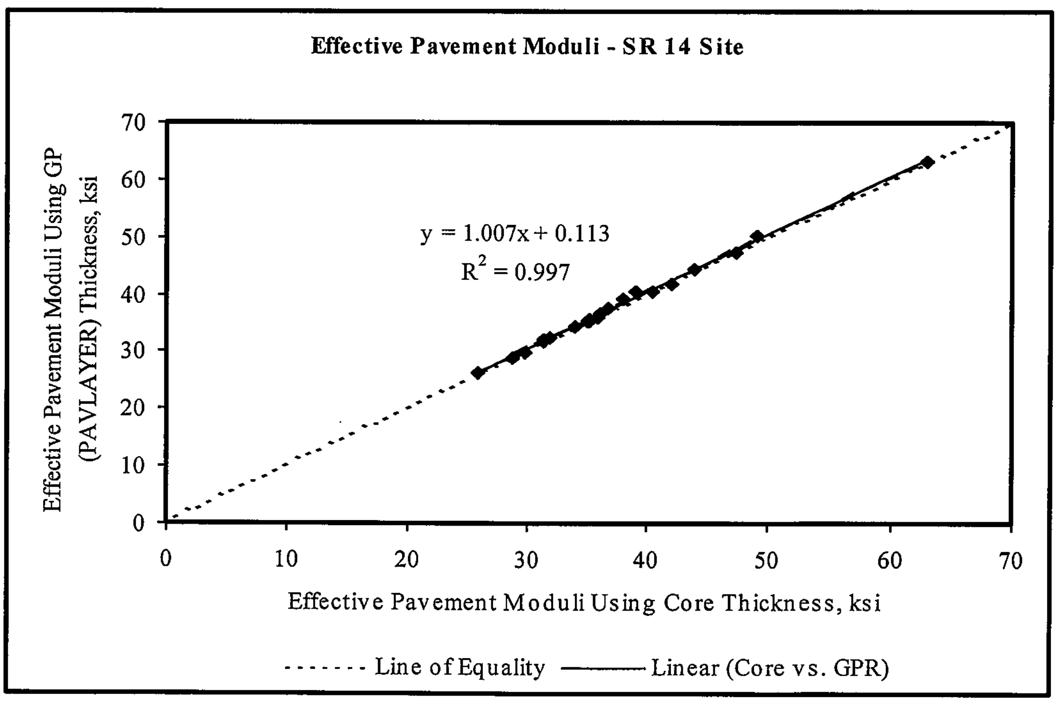

Figure F.2 Effective Pavement Moduli of SR 14 Site - Core vs. PAVLAYER Thickness (DARWin)

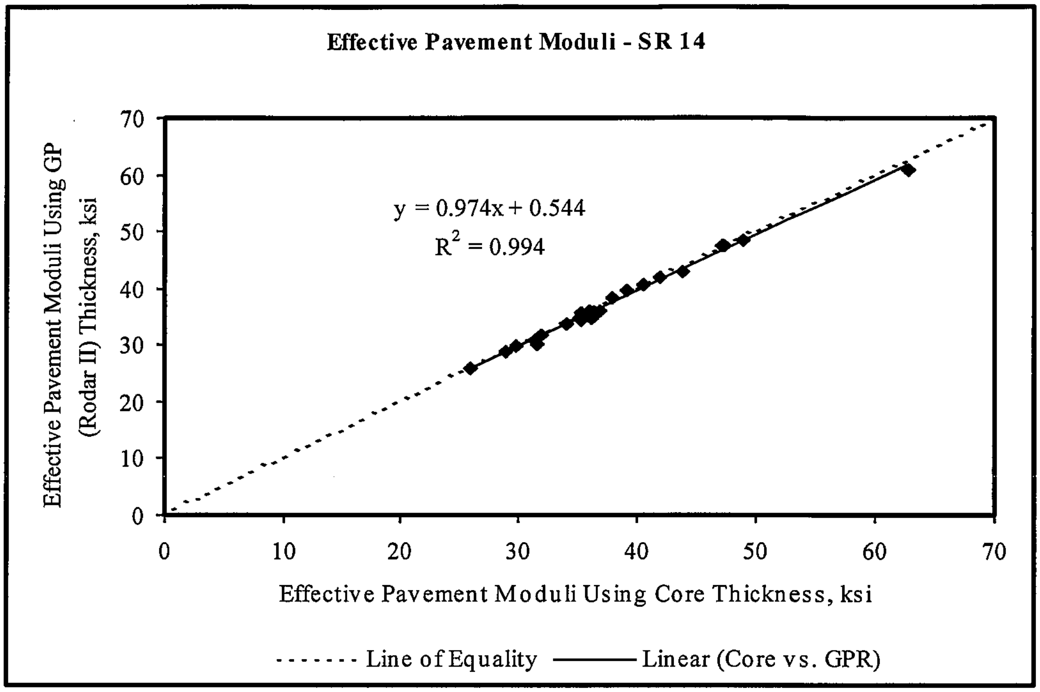

Figure F.3 Effective Pavement Moduli of SR 14 Site - Core vs. Rodar II Thickness (DARWin)

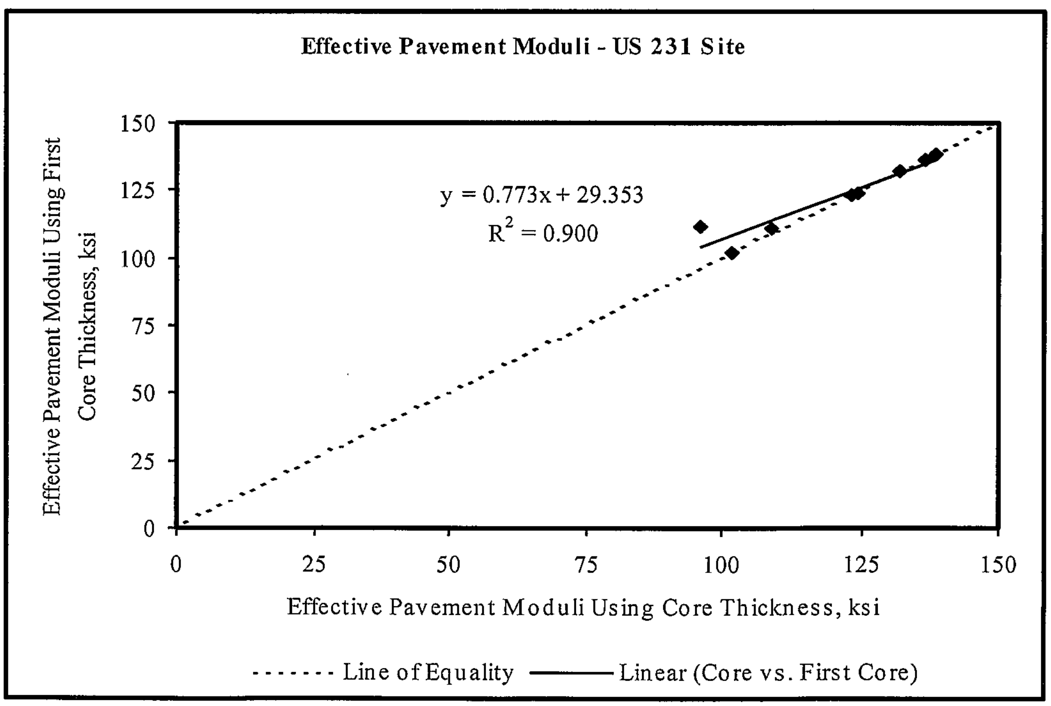

Figure F.4 Effective Pavement Moduli of US 231 Site - Core vs. First Core Thickness (DARWin)

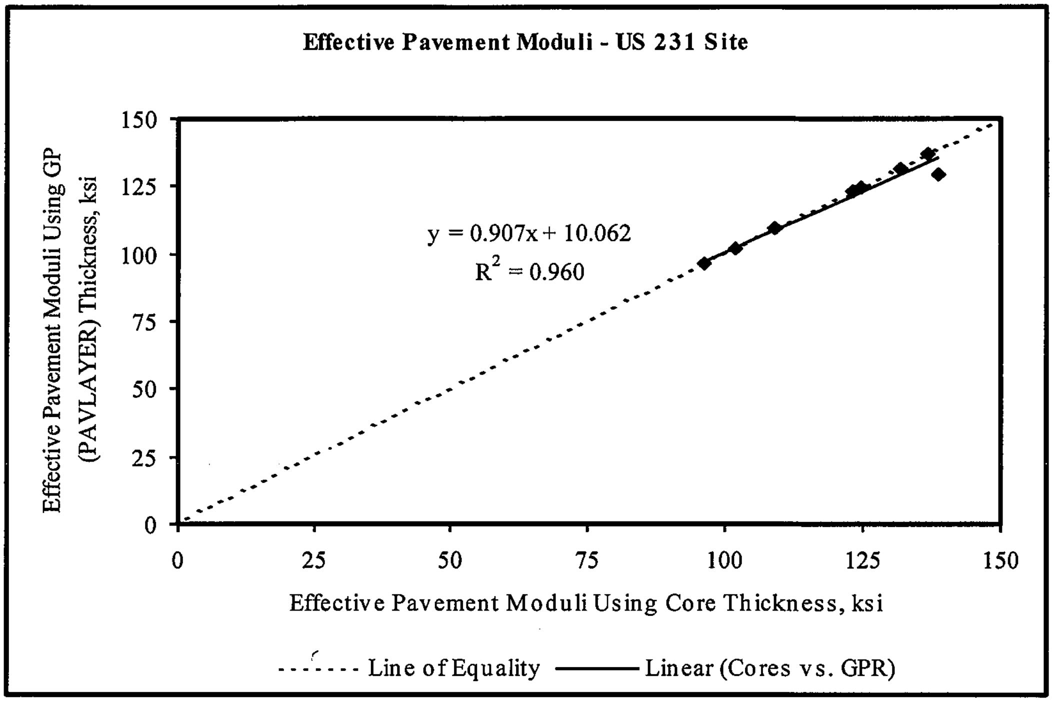

Figure F.5 Effective Pavement Moduli of US 231 Site - Core vs. PAVLAYER Thickness (DARWin)

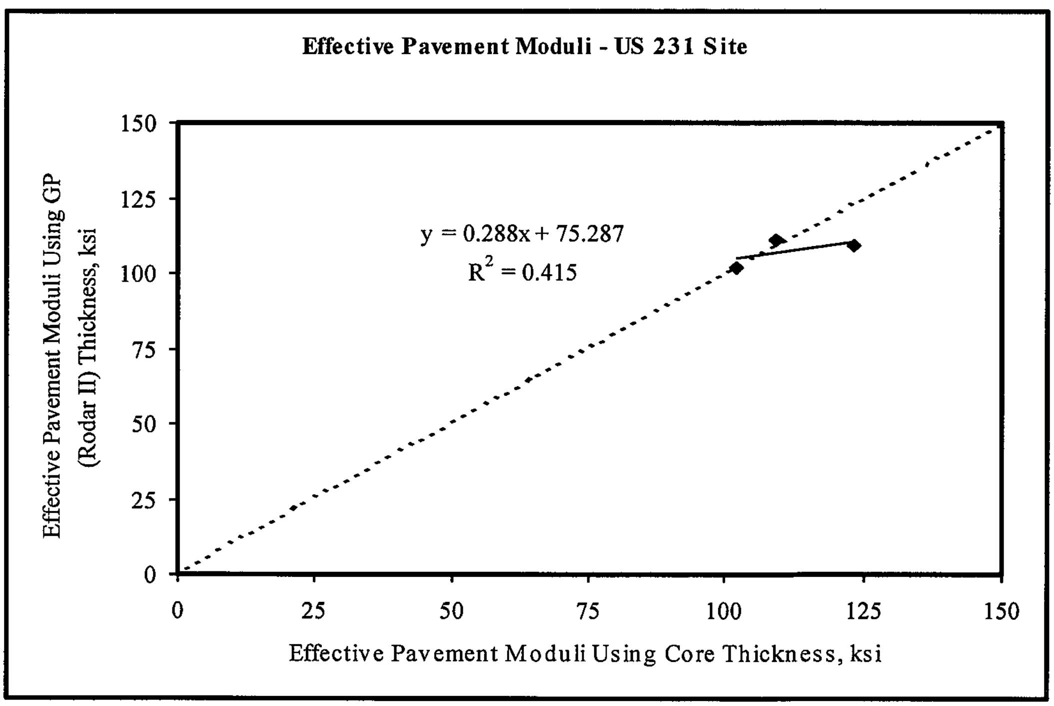

Figure F.6 Effective Pavement Moduli of US 231 Site - Core vs. Rodar II Thickness (DARWin)

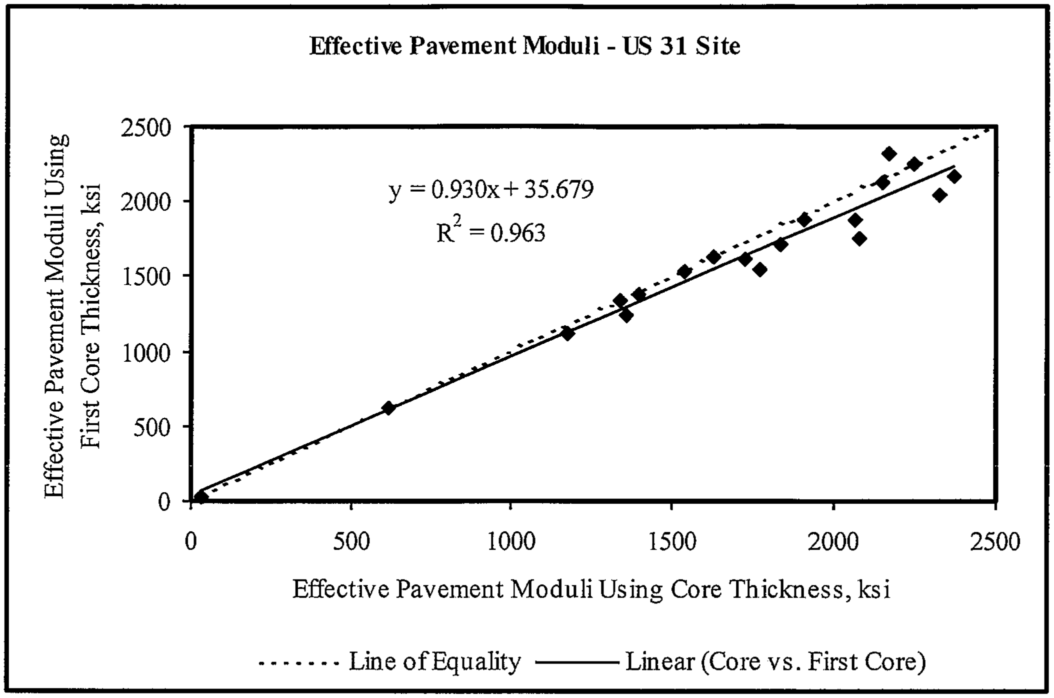

Figure F.7 Effective Pavement Moduli of US 31 Site - Core vs. First Core Thickness (DARWin)

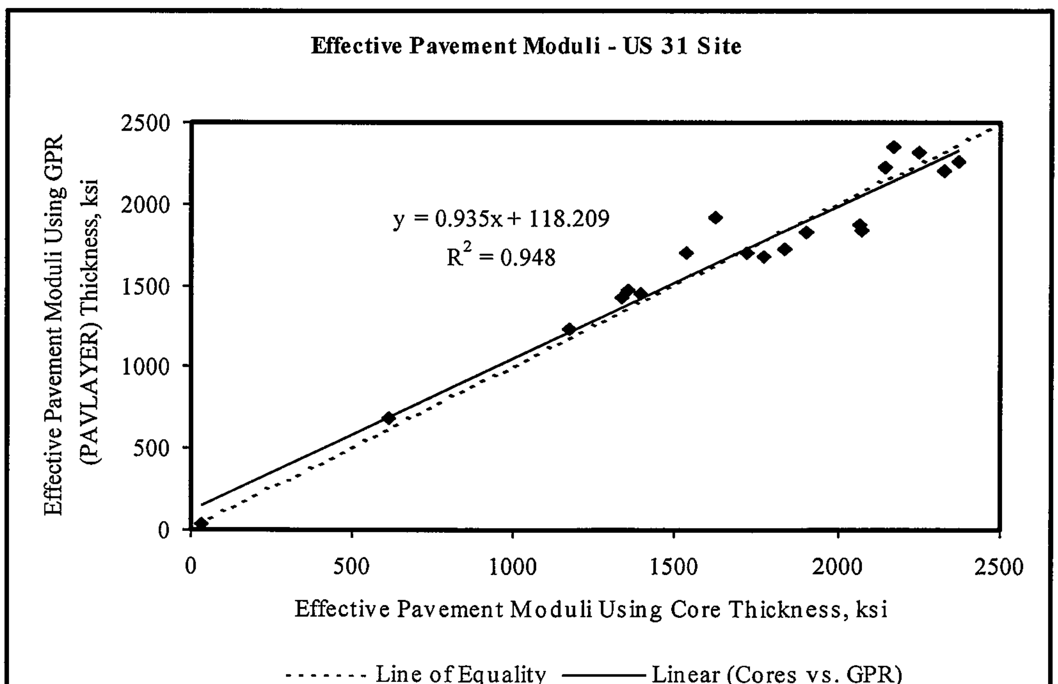

Figure F.8 Effective Pavement Moduli of US 31 Site - Core vs. PAVLAYER Thickness (DARWin)

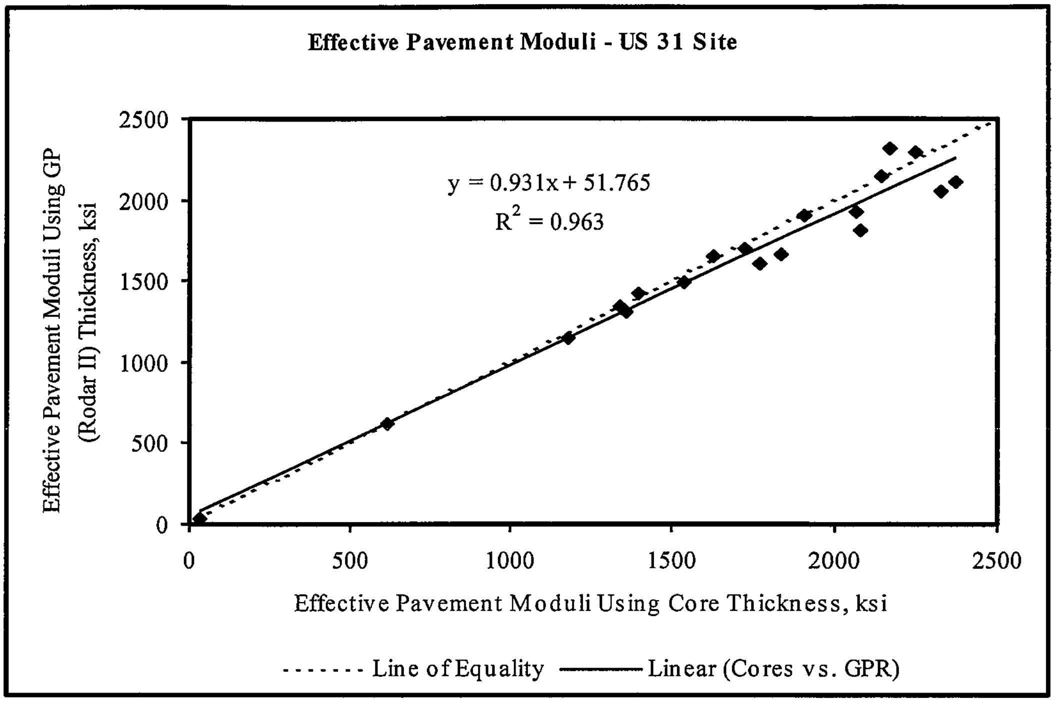

Figure F.9 Effective Pavement Moduli Moduli of US 31 Site - Core vs. Rodar II Thickness (DARWin)

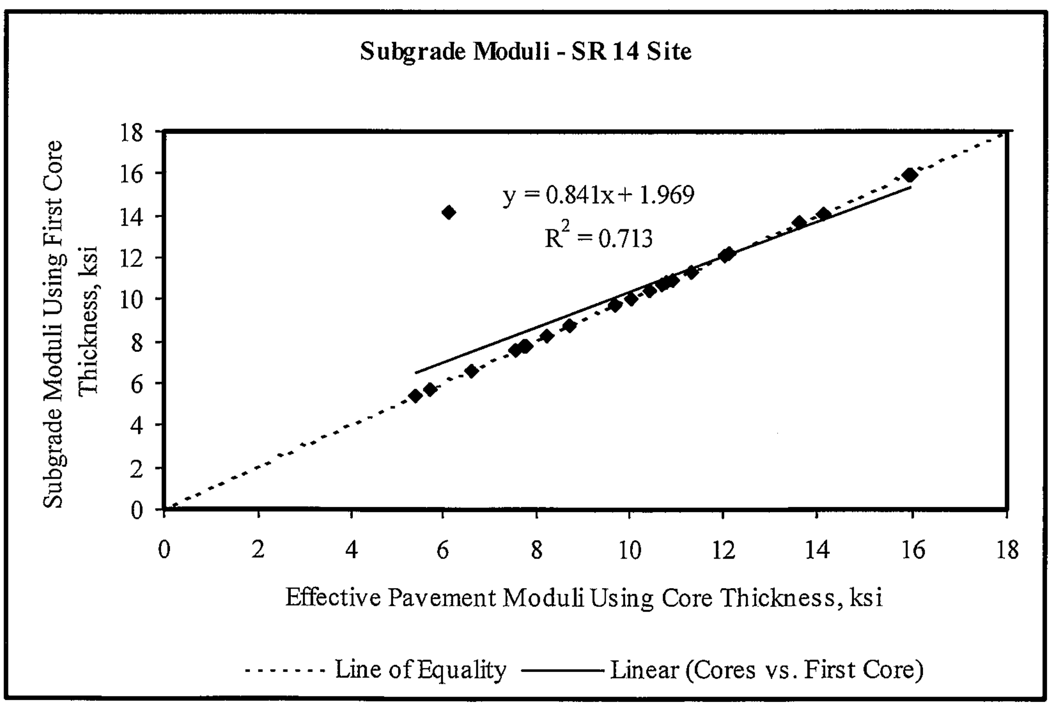

Figure F.10 Subgrade Moduli of SR 14 Site - Core vs. First Core Thickness (DARWin)

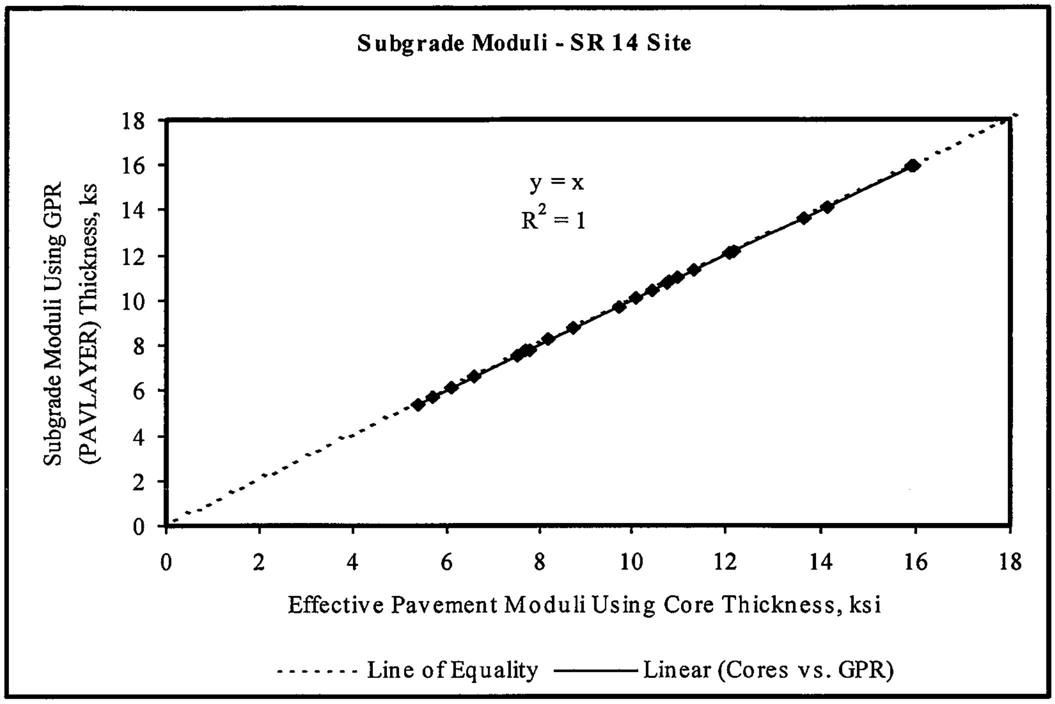

Figure F.11 Subgrade Moduli of SR 14 Site - Core vs. PAVLAYER Thickness (DARWin)

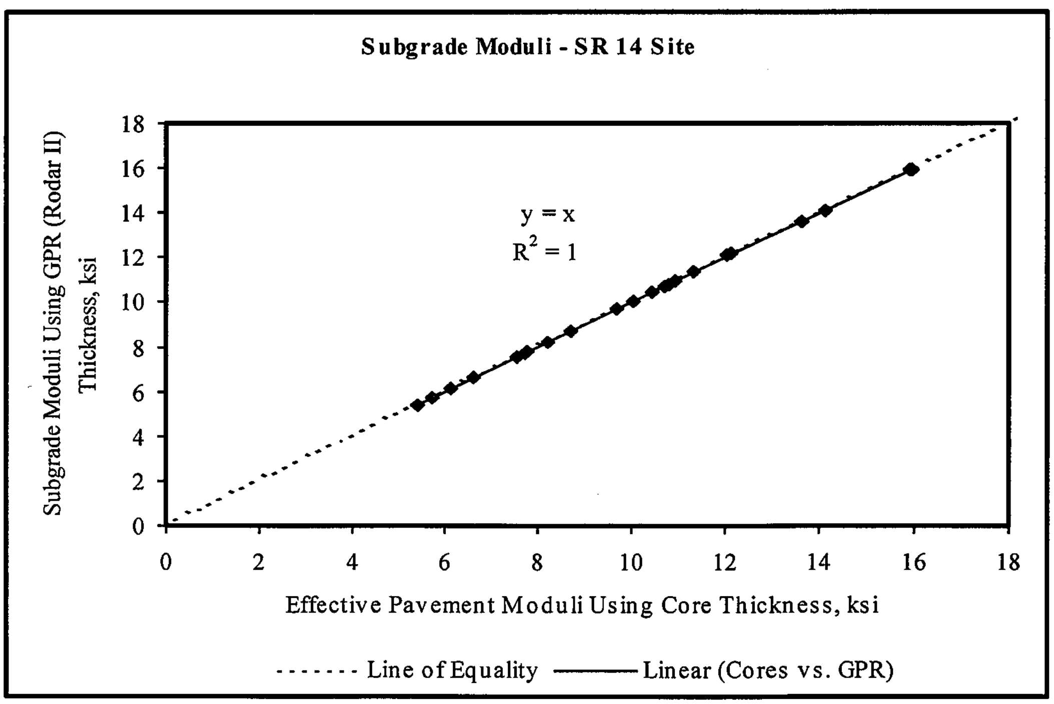

Figure F.12 Subgrade Moduli of SR 14 Site - Core vs. Rodar II Thickness (DARWin)

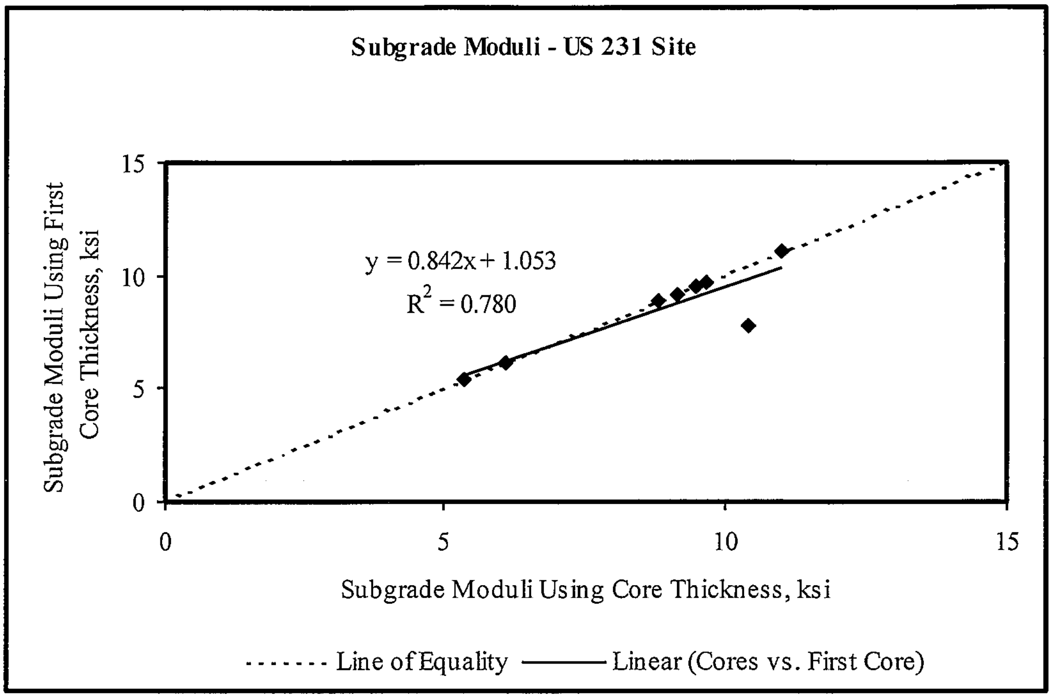

Figure F.13 Subgrade Moduli of US 231 Site - Core vs. First Core Thickness (DARWin)

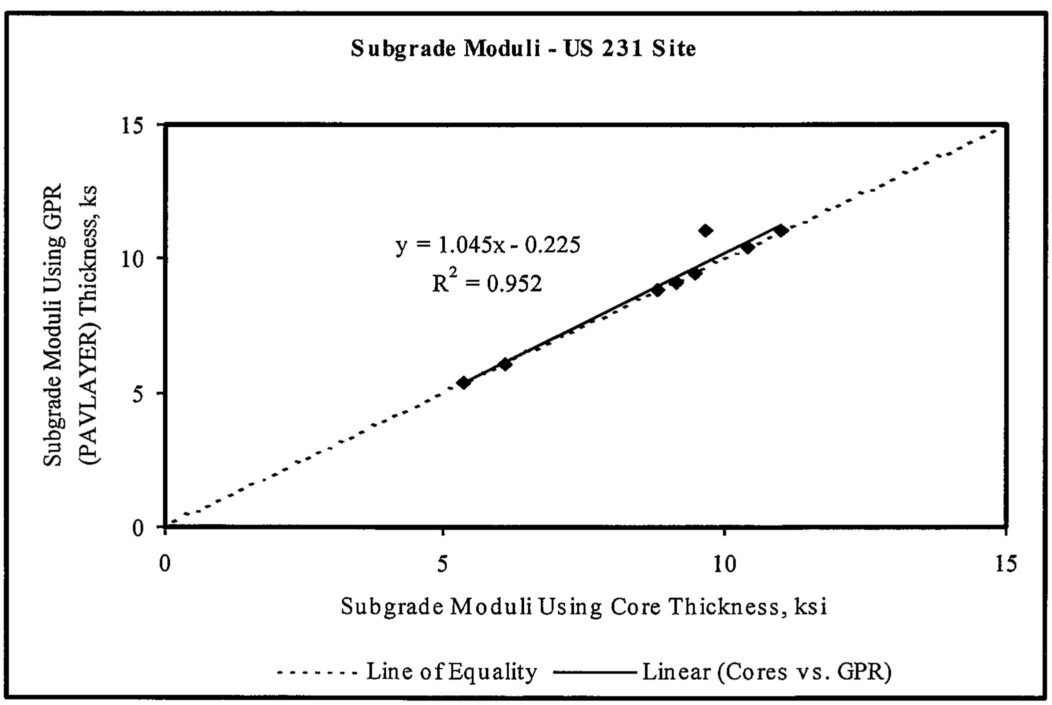

Figure F.14 Subgrade Moduli of US 231 Site - Core vs. PAVLAYER Thickness (DARWin)

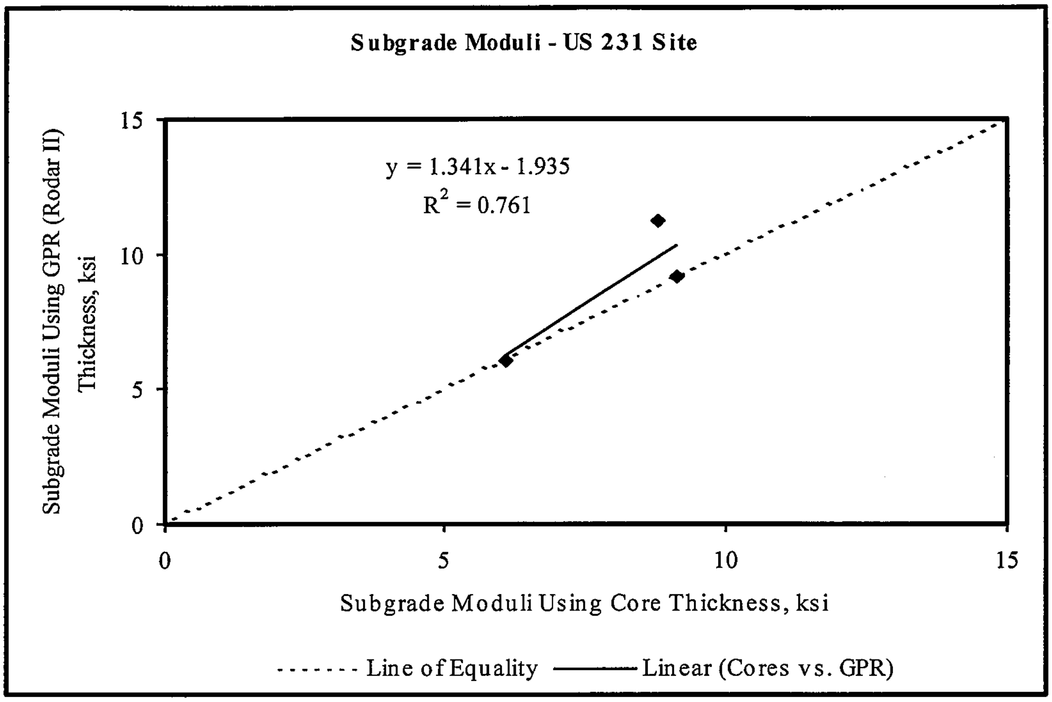

Figure F.15 Subgrade Moduli of US 231 Site - Core vs. Rodar II Thickness (DARWin)

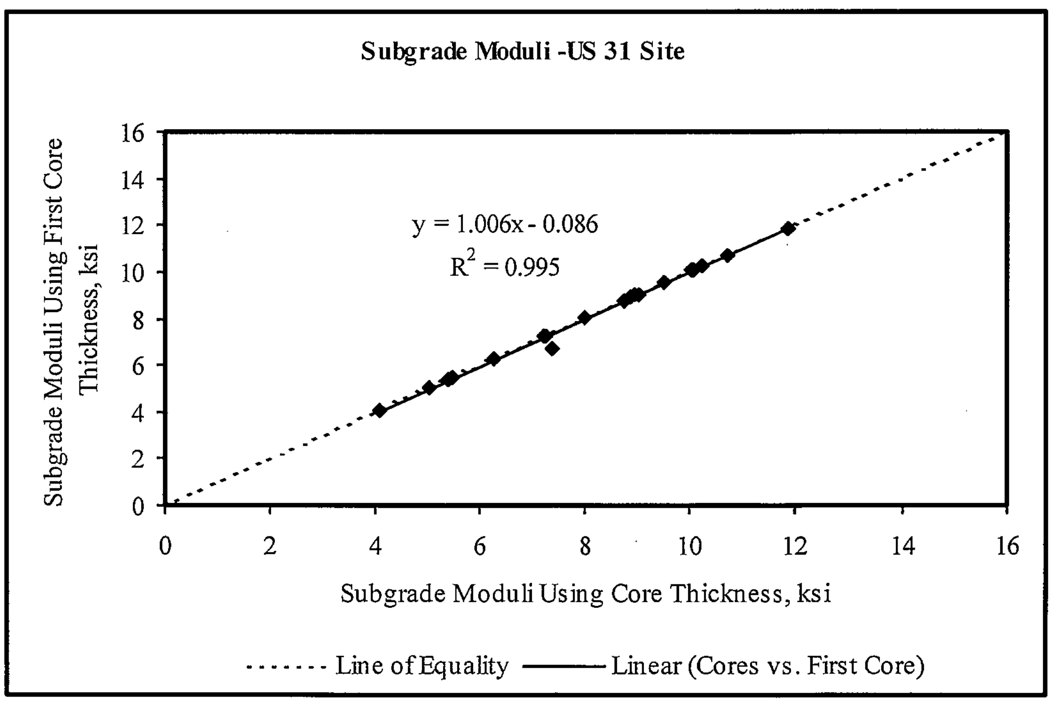

Figure F.16 Subgrade Moduli of US 31 Site - Core vs. First Core Thickness (DARWin)

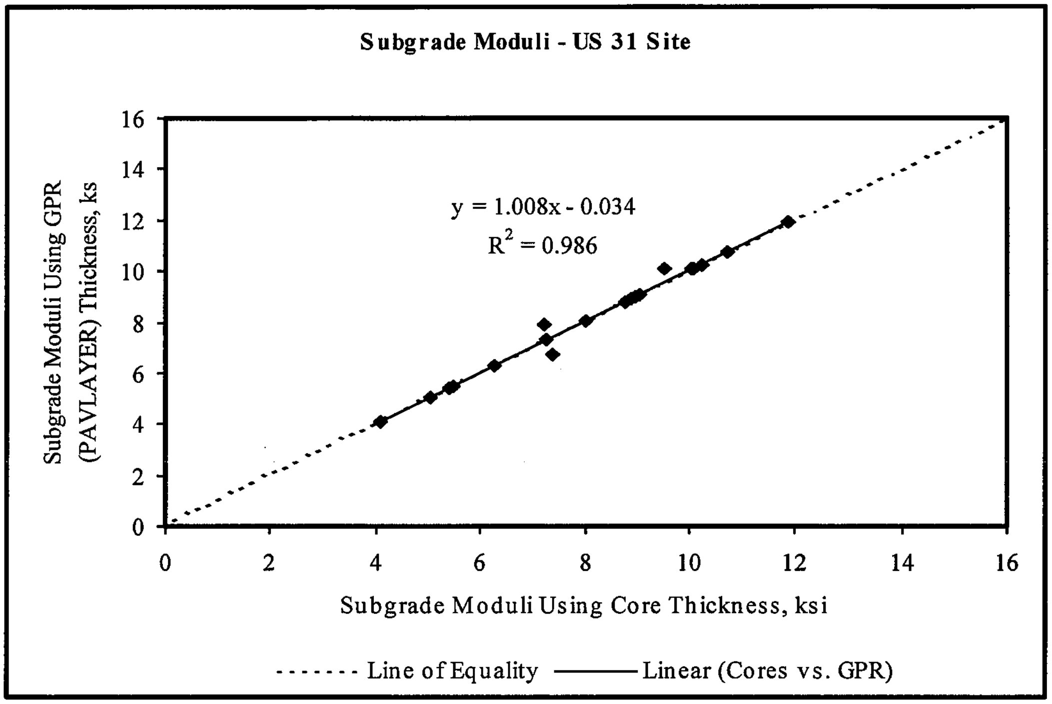

Figure F.17 Subgrade Moduli of US 31 Site - Core vs. PAVLAYER Thickness (DARWin)

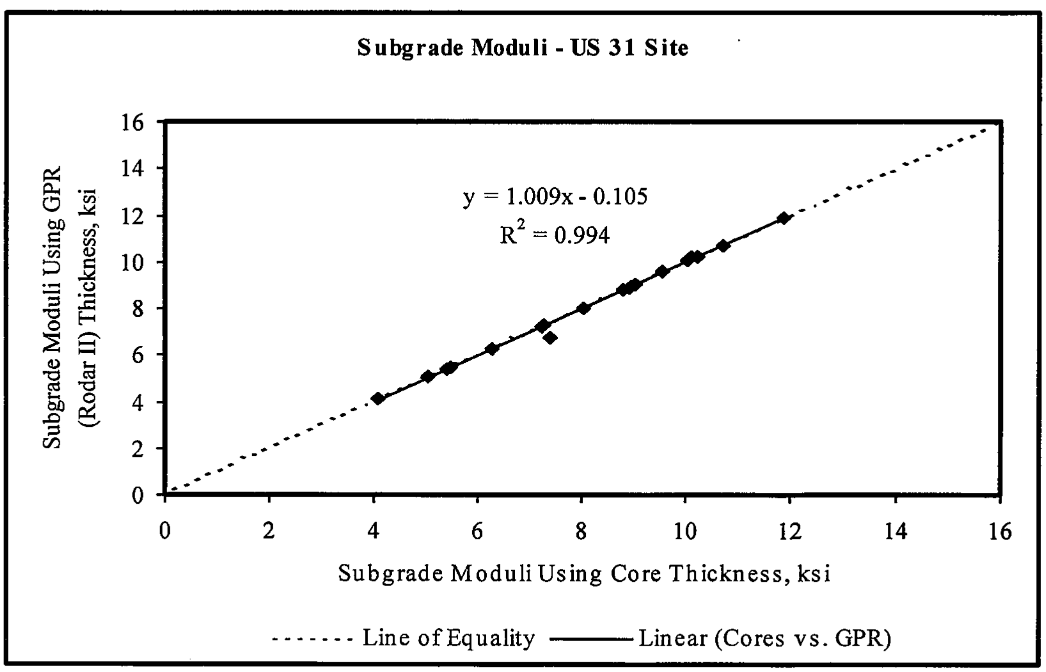

Figure F.18 Subgrade Moduli of US 31 Site - Core vs. Rodar II Thickness (DARWin0