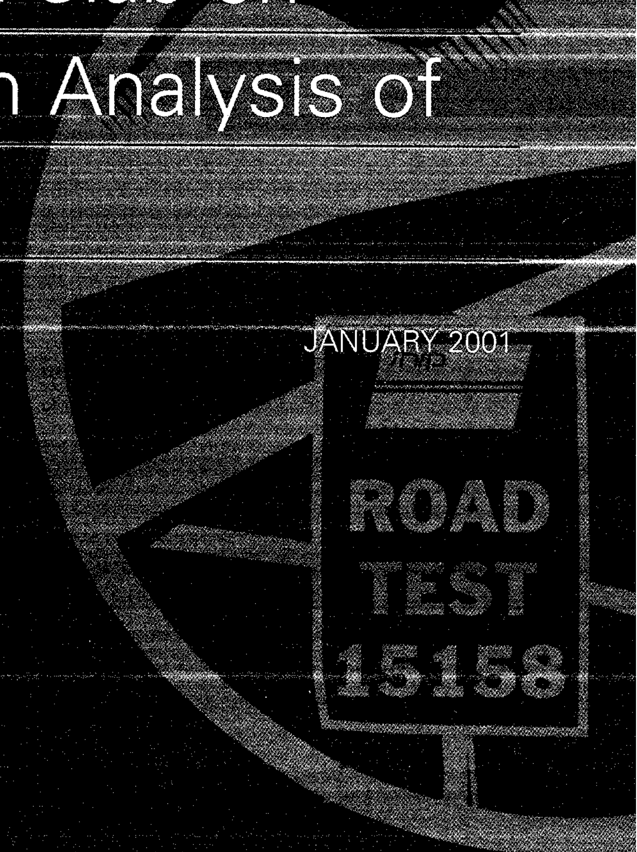
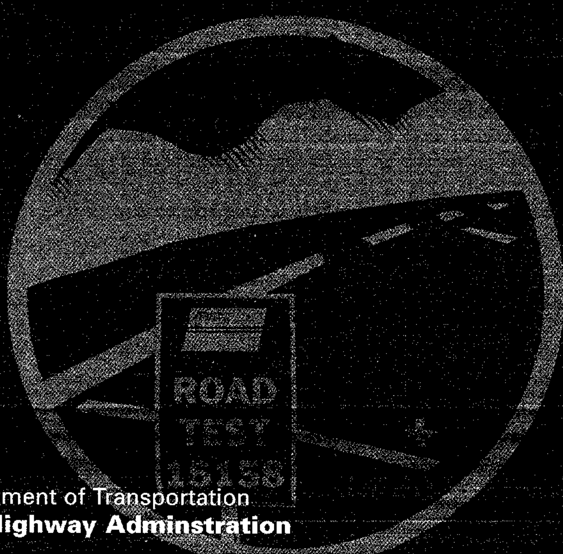
Backcalculation of Layer Parameters for LTPP Test Sections, Volume I: Slab on Elastic Solid and Slab on Dense-Liquid Foundation Analysis of Rigid Pavements

PUBLICATION NO. FHWA-RD-00-086

JANUARY 2001





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Federal Highway Adminstration

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LTPP

FOREWORD

This report documents a study conducted to backcalculate layer material parameters for rigid pavements included in the Long Term Pavement Performance (LTPP) program. Using the "best-fit" algorithm, layer material properties were backcalculated using both the slab on elastic solid foundation and the slab on dense-liquid foundation models. The analysis was conducted for all General Pavement Studies (GPS), Special Pavement Studies (SPS), and Seasonal Monitoring Program (SMP) test sections. Data tables that include the backcalculation results were developed for inclusion in the LTPP Information Management System (IMS).

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Director
Office of Infrastructure
Research and Development

NOTICE

Technical Report Documentation Page

1. Report No. FHWA-RD-00-086	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle BACKCALCULATION OF LAYER PARAMETERS FOR LTPP TEST SECTIONS, Volume I: Slab on Elastic Solid and Slab on Dense-Liquid Foundation Analysis of Rigid Pavements		5. Report Date January 2001 6. Performing Organization Code
7. Author(s) Lev Khazanovich, Shiraz D. Tayabji, and Michael I. Darter		8. Performing Organization Report No.
9. Performing Organization Name and Address ERES Consultants, Inc. 9030 Red Branch Road, Suite 210 Columbia, Maryland 21045		10. Work Unit No. (TRAIS) C6B 11. Contract or Grant No. DTFH61-96-C-00003
12. Sponsoring Agency Name and Address Office of Infrastructure Research and Development Federal Highway Administration 6300 Georgetown Pike McLean, Virginia 22101-2296		13. Type of Report and Period Covered Final Report Aug 1997 to July 1998 14. Sponsoring Agency Code

15. Supplementary Notes
Contracting Officer's Technical Representative (COTR): Cheryl Allen Richter, HRDI-13

16. Abstract

This report documents the results of backcalculation of layer material properties for rigid pavements included in the Long Term Pavement Performance (LTPP) program in the United States and Canada using deflection testing data.

This study backcalculated the layer material properties for rigid pavements using the slab on elastic solid foundation and the slab on dense-liquid foundation procedures. The "best fit" algorithm was used after consideration of alternative methods of backcalculation. Pre-processing and post-processing utility software were developed to facilitate data handling. The backcalculation analysis was conducted for all General Pavement Studies (GPS), Special Pavement Studies (SPS), and Seasonal Monitoring Program (SMP) test sections. Data tables that include backcalculation parameters were developed for inclusion in the LTPP Information Management System (IMS). Key findings include the following:

1. The "best fit" method was selected as the primary backcalculation method for both dense-liquid (DL) and elastic solid (ES) subgrade models.
2. Reasonable backcalculation results were obtained for the large majority of GPS, SPS, and SMP sections. Typical modulus values and ranges are provided for the PCC slab, many types of bases, and the subgrade.
3. Strong correlations were found between backcalculated parameters using DL and ES subgrade models.
4. Temperature curling during the day had a profound effect on the results of backcalculation [making it important to conduct falling weight deflectometer (FWD) basin testing early in the morning to reduce variability in backcalculated values].
5. Poor correlation was found between backcalculated and laboratory elastic moduli of the concrete slab.
6. A bonded interface between the slab and base produced the best layer moduli for a large majority of the sections (center slab backcalculation).

17. Key Words Backcalculation analysis, concrete pavements, deflection testing, falling weight deflectometer, LTPP, pavement testing, rigid pavements.		18. Distribution Statement No restrictions. This document is available to the public through the National Technical Information Service, Springfield, VA 22161.	
19. Security Classification (of this report) Unclassified	20. Security Classification (of this page) Unclassified	21. No. of Pages 125	22. Price

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SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yards	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
NOTE: Volumes greater than 1000 l shall be shown in m^3.				
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5(F-32)/9 or (F-32)/1.8	Celcius temperature	°C
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.71	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
		TEMPERATURE (exact)		
°C	Celcius temperature	1.8C + 32	Fahrenheit temperature	°F
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

* SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380.

(Revised September 1993)

TABLE OF CONTENTS

TABLE OF CONTENTS (Continued)

LIST OF FIGURES

Figure **Page**

LIST OF FIGURES (Continued)

Figure **Page**

LIST OF FIGURES (Continued)

Figure **Page**

LIST OF FIGURES (Continued)

Figure **Page**

LIST OF TABLES

CHAPTER 1. INTRODUCTION

An extensive data collection effort has been under way since 1989 for the Long Term Pavement Performance (LTPP) program. As part of the monitoring data collection, falling weight deflectometers (FWDs) are being used to obtain deflection measurements at General Pavement Study (GPS) and Special Pavement Study (SPS) test sections in the United States and Canada. The deflection response of the pavement to an applied load is an important indicator of the structural capacity, material properties, and seasonal variations of the pavement. In the LTPP program, deflection testing is conducted periodically (every few years) at GPS and SPS sections. However, at the 64 sections designated for the Seasonal Monitoring Program (SMP), FWD testing is conducted more frequently, about 12 to 14 times per year.

The backcalculation of material response parameters for each layer in a rigid pavement structure using the deflection data has been performed using two approaches:

1. Backcalculation of layer material properties using elastic layer based procedures. This approach was used for both flexible and rigid pavements. Under this approach, Program MODCOMP was used. This work was published as a separate report.(1)
2. Backcalculation of layer material properties using the slab on elastic solid (ES) or dense-liquid (DL) foundation based procedures. This approach is used for rigid pavements only.

This report presents the results of the backcalculation analysis conducted for rigid pavement sections in the LTPP program using the slab on elastic solid and dense-liquid foundation based procedures.

In the past decade, much progress has been made in the development of reliable methods for backcalculation of concrete slab and foundation moduli from deflection measurements. Recently, studies conducted by Darter et al.(1) and Hall et al.(2) made significant contributions to the improvement of rigid pavement backcalculation procedures. Nevertheless, backcalculation for rigid pavements remains a challenging problem. To obtain realistic results from backcalculation, a thorough analysis of all factors is required. The effects of sensor configuration, base layer, joint spacing, and temperature conditions on the backcalculation results should be taken into account.

Deflection Testing Details

Backcalculation of rigid pavements utilizes the deflection basins measured at the center of the slab. The LTPP deflection basin testing uses seven deflection sensors placed 0, 203, 305, 457, 610, 914, and 1524 mm from the center of the load plate to define the shape of the deflection basin.

The load sequence, as stored in the database, for rigid pavement testing is as follows:

Height	No. of Drops	Target Load, kN	Acceptable Range, kN
2	4	40.0	36.0 to 44.0
3	4	53.3	48.1 to 58.7
4	4	71.1	64.1 to 78.3

For jointed rigid pavements, deflection basin tests are performed along the mid-lane path at each tested slab, and the test locations are designated as J1. The number of panels can vary from as few as 9 or 10 to as many as 35 or more on a 152.4-m-long section. Regardless of the total number of panels present, no more than 20 panels are tested at a section.

For the continuously reinforced concrete pavements (CRCP), deflection basin tests are also performed along the mid-lane path at a spacing of about 7.6 m, and the test locations are designated as C1. These tests are performed at mid-length of an effective panel, which is defined by two adjacent transverse cracks typically at a spacing of 0.3 to 2.5 m. For CRCP sections, tests are performed at 20 effective panels.

It should be noted that slab temperature gradient measurements are conducted at the time of the deflection testing. However, no attempt was made to address temperature conditions at the time of testing in the backcalculation analysis. For rigid pavements, slab curling does play a critical role in FWD deflection measurements. As such, any interpretation of backcalculation results should account for the effect of slab curling.

Scope of Work

The scope of the backcalculation analysis study for LTPP rigid pavement sections included the following:

1. Selection of one or more procedures to compute the modulus of elasticity of the concrete slab, the base course, and the elastic solid foundation and also to compute the modulusof subgrade reaction of the foundation.
2. Modification, if necessary, of the selected procedures to meet the specific needs of the LTPP program.
3. Development of pre-processing and post-processing utility software to facilitate data handling.
4. Performing backcalculation analysis for SMP, GPS, and SPS test sections.
5. Development of data tables for uploading appropriate backcalculation analysis results to the LTPP Information Management System (IMS).
6. Performing preliminary assessment of the backcalculated materialproperties.

Report Organization

This report documents the research effort and findings of the LTPP rigid pavement backcalculation analysis effort. Chapter 1 discusses background information. Chapter 2 provides details on the selection of the backcalculation methodology for rigid pavements. Chapter 3 presents results of the backcalculation analysis for GPS and SPS test sections. Chapter 4 presents results of the backcalculation analysis for SMP test sections. Chapter 5 discusses limitations of the current backcalculation analysis procedures. A summary and recommendations are presented in chapter 6.

Typical examples of the results from the backcalculation analysis are given in appendix A for GPS test sections.

CHAPTER 2. SELECTION OF BACKCALCULATION METHODOLOGY FOR RIGID PAVEMENTS

Several methods for backcalculating the portland cement concrete (PCC) slab, base, and subgrade moduli or moduli of subgrade reaction (k) are available. Each method has its strengths and its limitations. The following procedures are typically considered for rigid pavements:

- Backcalculation software and procedures based on elastic layer analysis typically used for flexible pavements.
- Backcalculation procedures specifically developed for rigid pavements that are based on slab on elastic solid or slab on dense-liquid models:
  - AREA method-based procedures.
  - Best fit-based procedures.

The following issues are addressed relative to backcalculation for rigid pavements:

- AREA method versus Best Fit method: Which should be used?
- Sensor configurations: Should outer sensors be omitted?
- Effect of a base layer: How should it be accounted for?
- Slab size effect: What slab size correction, if any, should be applied?
- Temperature effects: Should temperature curling correction factors be used? If so, what should they be?

This report does not address the issue of which is the most realistic subgrade characterization method: ES model versus DL model. In this study, both models were used. The backcalculated parameters obtained using DL and ES models are compared. Several correlations between the models were found, and these correlations may be useful for development of subgrade characterization guidelines for the 2002 Design Guide being developed under National Cooperative Highway Research Program (NCHRP) Project 1-37A.

Backcalculation Algorithms for DL Foundation

Two backcalculation procedures based on plate theory were evaluated in this study. The Best Fit method solves for a combination of the radius of relative stiffness, *l*, and the coefficient of subgrade reaction, k, that produces the best possible agreement between the predicted and measured deflections at each sensor. The AREA method is included in the 1993 AASHTO Guide and estimates the radius of relative stiffness as a function of the AREA of the deflection basin. This estimation, along with the subsequent calculation of subgrade reaction, k, and slab modulus of elasticity, E, is made using simple closed form equations. Both methods are based on Westergaard's solution for the interior loading of a plate consisting of a linear elastic, homogeneous, and isotropic material resting on a dense-liquid foundation. Under a load distributed uniformly over a circular area of radius, a, the distribution of deflections, w(r), may be written as:(3)

$$w(r) = \frac{p}{k} f(r, l) \tag{1}$$

$$f(r) = 1 - C_1(a_l)\, ber(s) - C_2(a_l)\, bei(s) \qquad for\ 0 < r < a \tag{2}$$

$$f(r) = C_3(a_l)\,\ker(s) + C_4(a_l)\,kei(s) \qquad for\ r > a \tag{3}$$

where

a_l	=	(a/*l*)
	=	dimensionless radius of the applied load
r	=	radial distance measured from the center of the load
s	=	(r/*l*)
	=	normalized radial distance
l	=	$(D/k)^{1/4}$
	=	radius of relative stiffness of plate-subgrade system for the dense-liquid foundation
D	=	$Eh^3/12(1-\mu^2)$
	=	flexural rigidity of the plate
E	=	plate elastic modulus
μ	=	plate Poisson's ratio
h	=	plate thickness
k	=	modulus of subgrade reaction
p	=	applied load intensity (pressure) = $P/(\pi a^2)$
P	=	total applied load

Note that *ber*, *bei*, ker, and *kei* are Kelvin Bessel functions that may be evaluated using appropriate series expressions available in the literature.(3)

A method for determining the constants C_1 through C_4 has been proposed by Ioannides.(3) However, that method is tedious and is valid only for a relatively small radius of the applied load. A more general and simple solution has been proposed by Korenev, who suggests that these constants have the following form for any value of the radius of the applied load:(4)

$$C_1 = -a_\lambda \ker' a_\lambda \tag{4}$$

$$C_2 = a_\lambda\, kei' a_\lambda \tag{5}$$

$$C_3 = -a_\lambda\, ber' a_\lambda \tag{6}$$

$$C_4 = -a_\lambda\, bei' a_\lambda \tag{7}$$

Where ker', *kei'*, *ber'*, and *bei'* are the first derivatives of the functions ker, *kei*, *ber*, and *bei*, respectively.

Best Fit Algorithm

The Best Fit backcalculation algorithm finds a combination of concrete elastic modulus and subgrade k-value for which the calculated deflection profile closely matches the measured profile.(2,5) The problem is formulated as the minimization of the error function, F, defined as follows:

$$F(E,k) = \sum_{i=0}^{n} \alpha_i \left(w(r_i) - W_i\right)^2 \tag{8}$$

where α_i is the weighting factor, $w(r_i)$ is the calculated deflection, and W_i is the measured deflection. The weighting factor might be set equal to 1, or $(1/W_i)^2$, or any other number. The ability to control the weights given to the various deflection measurements adds some flexibility to the Best Fit solution process.

Using equation 1, the error function, F, can be presented in the following form:

$$F(E,k) \equiv F(l,k) = \sum_{i=0}^{n} \alpha_i \left(\frac{p}{k} f_i(l) - W_i \right)^2 \tag{9}$$

To obtain the minimum of the error function, F, the following conditions should be satisfied:

$$\frac{\partial F}{\partial k} = 0 \tag{10}$$

$$\frac{\partial F}{\partial l} = 0 \tag{11}$$

Substitution of the error function equation into the equation for the first condition yields the following equation for the k-value:

$$k = p \frac{\sum_{i=0}^{n} \alpha_i \left(f_i(l_k) \right)^2}{\sum_{i=0}^{n} \alpha_i W_i f_i(l_k)} \tag{12}$$

Substitution of the error function equation into the equation for the second condition yields the following equation for the radius of relative stiffness:

$$\frac{\sum_{i=0}^{n} \alpha_i f_i(l_k) f_i'(l_k)}{\sum_{i=0}^{n} \alpha_i \left(f_i(l_k) \right)^2} = \frac{\sum_{i=0}^{n} \alpha_i W_i f_i'(l_k)}{\sum_{i=0}^{n} \alpha_i W_i f_i(l_k)} \tag{13}$$

The solution of equation 13 has been facilitated by development of a computer program. The execution time per backcalculation on a PC is only a fraction of a second. The primary advantage of the Best Fit method is that it can provide the best fit between the calculated and the measured deflections for any sensor configuration.

In this study, the following procedures were used to apply the Best Fit algorithm to backcalculation of subgrade k-values:

1. Assign weighting factors for equation 8. In this study, they were set equal to 0 or 1, depending on whether the sensor is being used for backcalculation.
2. Determine the radius of relative stiffness that satisfies the l equation from equation 13.

3. Use equation 12 to determine the modulus of subgrade reaction.

Knowing the calculated values of l_k and k, the elastic modulus for the plate, E_{PL}, may be determined from the following relationship:

$$E_{PL} = \frac{12\left(1-\mu_{PL}^{2}\right) l^4 k}{h_{PL}^{3}} \tag{14}$$

where

h_{PL} = plate slab thickness
k = subgrade k-value
μ_{PL} = PCC Poisson's ratio

AREA Algorithm

Hoffman and Thompson first proposed the use of a parameter called AREA for interpreting flexible pavement deflection basins.(6) This parameter combines the effect of several measured deflections in the basin and is defined as follows:

$$AREA = \frac{1}{2W_0}\left[W_0\ r_1 + \left(\sum_{i=1}^{n-1} W_i\ (r_{i+1} - r_i)\right) + W_n(r_n - r_{n-1})\right] \tag{15}$$

where

W_i = measured deflections (i = 0, n)
n = number of FWD sensors minus one
r_i = distances between the center of the load plate and sensors

The AREA algorithm has been used extensively to analyze concrete pavement deflection basins since 1980. Ioannides et al. identified the unique relationship between AREA and the radius of relative stiffness.(7) Hall obtained simple approximations for this relationship for different AASHTO and SHRP sensor configurations.(8) The AREA parameter is not truly an area, but rather has dimensions of length, since it is normalized with respect to one of the measured deflections in order to remove the effects of load magnitude. For a given number and configuration of deflection sensors, AREA may be computed using the trapezoidal rule. The AREA method was examined using the following equations for the four sensor configurations by Hall et al.:(2)

SHRP sensor configuration (at 0, 203, 305, 457, 610, 914, and 1524 mm) - Method A7:

$$A7 = 4 + 6\left(\frac{d_8}{d_0}\right) + 5\left(\frac{d_{12}}{d_8}\right) + 6\left(\frac{d_{18}}{d_0}\right) + 9\left(\frac{d_{24}}{d_0}\right) + 18\left(\frac{d_{36}}{d_0}\right) + 12\left(\frac{d_{60}}{d_0}\right) \tag{16}$$

where A7 = AREA parameter for sensors at 0, 203, 305, 457, 610, 914, and 1524 mm

SHRP outer sensor configuration (at 305, 457, 610, 914, and 1524 mm) – Method A5:

$$A5 = 3 + 6\left(\frac{d_{18}}{d_{12}}\right) + 9\left(\frac{d_{24}}{d_{12}}\right) + 18\left(\frac{d_{36}}{d_{12}}\right) + 12\left(\frac{d_{60}}{d_{12}}\right) \tag{17}$$

where A5 = AREA parameter for sensors at 305, 457, 610, 914, and 1524 mm

AASHTO sensor configuration (at 0, 305, 610, and 914 mm) – Method A4:

$$A4 = 6 + 12\left(\frac{d_{12}}{d_0}\right) + 12\left(\frac{d_{24}}{d_0}\right) + 6\left(\frac{d_{36}}{d_0}\right) \qquad (18)$$

where A4 = AREA parameter for sensors 0, 305, 610, and 914 mm

AASHTO outer sensor configuration (at 305, 610, and 914 mm) – Method A3:

$$A3 = 6 + 12\left(\frac{d_{24}}{d_{12}}\right) + 6\left(\frac{d_{36}}{d_{12}}\right) \qquad (19)$$

where A3 = AREA parameter for sensors 305, 610, and 914 mm

Methods A4 and A7 were considered for rigid pavement backcalculation, and methods A3 and A5 were recommended for composite pavement backcalculation.

AREA Method Versus Best Fit Method

The results of backcalculation obtained by the Hall et al. studywere used to compare backcalculated k-values using the Best Fit and AREA procedures and various sensor configurations. The methods and sensor configurations are as follows:(2)

Configuration Name	Procedure	Sensor Position (mm)
B7	Best Fit	0, 203, 305, 457, 610, 914, and 1524
B4	Best Fit	0, 305, 610, and 914
A7	AREA	0, 203, 305, 457, 610, 914, and 1524
A4	AREA	0, 305, 610, and 914

It was observed that these procedures produce different results. Figures 1 through 3 show comparisons of B7, A4, and A7 versus B4 configuration/procedure, respectively. In this study, the following simple relationships were found between the backcalculated k-values using B4 and the remaining methods:

$$k_{B7} = 0.867k_{B4} \qquad R^2=0.970 \qquad (20)$$
$$k_{A7} = 0.984k_{B4} \qquad R^2=0.988 \qquad (21)$$
$$k_{A4} = 1.148k_{B4} \qquad R^2=0.976 \qquad (22)$$

where k_{B4}, k_{B7}, k_{A7}, and k_{A4} are k-values obtained using the B4, B7, A7, and A4 methods, respectively.

The closest relationship was observed between B4 and A7. Good agreement between these two methods for a large number of sections was also found in the Federal Highway Administration (FHWA) rigid pavement research study.(5) The R^2 values for all but one relationship exceed 0.97, which means that these linear relationships explain more than 97 percent of all variability in the results.

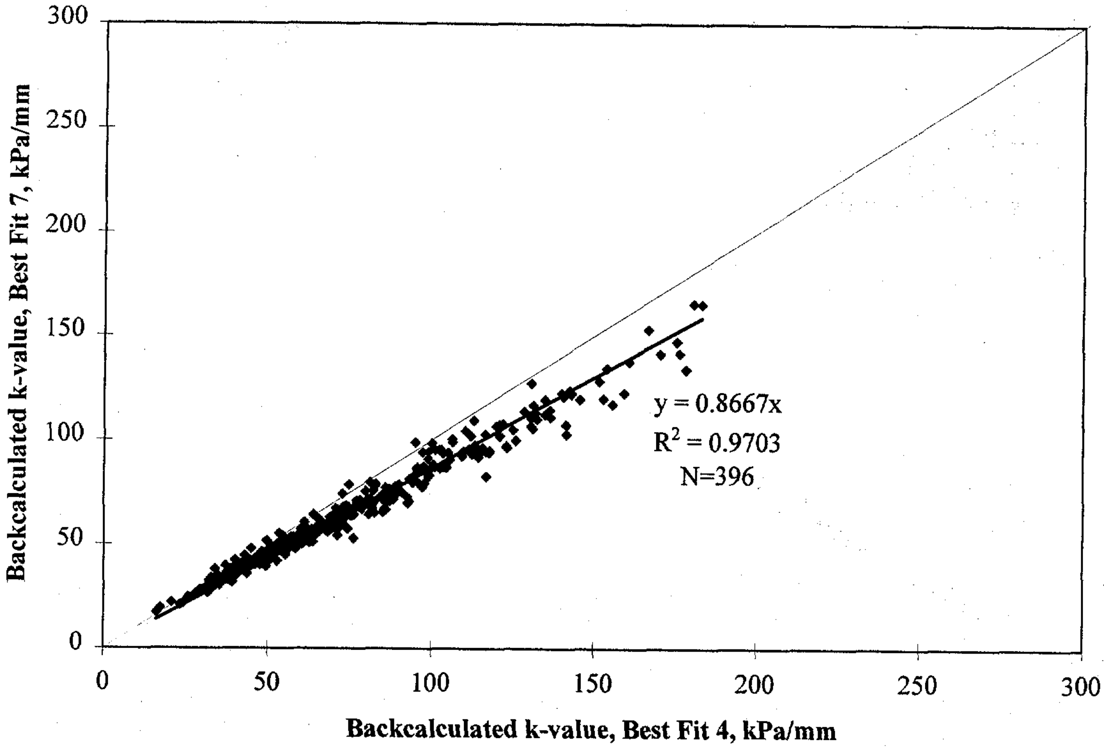


Figure 1. Backcalculated dynamic k-value for LTPP concrete pavement sections, Best Fit 7 versus Best Fit 4.

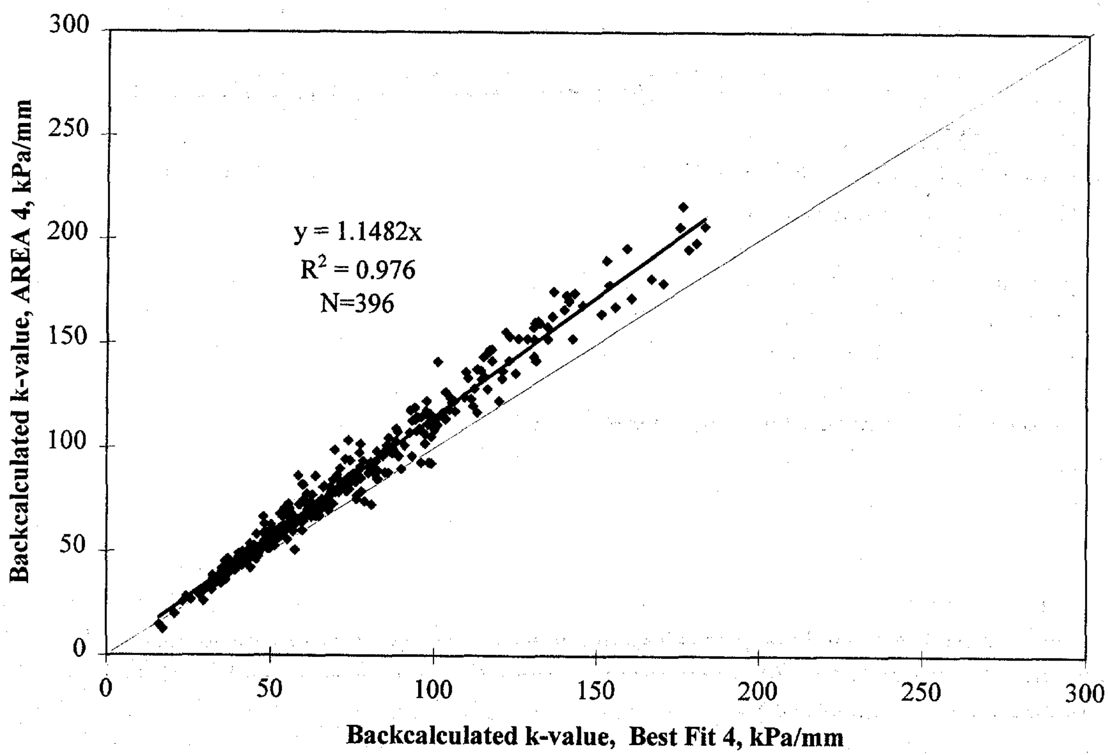


Figure 2. Backcalculated dynamic k-value for LTPP concrete pavement sections, Best Fit 4 versus AREA4.

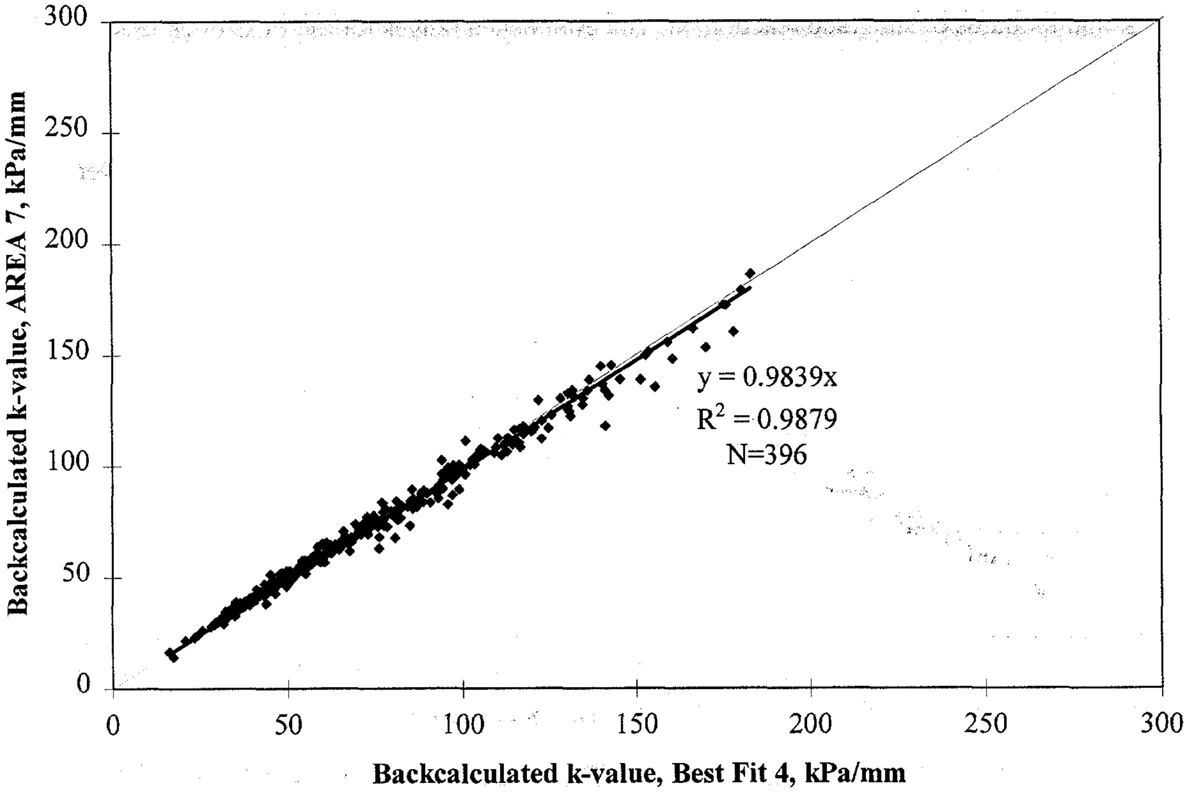


Figure 3. Backcalculated dynamic k-value for LTPP concrete pavement sections, AREA7 versus Best Fit 4.

The relationships presented were obtained from FWD data collected for a large number of rigid pavements having different design and site conditions. Although good correlationships were observed, it is necessary to provide a theoretical basis for the discrepancies between the different methods since both backcalculation methods are based on plate theory.

A very important assumption associated with plate theory is that no compression of the upper layer exists and all of the deflection is attributed to compression of the subgrade and bending of the plate. As observed, the discrepancy between the Best Fit and AREA methods is higher if the maximum deflection (deflection under the center of the load plate) is used in backcalculation. At this location, the plate theory prediction of deflections deviates the most from the theory of elasticity predictions due to compressibility in the concrete layer. Therefore, it is reasonable to suggest that deviation of the PCC slab behavior from the plate theory prediction is a significant source of discrepancy between different backcalculation methods.

To investigate this hypothesis, the computer program DIPLOMAT was used.[9,10] Similar to conventional layered elastic analysis programs, DIPLOMAT can accommodate multi-layered pavement systems loaded by multiple wheel loads. In addition, it allows the user the option to treat one or more of the constructed layers as compressible elastic layers or plates and treat the last layer in the pavement system as a Winkler foundation.

For this study, DIPLOMAT was used to model the PCC layer as an elastic layer, rather than as a plate, allowing for vertical compression through the thickness of the slab. The subgrade was modeled as a Winkler foundation (springs).

DIPLOMAT runs were conducted using a randomly generated set of inputs for PCC thickness, PCC modulus, and modulus of subgrade reaction, k. The established ranges for the PCC thickness, PCC modulus, and the modulus of subgrade reaction were 152 to 305 mm, 28 to 56 GPa, and 13.5 to 135 kPa/mm, respectively.

Comparisons of results using B7 versus A7, B4 versus A4, and B3 versus A3 procedures showed the same trends observed in the Hall et al.(2) study. In every case, the AREA method produces slightly higher k-values than the Best Fit method. The A7 and A4 k-values are, on average, 6.8 and 9.8 percent higher than the B7 and B4 results, respectively. Figures 4 and 5 show comparison of k-values from B4 versus B7 and A4 comparison. This analysis supports the hypothesis that PCC layer compressibility is one of the major sources of discrepancy between the Best Fit and AREA methods. Figure 6 shows that good agreement was observed between the B4 and A7 methods. This supports the recommendation made by Hall et al. to use the A7 method if the Best Fit backcalculation program is not available.(2)

As was done for the GPS LTPP data, the relationships between the results of backcalculation for the theoretical deflection basins using the B4 method and the remaining methods were obtained. Good correlation with R^2 greater than 0.988 were observed. Table 1 presents a comparison of the results of these studies. Similar trends exist for the LTPP field data and DIPLOMAT theoretical data backcalculated k-values. The differences are generally greater for the field data, most likely due to the effects of factors not considered in this study [e.g., departure of true pavement behavior from the theoretical models and the effects of joints (slab size)].

Table 1. Comparison of LTPP and DIPLOMAT results.

Comparison	Mean Difference, percent	
	LTPP	**DIPLOMAT**
B7 versus B4 procedure	13.3	4.2
A7 versus B4 procedure	1.6	-2.5
A4 versus B4 procedure	-14.8	-9.6

Analysis of the results of backcalculation from the Hall et al. study and from the theoretical examination indicated that backcalculation method and sensor configuration may significantly affect backcalculated moduli.(2) Therefore, two questions need to be answered:

1. What backcalculation method (AREA or Best Fit) should be used?
2. What sensor configuration should be selected?

The first problem was addressed in the Hall et al. study.(2) The coefficients of variation of backcalculated k-values for the GPS-3 (jointed plain concrete pavement) sections from multiple drops contained in the LTPP database were compared. The results of that analysis are shown in figure 7. For any sensor configuration, the Best Fit method yields a lower coefficient of variation in backcalculated k-values from multiple drops than the AREA method. Therefore, the Best Fit method was considered the preferred backcalculation procedure. The Best Fit method is also less sensitive to the randomness in measurement of maximum deflection and it provides better correspondence between measured and calculated deflection basins.

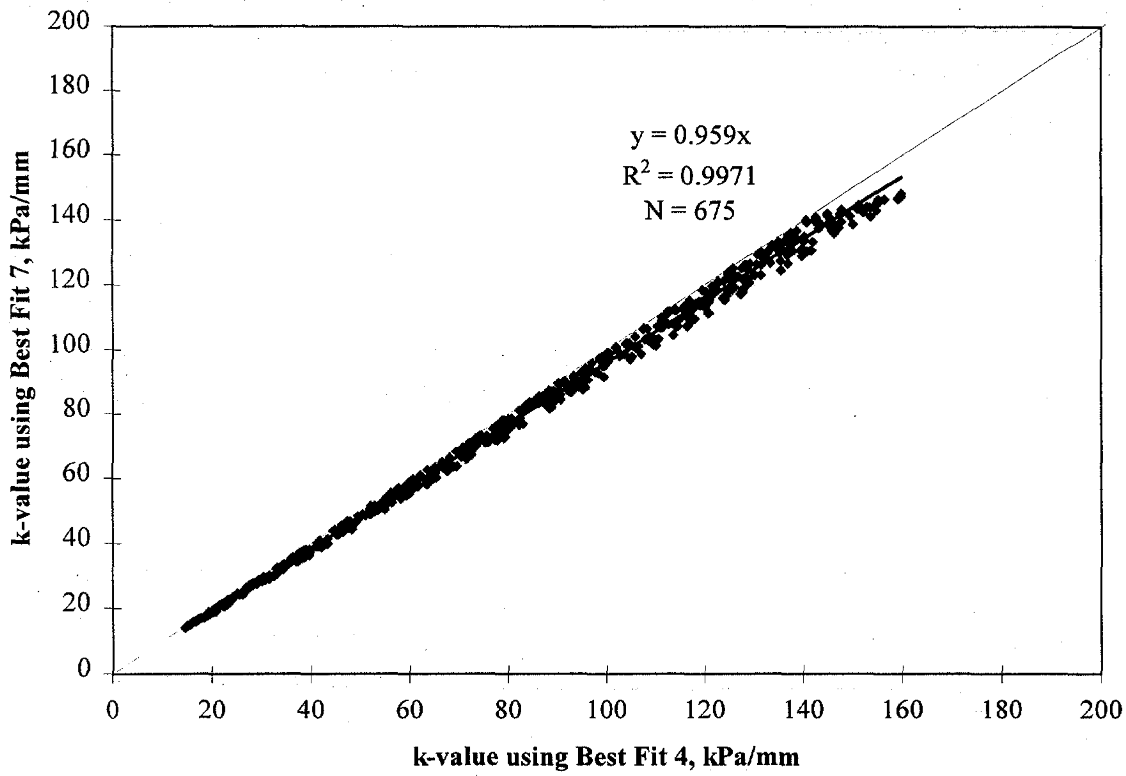


Figure 4. Backcalculated k-value from the theoretical deflection basins, Best Fit 7 versus Best Fit 4.

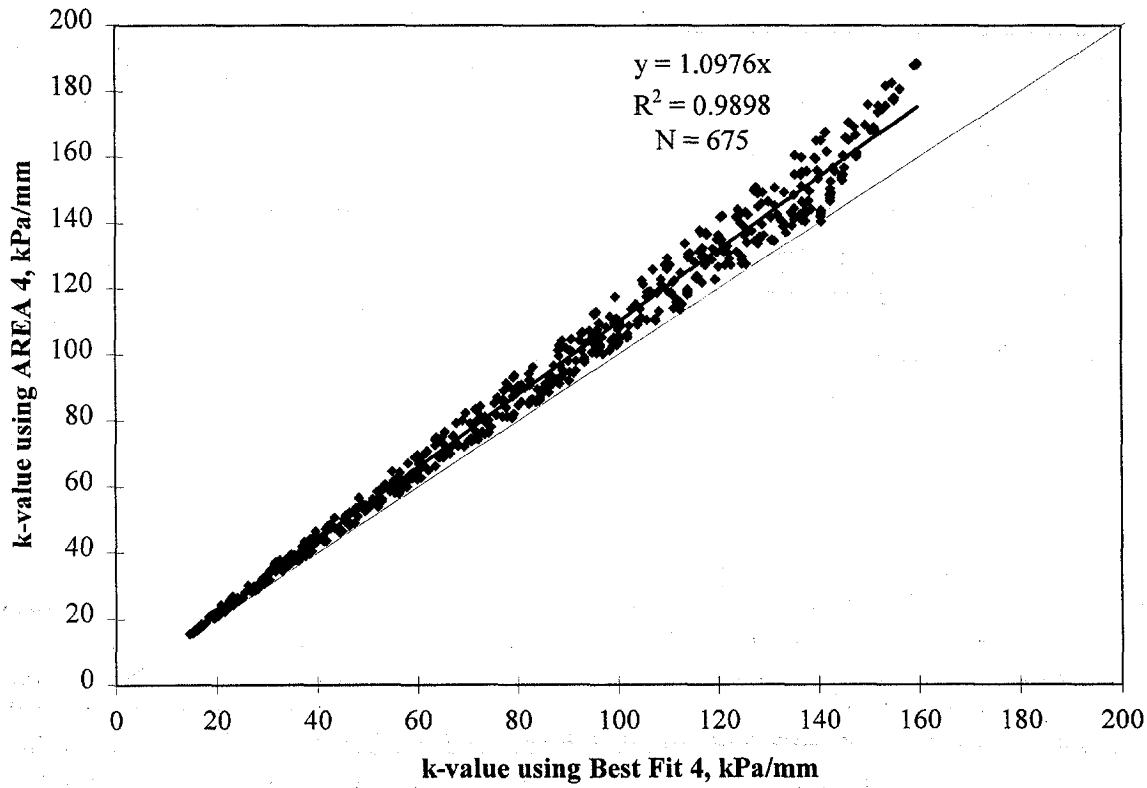


Figure 5. Backcalculated k-value from the theoretical deflection basins, AREA4 versus Best Fit 4.

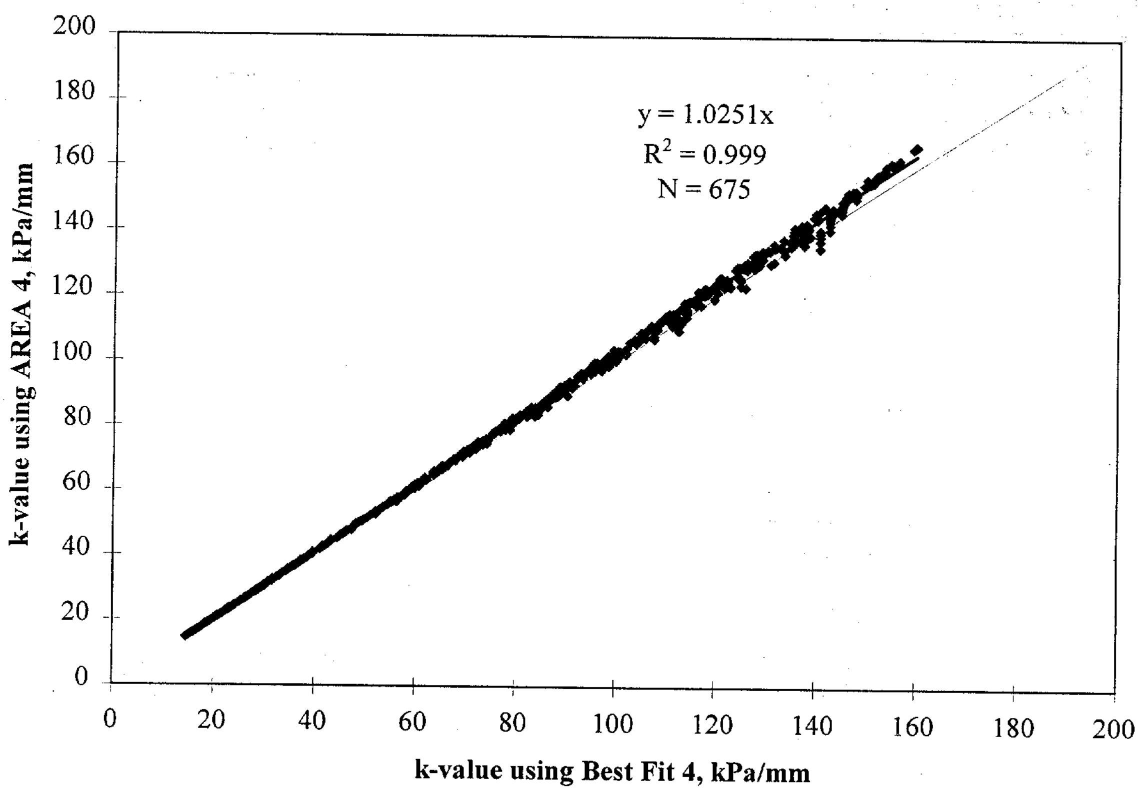


Figure 6. Backcalculated k-value from the theoretical deflection basins, AREA7 versus Best Fit 4.

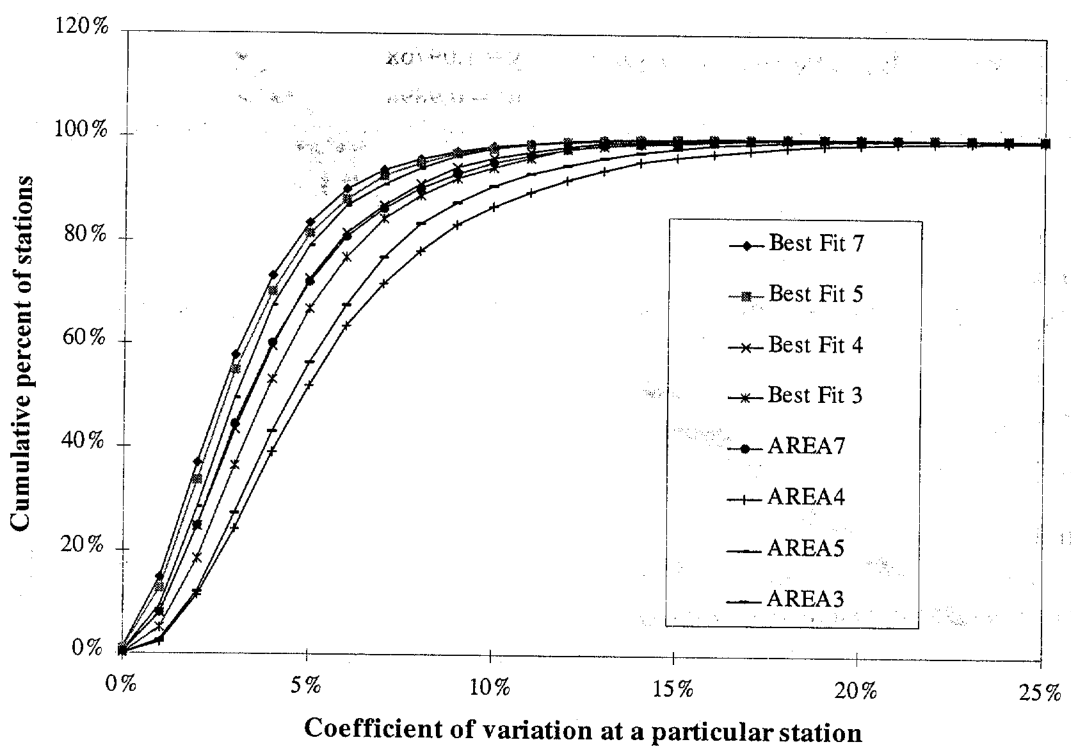


Figure 7. Coefficient of variation in backcalculated k-value for multiple load drops and load level, LTPP concrete pavement sections.

Best Fit Procedure for the Elastic Solid (ES) Model

Since the Best Fit procedure was selected as the primary procedure for DL foundations, the decision was made to adopt this algorithm for ES foundations also. The procedure developed in this study is based on Losberg's solution for a plate on an elastic solid.(11) Under a load distributed uniformly over a circular area of radius, *a*, the distribution of deflections, *w(r)*, may be written as:

$$w(r) = \frac{p}{E_s} f(r) \tag{23}$$

where

$$f(r) = 2a(1-\mu_s^2)\int_0^\infty \frac{J_0(\alpha r)J_1(\alpha a)}{\alpha(1+\alpha^3 l_e^3)}d\alpha \tag{24}$$

a	=	radius of the applied load
p	=	applied pressure
r	=	radial distance measured from the center of the load
l_e	=	$(D/C)^{1/3}$
	=	radius of relative stiffness of plate-subgrade system for the dense-liquid foundation
D	=	$Eh^3/12(1-\mu_{PL}^2)$
C	=	$E_s/(1-\mu_s^2)$
E_S	=	modulus of elasticity of subgrade
μ_s	=	Poisson's ratio for subgrade
J_0	=	Bessel function of zero order
J_1	=	Bessel function of first order

Using equation 23, the error function, *F,* from equation 8 can be presented in the following form:

$$F(E,E_s) \equiv F(E,E_s) = \sum_{i=0}^{n}\alpha_i\left(\frac{p}{E_s}f_i(l_e) - W_i\right)^2 \tag{25}$$

To obtain the minimum of the error function, *F*, the following conditions should be satisfied:

$$\frac{\partial F}{\partial E_s} = 0 \tag{26}$$

$$\frac{\partial F}{\partial l_e} = 0 \tag{27}$$

Substitution of the error function equation into the equation for the first condition yields the following equation for the subgrade modulus of elasticity:

$$E_s = p\frac{\sum_{i=0}^{n}\alpha_i (f_i(l_e))^2}{\sum_{i=0}^{n}\alpha_i W_i f_i(l_e)} \tag{28}$$

Substitution of the error function equation into the equation for the second condition yields the following equation for the radius of relative stiffness:

$$\frac{\sum_{i=0}^{n}\alpha_i f_i(l_e) f_i'(l_e)}{\sum_{i=0}^{n}\alpha_i (f_i(l_e))^2} = \frac{\sum_{i=0}^{n}\alpha_i W_i f_i'(l_e)}{\sum_{i=0}^{n}\alpha_i W_i f_i(l_e)} \tag{29}$$

The solution of equation 29 has been facilitated by development of a computer program. The Microsoft® IMSL library was used for numerical evaluation of Bessel functions. The execution time per backcalculation on a PC is only a fraction of a second. The primary advantage of the Best Fit method is that it is able to provide the best fit between the calculated and the measured deflections for any sensor configuration.

The procedure for backcalculation using the ES subgrade model is similar to that used for DL foundations:

1. Assign weighting factors for equation 8. In this study, they were set equal to 0 or 1, depending on whether the sensor is not being used (0) or is being used (1).
2. Determine the radius of relative stiffness that satisfies the *le* equation from equation 29.
3. Use equation 28 to determine the modulus of elasticity of subgrade, E_S.

From the calculated values of l_e and k, the elastic modulus for the concrete layer, E_{PCC}, may be determined from the following relationship:

$$E_{PCC} = \frac{6(1-\mu_{PCC}^2) l_e^3 E_s}{h_{PCC}^3 (1-\mu_s^2)} \tag{30}$$

where h_{PCC} = PCC slab thickness
E_S = subgrade modulus of elasticity
μ_S = subgrade Poisson's ratio
μ_{PCC} = PCC Poisson's ratio

The procedure was verified using the computer program DIPLOMAT. A close agreement (less than 1 percent difference) between backcalculated and input elastic parameters was observed.

Effect of a Base Layer

Concrete pavements are generally analyzed as slab-on-grade structures, with no structural contributions attributed to the underlying base or subbase layers. However, it is known that these underlying layers can have a significant effect on the structural performance of the pavement, particularly if bonding between the slab and base occurs. If such bonding develops, the effective pavement structure is now greater, and the manner in which the pavement reacts to loading is altered. Because multi-layered concrete pavements are quite common, the ability to evaluate these structures as multi-layered systems is quite valuable to both new and rehabilitation design activities.

The approach for the backcalculation of two-layered slab-on-grade is discussed in the next sections, based on a methodology proposed by Ioannides and Khazanovich.(12) The two constructed layers may be bonded or unbonded and are assumed to act as plates. Thus, no through-the-thickness compression is assumed. The backcalculation procedure described represents an adaptation of the forward calculation approach for such pavement systems, which was presented by Ioannides et al.(13) The resulting scheme was combined in a computer program with the Best Fit procedure.

Unbonded Case

In accordance with the derivations presented by Ioannides et al., two distinct cases may be recognized, depending on the interface condition between the two constructed layers.(13) The case of two unbonded plates is considered first. Such plates will act independently, although their respective deflected shapes will remain identical if there is to be no separation between them. Under these conditions, it has been shown that:

$$D_e = D_1 + D_2 \qquad (31)$$

where

- D_1 = flexural stiffness of the upper plates
- D_2 = flexural stiffness of the lower plate
- D_e = corresponding stiffness of a fictitious "effective," composite, homogeneous plate, which deforms in an identical manner to the actual two-plate system

In one sense, slab-on-grade backcalculation schemes may be thought of as producing an estimate of D_e when applied to a three-layer PCC pavement system. The apparent task that remains, therefore, is to subdivide D_e into its component parts, namely D_1 and D_2. This cannot be accomplished merely by reference to the field measurements of the deflection profile. An additional input parameter is needed. This requirement is akin to the need to provide seed moduli for conventional multi-layered AC pavement system backcalculation. In this case, it is convenient to introduce the modular ratio, β, of the two plates as the additional input parameter. Furthermore, it may be assumed with no loss of generality that the thickness of the "effective" plate, h_e, is equal to the thickness of the upper plate, h_1. As a result, the backcalculated E-value from a slab-on-grade analysis is E_e, such that:

$$\frac{E_e h_e^3}{12\left(1-\mu_e^2\right)} = D_e \qquad (32)$$

It is convenient at this point to introduce the additional assumption that:

$$\mu_1 = \mu_2 = \mu_e \qquad (33)$$

Thus, it follows that:

$$E_e h_e^3 = E_e h_1^3 = E_1 h_1^3 + E_2 h_2^3 \qquad (34)$$

where

- E_1 = modulus of upper plate
- E_2 = modulus of lower plate

h_2 = thickness of lower plate

Therefore,

$$E_1 = \frac{h_1^3}{h_1^3 + \beta h_2^3} E_e \tag{35}$$

and

$$E_2 = \frac{\beta h_1^3}{h_1^3 + \beta h_2^3} E_e \tag{36}$$

where

$$\beta = \frac{E_2}{E_1} \tag{37}$$

Given the values for β and for the real plate thicknesses h_1 and h_2, equations 37 and 36 may be used with the E_e value backcalculated from slab-on-grade analysis (assuming $h_e = h_1$), to yield E_1 and E_2 for the two plates.

<u>Bonded Case</u>

For the case of two bonded plates, the flexural stiffness of the fictitious "effective," homogeneous, composite plate is no longer a linear sum of the two actual plate stiffnesses, but may be derived using the parallel axes theorem. Thus:

$$\frac{E_e h_e^3}{12} = \frac{E_1 h_1^3}{12} + E_1 h_1 \left(x - \frac{h_1}{2} \right)^2 + \frac{E_2 h_2^3}{12} + E_2 h_2 \left(h_1 - x + \frac{h_2}{2} \right)^2 \tag{38}$$

where

$$x = \frac{\frac{h_1^2}{2} + \beta h_2 \left(h_1 + \frac{h_2}{2} \right)}{h_1 + \beta h_2} \tag{39}$$

Proceeding as for the unbonded plates, it may be assumed that $h_e = h$, which means that the backcalculated E-value from slab-on-grade analysis is E_e. Therefore:

$$E_1 = \frac{h_1^3}{h_1^3 + \beta h_2^3 + 12 h_1 \left(x - \frac{h_1}{2} \right)^2 + 12 \beta h_2 \left(h_1 - x + \frac{h_2}{2} \right)^2} E_e \tag{40}$$

Equations 39 and 40 for the bonded plates correspond to equations 35 and 36 for the unbonded plates and may be used in a manner analogous to the latter in backcalculating E_1 and E_2 for the two plates.

Effect of the Moduli Ratio

The backcalculation procedures presented above require the modular ratio as an input parameter. This ratio should be assigned based on engineering judgment. It is assumed that, if the ratio is assigned within the reasonable limits, the results of backcalculation are insensitive to the ratio. To verify this assumption, consider a 225-mm-thick PCC slab placed over a 150-mm-thick base. A bonded interface condition is assumed. Let E_e be the backcalculated modulus if the base is ignored. Figure 8 presents the relationship between backcalculated PCC modulus, E_{PCC}, normalized to E_e, and PCC to base modular ratio. One can observe that if the modular ratio is between 10 and 100, significant change in the ratio produces significant change in PCC modulus. If the ratio is greater than 100, then the PCC modulus is practically insensitive to the modular ratio.

This conclusion was further verified in the recent FWHA-sponsored study.(5) Two sets of the ratios between the moduli of elasticity of base materials and PCC were assigned. Figures 9 and 10 present comparison of backcalculated moduli of PCC slab using two data sets for unbonded and bonded interface conditions, respectively. One can observe that the influence of the moduli ratio is not significant in the vast majority of the projects.

The base modulus is more sensitive to change in the modular ratio. Figure 11 shows that this is true even for very high values of modular ratios. This indicates that the proposed procedure is not applicable for determination of moduli of elasticity of granular bases. Indeed, for granular bases the ratios are high. The error in the moduli ratio, which does not affect backcalculated PCC modulus, may lead to erroneous backcalculated base modulus.

Table 2 presents the proposed modular ratios of PCC and base moduli for each type of base layer. It should be noted that β from equation 37 is defined as a ratio of base to PCC moduli. That was done to make it stable for the case of weak base (β approaches). Therefore, the ratios from table 2 should be inverted before using them in the procedure described above.

Effect of Sensor Configuration

To develop recommendations regarding the preferred sensor configuration, the results of backcalculation for 19 SMP sections (605 FWD passes) using the Best Fit 4 and Best Fit 7 methods were compared. The results of backcalculation are summarized in this section. These results were analyzed to develop recommendations regarding the preferred sensor configuration.

The Best Fit 7 method could determine representative values for only 447 FWD passes (74 percent of all FWD visits), meaning that the remaining 158 passes did not satisfy convergence tests. The Best Fit 4 method obtained values for 544 FWD passes (94 percent of the total FWD visits). Figure 12 presents a comparison of backcalculated k-values for those FWD visits. Once again, a strong correlation between backcalculated k-values from these two methods exists and has the following form:

$$k_{B7} = 0.864 k_{B4} \qquad R^2 = 0.920$$

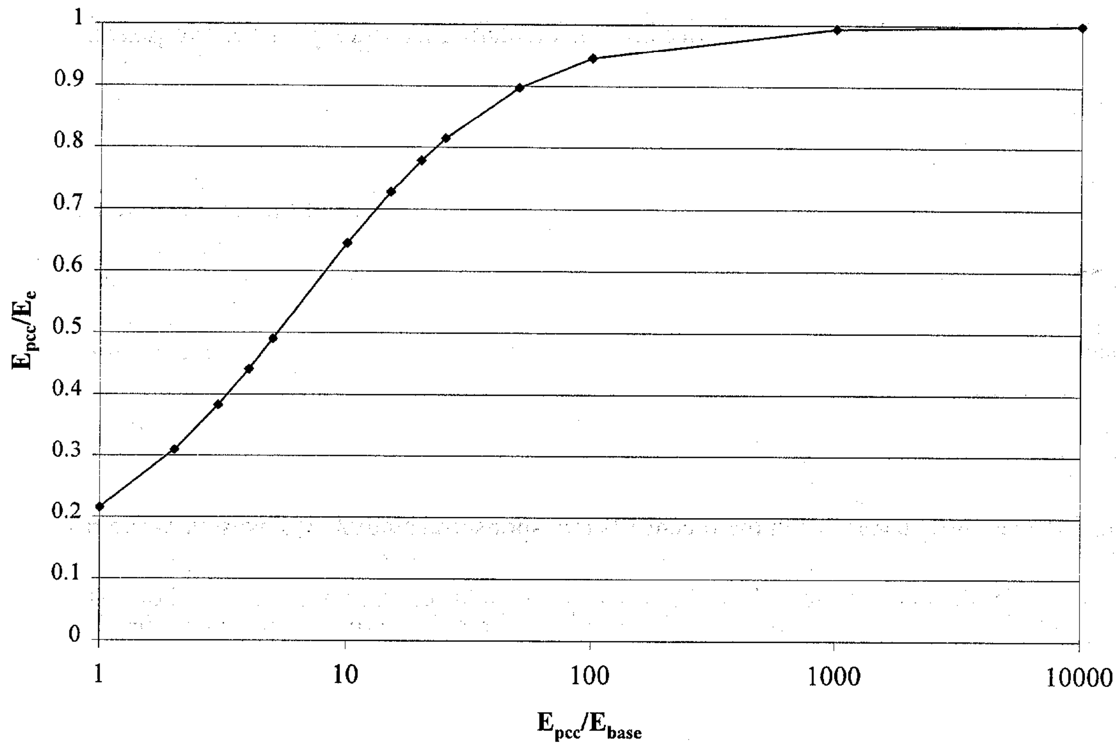


Figure 8. Effect of modular ratio on backcalculated PCC modulus of elasticity.

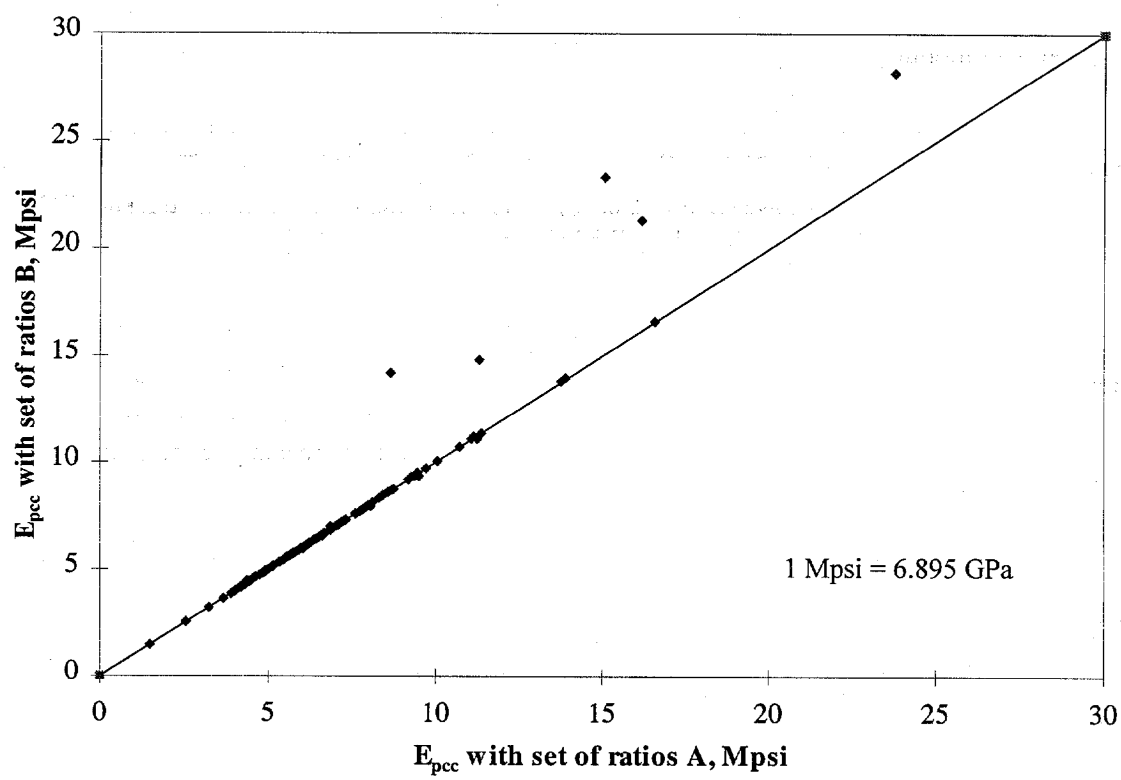


Figure 9. Comparison of backcalculated PCC moduli for two sets of modular ratio, bonded interface between PCC plate and base.

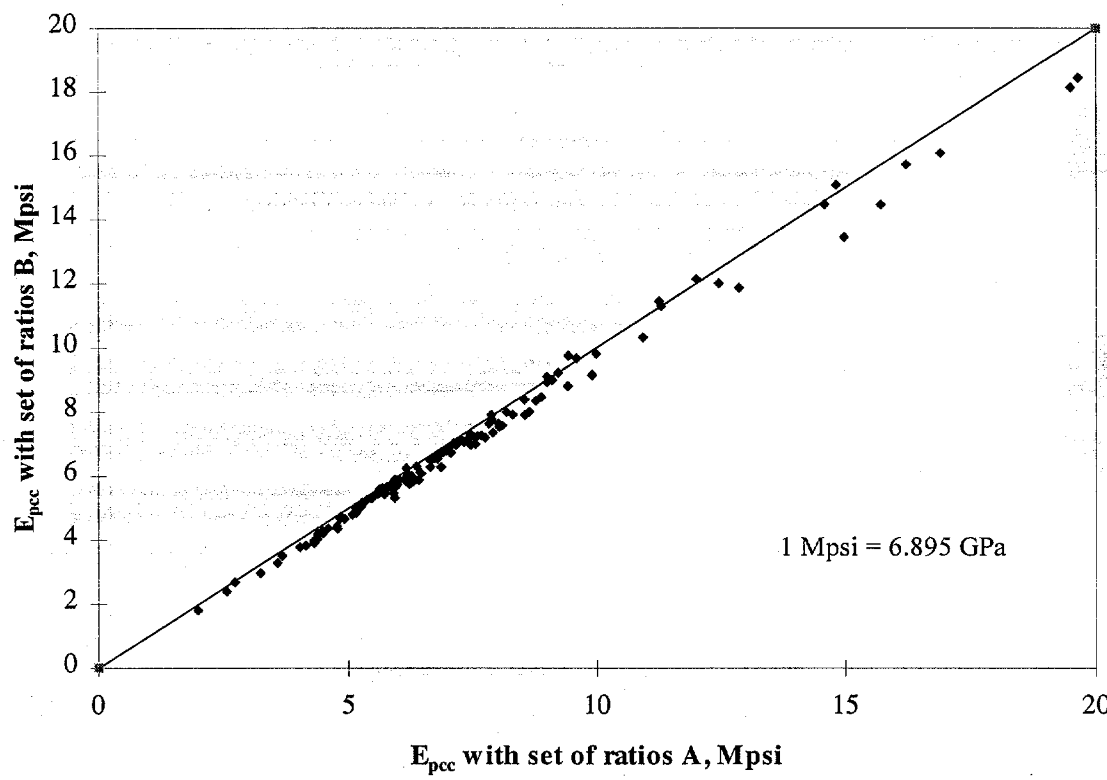


Figure 10. Comparison of backcalculated PCC moduli for two sets of modular ratio, unbonded interface between PCC plate and base.

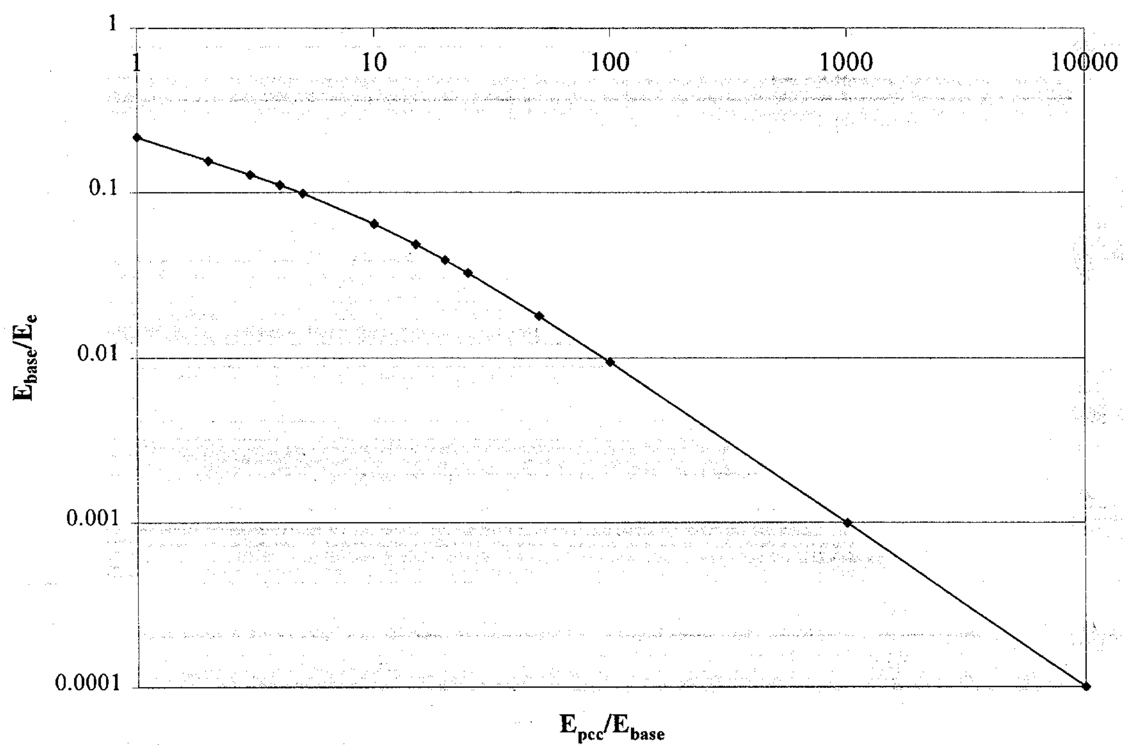


Figure 11. Effect of modular ratio on backcalculated PCC modulus of elasticity.

Table 2. Proposed moduli ratios, E_{PCC}/E_{base}.

LTPP Code	Base Type	Ratio $\beta^*=1/\beta$
1	Hot-Mixed, Hot-Laid Asphalt Concrete (AC), Dense Graded	10
2	Hot-Mixed, Hot-Laid AC, Open Graded	15
3	Sand Asphalt	50
4	Jointed Plain Concrete Pavement (JPCP)	1
5	Jointed Reinforced Concrete Pavement (JRCP)	1
6	Continuously Reinforced Concrete Pavement (CRCP)	1
7	PCC (Prestressed)	1
8	PCC (Fiber Reinforced)	1
9	Plant Mix (Emulsified Asphalt) Material, Cold Laid	20
10	Plant Mix (Cutback Asphalt) Material, Cold Laid	20
13	Recycled AC, Hot Laid, Central Plant Mix	10
14	Recycled AC, Cold-Laid, Central Plant Mix	15
15	Recycled AC, Cold-Laid, Mixed-in-Place	15
16	Recycled AC, Heater Scarification/Recompaction	15
17	Recycled JPCP	100
18	Recycled JRCP	100
19	Recycled CRCP	100
181	Fine-Grained Soils: Lime-Treated Soil	100
182	Fine-Grained Soils: Cement-Treated Soil	50
183	Bituminous Treated Subgrade Soil	100
292	Crushed Rock	150
302	Gravel, Uncrushed	200
303	Crushed Stone	150
304	Crushed Gravel	175
305	Crushed Slag	175
306	Sand	250
307	Soil-Aggregate Mixture (Predominantly Fine-Grained)	400
308	Soil-Aggregate Mixture (Predominantly Coarse-Grained)	250
319	Hot-Mixed AC	15

LTPP Code	Base Type	Ratio $\beta^*=1/\beta$
320	Sand Asphalt	50
321	Asphalt-Treated Mixture	50
322	Dense-Graded, Hot-Laid, Central Plant Mix AC	10
323	Dense-Graded, Cold-Laid, Central Plant Mix AC	15
324	Dense-Graded, Cold-Laid, Mixed-in-Place AC	15
325	Open-Graded, Hot-Laid, Central Plant Mix AC	15
326	Open-Graded, Cold-Laid, Central Plant Mix AC	15
327	Open-Graded, Cold-Laid, Mixed-in-Place AC	15
328	Recycled AC, Plant Mix, Hot Laid	10
329	Recycled AC, Plant Mix, Cold Laid	15
330	Recycled AC, Mixed in Place	15
331	Cement Aggregate Mixture	5
332	Econocrete	4
333	Cement-Treated Soil	50
334	Lean Concrete	2
335	Recycled Portland Cement Concrete	100
338	Lime-Treated Soil	100
339	Soil Cement	10
340	Pozzolanic-Aggregate Mixture	100
341	Cracked and Seated PCC Layer	25
351	Treatment: Lime, All Classes of Quick Lime and Hydrated Lime	100
352	Treatment: Lime-Flyash	150
353	Treatment: Lime and Cement Flyash	150
354	Treated: Portland Cement	50
355	Treatment: bitumen (Includes All Classes of Bitumen and Asphalt Treatments)	100
700	AC	15
730	PCC	1
999	No Base (Fictitious Base)	10000

Although these FWD tests were performed at different seasons and times of day, the relationship obtained is remarkably close to that obtained from the results of backcalculation for GPS sections under the FHWA-RD-96-198 study. This supports the present findings. A similar relationship was found for E_{PCC} (see figure 13). The following observations were also made:

1. The Best Fit 4 method was successful for a substantially higher number of FWD passes than the Best Fit 7 method.
2. For those passes for which the Best Fit 7 method was not successful, more than 90 percent of backcalculated k-values and E_{PCC} from the Best Fit 4 method are within reasonable limits (see figures 14 and 15).
3. In addition, if the outer sensor is placed near a transverse joint, Westergaard or Losberg's solutions cannot properly describe its deflection, since these solutions are developed for the interior loading case. This discrepancy should be larger for the DL model, since the ratio between the edge and interior deflections is higher for Westergaard's model than for Losberg's model.(14) Because the four-sensor configuration was recommended in other studies, the Best Fit 4 method was selected as the primary method for rigid pavement backcalculation.(2)

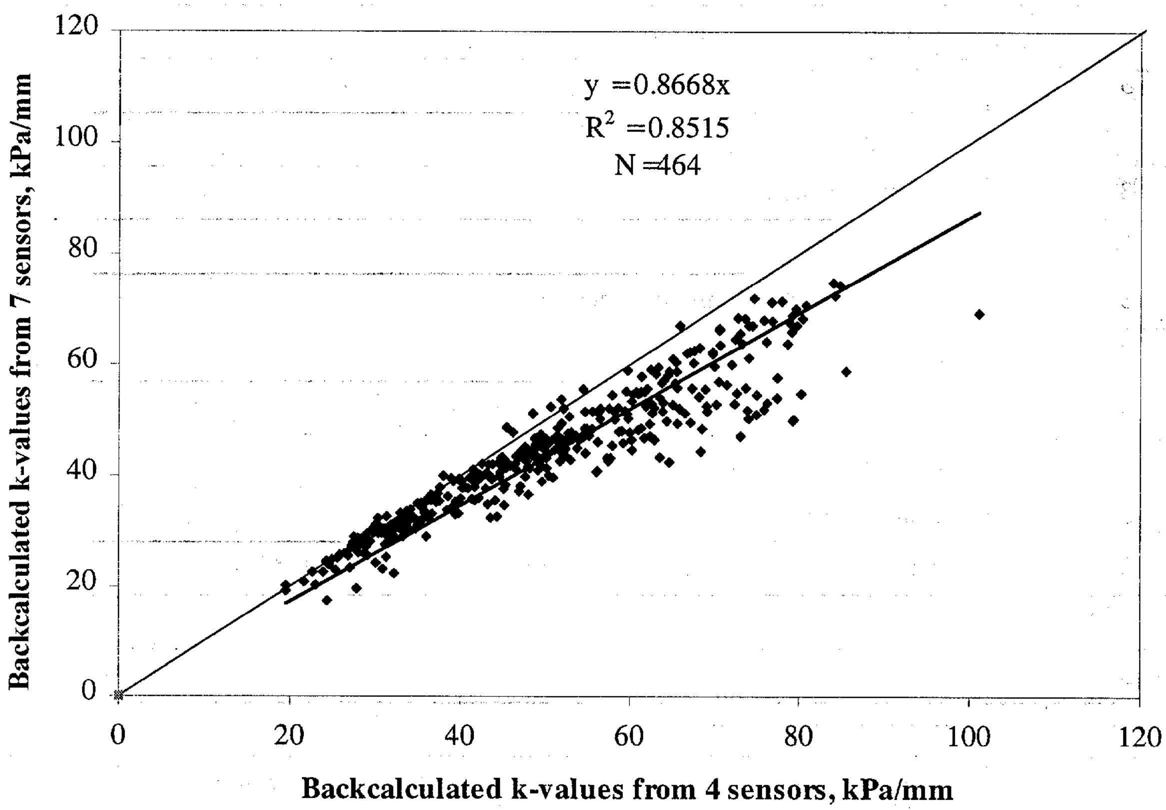


Figure 12. Backcalculated dynamic k-value for LTPP SMP sections, Best Fit 7 versus Best Fit 4.

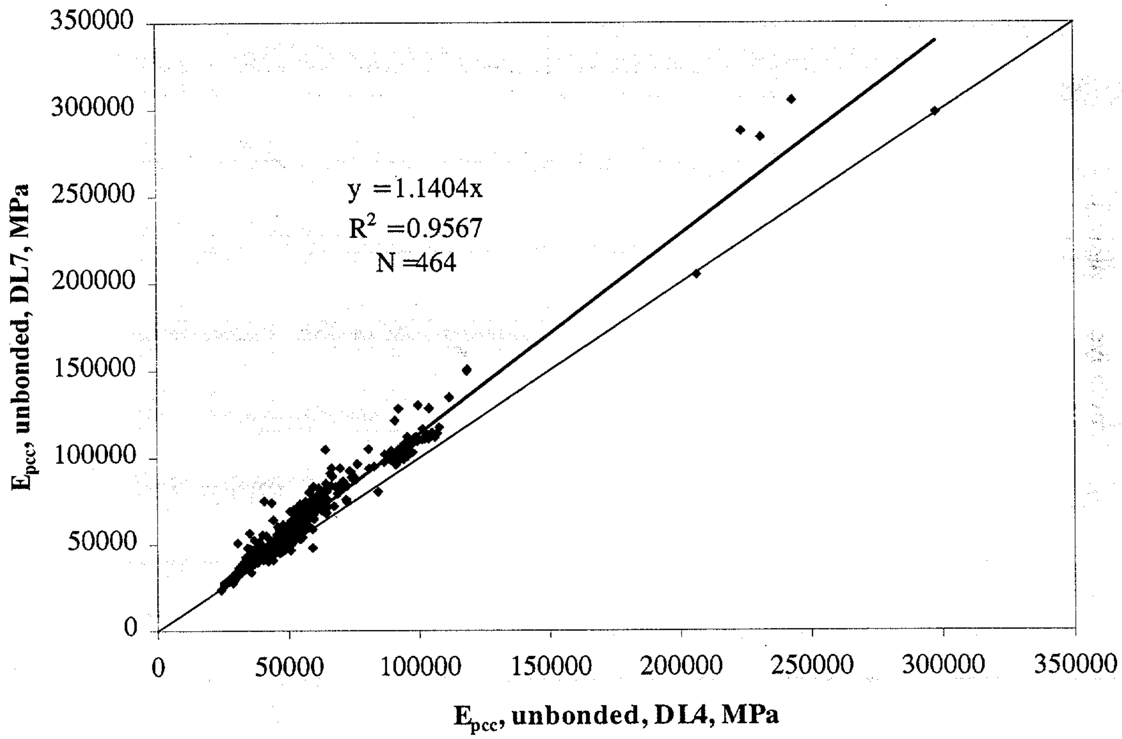


Figure 13. Backcalculated E_{PCC} for LTPP SMP sections, Best Fit 7 versus Best Fit 4 methods.

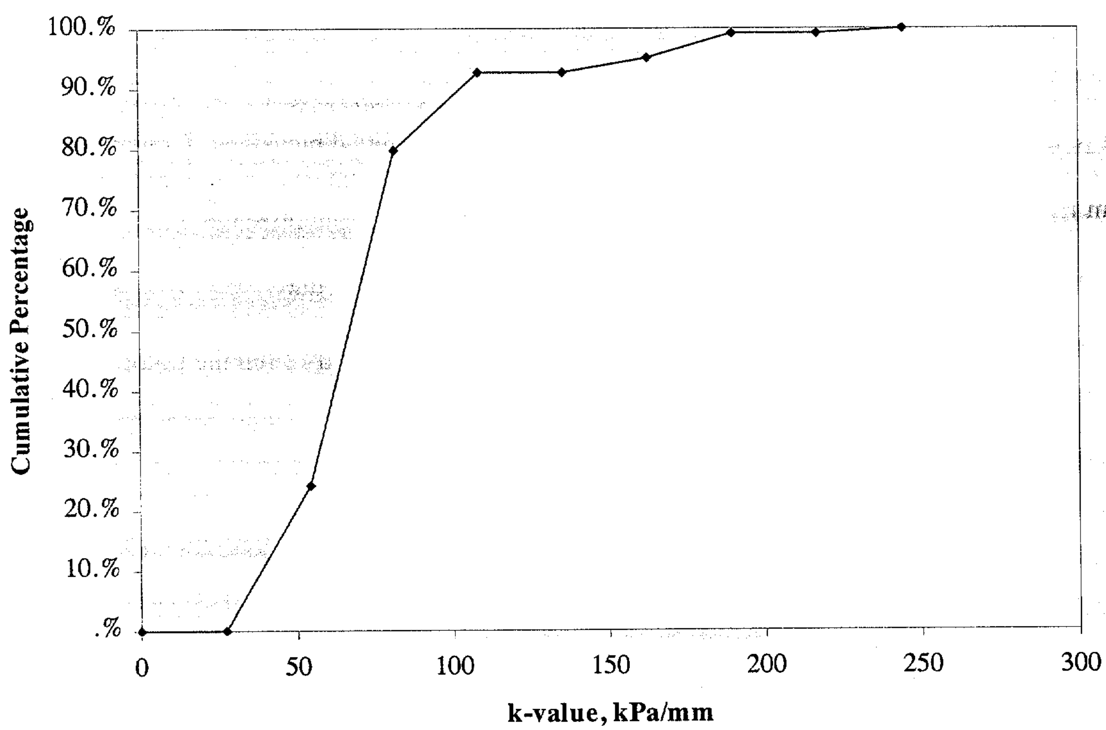


Figure 14. Distribution of k-values from Best Fit 4 method for the FWD passes for which Best Fit 7 was not successful.

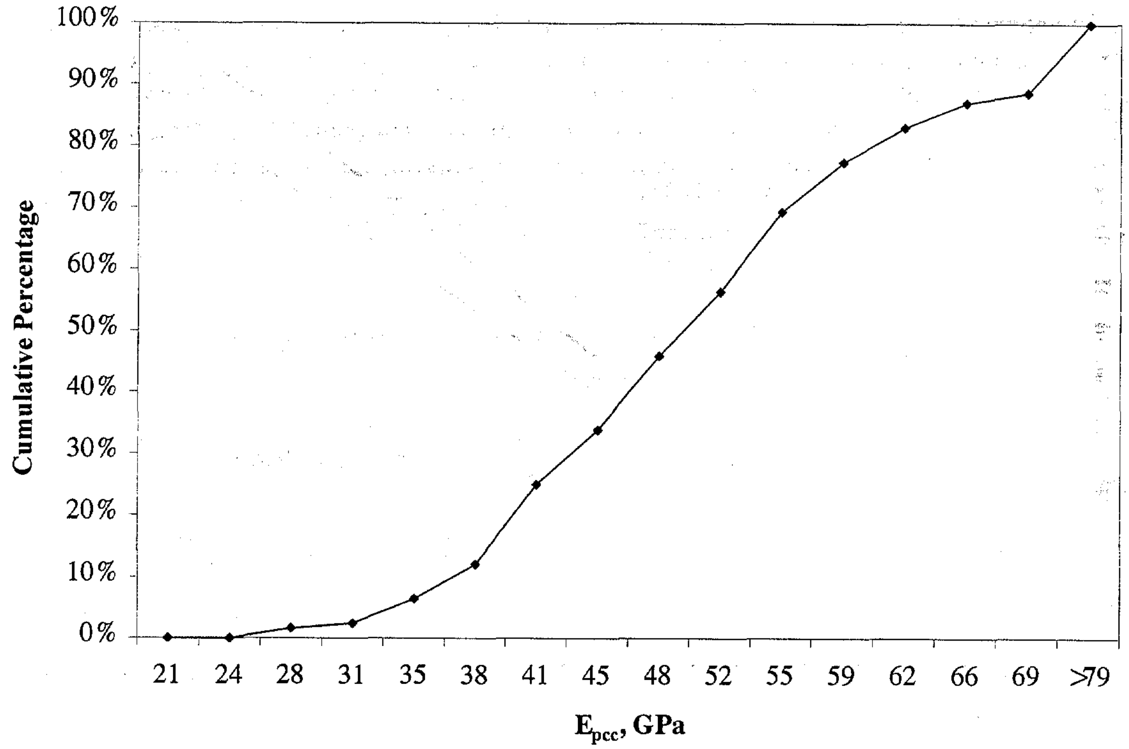


Figure 15. Distribution of E_{PCC} from Best Fit 4 method for the FWD passes for which Best Fit 7 was not successful.

Slab Size Effect

The backcalculation procedures presented above are based on Westergaard or Losberg's solutions for interior loading of an infinite plate. However, a concrete slab has finite dimensions. Crovetti developed a slab size correction for a square slab based on the results of finite element analysis using the computer program ILLI-SLAB.[14] For interior loading, he developed the following procedure:

1. Estimate ℓ_{est} from the infinite slab size backcalculation procedure.
2. Calculate L/ℓ_{est}, where L = square slab size.
3. Calculate adjustment factors for maximum deflection (d_0) and ℓ from the following equation.

$$AF_{\lambda_{est}} = 1 - 0.89434 e^{-0.61662\left(\frac{L}{\lambda_{est}}\right)^{1.04831}}$$
$$AF_{d_0} = 1 - 1.15085 e^{-0.71878\left(\frac{L}{\lambda_{est}}\right)^{0.80151}} \qquad (41)$$

4. Calculate adjusted d_0 = measured d_0 * AF_{d0}.
5. Calculate adjusted ℓ = ℓ_{est} * AF_l.
6. Backcalculate k-value and concrete E using adjusted d_0 and ℓ.

In a recent LTPP study, Crovetti's procedure was verified using an analytical closed form solution and modified for a case of a rectangular slab, eliminating the need to correct k-value based on the maximum deflection only.[2] To verify this procedure, an alternative procedure was developed using an analytical solution for interior loading of a finite size slab obtained by Korenev.[4] The solution generalizes Westergaard's solution for deflection of an infinite slab to the case of a circular slab. To find the deflection distribution in a rectangular and not very long slab for points located not too close to the edges, Korenev recommended using the solution for a circular slab with a surface area equal to the rectangular slab's area. In this study, Korenev's recommendation was modified. It is proposed that Crovetti's correction factors be applied using an equivalent square slab, L, that provides the same surface area of the rectangular and square slabs, that is,

$$L = \sqrt{L_1 L_2} \qquad (42)$$

where L_1 and L_2 are slab width and length, respectively.

This recommendation should be applied only if the slab length is no more than twice the slab width. For longer slabs, an equivalent slab size is equal to:

$$L = \sqrt{2}\, L_1 \qquad (43)$$

An alternate correction for k-value was developed. Steps 4 and 6 above are replaced by the following equation for k-value:

$$k = \frac{k_{est}}{AF_{\lambda_{est}}^{2}\, AF_{d_0}} \qquad (44)$$

This correction factor can be applied with any backcalculation procedures based on Westergaard's theory, including the Best Fit procedures.

Although the slab size correction procedure is very simple and straightforward, its application requires that slab sizes be assigned properly. This might be a significant problem for two reasons:

- Load transfer to the adjacent slabs may significantly affect effective slab length and width. Even if the load transfer efficiency at the transverse joints can be estimated from the tests at J5 and J4 (transverse joint leave and approach slab, respectively) locations, the load transfer efficiency at the longitudinal joints and at the shoulder are not known.
- For pavements with a random joint spacing, it is difficult to determine the slab length corresponding to a particular station. It is more realistic to apply slab size correction to the representative backcalculated moduli based on the average joint spacing, if necessary.

Based on these observations, it was decided not to apply any slab size correction.

Acceptability of the Results of Backcalculation

A level of discrepancy between the predicted and measured deflection basins was selected as a criterion for acceptance of backcalculation results. A relative error between measured sensor deflections and deflections calculated using backcalculated elastic parameters is defined using the following equation:

$$\varepsilon_i = \frac{w_{i,c} - w_{i,m}}{w_{i,m}} * 100\% \tag{45}$$

where ε_i = relative error for sensor i
$w_{i,c}$ = computed deflection for sensor i
$w_{i,m}$ = measured deflection for sensor i

The mean absolute relative error for a deflection basin is defined using the following equation:

$$\varepsilon_m = \frac{|\varepsilon_1| + |\varepsilon_3| + |\varepsilon_5| + |\varepsilon_6|}{4} \tag{46}$$

where ε_1, ε_3, ε_5, and ε_6 are relative errors of the sensors located 0, 305, 610, and 914 mm from the center of the FWD plate.

High mean absolute relative error indicates that the backcalculation results are not reliable. There are several reasons why this might happen. Possible error in sensor deflection measurements and deviation of the pavement system behavior from the structural model behavior can be mentioned among others (cracked slabs). Use of the backcalculated parameters with high mean error for determination of mean elastic parameters for the entire pavement sections may make those parameters less reliable. On the other hand, rejection of too many basins is also undesirable because it reduces a number of basins used for mean parameter determination. In this study, an acceptable level of the mean error was initially selected equal to 2 percent. To verify this recommendation, the following analysis was performed:

- Distribution of the mean relative errors for the GPS and SPS LTPP pavement sections were analyzed.
- Mean coefficients of subgrade reaction were calculated for the GPS and SPS LTPP pavement sections using different cutoff levels for the mean relative error.

Figures 16 and 17 present cumulative distribution of the mean relative error for DL and ES foundation models, respectively. For both foundation models, the GPS sections exhibited a higher level of discrepancy between measured and calculated deflection basins. Several factors may contribute to this effect:

- On average, the GPS sections are older than the SPS sections and exhibit higher levels of distress.
- Pavement structures of the SPS sections are more uniform than those for the GPS sections.

For the GPS sections, the backcalculation performed using both ES and DL models resulted in about 75 percent of backcalculated parameters for which ε_a is less than 2 percent. For SPS sections, more than 85 percent of backcalculated parameters were obtained for which ε_a is less than 2 percent. This leads to the conclusion that the tolerance level for ε_a is a reasonable requirement for basin acceptance in terms of numbers of retaining basins. Very few additional backcalculated points are obtained if larger than 2 percent error are included given the slope of the plots in figures 16 and 17.

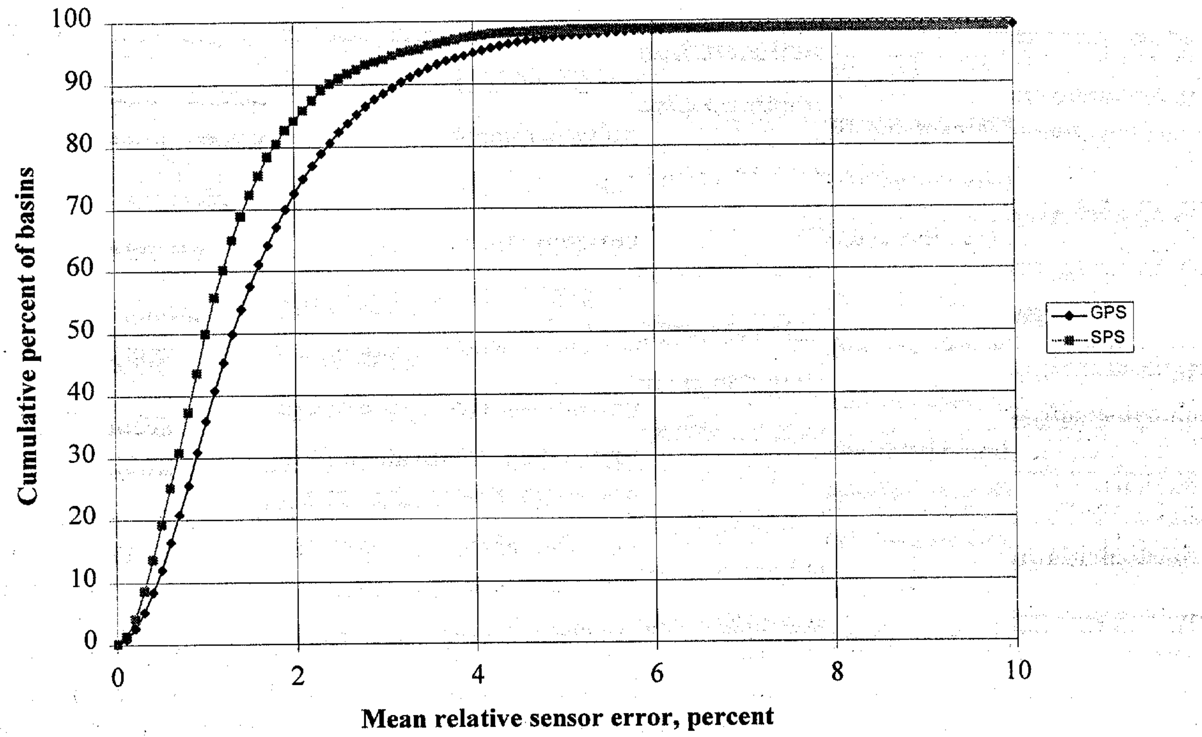


Figure 16. Cumulative chart of mean absolute values of relative errors for LTPP GPS and SPS sections (DL subgrade model).

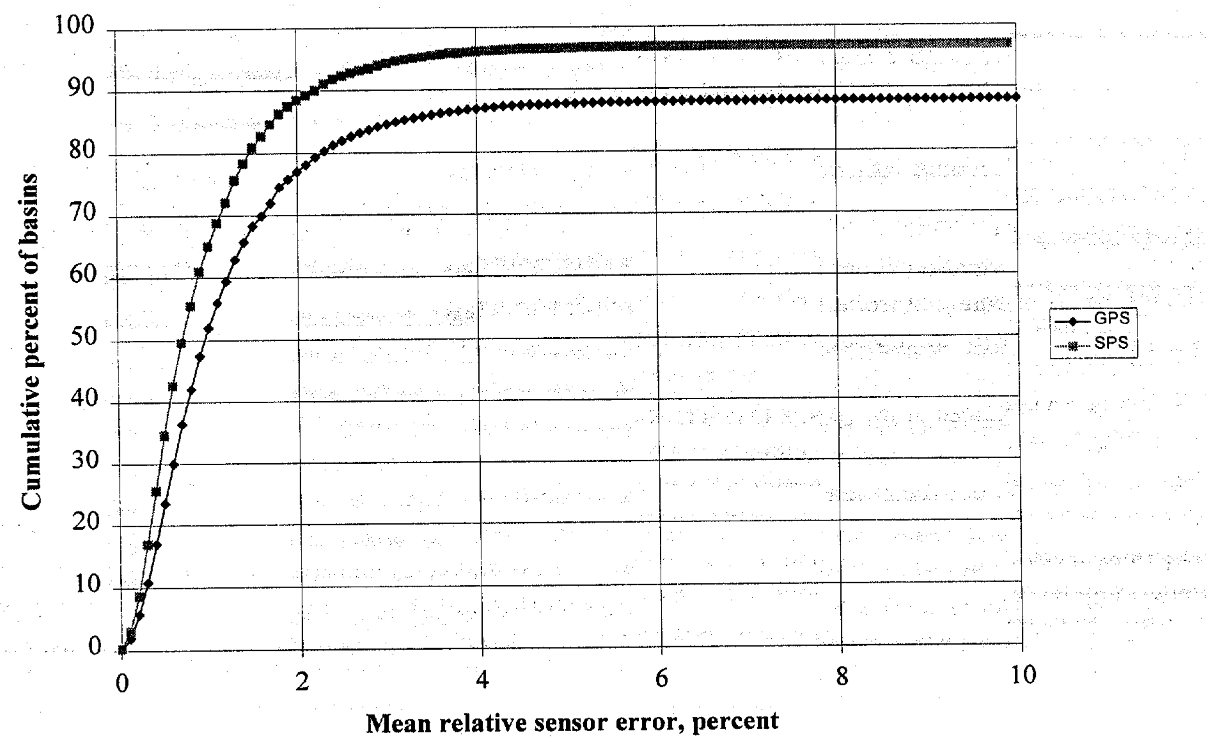


Figure 17. Cumulative chart of mean absolute values of relative errors for LTPP GPS and SPS sections (ES subgrade model).

Although a large majority of the basins resulted in less than 2 percent error, a significant number of basins exhibited a higher level of error. To investigate the effect of inclusion of those basins in the determination of the representative parameters for the LTPP sections, the mean values of the coefficients of subgrade reactions were determined for the LTPP GPS and SPS pavement sections using 2 percent, 5 percent, and 10 percent cutoff limits for acceptability of the backcalculated k-values. Figures 18 and 19 present comparisons of the mean k-values for 2 and 5 percent cutoff limits for the GPS and SPS sections, respectively. Figures 20 and 21 present such comparisons of the mean k-values for 5 and 10 percent cutoff limits for the GPS and SPS sections, respectively.

One can observe that for the vast majority of the sections a change in cutoff limit does not significantly affect mean values for the sections. On the other hand, for those sections where the effect is pronounced, an increase in cutoff leads to an increase in mean backcalculated k-values, pushing the latter to unrealistically high levels. This leads to the conclusion that the tolerance level of 2 percent for ε_a is a reasonable requirement for basin acceptance to prevent unrealistically high values of the k-value on some sections.

Backcalculation for LTPP Sections

This section describes the step-by-step procedures that were developed for routine interpretation of FWD deflection data and computation of representative elastic moduli for the LTPP test sections:

1. Obtain raw FWD deflection data and section information from IMS database.
2. Determine backcalculation pavement structure.
3. Conduct backcalculation of FWD deflection data.
4. Select interface condition between the PCC slab and the base.
5. Select backcalculated parameters for PCC layer and base.

Each step is discussed in detail in the following sections.

Determine Backcalculation Pavement Structure

Information about LTPP pavement section layers was obtained from IMS table TST_L05B. A table was created with information about layer thicknesses, material codes, and other material properties. Based on the information obtained from this table, the pavement structures used in backcalculation were determined. The following backcalculation system information was assigned:

- Thickness of the top PCC layer.
- Thickness of the base layer.
- Ratio between the PCC slab and base moduli.

The thickness of the PCC layer was assigned as an average thickness of the top PCC layer. If the underlying base layer was nonstabilized and all layers beneath this layer were of similar or lower stiffness or if the underlying base layer was stabilized and all layers beneath this layer were of lower stiffness (based on layer material classification), then the thickness and type of the base layer were assigned to be the base layer. The ratio between the PCC slab and base moduli was assigned based on base material type. Table 2 presents the proposed modular ratios of PCC and base moduli for each type of base layer.

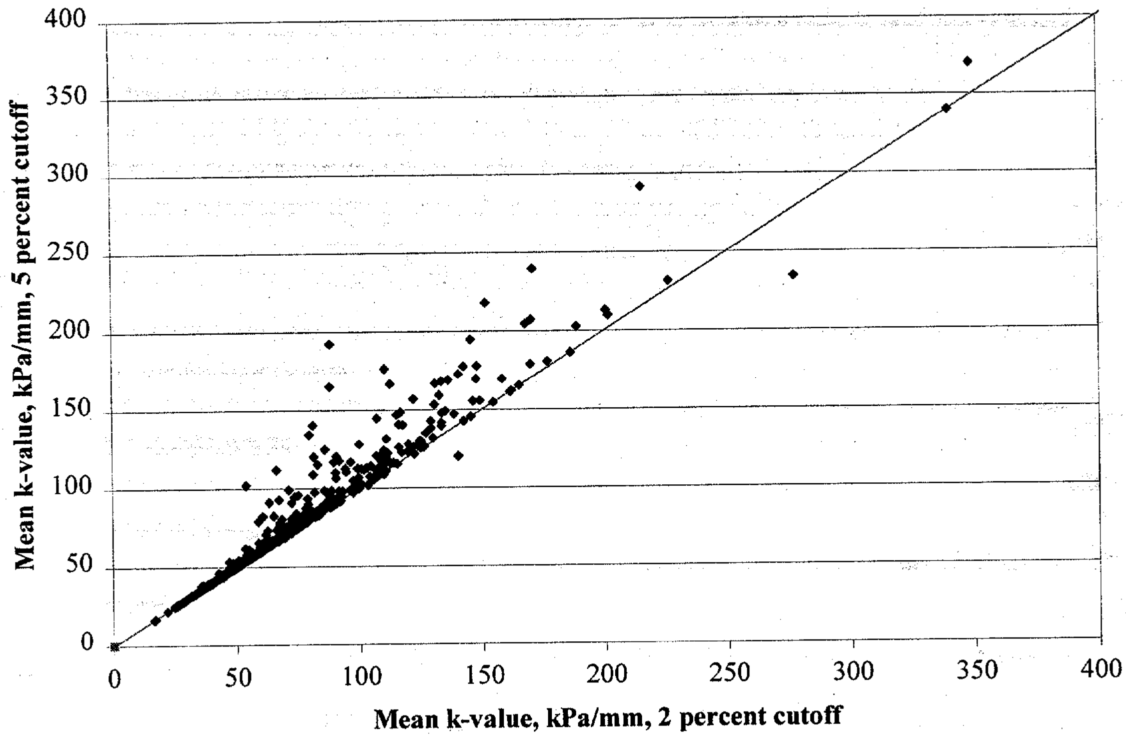


Figure 18. Comparison of mean k-values with 2 and 5 percent cutoff limit for deflection basin acceptance for LTPP GPS section.

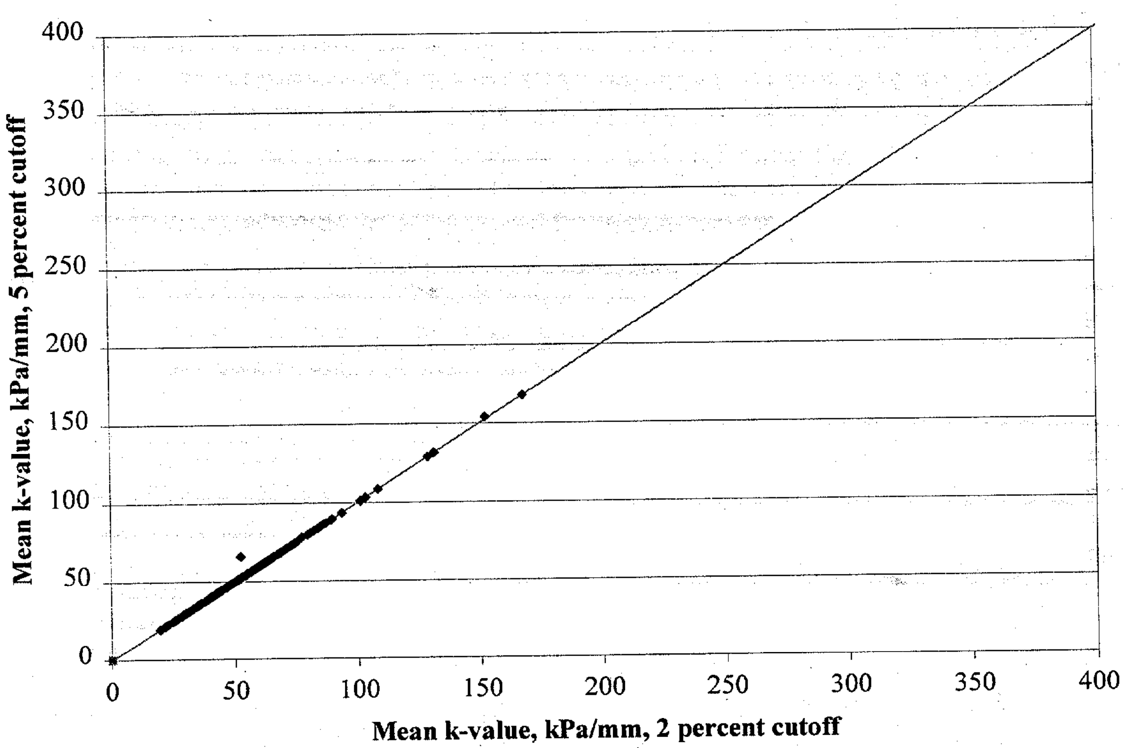


Figure 19. Comparison of mean k-values with 2 and 5 percent cutoff limit for deflection basin acceptance for LTPP SPS section.

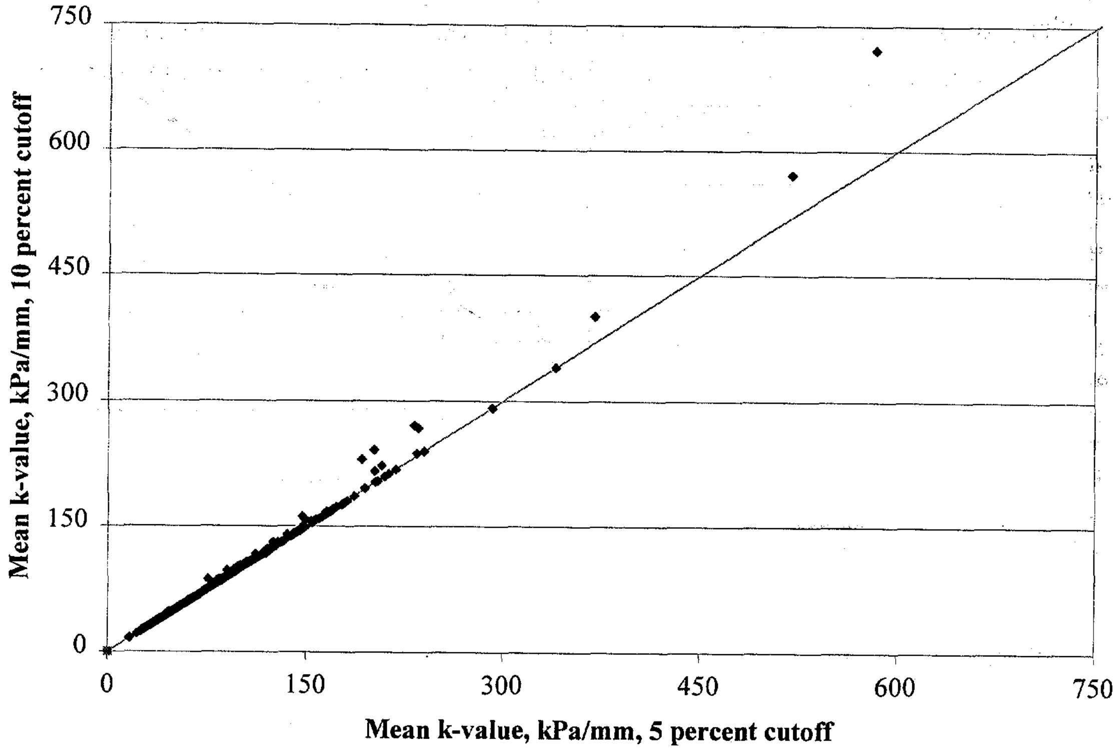


Figure 20. Comparison of mean k-values with 5 and 10 percent cutoff limit for deflection basin acceptance for LTPP GPS section.

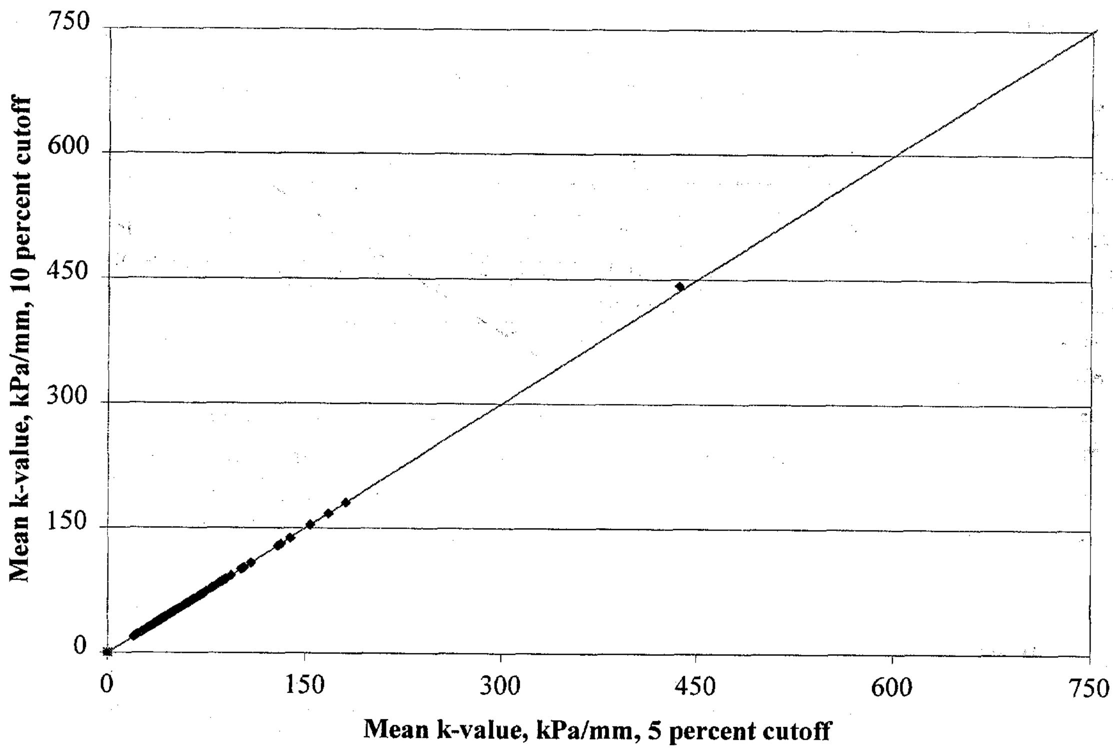


Figure 21. Comparison of mean k-values with 5 and 10 percent cutoff limit for deflection basin acceptance for LTPP SPS section.

Engineering judgment was applied if a more complex system was encountered. If necessary, two or more layers were combined. In several cases, two layers with thickness equal to h_1 and h_2 and a PCC modulus to base modulus ratio equal to β_1 and β_2 were replaced by an equivalent layer with a thickness defined as

$$h_{eff} = h_1 + h_2 \tag{47}$$

and a PCC modulus to base modulus ratio, β_{eff}, equal to

$$\beta_{eff} = \frac{h_1^3}{h_1^3 + \beta_{12}\, h_2^3 + 12\, h_1 \left(x - \frac{h_1}{2}\right)^2 + 12\, \beta_{12}\, h_2 \left(h_1 - x + \frac{h_2}{2}\right)^2} \beta_1 \tag{48}$$

where

$$x = \frac{\frac{h_1^2}{2} + \beta_{12}\, h_2 \left(h_1 + \frac{h_2}{2}\right)}{h_1 + \beta_{12}\, h_2} \tag{49}$$

and

$$\beta_{12} = \frac{\beta_1}{\beta_2} \tag{50}$$

This ratio was later used for determination of the modulus of elasticity of the equivalent base layer.

Conduct Backcalculation of FWD Deflection Data

A computer program, ERESBACK 2.0, was modified under this project into a version ERESBACK 2.2 to preprocess deflection data, perform backcalculation, and calculate a statistical summary for each FWD visit.(5) The program includes the following capabilities:

- Checks for nondecreasing deflections.
- Averages deflection basin from the same drop height at the same location.
- Backcalculates the structural properties of the slab and subgrade. Methods utilized include two subgrade models for 0, 305, 610, and 914 mm sensor configurations.
- Reports a summary of the meaningful statistics for each section.

The program was verified using the following procedure:

- Random basin results were chosen from the beginning, middle, and end of the backcalculation results file. Each basin has Best Fit results for the DL and ES subgrade models.
- The test basins were backcalculated using the AREA backcalculation method for rigid pavements.

- The results of the ERESBACK2.2 and AREA backcalculation were used as input parameters for DIPLOMAT to obtain deflections to compare with measured deflections.
- DIPLOMAT was run for each basin, treating the PCC slab as a rigid plate layer. The appropriate subgrade model was chosen (i.e., elastic half-space for ES and independent springs for DL).
- All three sets of deflections (measured from LTPP results and from AREA results) were plotted for each point and for each result.

The three sets of deflection data showed very close agreement in all cases.

Pre-Process the Raw FWD Deflection Data, Average Deflection Basins for Each Load Level, and Determine Basin Type

In the LTPP program, four individual drops at four load levels are collected at each point. In this study, for each load level, the deflection basins and the applied load were averaged using the following procedure:

- If all deflection basins are decreasing (i.e., sensor deflections decrease with an increase of distance from the center of the load plate to the sensor) then for each sensor the deflections were averaged along with the applied load.
- If all deflection basins are non-decreasing (i.e., sensor deflection for at least one sensor is higher than for a sensor located closer to the load plate) then for each sensor the deflections were averaged along with the applied load and an appropriate flag is reported.
- If at least one deflection basin for a given drop height is decreasing, all non-decreasing deflection basins and corresponding applied loads were excluded from averaging.

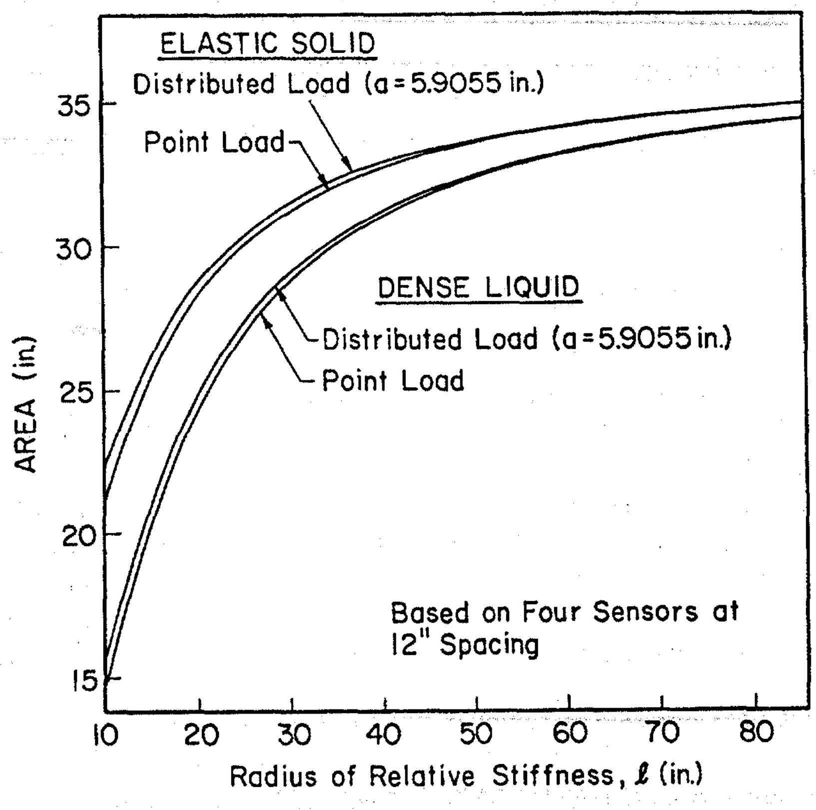
Backcalculate Subgrade Moduli and Radii of Relative Stiffness

The backcalculation program reads averaged deflection basins from the file created in the previous step. For each deflection basin with test type J1 (center of slab of JPCP or JRCP) or C1 (center of CRCP), it performs backcalculation using the Best Fit procedure using deflections from four sensors located 0, 305, 610, and 914 mm from the center of the FWD plate. The backcalculated parameters are determined for both DL and ES foundation models. Backcalculation for the DL model results in a radius of relative stiffness and a coefficient of subgrade reaction. Backcalculation using the ES model results in a radius of relative stiffness and a modulus of elasticity of the subgrade. If the resulting radius of relative stiffness is not within a reasonable interval (i.e., if it is less than 500 mm or greater than 2250 mm for the DL model and less than 500 mm or greater than 2000 mm for the ES model), then the basin is ignored.

The lower limit was selected based on the consideration that behavior of the pavement systems with too low radii of relative stiffness cannot be adequately described using a slab-on-grade model. A layered elastic model is a more appropriate analytical tool and a layered elastic backcalculation procedure should be used for backcalculation. The upper limit was assigned to recognize that backcalculation cannot also be reliable for every rigid system. As was found by Ioannides et al. (1989), an AREA-radius of relative stiffness relationship becomes almost flat for high radii of relative stiffness (see figure 22). This means that small variability in a measured basin may cause significant variability in the backcalculated radius of relative stiffness. Different upper limits for DL and ES models were selected based on the following observations:

- Radii of relative stiffness for the DL and ES models are calculated using different equations. Usually, a radius of relative stiffness is higher for the DL than for the ES model.

- As was found by Ioannides et al. (1989), the AREA-radius of relative stiffness becomes flat for lower values of ES radii of relative stiffness than for DL radii of relative stiffness.



Note: 1 in = 25.4 mm

Figure 22. Variation of AREA with radius of relative stiffness.(7)

Calculate Mean Absolute Errors

For each deflection basin, the mean absolute relative error is calculated using equations 45 and 46. For the basins for which backcalculation was not successful (i.e., no set elastic parameters were determined), an appropriate flag (relative errors equal to 99.9 percent) are reported.

For Each Deflection Basin Used in Backcalculation, Determine Backcalculated Moduli of Elasticity of the PCC Layer and Base for ES and DL Subgrade Models Separately, Using the Following Procedure:

1. Determine effective modulus of elasticity assuming effective pavement thickness equal to the thickness of the PCC layer.
2. Determine assumed ratio of moduli of elasticity of PCC and base layer using the base code.
3. Considering full bond and full slip, determine moduli of elasticity of the PCC layer and the base using the procedure developed by Ioannides and Khazanovich (equations 35, 36, 39, and 40).(12)

This procedure results in a set of four moduli of elasticity for the PCC layer and four moduli of elasticity of base layer (full bond with the base layer, DL model; full slip with the base layer, DL model; full bond with the base layer, ES model; full slip with the base layer, ES model).

Compute Statistical Summary of Backcalculated Parameters for Each FWD Pass

For each FWD pass, the mean and standard deviation parameters are determined for backcalculated radii of relative stiffness, subgrade moduli, PCC moduli, and base moduli. Only deflection decreasing basins that result in backcalculation with an average absolute error less than 2 percent are used for computing these parameters. Note that a statistical summary computation is performed independently for DL and ES subgrade models. A basin may be acceptable for the DL model but be rejected for the ES model, or vice versa.

For each FWD pass, the following parameters are determined for backcalculated radii of relative stiffness, subgrade moduli, PCC moduli, and base moduli:

- Mean value.
- Minimum value.
- Maximum value.
- Standard deviation.

Selection of the mean error equal to 2 percent as a cutoff criterion for acceptability of the backcalculation results is discussed below.

Screen Backcalculated Parameters

The backcalculated parameters for each deflection basin are compared with the corresponding mean value. If the backcalculated value differs more than two corresponding standard deviations from the mean value, an appropriate flag is reported for backcalculated values.

<u>Identify Interface Condition Between the PCC Slab and the Base</u>

In this step, the bonding conditions between the PCC slab and the base are estimated for each FWD pass. The following sub-steps are performed.

1. Import files created in the previous step into a spreadsheet.

2. If backcalculation is not successful for an FWD pass (no average modulus is reported), then the bond index is equal to 3 (interface condition is unknown).

3. Assign interface condition independently for DL and ES subgrade model backcalculation results. If the mean value for PCC modulus of elasticity assuming bonded interface is greater than 27 GPa for the DL model or 21 GPa for the ES model, then assign a bonding index equal to 1 (full bond interface); otherwise, assign a bonding index equal to 2 (full slip interface). The "cut off" limits of 27 and 21 GPa were selected by the group of experts on the basis of past experience in rigid pavement backcalculation.

4. Compare the results of backcalculations for the same sections but from different FWD passes. If the results are different, consider changing the interface condition for an FWD

pass with lower backcalculated PCC modulus to "unbonded" if it will bring the results significantly closer to each other. The justification for the interface condition adjustment is the observation that the bond interface condition does not necessarily mean presence of a physical bond between the PCC and base layers. If a PCC layer and a base are in full contact, they usually exhibit strong bond type behavior due to interface friction. However, PCC slab curling may cause separation of the PCC slab from the base. In this case, behavior of the PCC slab and the base will be more realistically described using unbonded interface condition. Since the actual interface condition is unknown, it is reasonable to assume that a significant portion of variation in backcalculated PCC moduli comes from the variation in the interface condition. Therefore, it is reasonable to adjust interface conditions appropriately if it results in less variability in backcalculated moduli.

5. Compare the results of bonding indices for the same FWD pass determined using the DL and the ES models. The following options are possible (engineering judgment should be applied):

Table 3. Bond index assigning rule.

Bond Index		
DL Model	**ES Model**	**Select**
3	3	3
3	2	2
3	1	1
2	3	2
2	2	2
1	3	1
1	1	1
2	1	2 or 1*
1	2	2 or 1*

1 - full bond interface; 2 - full slip interface; 3 - unknown interface

If both methods result in successful backcalculation but different bond indices, select the bond index that provides a PCC modulus of elasticity that is more realistic and closer to the results from other FWD passes.

Select PCC Layer and Base Backcalculated Parameters

Based on the bond index determined from the previous step, select appropriate statistical parameters for backcalculated moduli of PCC and base layers for inclusion in the LTPP database.

CHAPTER 3. BACKCALCULATION FOR GPS AND SPS SECTIONS

This section presents the results of backcalculation for GPS and SPS rigid pavement sections. The backcalculation analysis was performed for 331 LTPP GPS and SPS rigid pavement test sections. Data from a total of 645 FWD visits were analyzed. The deflection data were downloaded during the spring of 1998 from IMS table MON_DYNATEST_DROP_DATA. Information about LTPP pavement section layers was obtained from IMS table TST_L05B (September 1999 release). This section presents specific aspects of implementation of the backcalculation procedure described in chapter 2 and discusses the results of backcalculation. It will be shown that, for the majority of cases, reasonable results were obtained.

Selection of Pavement Structure

As discussed in chapter 2, backcalculation procedures used in this study model rigid pavement systems as two-layered plates resting on a DL or ES foundation. To backcalculate subgrade elastic parameters, k-value and modulus of elasticity of subgrade, and radii of relative stiffness, no additional information is required. However, to determine elastic moduli of the plate layers, the thicknesses of these layers must be assigned. The procedure also requires the user to assign a ratio between the elastic moduli of these layers. For all LTPP GPS and SPS sections, thickness of the upper layer was assigned as the average thickness of the top PCC layer obtained from the IMS database. The ratios were assigned based on the material code of the base layer (see table 2 and the discussion in chapter 2).

For the majority of the sections, the thickness of the lower layer in the backcalculation analysis was assigned as the average thickness of the second from the top layer. Exceptions were made for the following sections shown in table 4.

Backcalculation of FWD Deflection Data

ERESBACK 2.2[3] was used in this project to pre-process deflection data, perform backcalculation, and calculate a statistical summary for each FWD site visit. Since FWD testing of LTPP rigid pavement sections is performed for three load levels, up to three deflection basins are available for each FWD station (some basins may have been rejected earlier for not passing quality control checks).

The total number of backcalculated basins for the GPS and SPS LTPP sections was 35,502. A total of 25,095 and 27,083 basins resulted in successful backcalculation for DL and ES foundation models, respectively. This corresponds to 70 and 76 percent of all basins. A basin could be rejected for one of three reasons:

- The deflection basin was nondecreasing.
- The backcalculation program was not able to determine proper elastic parameters.
- The mean of absolute values of relative error for all four sensors was higher than the tolerable level of 2 percent.

The main parameter used to evaluate the results of backcalculation was the mean of absolute values of relative sensor errors, ε_a, defined by equation 46. For most sections, only a small fraction of the total number of FWD basins was rejected.

Table 4. Exceptions in assignment of base parameters.

Sections	Assigned Base
133011 and 133015	The total thickness of the second and the third from the top layers was assigned. The ratio was assigned based on the code of the third layer
069048, 069049, 069017, 089019, 089020, 189020, 209037, 269029, 269030, 276300, 279075, 289030, 395569, 399006, 399022, 404155, 429027, 483569, 483845, 489167, 489355, 899018	PCC overlays. The thickness of the underlying PCC layer was assigned.
327084	The total thickness of the second, third, and fourth from the top layers was assigned. These layers have the same code, which was assigned as a code for the base layer.
284024,285006,313033,385002,403018,483003,483010,483699,483719,484146,484152,485024,485154,485287,485301,485310,485317,485323,485335,485336	The total thickness of the second and the third from the top layers was assigned. The equivalent ratio was derived using the procedure described in chapter 2.
485283 and 485284	The total thickness of the third and the forth from the top layers was assigned. The equivalent ratio was derived using the procedure described in chapter 2.

For some sections, only a few deflection basins along the section obtained acceptable backcalculated parameters. Figure 23 shows the frequency distribution of the percentage of rejected deflection basins after backcalculation using the DL model. For more than 85 percent of the FWD site visits, more than 30 percent of backcalculation basins within the site were accepted. On the other hand, many sections with less than 30 percent accepted basins within the site exhibited unrealistic mean values of backcalculated parameters. Figures 24 and 25 present comparisons of mean values of distributions of backcalculated k-values for all sections and sections with greater than 30 percent accepted basins (screened sections) for the GPS and SPS tests, respectively. One can observe that screened sections exhibit a smaller percentage of unrealistically high k-values. Based on these observations, it was decided to exclude FWD site visits for a section with more than 70 percent rejected basins and to not include a statistical summary for these sections in the IMS database.

Effect of Load Level

It is known that the results of backcalculation for concrete pavements usually do not depend on load level if the load level is sufficiently large. The results of this study support this conclusion. Figures 26 and 27 show histograms of coefficient of variation in backcalculated k-value at a particular location based on backcalculation using the DL model from three load levels. Figures 28 and 29 show histograms of coefficient of variation in backcalculated modulus of elasticity of subgrade and corresponding radii of relative stiffness based on ES backcalculation. The highest variability was observed in backcalculated k-values, although the median coefficient of variation in k-value is less than 5 percent and, for more than 80 percent of the stations, the coefficient of variation is less than 10 percent. Variability in backcalculation results from the ES model was smaller than from the DL model, and variability in subgrade parameter is significantly higher than in radii of relative stiffness for both models.

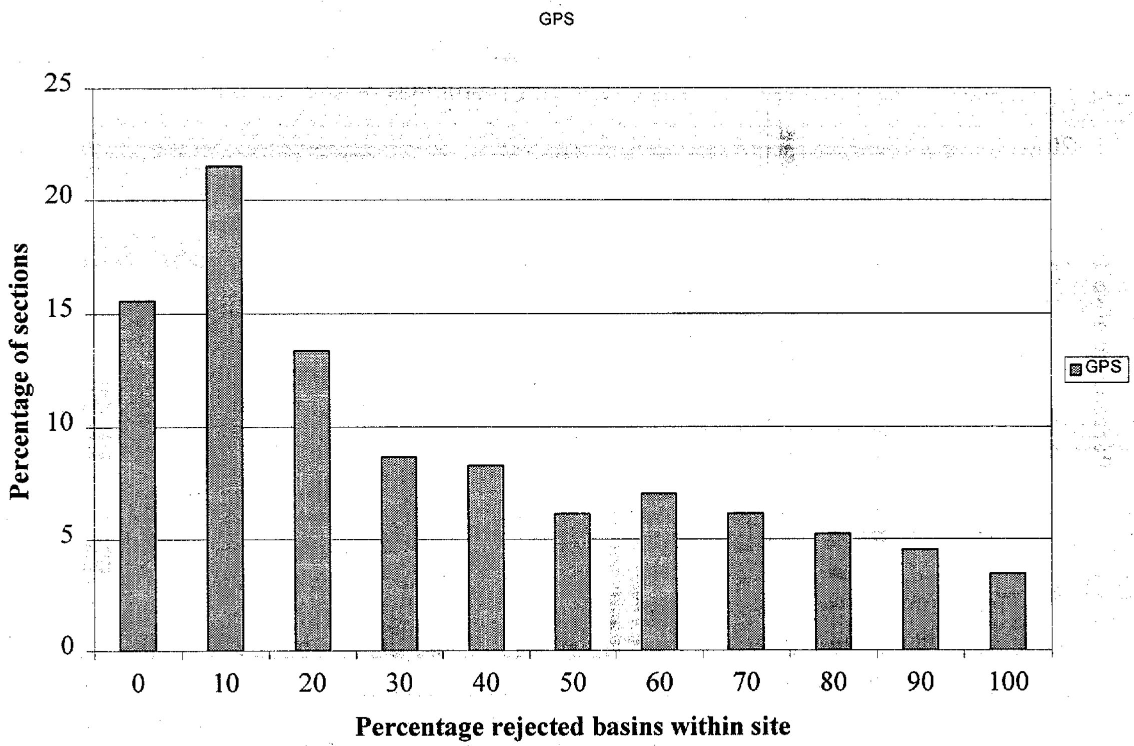


Figure 23. Percentage of rejected backcalculation basins for FWD visits for GPS sections.

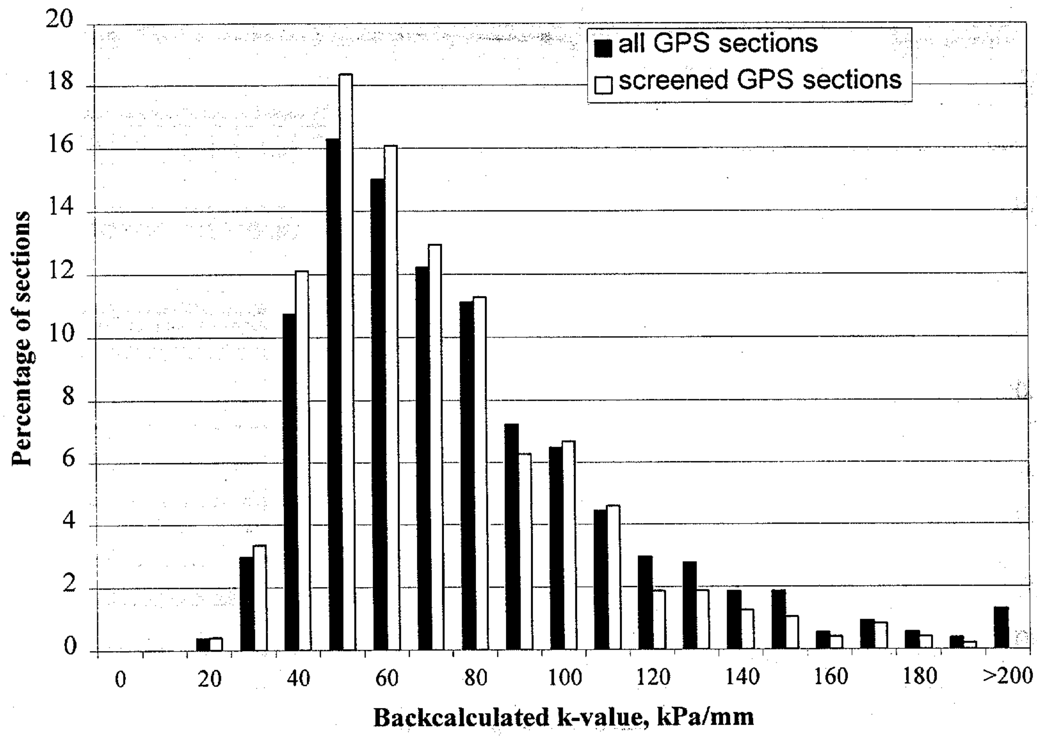


Figure 24. Frequency distribution of backcalculated k-values for GPS LTPP sections (screened sections are those with less than 30 percent deflection basins rejected).

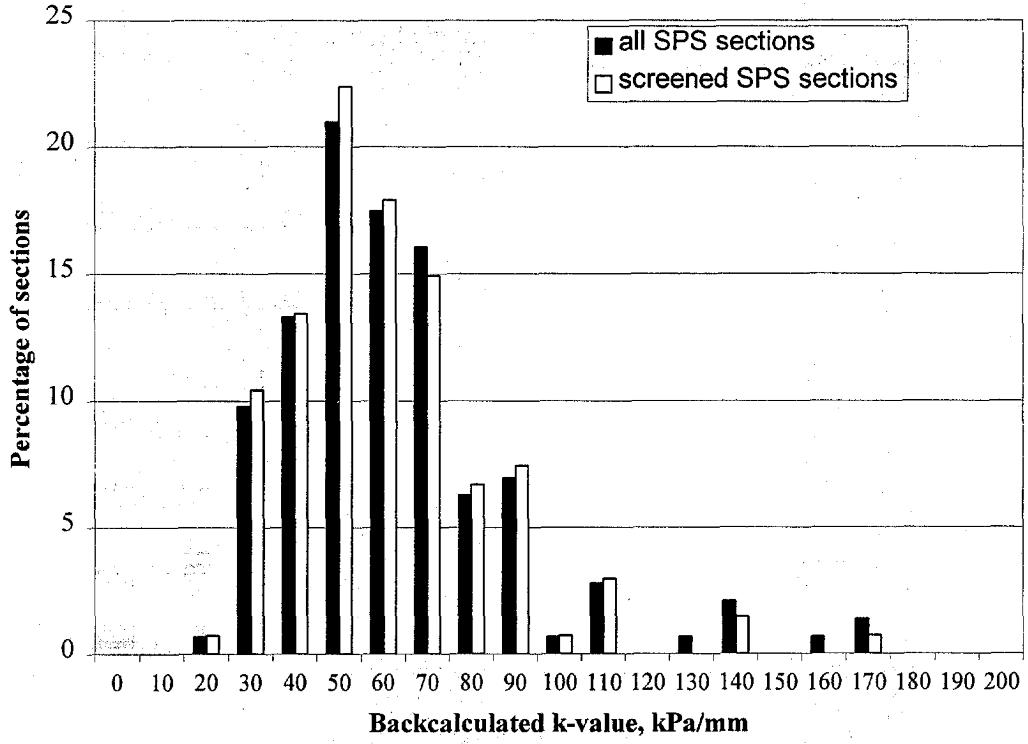


Figure 25. Frequency distribution of backcalculated k-values for SPS LTPP sections.

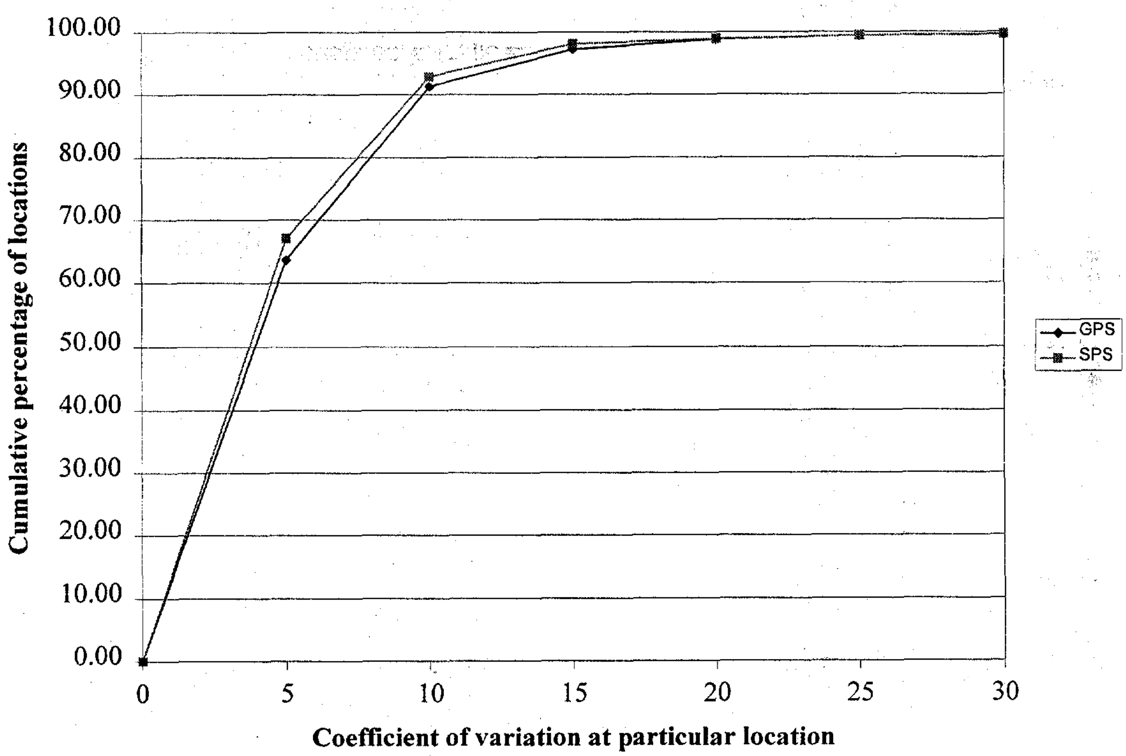


Figure 26. Coefficient of variation in backcalculated k-value for multiple load levels (GPS and SPS sections).

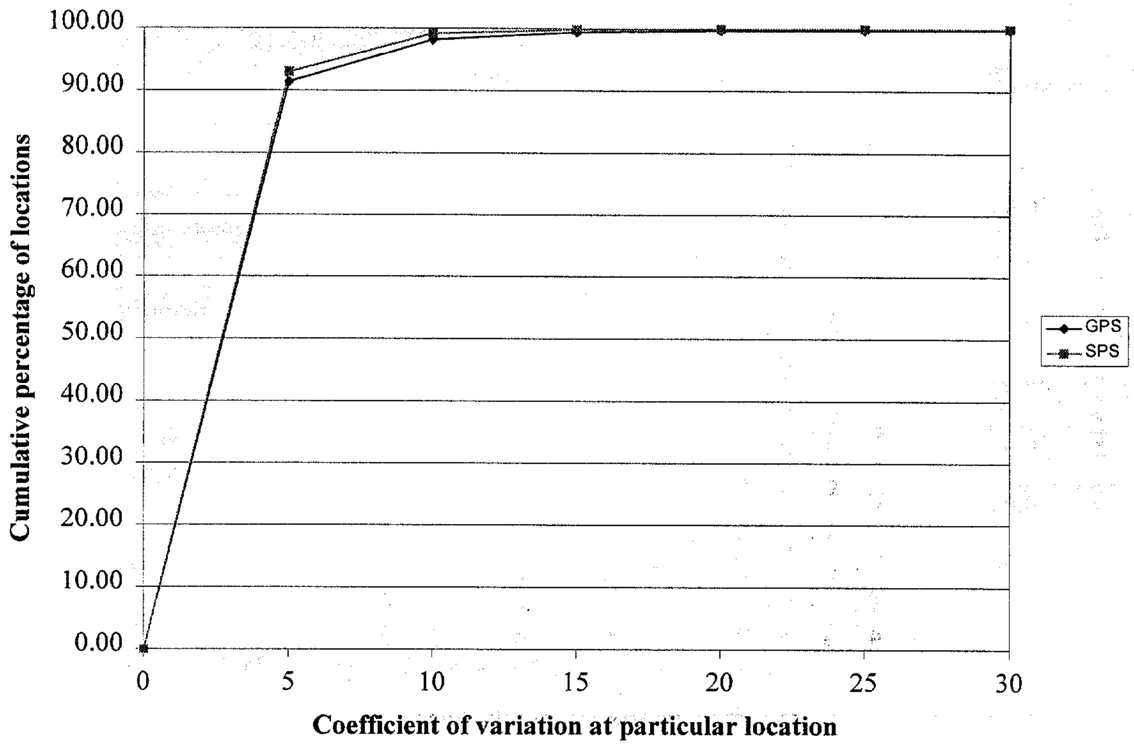


Figure 27. Coefficient of variation in radius of relative stiffness (DL model) for multiple load levels (GPS and SPS sections).

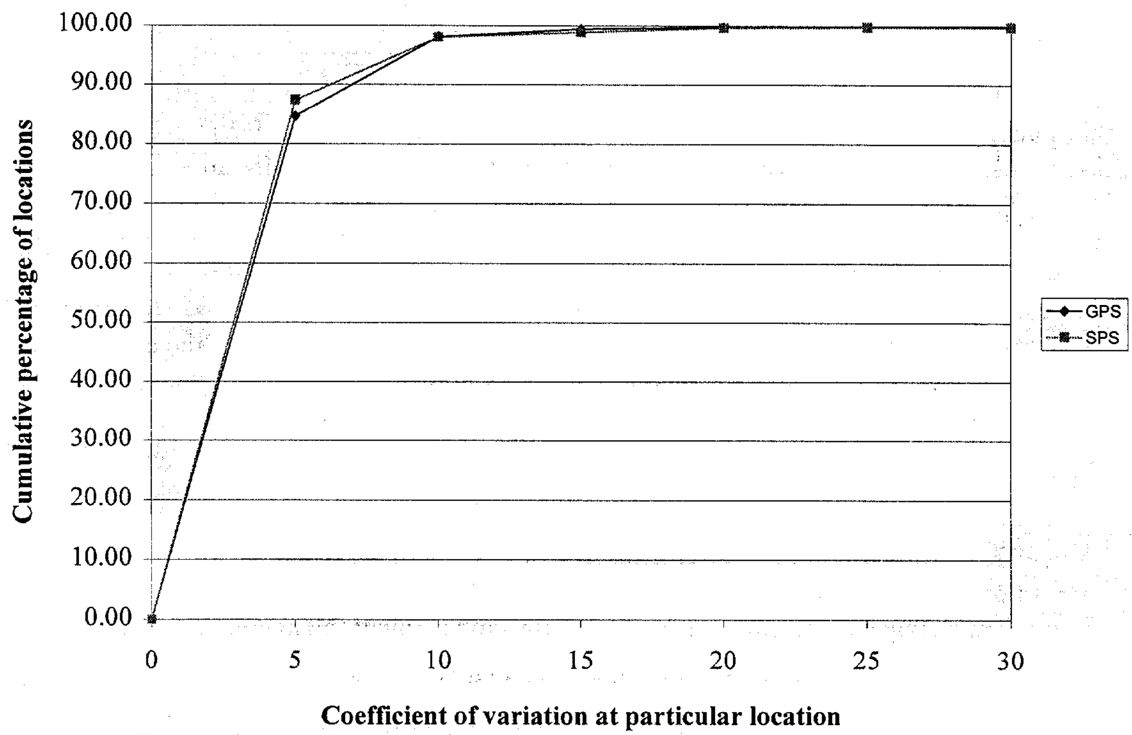


Figure 28. Coefficient of variation in backcalculated modulus of elasticity of subgrade for multiple load levels (GPS and SPS sections).

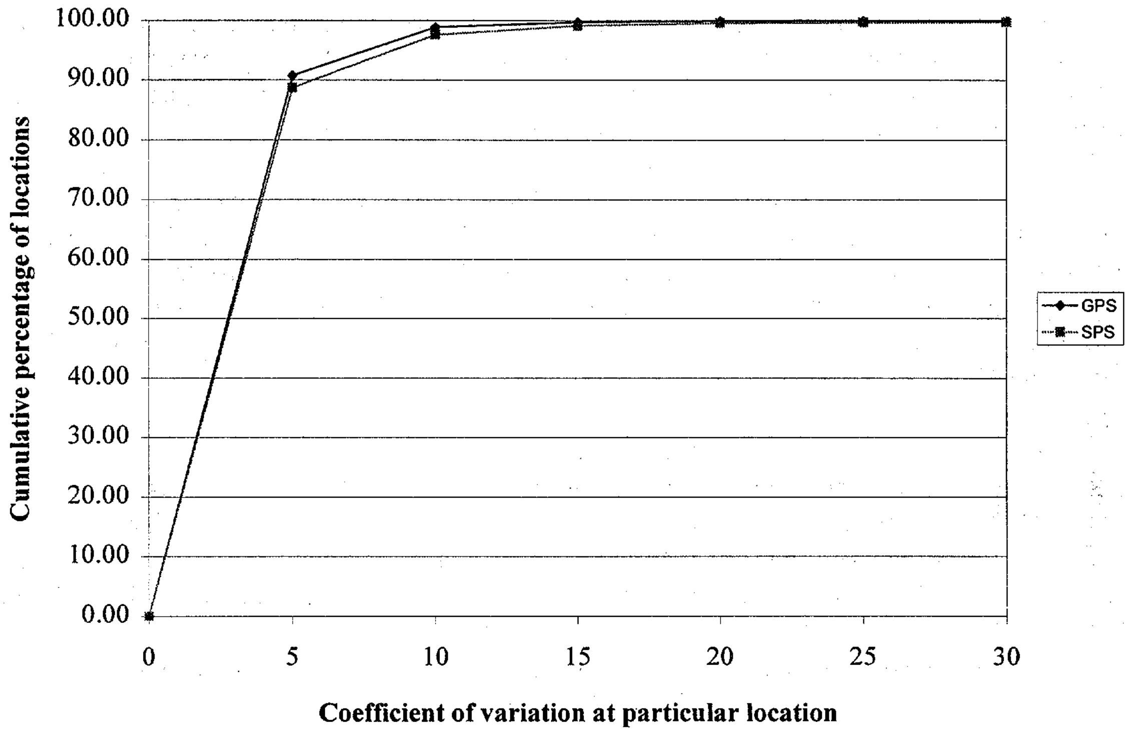


Figure 29. Coefficient of variation in radius of relative stiffness (ES model) for multiple load levels (GPS and SPS sections).

Variability in Backcalculated Parameters Along Section Length

In this study, mean values and standard deviations were calculated for all FWD visits to GPS and SPS sections. The mean backcalculated values are stored in the LTPP IMS table MON_DEFL_RGD_BAKCAL_SECT. However, only parameters from FWD visits that resulted in more than 30 percent of acceptable backcalculation basins were recommended for inclusion in the IMS database. To further examine how well these mean values represent pavement section properties, distributions of coefficients of variation of backcalculated parameters for FWD visits were analyzed. Figures 30 and 31 show cumulative frequency distributions of the coefficient of variation of backcalculated subgrade moduli, moduli of elasticity of concrete, and radii of relative stiffness obtained using the DL and ES models. The coefficient of variation in backcalculated parameters is less than 20 percent for about 80 percent of pavement sections. As stated by Hall et al.:(2)

> A coefficient of variation in backcalculated k that is less than 20 percent after screening of outliers is reasonable. Significantly higher k coefficients of variation suggest significant changes in the subgrade soil type, the embankment thickness, or the depth to bedrock.

Other sources of variability, such as variability in layer thickness and layer conditions, may play a role. Similar observations apply for moduli of elasticity of subgrade determined using the ES model, as well as for concrete moduli of elasticity.

For radii of relative stiffness, a lower level of a coefficient of variation is required because other results of backcalculation are very sensitive to this parameter. As a rule of thumb, a coefficient of variation in backcalculated radius of relative stiffness less than 10 percent after screening of outliers is considered reasonable. For both DL and ES subgrade models, more than 80 percent of pavement sections have a coefficient of variation less than 10 percent.

Although the majority of the pavement sections exhibit acceptable coefficients of variation, for some sections variability of backcalculated parameters along section length was found to be significant. In this case, mean values may not be representative parameters for the sections. One of the options explored in this study was to divide the LTPP sections with high variability in backcalculated values into smaller subsections with more uniform characteristics. This option was rejected for two reasons:

- Several sections with high variability did not show noticeable trends in backcalculated parameters from one end to another. Therefore, no uniform subsections could be identified. For example, the coefficient of variation of backcalculated k-value for section 537409 from the FWD visit on April 15, 1997, was 41 percent. However, as shown in figure 32, the section cannot be divided into two uniform subsections.
- Several sections showed uniform subsections for one FWD visit but showed different trends for another visit. Figure 33 shows backcalculated subgrade modulus of elasticity for section 553014 for different test dates. It can be seen from the results from April 15, 1993, that the subgrade is becoming stiffer near the end of the sections. The FWD testing conducted on August 18, 1993, shows the reverse trend, with subgrade stiffness decreasing near the end of the section.

In addition, variation in backcalculated values may be caused by changes in curling conditions during FWD testing throughout a day rather than variation in the material properties. Therefore, it was recommended that the mean values be reported in the NIMS along with the corresponding standard deviations, and minimum and maximum values because high variability in backcalculation results may be useful information for future research studies.

Subgrade Moduli

One purpose of backcalculation is to evaluate the level of support provided by the lower layer in the pavement system, including natural subgrade. Backcalculation using DL and ES subgrade models results in characterization of subgrade using two different parameters: k-value and modulus of elasticity of subgrade. GPS and SPS LTPP rigid pavement section support conditions vary from soft, fine-graded material to rock subgrade. Therefore, it is not surprising that backcalculated parameters vary widely.

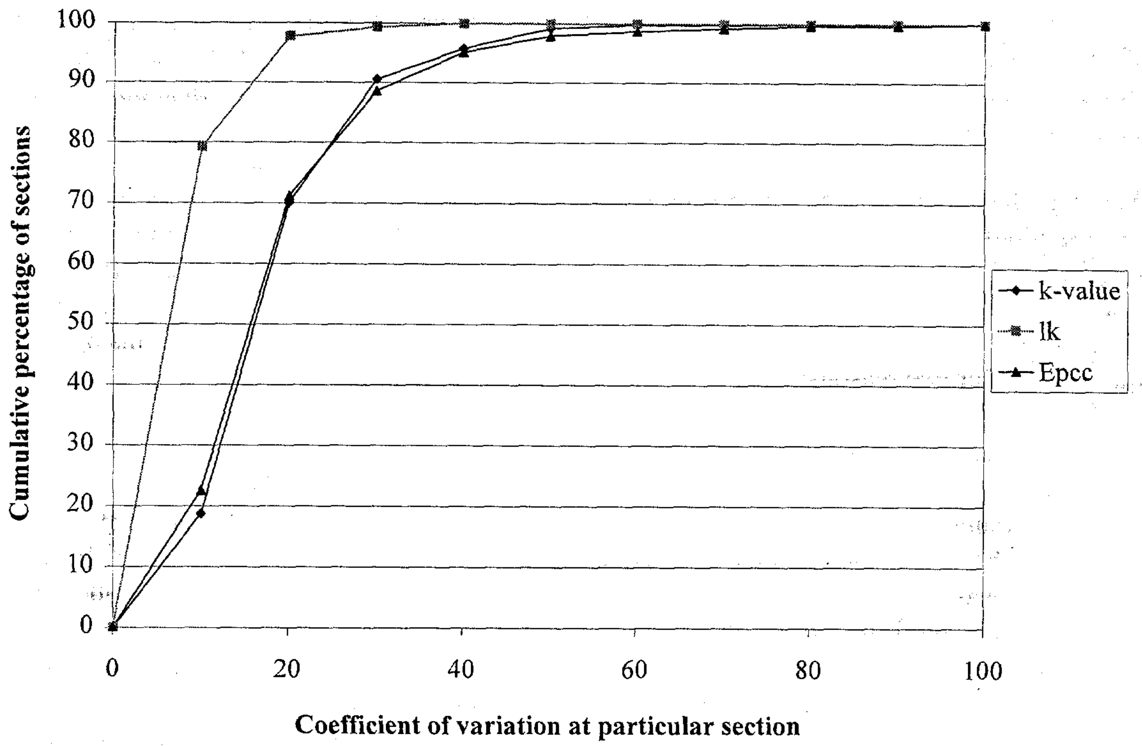


Figure 30. Coefficient of variation in backcalculated parameters along project length (DL model).

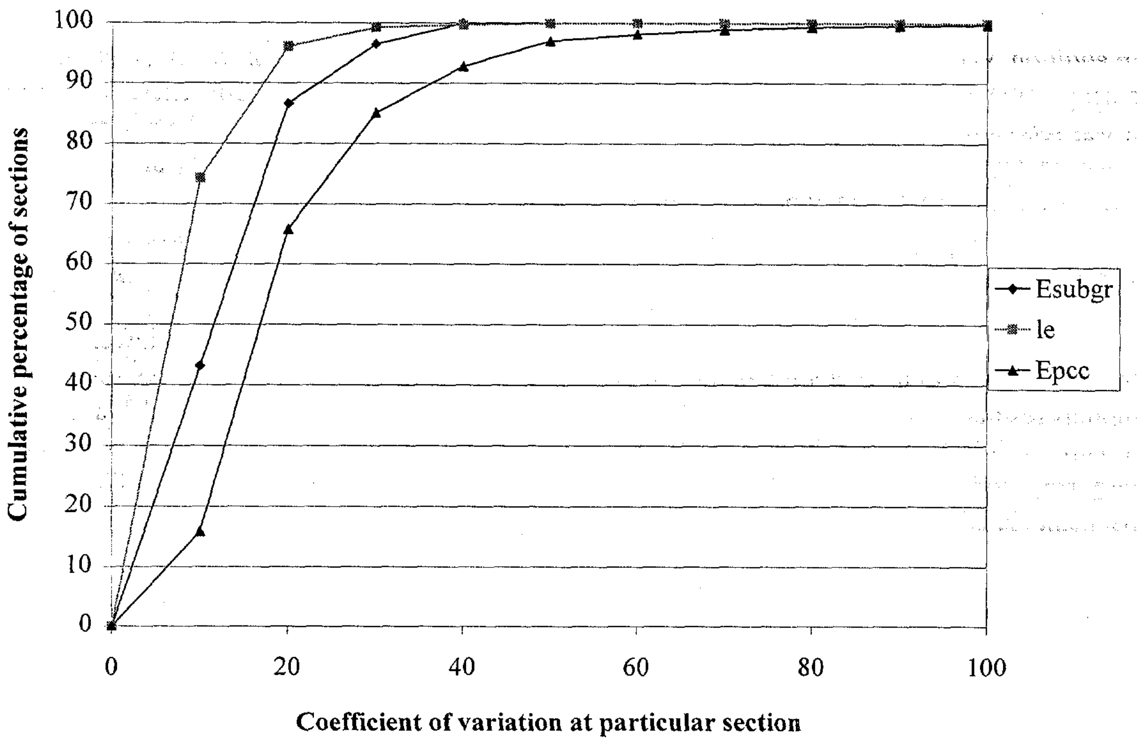


Figure 31. Coefficient of variation in backcalculated parameters along project length (ES model).

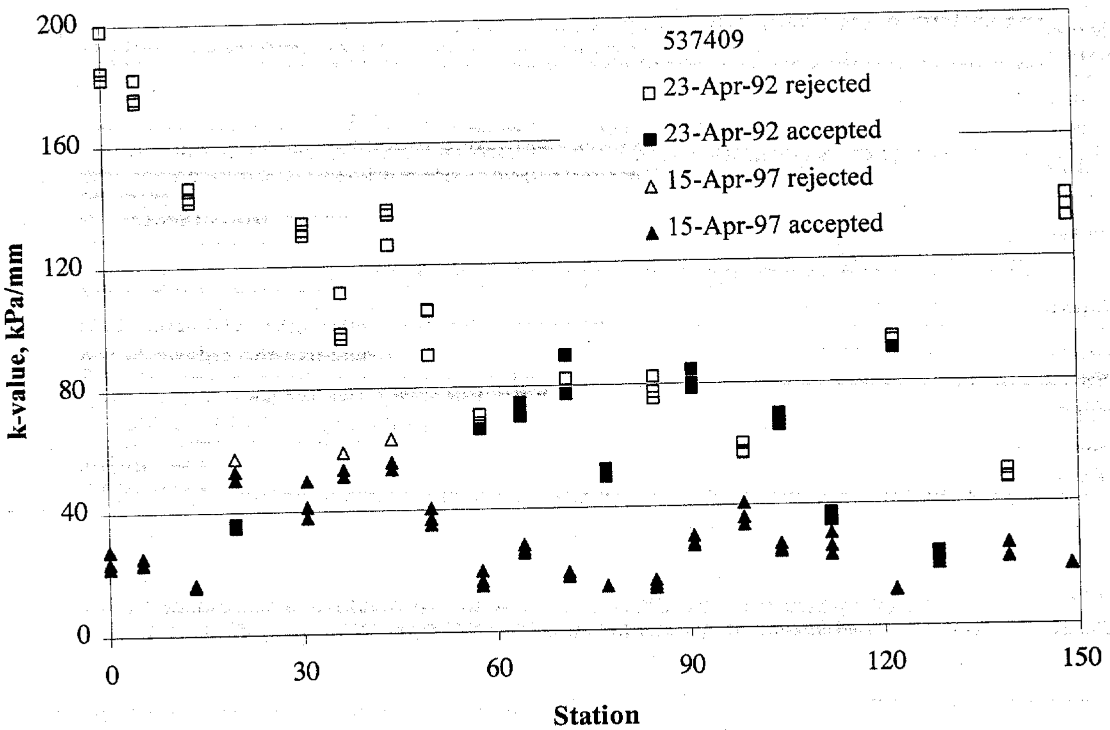


Figure 32. Backcalculated k-values for section 537409.

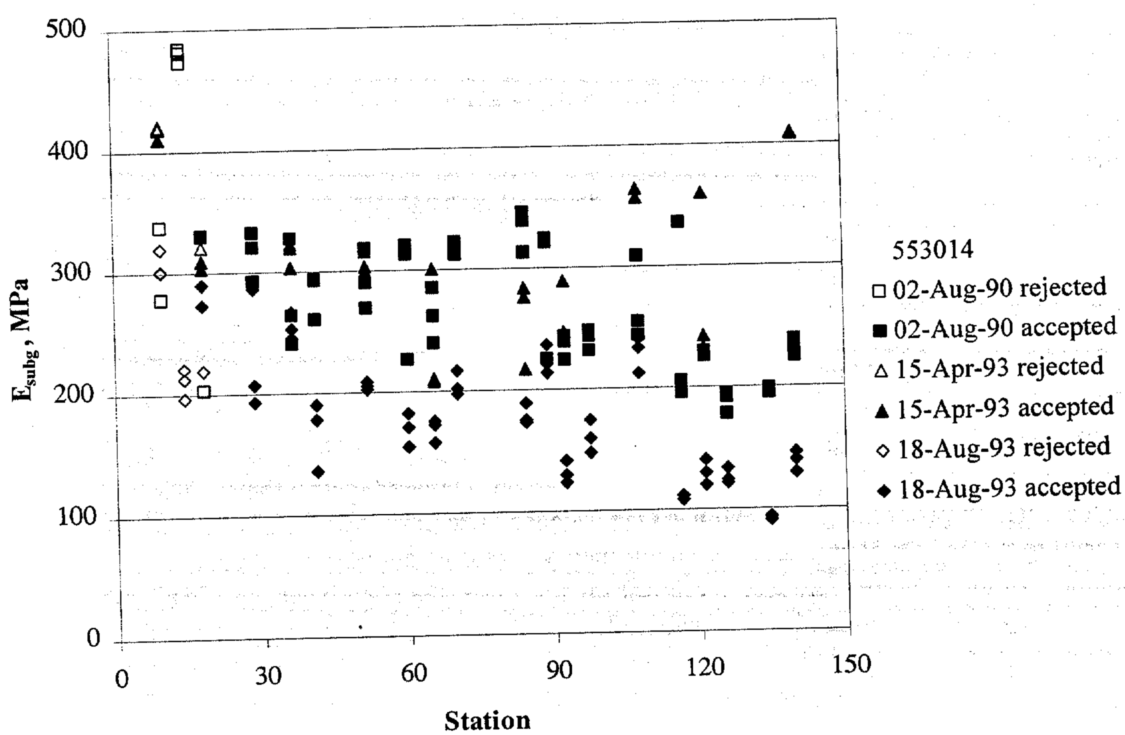


Figure 33. Backcalculated modulus of elasticity of subgrade for section 553014.

Figures 34 and 35 present the frequency distribution of mean backcalculated k-values and moduli of elasticity for GPS and SPS LTPP rigid pavement sections. As expected, the majority of the sections exhibited k-values between 40 and 110 kPa/mm and subgrade moduli of elasticity between 100 and 275 MPa. Only a few sections exhibited much higher subgrade moduli. The most likely explanation of this effect is the presence of stiff subbase layers and coarse-grained subgrade (sections 323013, 465020, 455017, and 455034) or shallow bedrock (sections 485301 and 42C430).

As in the recent FHWA-sponsored study (Hall et al.[2]), poor correlation between subgrade type and subgrade parameters was found. This is thought to happen because the subgrade types identified in the LTPP database may only describe the top 1 to 2 m of material beneath the pavement layers. However, on average, coarse-grained subgrade exhibited higher values of subgrade reaction and modulus of elasticity than fine-grained subgrades, as shown in figures 36 and 37. The results of the statistical t-test confirmed the significance of the difference (p-value is less than 0.0001 for k-values and moduli of elasticity).

The results of backcalculation for the rigid LTPP GPS and SPS sections were used to compare backcalculated mean coefficient of subgrade reactions for each section with the corresponding backcalculated subgrade moduli of elasticity. Figure 38 shows that, as expected, higher moduli of elasticity correspond to higher coefficients of subgrade reaction, and a very good correlation was observed. A simple linear regression resulted in the following model:

$$k = 0.296\ E_{subgr}$$

$$R^2 = 87.2\%$$
$$N = 596$$
$$SEE = 9.37\ \text{kPa/mm}$$

where

k = coefficient of subgrade reaction, kPa/mm
E_{subgr} = subgrade modulus of elasticity, MPa

Even though this equation shows a very good correlation between the k-value and modulus of elasticity of the subgrade, it should be used with caution. Specifically, the equation provides a relationship between (1) the backcalculated subgrade k-value (based on plate-theory) with (2) the backcalculated modulus of elasticity of an elastic half-space (based on plate-theory) for the same LTPP section pavement structure. This subgrade modulus of elasticity (based on plate-theory) may be different from the modulus of elasticity based on layered elastic theory using a backcalculation program such as MODCOM because different "structures" are used for describing the constructed layers (i.e., plate-theory versus elastic layered-theory characterization). Moreover, accounting for the presence of a rigid layer in MODCOM will also significantly alter the backcalculated subgrade modulus of elasticity results. Therefore, considerable caution should be exercised when using this equation to estimate a subgrade k-value given a backcalculated subgrade modulus of elasticity obtained from elastic layered theory.

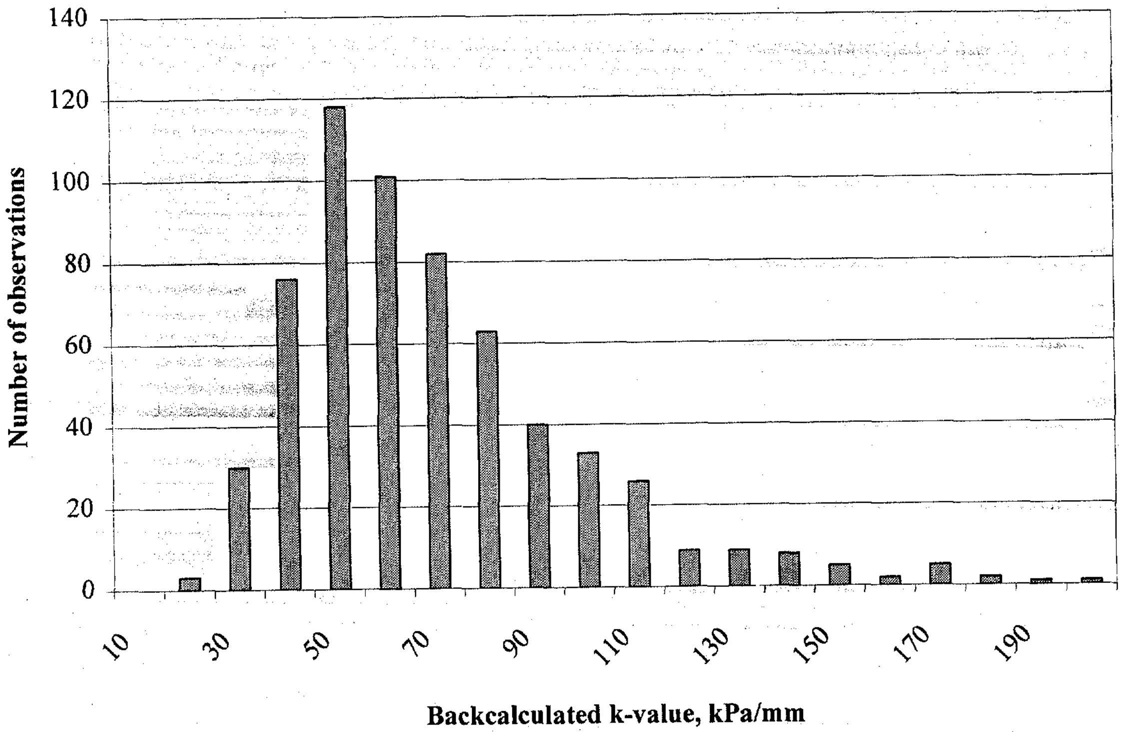


Figure 34. Frequency distribution of backcalculated k-values for GPS and SPS LTPP sections.

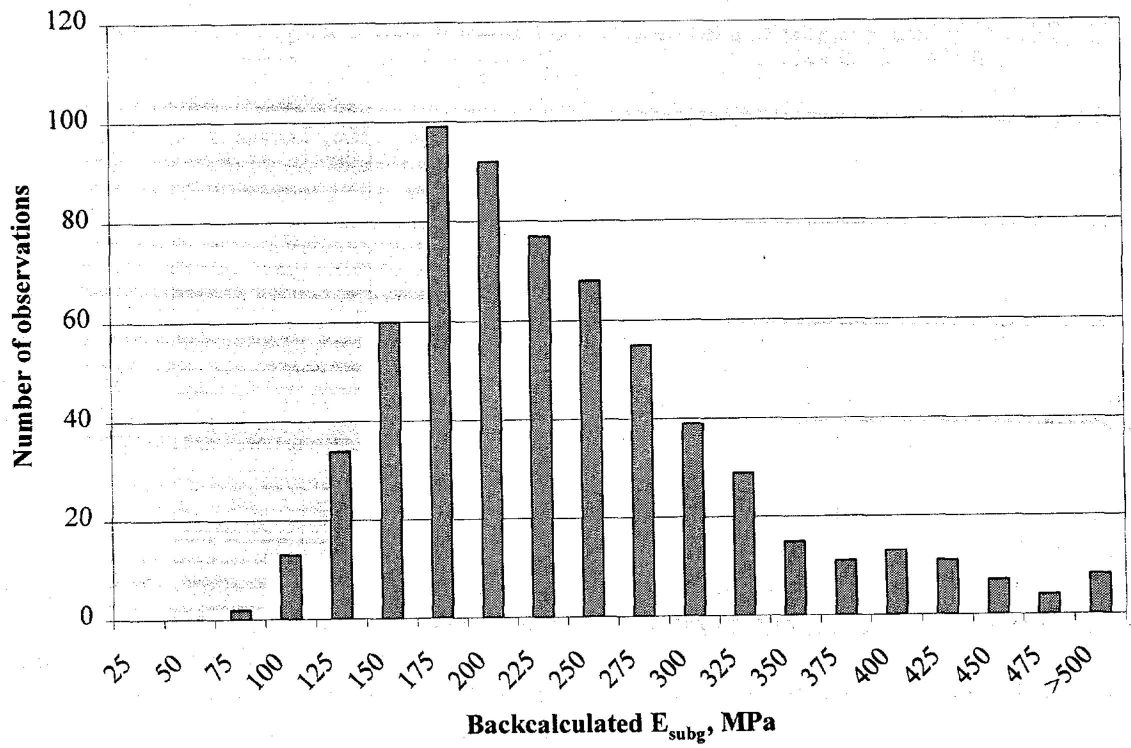


Figure 35. Frequency distribution of backcalculated subgrade elastic modulus for GPS and SPS LTPP sections.

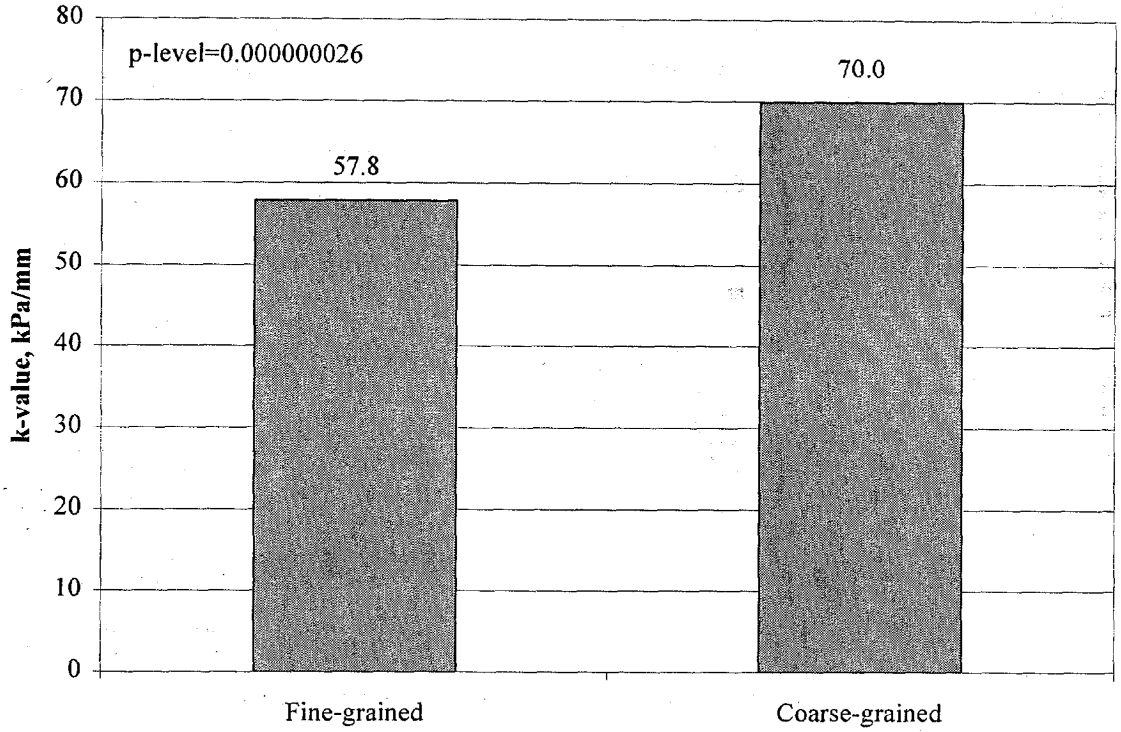


Figure 36. Comparison of mean k-values of fine- and coarse-grained subgrades (GPS and SPS sections).

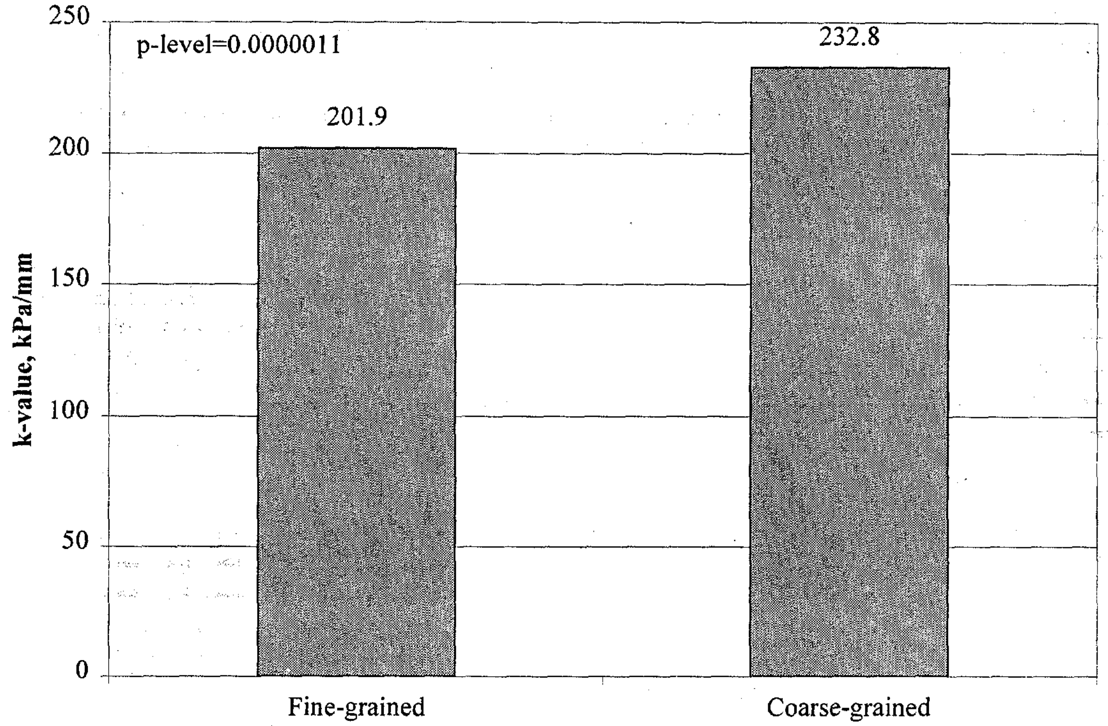


Figure 37. Comparison of mean moduli of elasticity of fine- and coarse-grained subgrades (GPS and SPS sections).

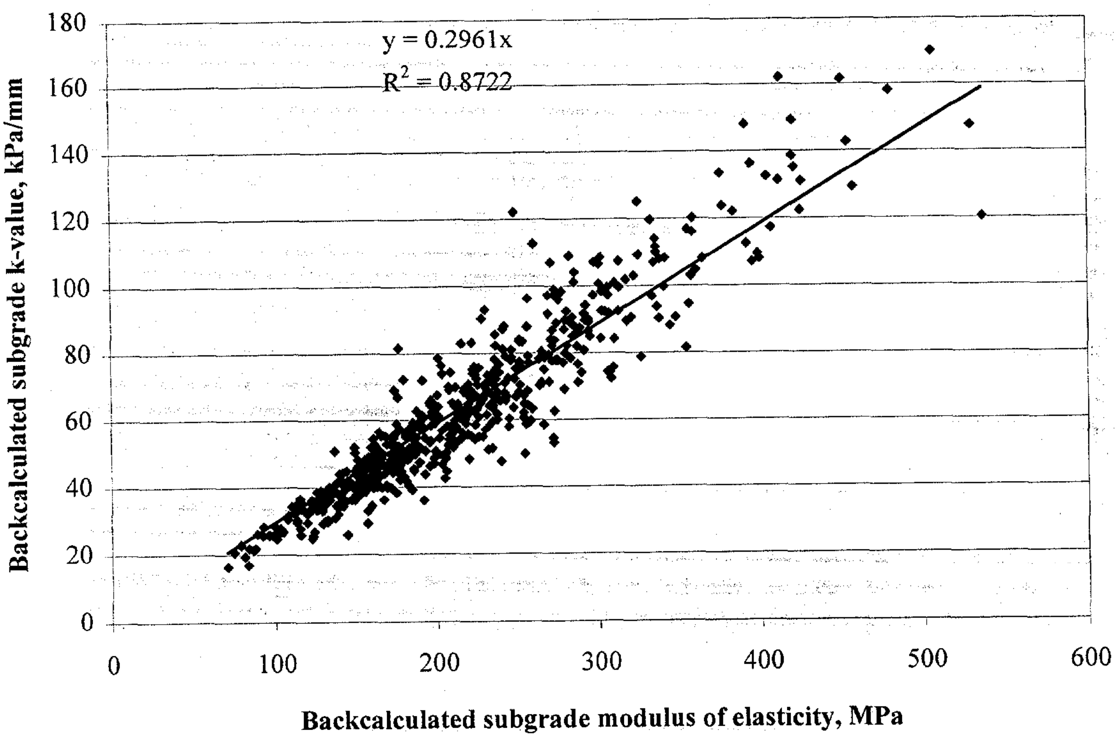


Figure 38. Subgrade modulus of elasticity versus coefficient of subgrade reaction (GPS and SPS sections).

Radii of Relative Stiffness

Radius of relative stiffness is an important characteristic of a rigid pavement structure that combines concrete modulus of elasticity of stiff pavement layers, their thickness, and elastic moduli of subgrade (k-value for DL model and E_{subgr} for ES model). Stiffer pavement systems have a higher radius of relative stiffness for both DL and ES models.

Figures 39 and 40 present the frequency distribution of mean backcalculated radius of relative stiffness for DL and ES subgrade models for GPS and SPS LTPP rigid pavement sections. As expected, the majority of the sections exhibited radii of relative stiffness between 800 and 1200 mm for the DL model and between 600 and 900 mm for the ES model.

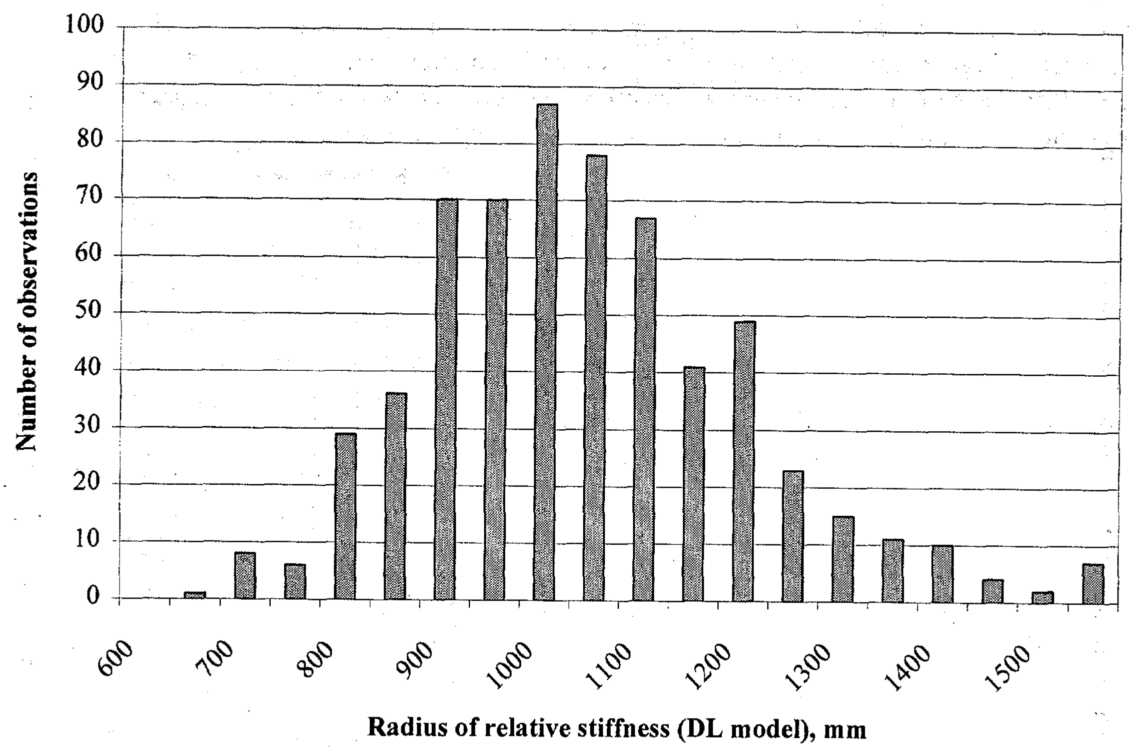


Figure 39. Frequency distribution of backcalculated k-values for GPS and SPS LTPP sections.

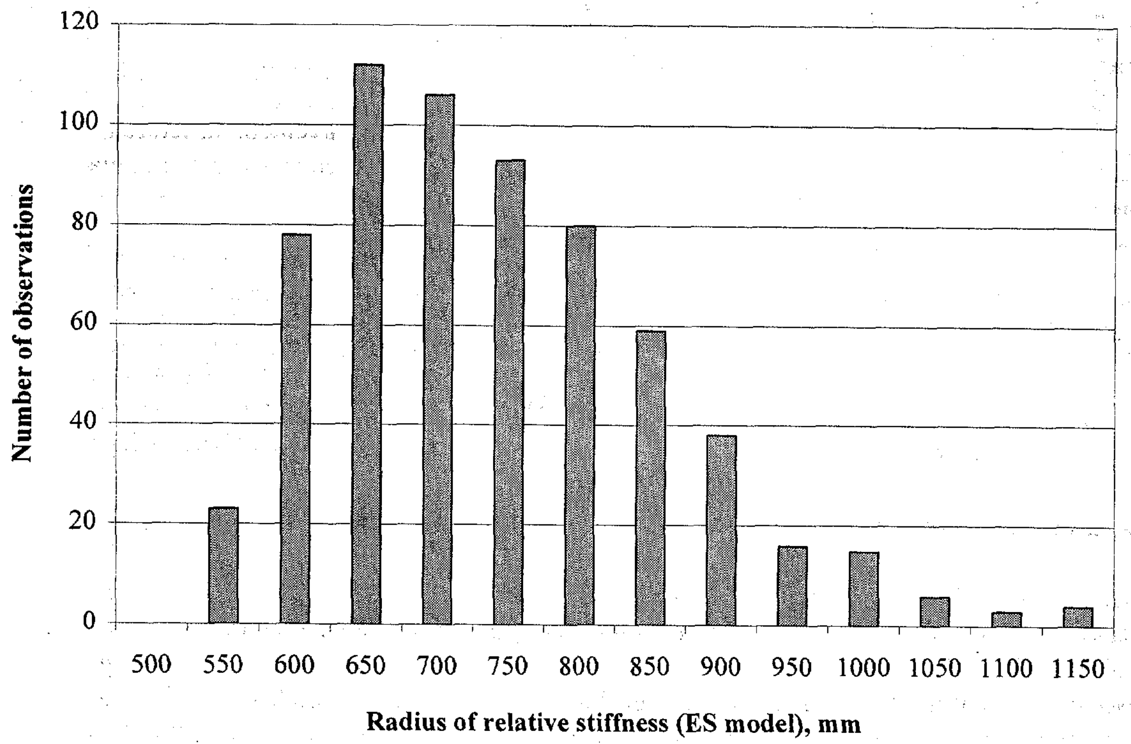


Figure 40. Frequency distribution of backcalculated subgrade modulus of elasticity for GPS and SPS LTPP sections.

The results of backcalculation for the rigid LTPP GPS and SPS sections were used to compare backcalculated mean radii of relative stiffness for the DL and ES models. Figure 41 shows that, as expected, higher radii of relative stiffness for the DL model correspond to higher radii of relative stiffness for the ES model. An excellent correlation between these two parameters was observed. A simple linear regression resulted in the following model:

$$l_k = 1.280\, l_{es} + 102.7$$
$$R^2 = 98.7\%$$
$$N = 596$$
$$SEE = 17.8 \text{ mm}$$

where

l_k	=	radius of relative stiffness (DL model), mm
l_{es}	=	radius of relative stiffness (ES model), mm

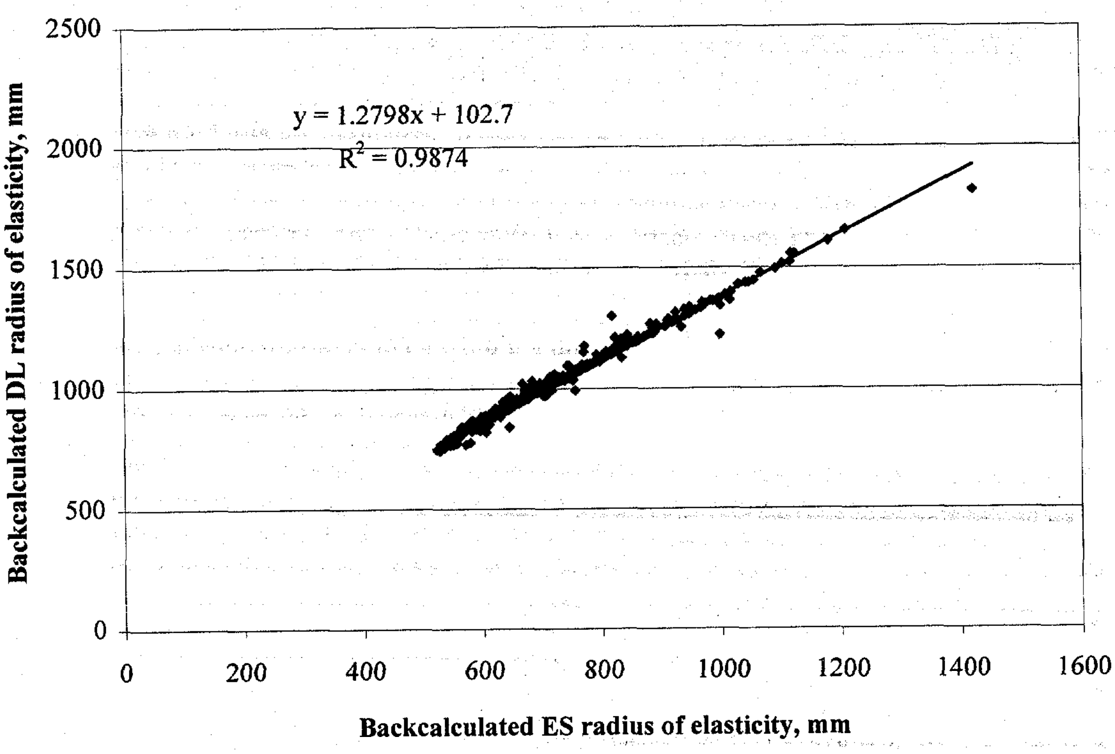


Figure 41. ES radius of relative stiffness versus DL radius of relative stiffness.

Bonding Condition Between PCC Slab and Base

The presence of a stabilized base may significantly alter PCC pavement responses (stresses and deflections) to applied loading. In turn, an interface condition between the PCC slab and the stabilized base dramatically affects the significance of base contribution to the overall pavement stiffness. The importance of accounting for the presence of a stabilized base and interface condition can be demonstrated by analyzing backcalculation results for two LTPP GPS and SPS rigid pavement sections, 105004 and 204052. Section 105004 is a 225-mm-thick CRCP placed over a 100-mm-thick cement-aggregate mixture. Section 204052 is 225-mm-thick JPCP placed on top of a 100-mm-thick econocrete base. Table 5 presents backcalculated PCC moduli of elasticity for these sections based on three different scenarios:

- The base layer is ignored.
- The base layer is in full friction with the PCC layer (full bond interface condition).
- The base layer is in full slip with the PCC layer (no bond interface condition).

Table 5. Effect of base and interface condition on backcalculated moduli of elasticity.

Section	No Base		No Bond		Full Bond	
	E_{PCC}, MPa	E_{base}, MPa	E_{PCC}, MPa	E_{base}, MPa	E_{PCC}, MPa	E_{base}, MPa
105004	31034	—	30501	6100	20283	4056
204052	8203	—	79569	19892	49871	12468

Neglecting the presence of the base layer overestimates modulus of elasticity of the concrete layers. This is especially clear for section 204052. For this section, even the assumption of unbonded interface between the PCC and base layer produces unrealistically high modulus of elasticity for both PCC and base layers. An assumption that the interface is bonded brings backcalculated moduli within the reasonable range. On the other hand, the assumption of full bond produces unrealistically lower elastic modulus for section 105004. Therefore, an unbonded interface condition should be assigned.

Full bond behavior of the pavement system exhibited during FWD testing does not necessarily indicate presence of a physical bond between the PCC slab and the base. The PCC slab may be in full contact with the base at the center of the slab and have substantial friction at that location while being lifted off the slab because of temperature curling and moisture warping at the slab edges. Moreover, at the same location, the slab may experience different friction conditions with the base layer. For example, the results for section 285025 shown in table 6 indicate that the PCC slab was in full friction with the base during the tests conducted in 1989 but showed full slip in the test conducted in 1994.

Table 6. Example of change of interface condition from test to test.

Section	Test Date	No Bond		Full Bond	
		E_{PCC}, MPa	E_{base}, MPa	E_{PCC}, MPa	E_{base}, MPa
285025	6-NOV-1989	60101	4007	**49901**	3327
285025	31-OCT-1994	**47701**	3180	39600	2640

Among 597 PCC and base section layer moduli obtained in this study using the DL model, 103 were assigned unbonded interface between the layers. In the remaining 494 cases, the layers were assigned a bonded interface condition, as shown in figure 42. For the ES foundation model, in 603 of 603 cases, a bonded interface was assigned. It should be noted, however, that if the bond/no bond condition did not dramatically affect backcalculated moduli, as was the case for the majority of nonstabilized bases, the interface was assumed to be bonded. However, even for stabilized bases, the bonded interface was usually observed, as shown in figure 43.

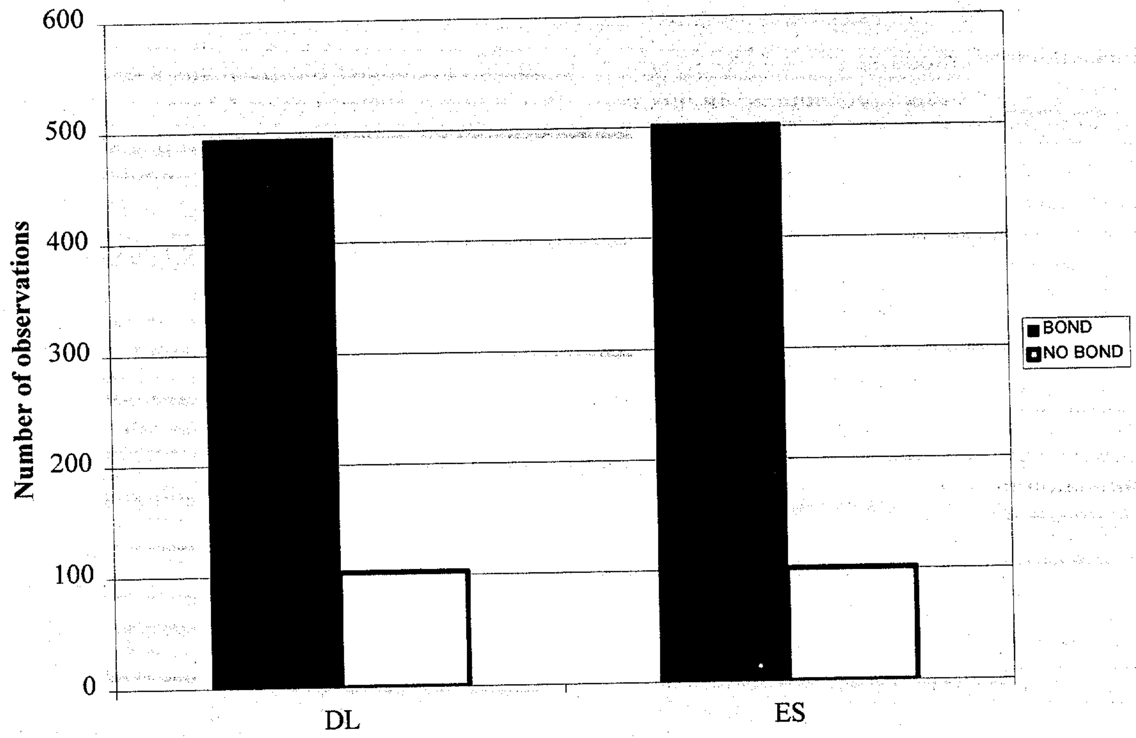


Figure 42. Distribution of bond/no bond interface condition for GPS and SPS LTPP sections.

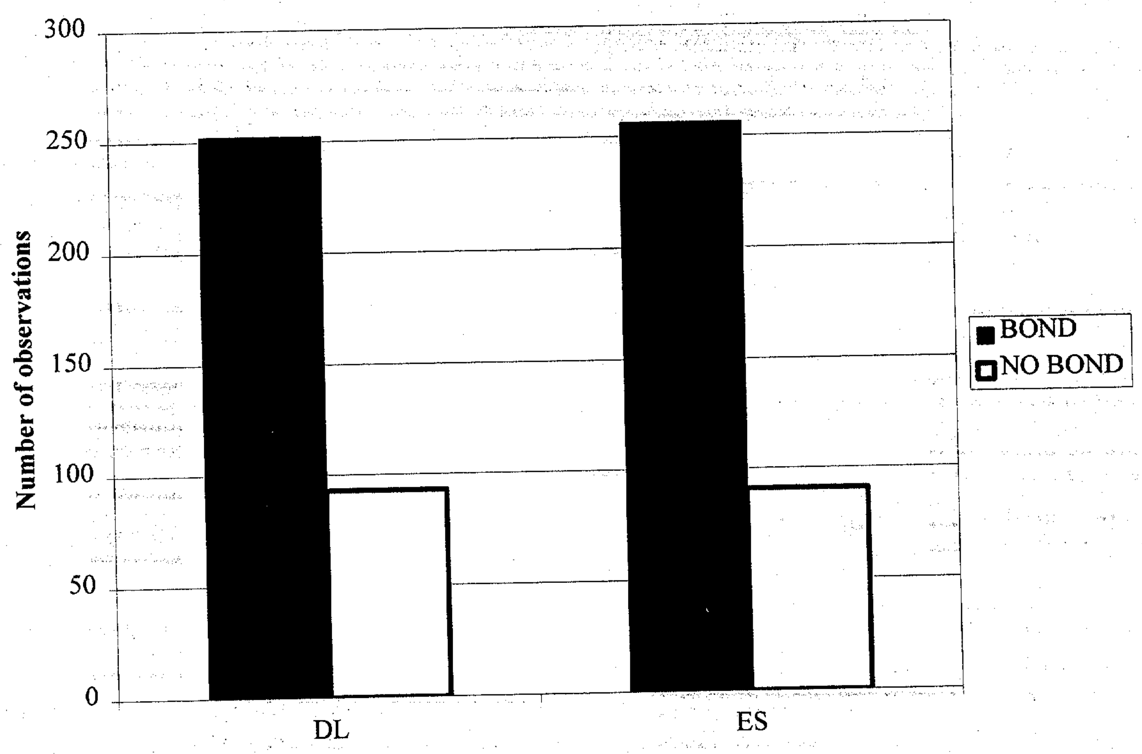


Figure 43. Distribution of bond/no bond interface condition for GPS and SPS LTPP sections with stabilized bases.

Backcalculated PCC Moduli

Backcalculated modulus of the PCC layer is an important parameter for mechanistic-empirical evaluation and design procedures. In this study, PCC layer properties were determined for 597 and 603 FWD visits of GPS and SPS LTPP sections using DL and ES subgrade models, respectively. Figures 44 and 45 show frequency histogram distributions for PCC moduli backcalculated using the DL and ES subgrade models. The majority of the backcalculated moduli are in the reasonable range from 25,000 to 55,000 MPa, supporting the conclusion of the robustness of the backcalculation approach.

Analysis of these plots shows that backcalculation using the ES subgrade model results in consistently lower PCC elastic moduli than backcalculation using the DL subgrade model. This is to be expected, because backcalculated moduli are not actual material properties but rather parameters of the corresponding structural systems used in backcalculation. Since an ES foundation provides significant shear redistribution and DL provides no shear load redistribution, it is reasonable to expect that higher stiffness of the upper layers resting on a DL foundation is required to provide the same deflections produced by a corresponding slab on an ES foundation.

Figure 46 shows backcalculated PCC moduli using the ES subgrade model versus backcalculated PCC moduli using the DL subgrade model. A very good correlation between these two sets of moduli is observed. A linear regression analysis resulted in the following relationships:

$$E_{PCC,DL} = 1.312\ E_{PCC,ES}$$

$$R^2 = 94\%$$
$$N = 591$$
$$SEE = 1.8\ \text{GPa}$$

where

$E_{PCC,ES}$	=	PCC modulus of elasticity backcalculated using ES model, MPa
$E_{PCC,DL}$	=	PCC modulus of elasticity backcalculated using DL model, MPa

This relationship indicates that backcalculated modulus of the PCC layer depends on the foundation model used in backcalculation. Therefore, if a transition from the ES to the DL foundation model needs to be made, moduli of elasticity of the upper layers also need to be adjusted. It is important to remember, however, that these relationships for the foundation parameters, radii of relative stiffness, and PCC moduli of elasticity were developed based on equivalency of the deflection basins under an interior loading condition. Development of the corresponding relationships based on equivalency of the maximum stresses or on equivalency of the pavement responses under the edge or corner loading conditions may require adjustments.

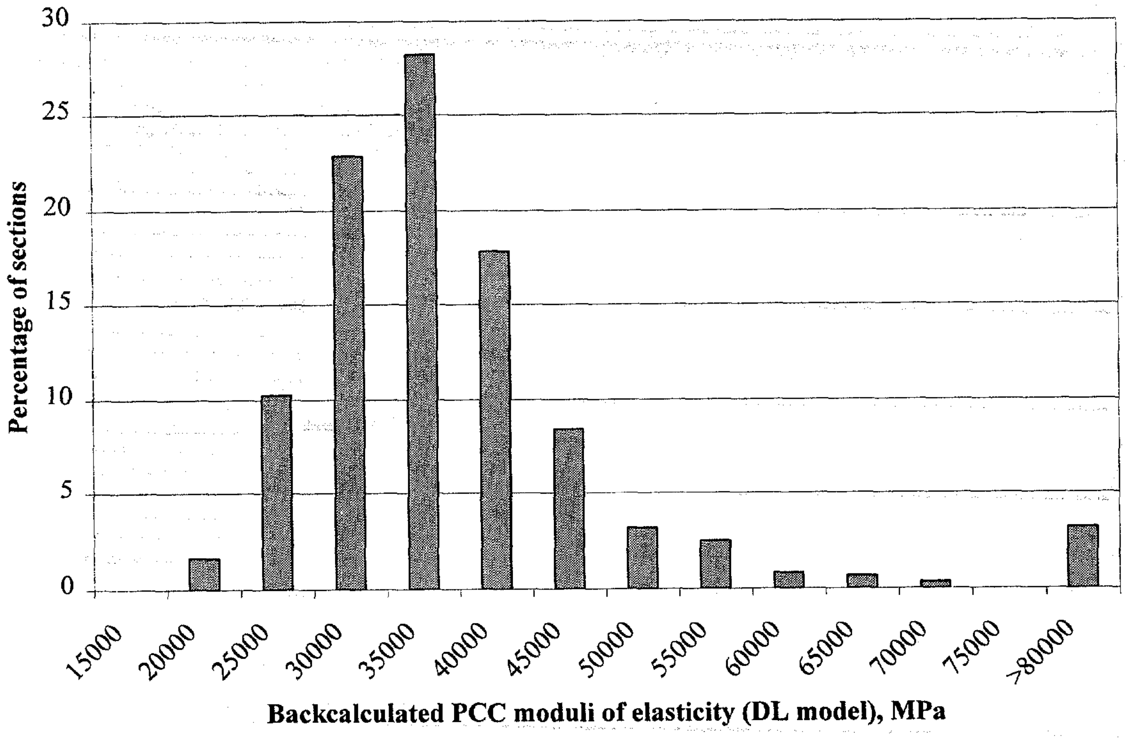


Figure 44. Frequency distribution of backcalculated PCC modulus of elasticity for GPS and SPS LTPP sections (DL model).

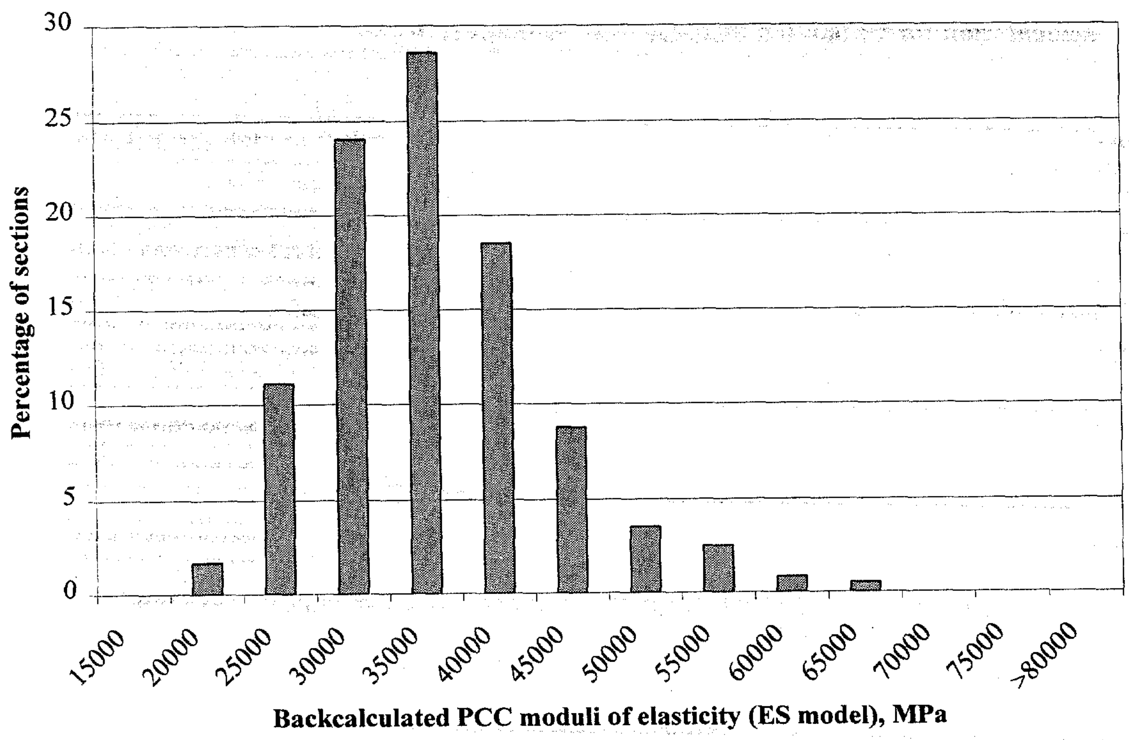


Figure 45. Frequency distribution of backcalculated PCC modulus of elasticity for GPS and SPS LTPP sections (ES model).

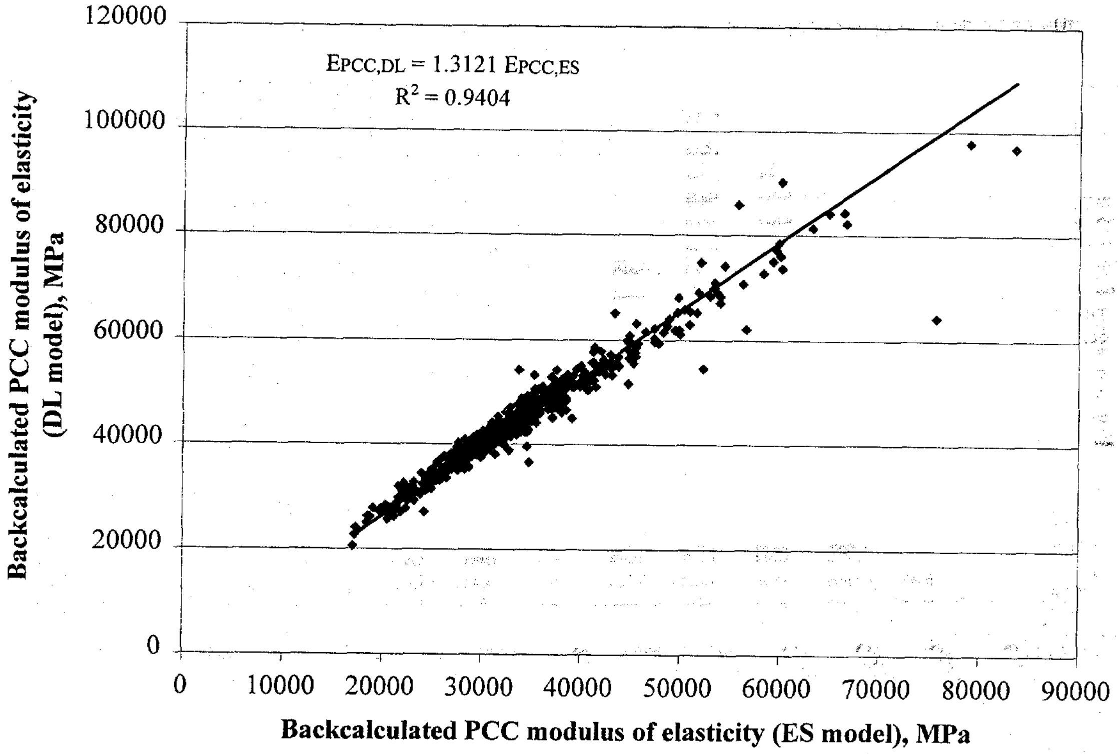


Figure 46. Backcalculated PCC modulus of elasticity (ES model) versus backcalculated PCC modulus of elasticity (DL model).

Backcalculation for Unbonded PCC Overlay Sections (GPS-9)

The backcalculated PCC moduli presented in this report do not include moduli for sections with unbonded PCC overlays. It is recommended that backcalculated PCC moduli for these sections not be uploaded into the IMS database, on the basis of the following observations:

- The backcalculated moduli are extremely sensitive to the assigned ratio between elastic moduli of the PCC overlay and the underlying PCC slab. Assigning this ratio is not a trivial task. On the one hand, old PCC in the underlying slab can be much stiffer than younger PCC of the unbonded overlay. On the other hand, cracks in the underlying slab may significantly reduce effective modulus of elasticity of this layer. In this study, the ratio between the moduli of unbonded PCC overlays and underlying slabs was assigned to be equal to 1 for all sections. However, analysis of figures 8 and 11 (chapter 2) shows that even a small change in this ratio could dramatically affect backcalculated values for both PCC layers. Table 7 shows the results for the top layer PCC slabs (unbonded overlay). These values are very erratic and some are unrealistic.
- For the many sections for which multiple FWD visits were available (for example, sections 069048, 069049, 089020, 279075, and 899018), low repeatability of the results was observed.

Table 7. Backcalculated PCC moduli of elasticity for unbonded overlay sections.

Section	Date	E_{PCC}, GPa			
		DL Model		ES Model	
		Unbonded	Bonded	Unbonded	Bonded
069048	11-Jan-90	50491.5	13137.1	38221.1	9944.5
069048	29-Jan-97	34358.1	8939.5	26055.2	6779.2
069049	29-Nov-89	85092.1	21283.7	66463.9	16624.3
069049	31-Mar-95	34439.4	8614.2	26730	6685.8
069107	16-Nov-89	62922.6	15991.5	49579.1	12600.3
089019	28-Jun-89	32395.6	8201.9	24099.5	6101.5
089019	8-Apr-92	39641.8	10036.5	29945.6	7581.6
089020	27-Jun-89	20017.3	5008.9	21407.3	5356.8
089020	9-Apr-92	55683.7	13933.8	42468.7	10627
134118	20-Aug-90	33315.5	8362.2	24613.2	6177.9
134118	10-Sep-92	31374.9	7875.1	23123.7	5804
189020	18-Jul-90	66778.6	16694.6	49062.7	12265.7
189020	25-Jul-94	51093.2	12773.3	39707.3	9926.8
209037	7-Sep-89	34240.4	9666.3	25709.8	7258.1
209037	13-May-94	32928.4	9295.9	24937.2	7039.9
269029	11-Jul-90	140774.1	35420.7	104394.1	26267
269029	4-Nov-93	NA	NA	71415.8	17969.2
269030	19-Jun-90	119291.3	31525	95157.7	25147.2
269030	1-Nov-93	74622	19720.3	54330.6	14357.9
276300	17-Jul-89	70621	17658.1	53838.2	13461.7
279075	5-Sep-90	49435	13098.1	37932.2	10050.3
279075	8-Sep-94	26050.1	6902.1	19478.2	5160.9
279075	1-Jun-95	57239.5	15165.9	44986.7	11919.5
289030	31-Oct-89	253363.9	65322.9	183010.1	47184.1
289030	3-Dec-92	159949.1	41238.5	138265.1	35647.9
316701	4-Aug-89	59704.4	14967.6	45010.9	11284
395569	20-Jul-94	26332.5	6772.6	19957.6	5133
399006	21-Jul-94	88284.7	22316.5	68184.5	17235.6
399022	18-Oct-90	72454.5	18635.1	65976.6	16969
399022	19-Jul-94	55228.9	14204.7	43020.8	11064.8
404155	5-Jun-90	72099.4	19829.7	54528.1	14997
404155	20-May-93	50587.6	13913.2	37716.9	10373.4
429027	5-Jun-89	47438.9	13407.6	35212.7	9952.1
429027	26-Jul-95	28735.6	8121.5	23375.5	6606.6
483569	1-May-90	81509.8	20415.5	64988.1	16277.4
483569	4-Jan-96	68708	17209.1	53917.6	13504.6
483845	8-May-90	62454.7	15683.5	47084.6	11823.8
483845	16-Aug-91	78141.6	19622.8	57496	14438.3
483845	22-Aug-96	NA	NA	44472.8	11167.9
489167	6-Apr-90	136670.7	35141.2	110215.5	28339
489167	3-Jan-96	93737.3	24102.1	79789.6	20515.8
489355	8-Aug-90	NA	NA	49625.7	12420.5
489355	16-Aug-93	NA	NA	NA	NA
899018	5-Oct-94	79600.5	21466	62554	16869
899018	12-Jun-95	51070.5	13772.3	38978	10511.3

Backcalculated Base Moduli

The main purpose for introduction of a base layer in the backcalculation analysis is to account for a structural contribution of the base layer to the overall pavement stiffness. This allows engineers to obtain much more realistic values for PCC moduli than when the base is ignored. The fact that the majority of the sections exhibited a bonded interface condition with the base layer indicates that the structural contribution of the latter is significant. Unfortunately, the presence of the stiff concrete layer on top of the base layer does not allow reliable backcalculation of the base moduli. Use of plate theory as a structural model for the pavement system makes it theoretically impossible. In this study, the base moduli were estimated as fractions of the PCC moduli using the ratios presented in table 2. Therefore, it is of interest to evaluate the reasonableness of the obtained moduli.

Tables 8 and 9 present mean, minimum, and maximum values of the backcalculated base moduli of GPS and SPS LTPP sections using DL and ES foundation models, respectively, for each base type. The backcalculated moduli are in reasonable ranges for all stabilized bases. For nonstabilized bases, the moduli obtained using the ES model are reasonable but often lower than corresponding backcalculated subgrade moduli. This is reasonable, since modeling of a granular layer as a plate layer (i.e., assuming an infinite shear modulus) significantly overestimates its stiffness in forward calculation. In backcalculation, it results in lower elastic modulus. Fortunately, a significant change in moduli ratio for a nonstabilized base has a small effect on backcalculated PCC moduli, although it significantly affects base moduli.

Table 8. Mean, maximum, and minimum backcalculated base moduli for GPS and SPS LTPP sections (DL model).

Base Material	Backcalculated Base Modulus, MPa		
	Mean	Minimum	Maximum
Asphalt-Treated Mixture	5746	3365	9178
Gravel, Uncrushed	178	115	418
Crushed Stone	225	177	280
Crushed Gravel	200	119	367
Sand	133	116	156
Soil-Aggregate Mixture (Predominantly Fine-Grained)	81	76	84
Soil-Aggregate Mixture (Predominantly Coarse-Grained)	160	101	267
Hot-Mixed AC	2227	1647	3565
Sand Asphalt	583	575	590
Asphalt-Treated Mixture	787	458	1298
Dense-Graded, Cold-Laid, Central Plant Mix AC	2048	1932	2191
Open-Graded, Hot-Laid, Central Plant Mix AC	2089	1953	2358
Cement Aggregate Mixture	6209	3409	15144
Econocrete	10339	8598	11957
Lean Concrete	14483	1898	21015
Soil Cement	2936	1989	4559

Table 9. Mean, maximum, and minimum backcalculated base moduli for GPS and SPS LTPP sections (ES model).

Base Material	Backcalculated Base Modulus, MPa		
	Mean	Minimum	Maximum
Asphalt-Treated Mixture	5746	3365	9178
Gravel, Uncrushed	178.2565	115.1285	417.792
Crushed Stone	225.4349	177.4473	279.6053
Crushed Gravel	200.4254	119.4006	367.0246
Sand	132.8438	116.2008	156.2364
Soil-Aggregate Mixture (Predominantly Fine-Grained)	80.96969	75.95625	84.2965
Soil-Aggregate Mixture (Predominantly Coarse-Grained)	159.6977	101.0056	266.6072
Hot-Mixed AC	2937	2154	4670
Sand Asphalt	774	762	785
Asphalt-Treated Mixture	988	558	1687
Dense-Graded, Cold-Laid, Central Plant Mix AC	2686	2535	2801
Open-Graded, Hot-Laid, Central Plant Mix AC	2850	2613	3372
Cement Aggregate Mixture	8145	4096	17167
Econocrete	13357	11736	14847
Lean Concrete	19656	3709	27519
Soil Cement	3929	2583	5867

Variability in Backcalculated Parameters Between FWD Visits

Several GPS and SPS LTPP sections were tested more than once. The backcalculation results obtained from different FWD visits were compared and the coefficients of variation were calculated. Figures 47 and 48 present cumulative frequency distributions of the coefficients of variation of backcalculated parameters for the ES and DL foundation models, respectively. The coefficient of variations of backcalculated subgrade moduli and concrete elastic moduli are less than 20 percent for about 80 percent of pavement sections (variability between visits). At the same time, more than 90 percent of the GPS and SPS LTPP sections exhibited a coefficient of variation in backcalculated radius of relative stiffness of less than 10 percent.

Although the majority of the pavement sections exhibit low coefficients of variation between visits, for some sections it was found to be much larger. Several factors may contribute to high variability, including seasonal variation in subgrade properties and variation in temperature gradients through the PCC slab thickness that result in slab curling variation.

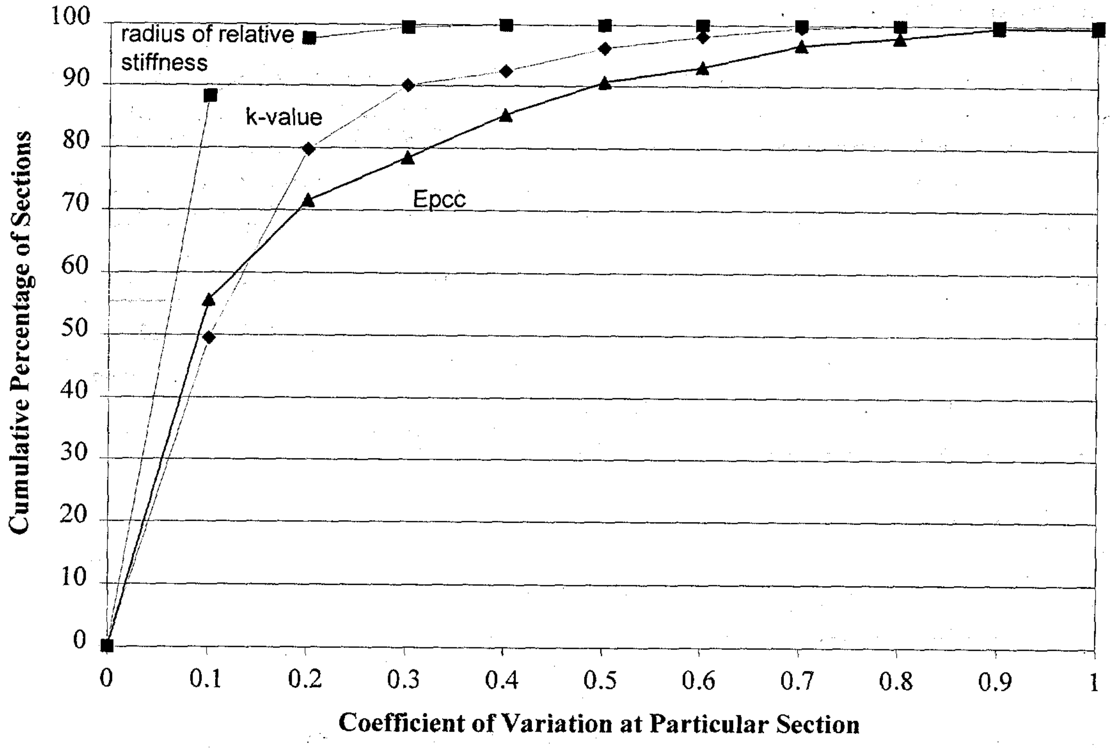


Figure 47. Coefficient of variation in backcalculated parameters (DL model) for GPS and SPS LTPP sections between different FWD visits.

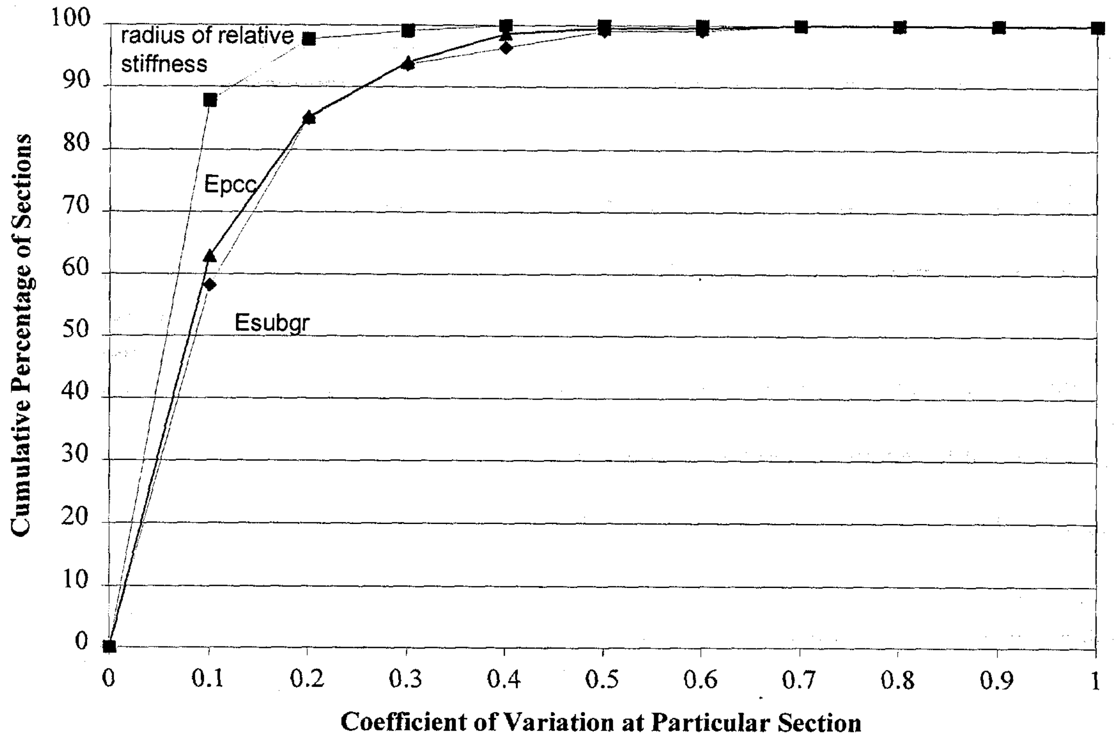


Figure 48. Coefficient of variation in backcalculated parameters (ES model) for GPS and SPS LTPP sections between different FWD visits.

Backcalculation Analysis Results

The results of point-by-point backcalculation for the GPS and SPS sections are given in the LTPP IMS table MON_DEFL_RGD_BAKCAL_POINT. A summary of the backcalculation analysis results for the GPS and SPS sections is given in the LTPP IMS table MON_DEFL_RGD_BAKCAL_SECT. The results are presented in terms of the mean values, minimum values, maximum values, and standard deviations of the following parameters:

Dense-Liquid Model

- k-value (modulus of subgrade reaction).
- E_{PCC} (modulus of elasticity of the PCC slab).
- E_{base} (modulus of elasticity of the base layer).

Elastic Solid Model

- E_{subgr} (modulus of elasticity of the subgrade).
- E_{PCC} (modulus of elasticity of the PCC slab).
- E_{base} (modulus of elasticity of the base layer).

Also, the bond condition between the concrete slab and the base layer is reported.

Typical plots of the above parameters are given in appendix A.

CHAPTER 4. BACKCALCULATION FOR SMP SECTIONS

The FWD data collected for the SMP LTPP sections allow for analysis of the effect of season and time of day on backcalculated values. Backcalculation analysis was performed for 19 SMP sections, with a total of 571 FWD passes. The number of passes is much higher than the number of sections because the sections could be tested several times a day and several times per year. The deflection data were downloaded during the fall of 1997 from IMS table MON_DYNATEST_DROP_DATA. Information about LTPP pavement section layers was obtained from IMS table TST_L05B.

Selection of Pavement Structure

The SMP LTPP sections were modeled in this study as two-layered plates resting on DL or ES foundations. For all LTPP SMP sections, thickness of the upper layer was assigned as an average thickness of the top PCC layer of the LTPP section obtained from the IMS database. For the majority of the sections, the thickness of the lower layer in the backcalculation model was assigned as an average thickness of the second from the top layer, and the ratios between PCC and base moduli were assigned based on the material code of the base layer (see table 2).

Backcalculation of FWD Deflection Data

ERESBACK 2.2 was used to process the raw FWD deflection data, average deflection basins for each load level, determine basin type, backcalculation, and post-process backcalculation results.

The total number of backcalculated basins for the SMP LTPP sections was 10,626. The number of basins resulting in successful backcalculation were 8,188 and 8,771 for DL and ES foundation models, respectively. This corresponds to 77 and 82 percent of all basins.

For most sections, only a small fraction of the total number of FWD basins was rejected. However, for some sections, only a few deflection basins were available to obtain acceptable backcalculated parameters. Figure 49 shows a distribution of the percentage of accepted deflection basins per section after backcalculation using DL and ES models. For the DL and ES foundation models, 37 and 48 percent of FWD passes resulted in 100 percent accepted deflection basins. Only a small fraction of the FWD passes that exhibited more than 30 percent of backcalculation basins were accepted (5 and 3 percent for DL and ES foundation models, respectively). Based on this observation, it was decided to exclude FWD passes with more than 30 percent rejected basins and to exclude mean values for these basins in the IMS database.

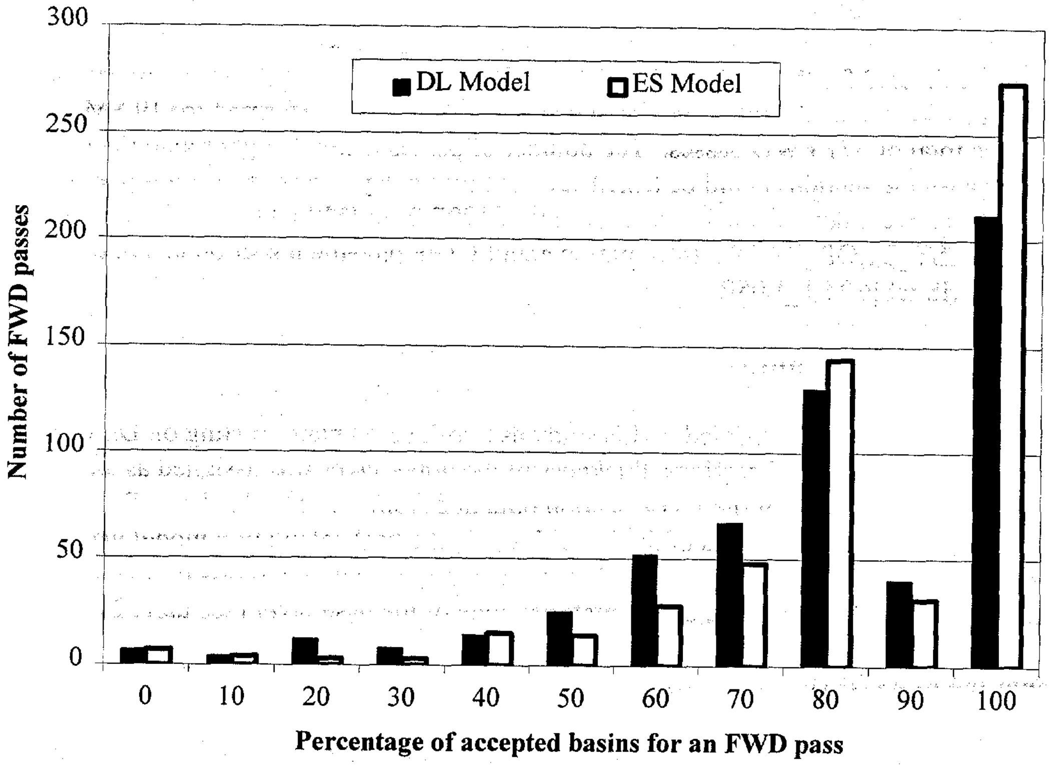


Figure 49. Percentage of accepted backcalculation basins for FWD passes of SMP LTPP sections.

The backcalculated mean values for 19 SMP LTPP PCC rigid pavement sections are presented in the LTPP IMS table MON_DEFL_RGD_BAKCAL_SECT. The backcalculation results are summarized in the following sections.

Effect of Load Level

As was observed for GPS and SPS rigid pavement sections, the results of backcalculation for SMP concrete pavement sections did not depend on load level. Figures 50 and 51 show histograms of coefficient of variation in backcalculated k-value at a particular location based on backcalculation using the DL model from three load levels. Figures 52 and 53 show histograms of coefficient of variation in backcalculated modulus of elasticity of subgrade and corresponding radii of relative stiffness based on ES backcalculation. The highest variability was observed in backcalculated k-values, although the median coefficient of variation in k-value is less than 4 percent (for almost 95 percent of the stations, the coefficients of variation are less than 10 percent). Variability in backcalculation results from the ES model was smaller than from the DL model, and variability in subgrade parameter is higher than in radii of relative stiffness for both models.

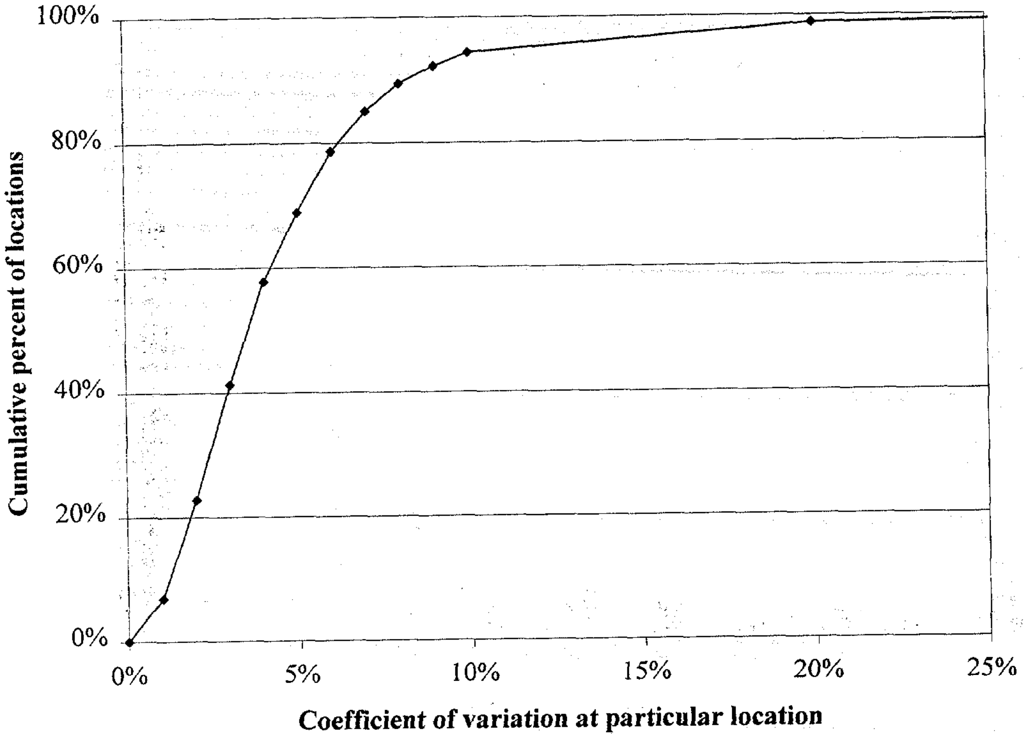


Figure 50. Coefficient of variation in backcalculated k-values for multiple load levels at a particular location (SMP sections).

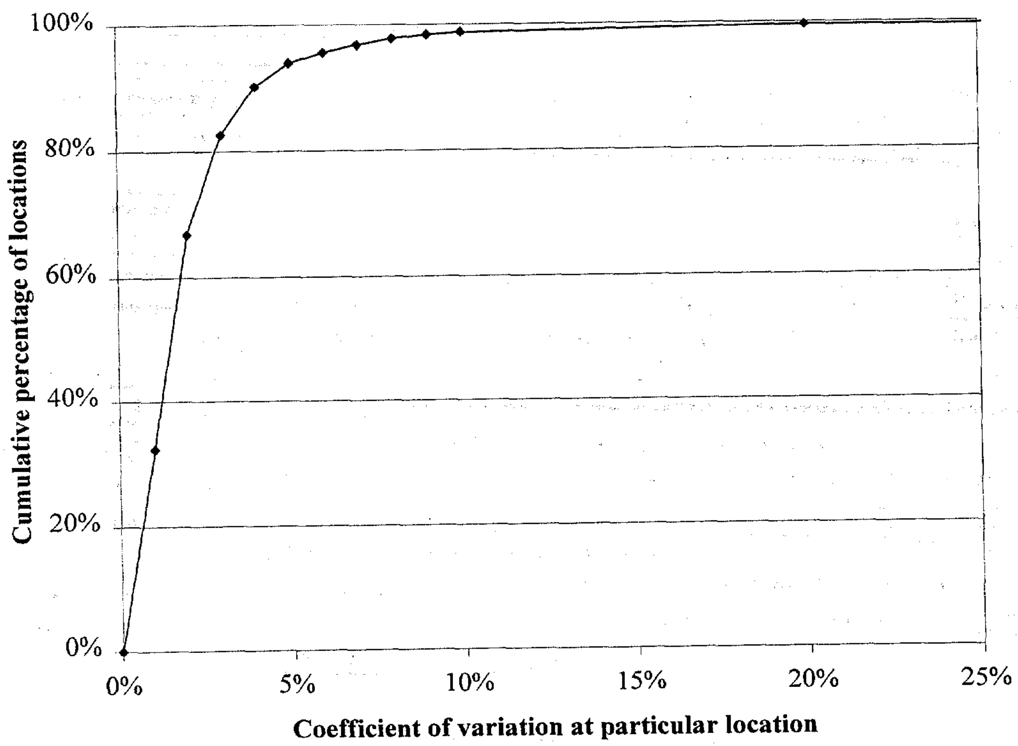


Figure 51. Coefficient of variation in radius of relative stiffness (DL model) for multiple load levels at a particular location (SMP sections).

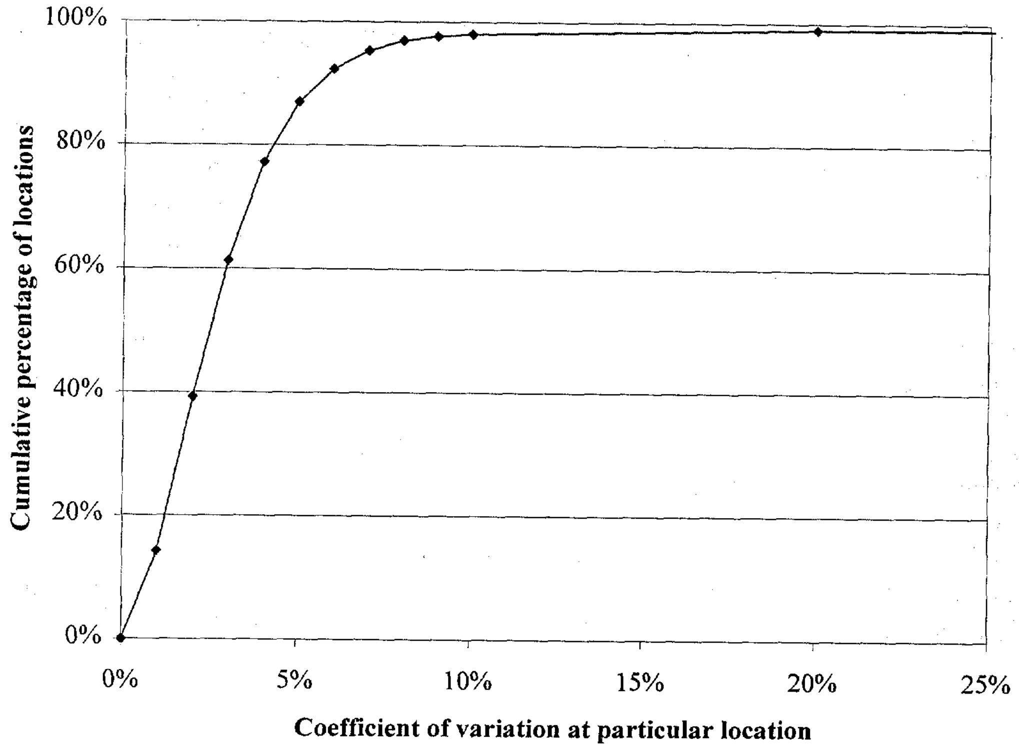


Figure 52. Coefficient of variation in backcalculated modulus of elasticity of subgrade for multiple load levels at a particular location (SMP sections).

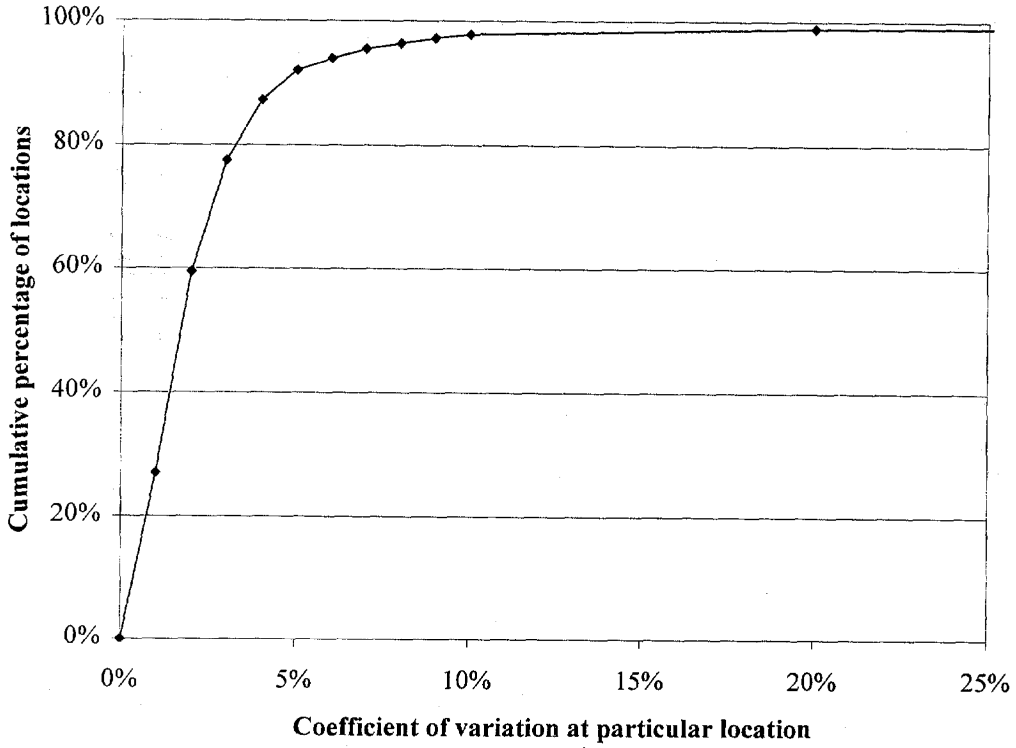


Figure 53. Coefficient of variation in radius of relative stiffness (DL model) for multiple load levels at a particular location (SMP sections).

Variability in Backcalculated Parameters Along Section Length

In this study, mean values and standard deviations along the project length were calculated for all FWD passes to SMP sections. However, only parameters from FWD passes that resulted in more than 70 percent of acceptable backcalculation basins were recommended for inclusion in the IMS database. To further examine how well these mean values represent pavement section properties, distributions of coefficients of variation of backcalculated parameters for FWD passes were analyzed.

Figures 54 and 55 show cumulative frequency distributions of the coefficient of variation of backcalculated subgrade moduli, moduli of elasticity of concrete, and radii of relative stiffness obtained using the DL and ES models, respectively. The coefficient of variation in backcalculated parameters is less than 20 percent for more than 80 percent of SMP sections. Sections 063042 and 893015 exhibited the highest variability in PCC modulus of elasticity. Variability in PCC thickness (both sections) or base thickness (section 063042) are the most likely reason for variability in backcalculated PCC modulus of these sections. Variability in backcalculated moduli does not remain constant for the same section—it substantially changes from one FWD pass to another. For example, for section 893015 it varies from 10 percent on October 6, 1994, to 46 percent on April 18, 1995.

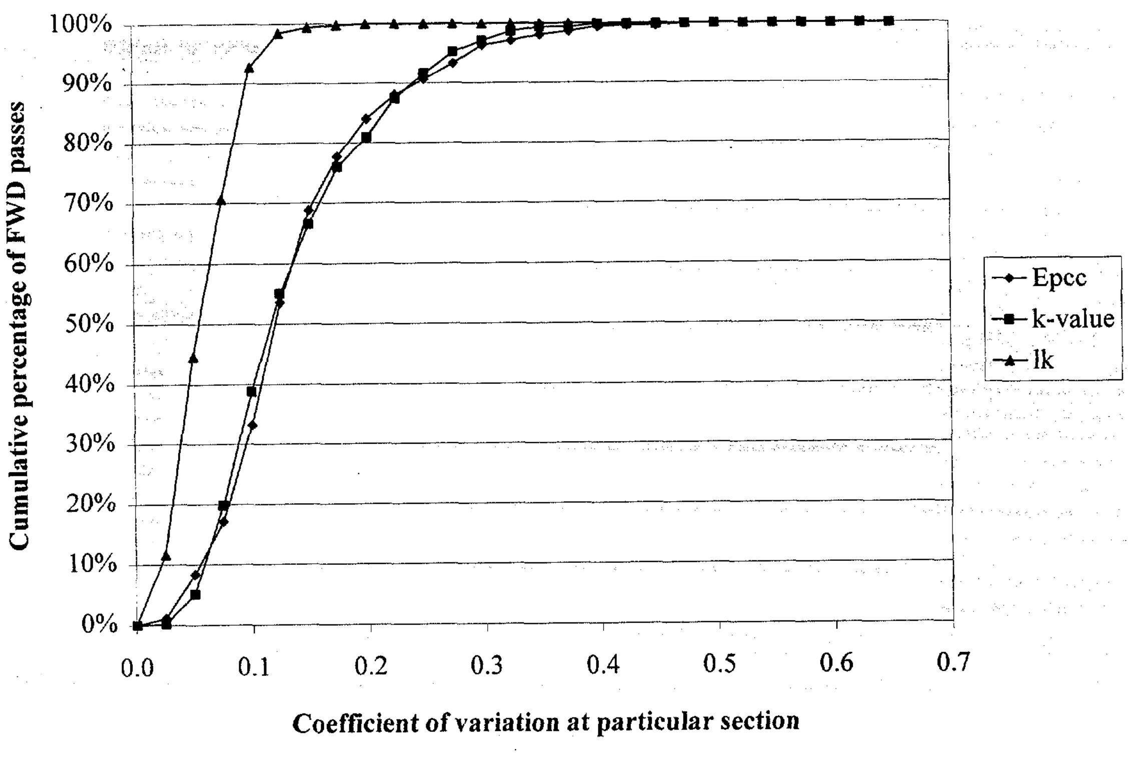


Figure 54. Coefficient of variation in backcalculated parameters along project length for SMP sections (DL model).

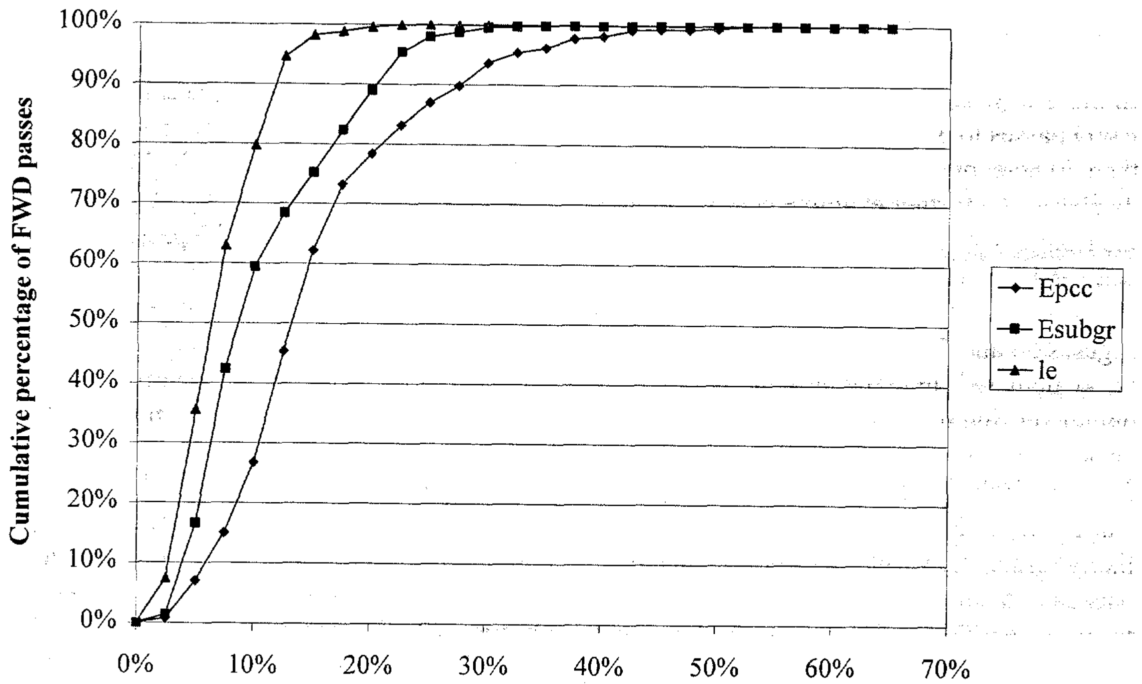


Figure 55. Coefficient of variation in backcalculated parameters along project length for SMP sections (ES model).

Subgrade Moduli

Backcalculation using DL and ES subgrade models results in characterization of subgrade using two different parameters: k-value and modulus of elasticity of subgrade. Figures 56 and 57 present frequency distributions of mean backcalculated k-values and subgrade moduli of elasticity for SMP LTPP rigid pavement sections. As expected, the majority of the sections exhibited k-values between 40 and 110 kPa/mm and moduli of elasticity between 100 and 275 MPa. As expected, several sections exhibited higher subgrade moduli from FWD testing during wintertime.

The results of backcalculation for the rigid LTPP SMP sections were used to compare backcalculated mean coefficient of subgrade reactions, k, for each section with the corresponding backcalculated subgrade moduli of elasticity, E_{subgr}. Figure 58 shows that, as expected, higher moduli of elasticity correspond to higher coefficients of subgrade reaction. A linear regression resulted in the following model:

$$k = 0.282\ E_{subgr}$$

$$R^2 = 86.3\%$$
$$N = 556$$
$$SEE = 9.12 \text{ kPa/mm}$$

where

k = coefficient of subgrade reaction, kPa/mm

E_{subgr} = subgrade modulus of elasticity, MPa

This equation is remarkably similar to the corresponding relationship obtained for the GPS and SPS sections. This verifies the stability of the backcalculation procedure. Figure 58 shows, however, that this relationship is not extremely accurate for high values of k-value and modulus of elasticity. The majority of those values are obtained from FWD testing of the sections located in a very cold climate in wintertime; however, the results of backcalculation from those FWD passes are not very reliable. Indeed, the measured deflections were relatively small, therefore, small measurement errors could significantly alter results. Moreover, it appears the DL model increases greatly for a frozen subgrade.

Radii of Relative Stiffness

To further examine results of backcalculation for the SMP LTPP sections, the distribution of backcalculated radii of relative stiffness was analyzed. Figures 59 and 60 present the frequency distribution of mean backcalculated radius of relative stiffness for DL and ES subgrade models for SMP LTPP rigid pavement sections. As expected, the majority of the sections exhibited radii of relative stiffness between 800 and 1200 mm for the DL model and between 600 and 900 mm for the ES model.

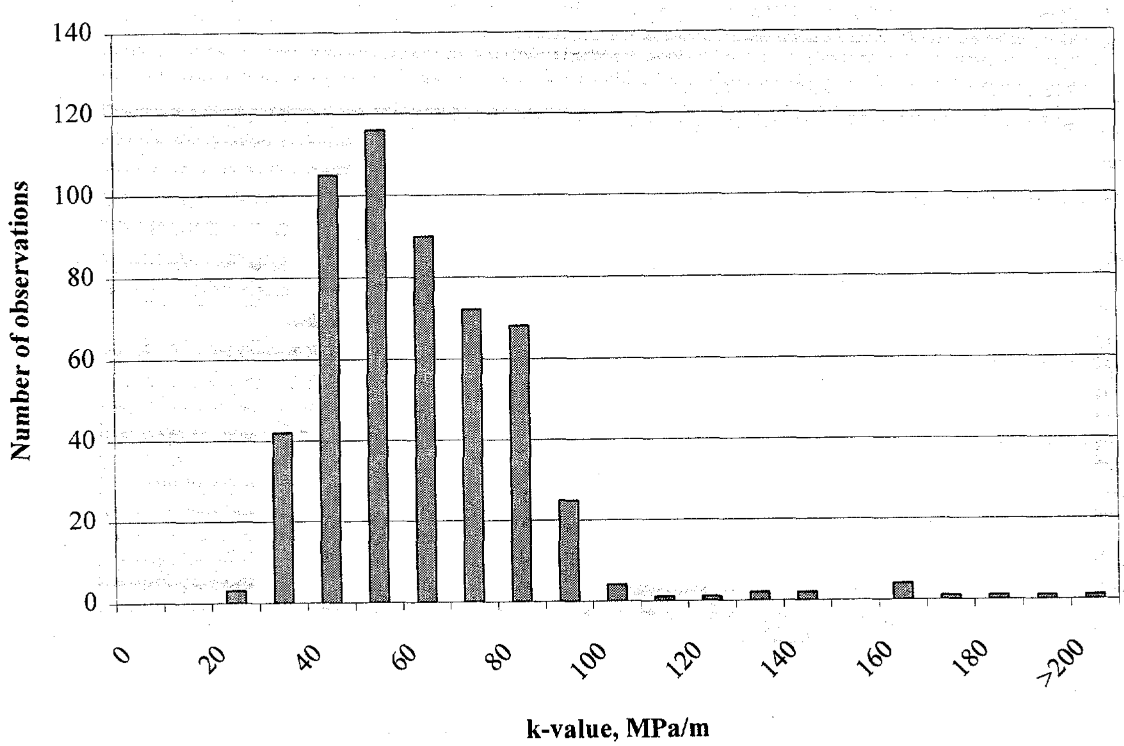


Figure 56. Frequency distribution of backcalculated k-values for SMP LTPP sections.

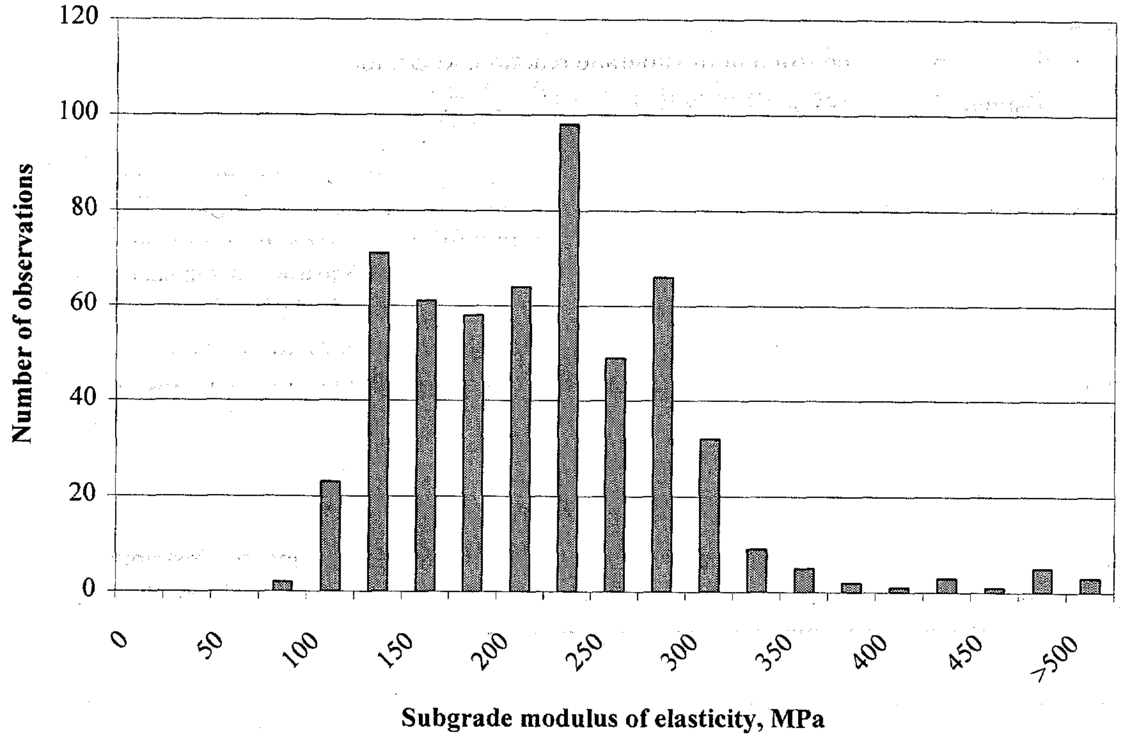


Figure 57. Frequency distribution of backcalculated subgrade elastic modulus for SMP LTPP sections.

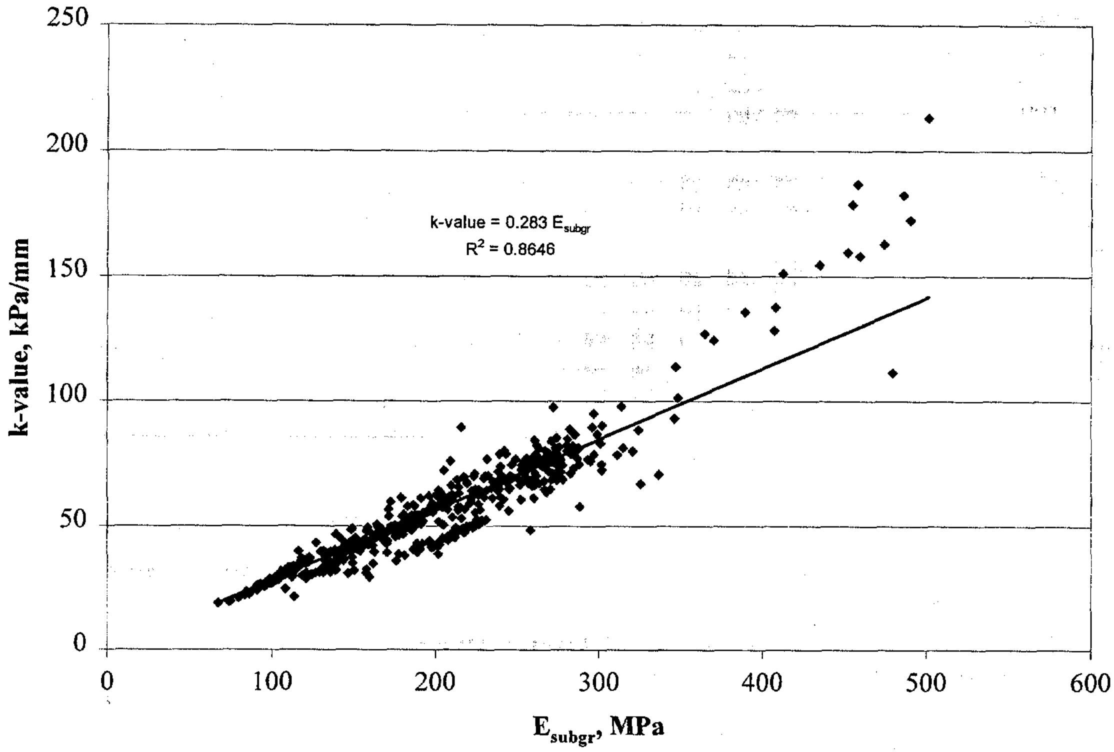


Figure 58. Subgrade modulus of elasticity versus coefficient of subgrade reaction (SMP sections).

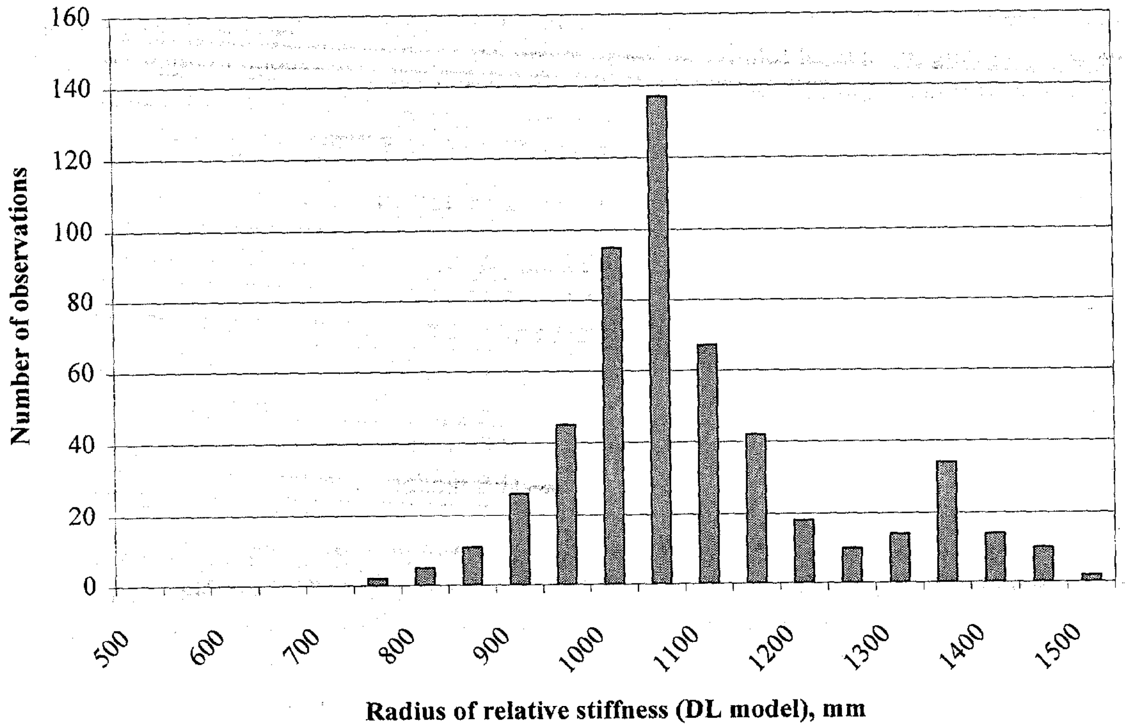


Figure 59. Frequency distribution of backcalculated radius of relative stiffness (DL model) for SMP LTPP sections.

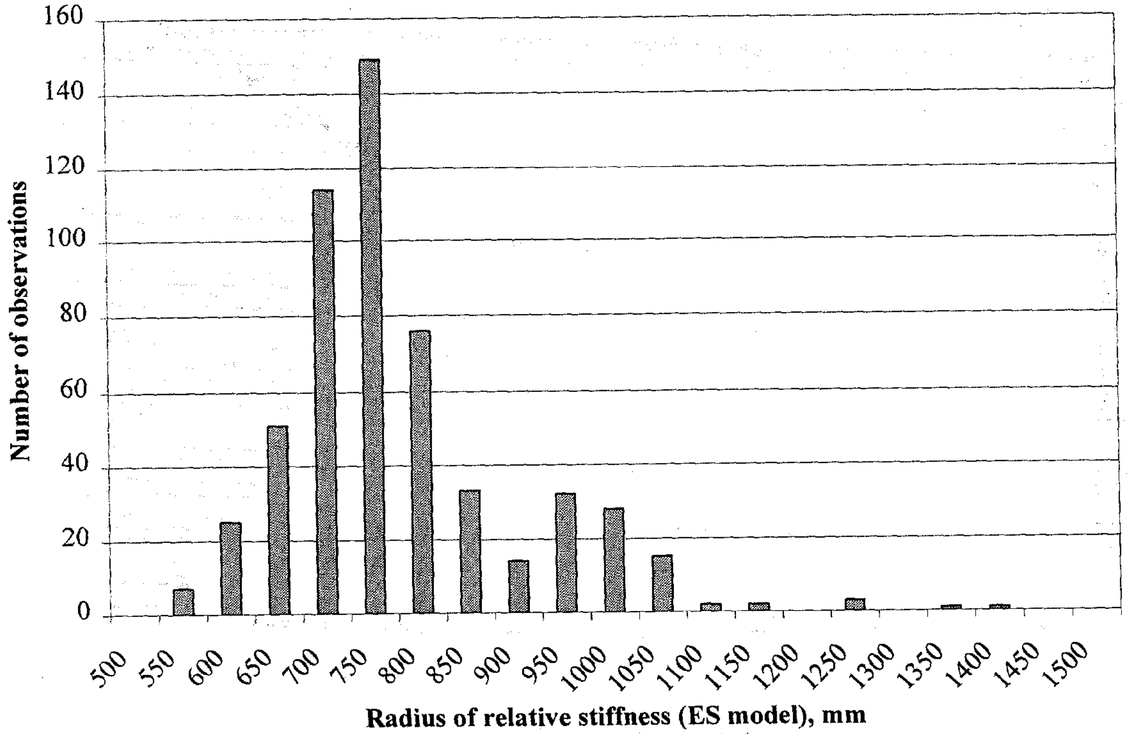


Figure 60. Frequency distribution of backcalculated radius of relative stiffness (ES model) for SMP LTPP sections.

The results of backcalculation for the rigid LTPP SMP sections were used to compare backcalculated mean radii of relative stiffness for the DL and ES models. Figure 61 shows that, as expected, higher radii of relative stiffness for the DL model correspond to higher radii of relative stiffness for the ES model. An excellent correlation between these two parameters was observed. A simple linear regression resulted in the following model:

$$l_k = 1.2444\, l_{es} + 130.73$$

$$R^2 = 99.2\%$$
$$N = 556$$
$$SEE = 13.77 \text{ mm}$$

where

l_k	=	radius of relative stiffness (DL model), mm
l_{es}	=	radius of relative stiffness (ES model), mm

It should be noted that although this relationship looks slightly different from the corresponding relationships obtained for SPS and GPS sections, they result in similar predicted radii of relative stiffness (DL model) if the corresponding radius of relative stiffness (ES model) is within reasonable limits for highway pavements.

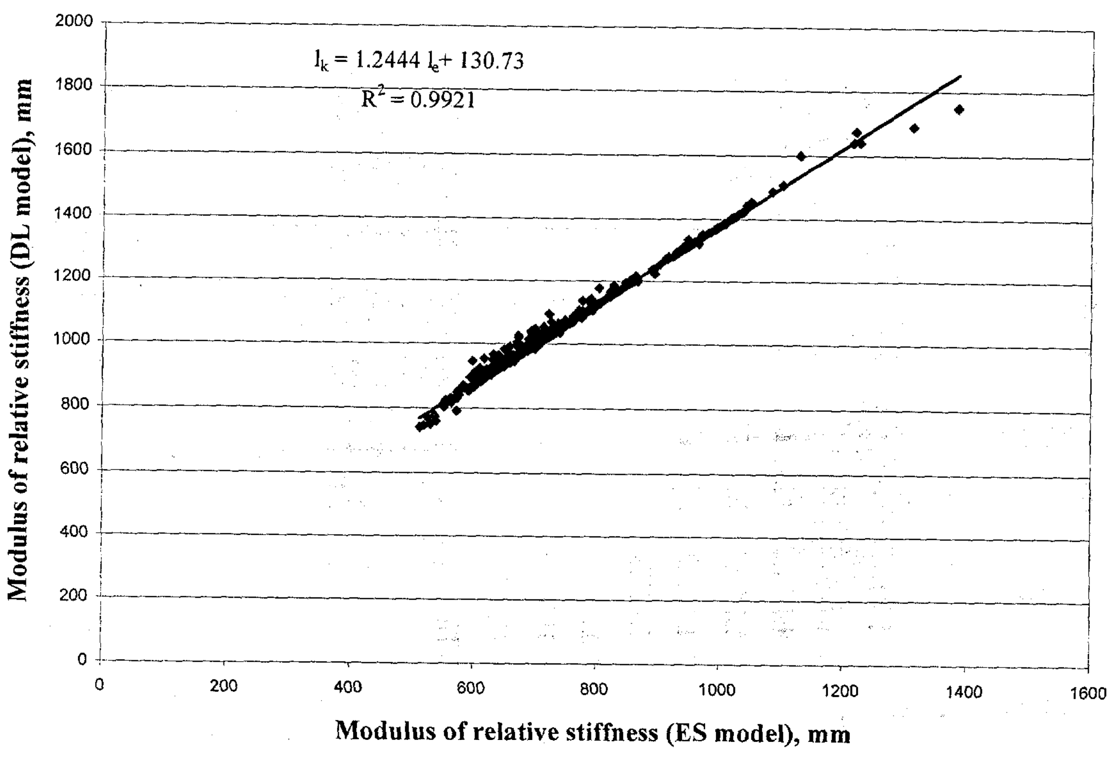


Figure 61. ES radius of relative stiffness versus DL radius of relative stiffness (SMP sections).

Bonding Condition Between PCC Slab and Base

Among 491 PCC and base section layer moduli obtained in this study using the DL model, only 19 were assigned an unbonded interface between the layers. In the remaining 472 cases, the layers were assigned a bonded interface condition, as shown in figure 62. For the ES foundation model, the same proportion between bonded and unbonded interface was observed. If the bond/no bond condition did not dramatically affect backcalculated results, the interface condition was assumed to be bonded. In the majority of cases, the bonded interface was observed even for stabilized bases, as shown in figure 63. It is important to note that the backcalculation is done at the slab center. Bonding may be different at the slab edge.

Backcalculated PCC Moduli

In this study, PCC layer properties were determined for 524 FWD passes of 19 SMP LTPP sections using DL and ES subgrade models. Figures 64 and 65 show frequency histogram distributions for PCC moduli backcalculated using the DL and ES subgrade models, respectively. The majority of the backcalculated moduli are in the reasonable range (from 25 to 55 GPa), supporting the conclusion of the robustness of the backcalculation approach.

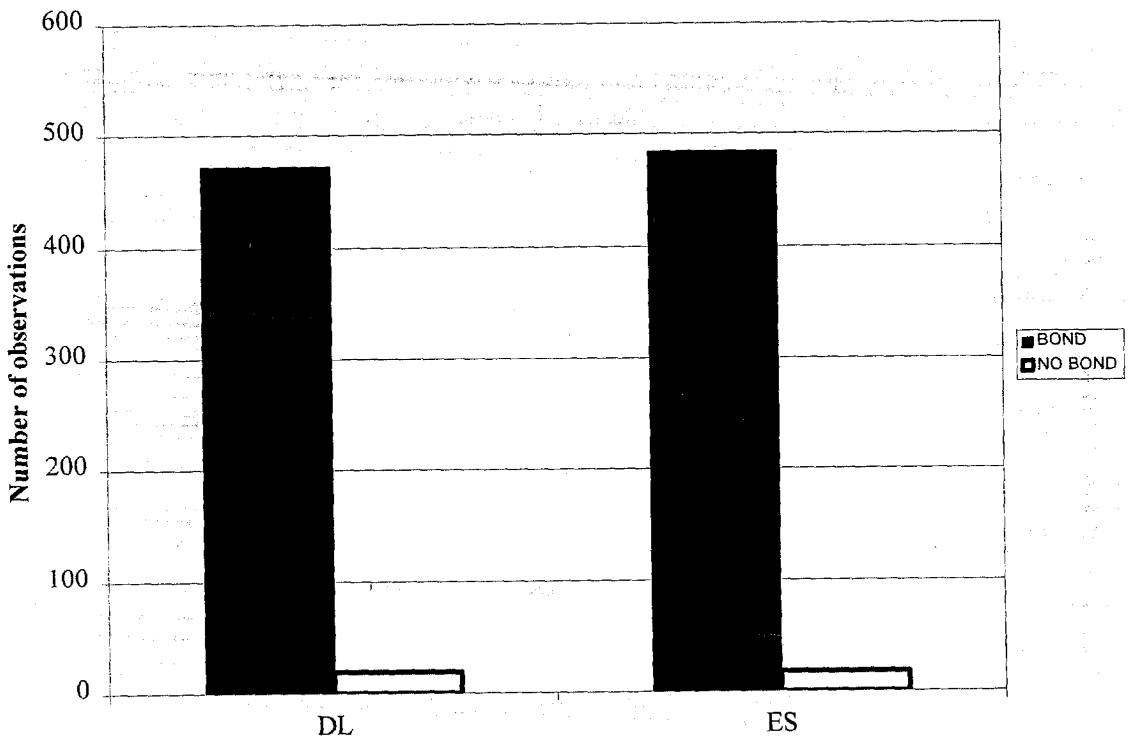


Figure 62. Distribution of bond/no bond interface condition for non-stabilized and stabilized SMP LTPP sections.

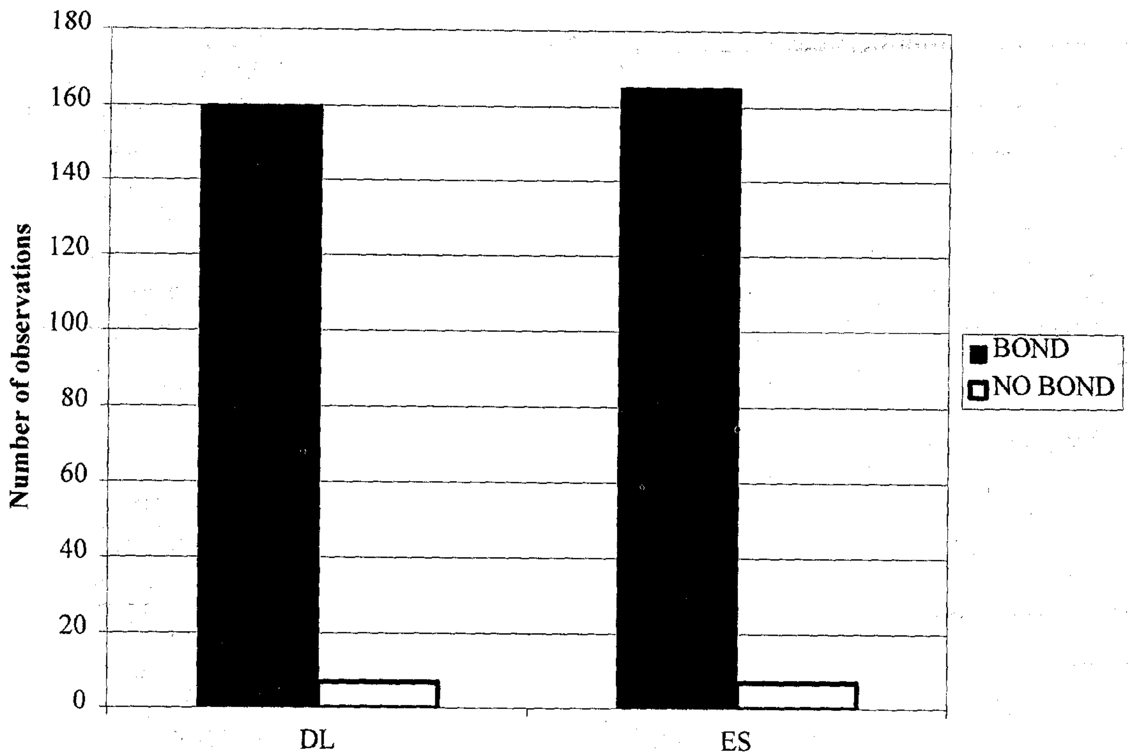


Figure 63. Distribution of bond/no bond interface condition for SMP LTPP sections with stabilized bases.

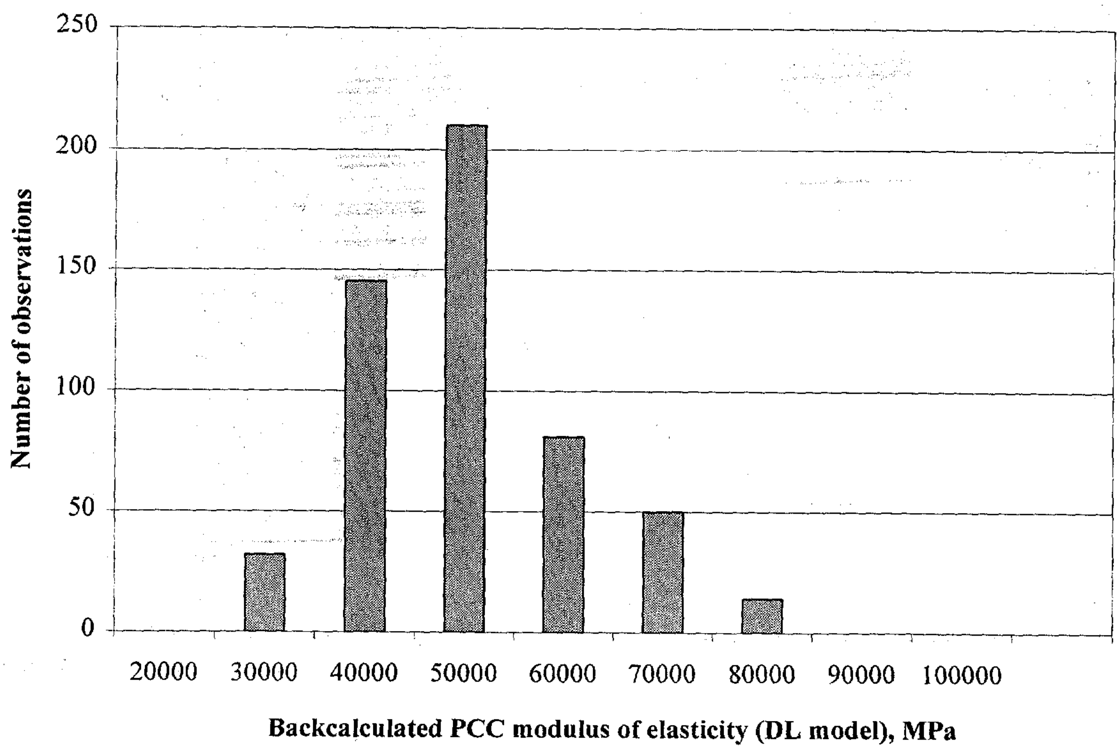


Figure 64. Frequency distribution of backcalculated PCC modulus of elasticity (DL model) for SMP LTPP sections.

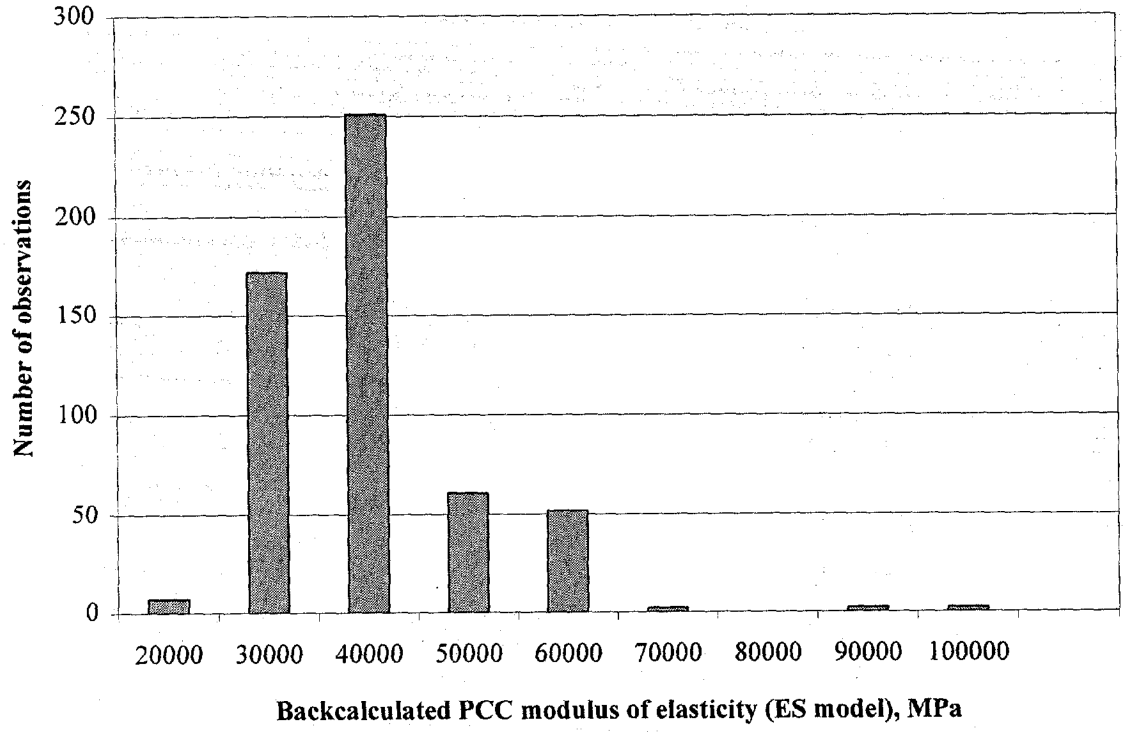


Figure 65. Frequency distribution of backcalculated PCC modulus of elasticity (ES model) for SMP LTPP sections.

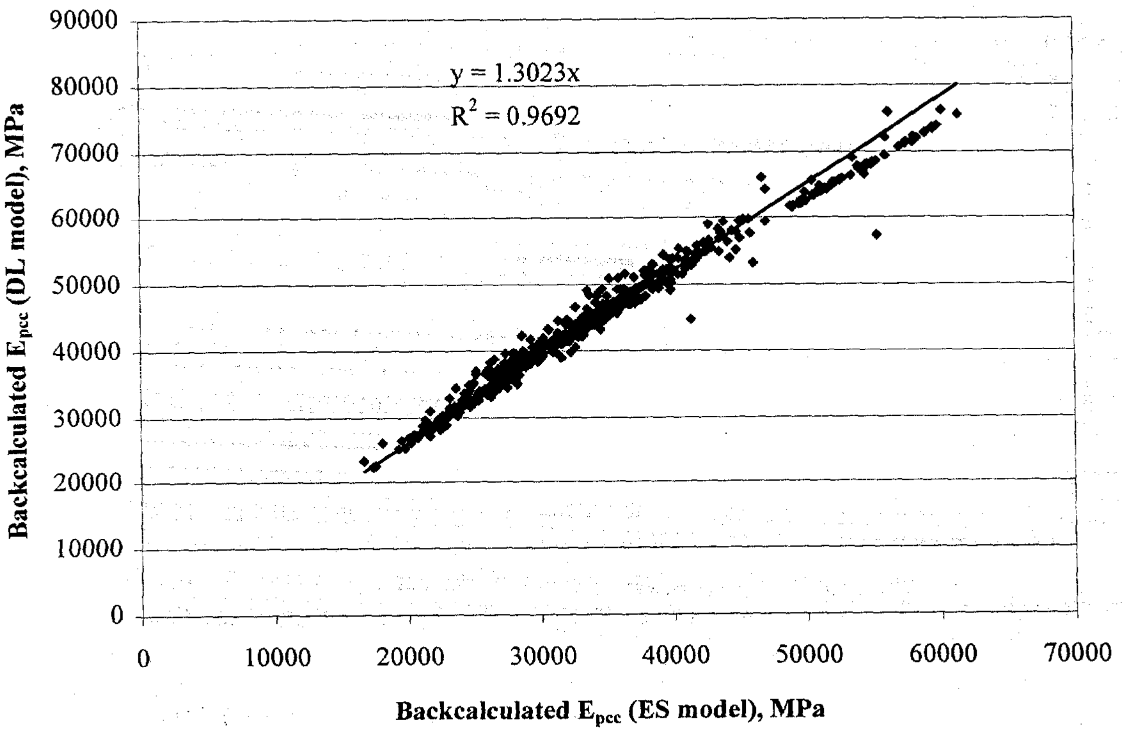


Figure 66. Backcalculated PCC modulus of elasticity (ES model) versus backcalculated PCC modulus of elasticity (DL model) for SMP sections.

However, several backcalculated PCC moduli are much higher than acceptable (greater than 80 GPa). These moduli were backcalculated from FWD passes of the sections located in a very cold climate (Manitoba, Minnesota, and Quebec) during wintertime, and there are indications that the subgrade was frozen during these tests. Although, theoretically, it should not significantly affect backcalculated PCC moduli, analysis of FWD deflection data SMP sections clearly shows that currently available backcalculation procedures may produce misleading results if a subgrade is frozen. Moreover, the majority of FWD passes of Manitoba, Minnesota, and Quebec sections during winter resulted in unsuccessful backcalculation. Therefore, it is not recommended to upload these high moduli to the IMS database.

Figure 66 shows backcalculated PCC moduli using the ES subgrade model versus backcalculated PCC moduli using the DL subgrade model. A very good correlation between these two sets of moduli is observed. A linear regression analysis resulted in the following relationship:

$$E_{PCC,DL} = 1.3023\ E_{PCC,ES}$$

$$R^2 = 96.92\%$$
$$N = 531$$
$$SEE = 1925\ \text{MPa}$$

where

$E_{PCC,ES}$	=	PCC modulus of elasticity backcalculated using ES model, GPa
$E_{PCC,ES}$	=	PCC modulus of elasticity backcalculated using DL model, GPa

Although this relationship is based on the results of backcalculation from the FWD passes of the pavement sections made during different times of the year and time of the day, it is very close to the corresponding model developed for the GPS and SPS sections. This supports the conclusion that when a transition from the ES to the DL foundation model needs to be made, moduli of elasticity of the upper layers also needs to be adjusted. It should be noted, however, that unrealistically high PCC moduli obtained from FWD testing of section 833802 (Manitoba) in November and December 1993 and December 1994 were excluded from the analysis.

Effect of Seasonal Variation and Time of Testing

The collected FWD data allow for analysis of the effect of season and time of day on backcalculated values. Typically, several passes are conducted each day on SMP sections to study the variations that may occur over a single day. Almost all sections showed dependence of backcalculated parameters on the time of the testing. Figures 67 and 68 show the subgrade support k-value and ES, respectively, for section 133919 (Georgia) obtained from backcalculation of the four FWD passes conducted in April 1996 at 7:30 a.m., 11 a.m., 2 p.m., and 5 p.m. The results show great variation over the course of the day. The lowest subgrade moduli are determined from the 2 p.m. testing when backcalculated subgrade moduli are about three times lower than from 7 a.m. testing. Backcalculated PCC moduli of elasticity followed the same trend for both DL and ES models, as shown in figures 69 and 70, although the difference among backcalculated values from different FWD passes was not as striking as for subgrade moduli.

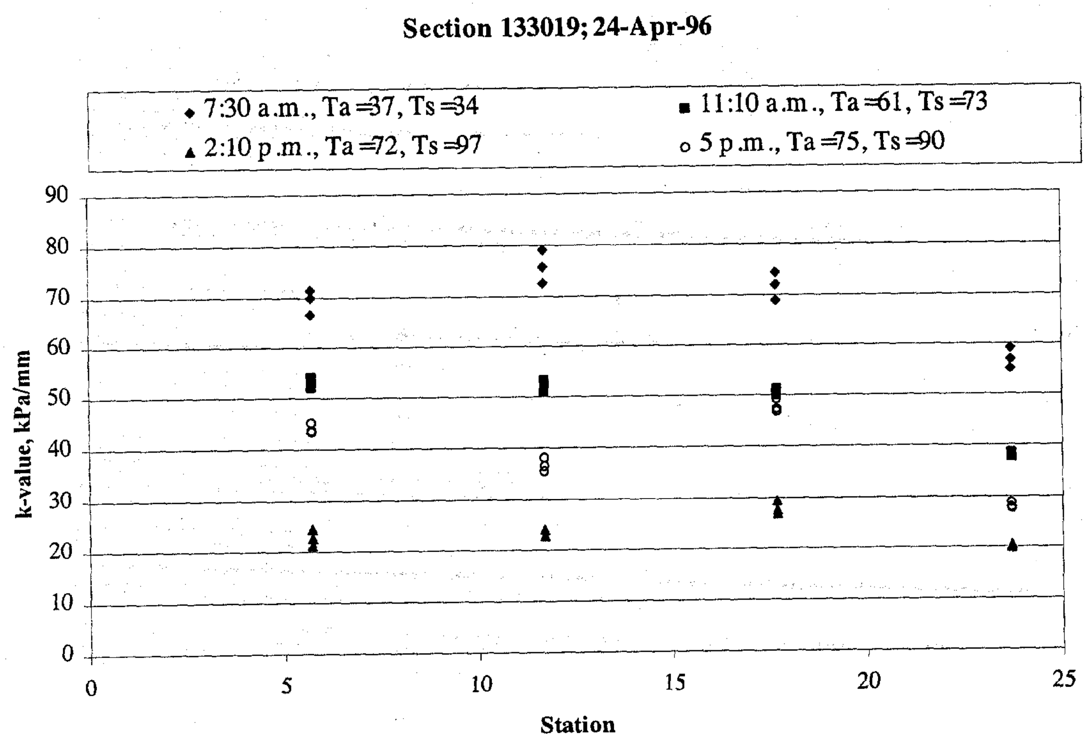


Figure 67. Daily variation in backcalculated k-value, section 133019 (April 1996).

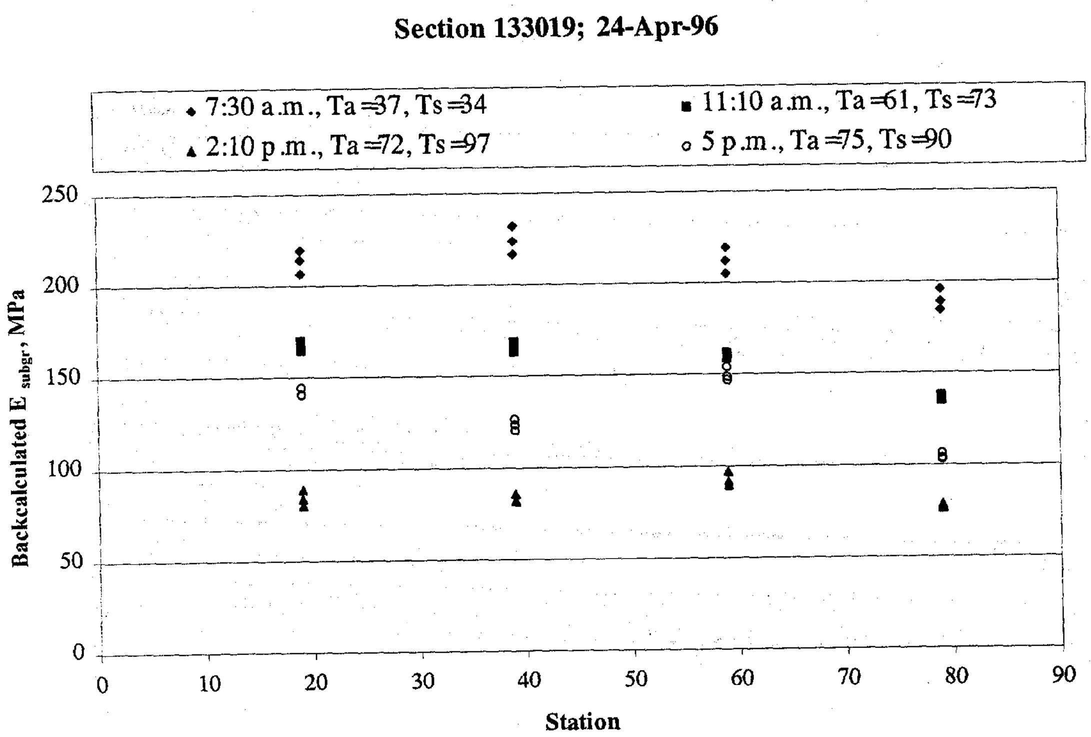


Figure 68. Daily variation in backcalculated subgrade modulus of elasticity, section 133019 (April 1996).

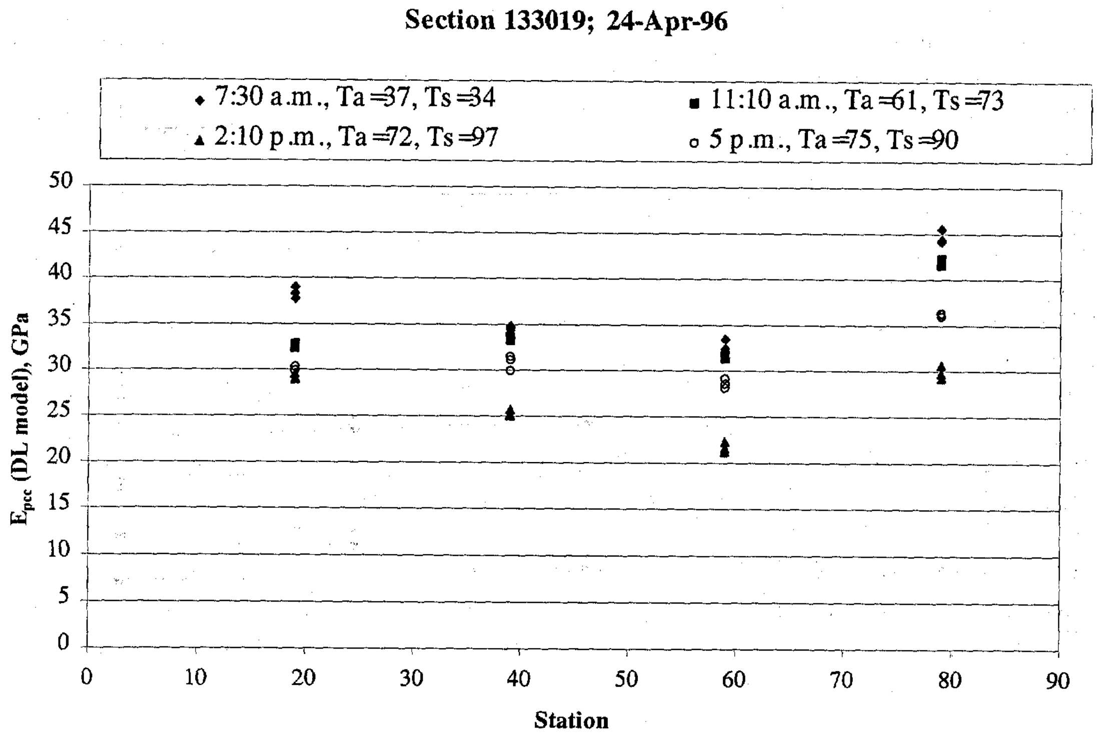


Figure 69. Daily variation in backcalculated PCC modulus of elasticity (DL model), section 133019 (April 1996).

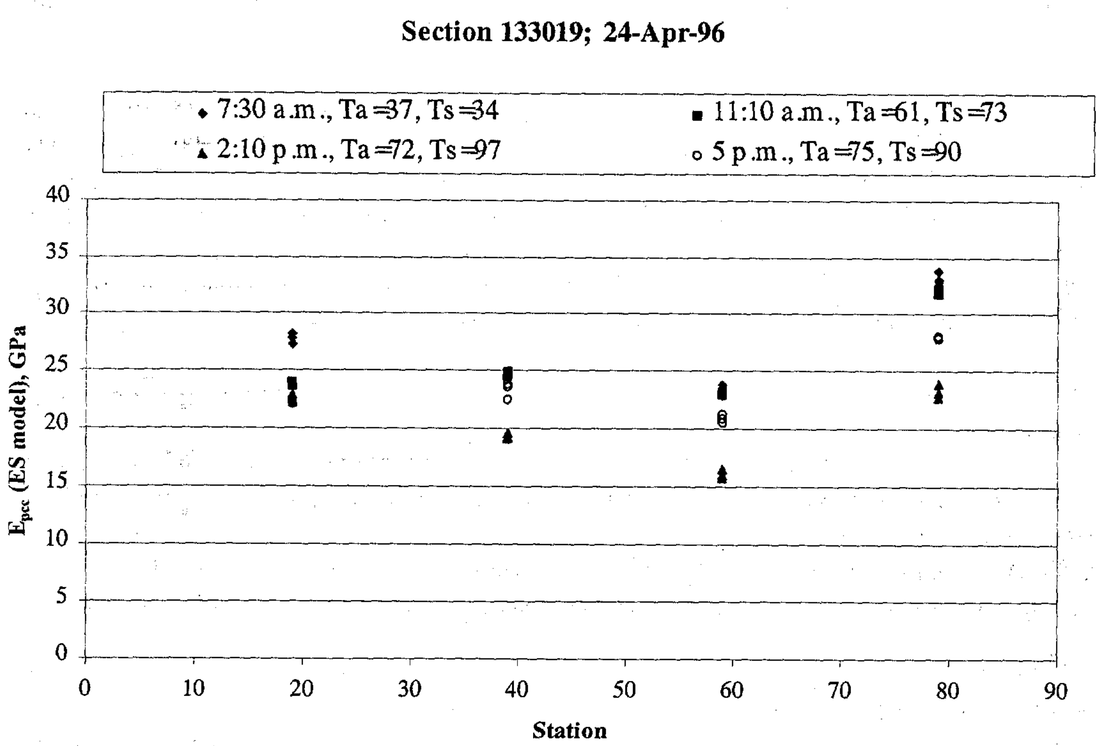


Figure 70. Daily variation in backcalculated PCC modulus of elasticity (ES model), section 133019 (April 1996).

Similar effects were observed for many sections located in different climatic regions. Figures 71 through 78 show the effect of time testing on the backcalculated parameters obtained for section 493011 (Utah) and 274040 (Minnesota). Once again, a significant change in backcalculated subgrade moduli from time of day was observed. For section 493011, change in backcalculated PCC moduli was also significant.

Tables 10 and 11 present mean and maximum coefficient of variation of the mean section backcalculated parameters for the SMP LTPP sections from different FWD passes made on the same day of testing. For 12 of the 16 SMP sections for which multiple FWD passes were available, a coefficient of variation in backcalculated k-value greater than 20 percent was observed on at least 1 day of testing. Although variability in radius of relative stiffness and PCC modulus of elasticity is lower, six sections (040215, 063042, 313018, 48 4142, 493011, and 893015) also exhibited significant (greater than 20 percent) variability in backcalculated PCC modulus. Sections 063042 and 133019 exhibited coefficient of variation in backcalculated radius of relative stiffness greater than 10 percent in at least one day of testing.

It is reasonable to conclude, therefore, that the time of day of FWD testing may significantly affect backcalculated moduli. This effect is most likely due to temperature differences and the resulting slab curling. Therefore, accounting for the effect of PCC slab curling is very important for reliable interpretation of FWD deflection data. However, development of a procedure for slab curling correction was outside the scope of this project.

As expected, the season of testing was found to affect backcalculated subgrade moduli. This effect is highly confounded, however, with the effect of the time of testing. To reduce the latter effect, only first FWD passes for each day of testing were considered in the analysis of seasonal variation in backcalculated values.

Figures 79 through 84 show mean backcalculated subgrade moduli and PCC moduli for sections 133019 (Georgia), 274040 (Minnesota), and 533813 (Washington) obtained from different days of testing for the first FWD pass on each day. Section 133019 shows much lower subgrade moduli in March 1996 than for any other days of testing. This could be explained by the effect of heavy early spring rain that softens the subgrade. Section 533813 shows lower subgrade moduli in June than in other months of the testing. For other testing times, these two sections show quite consistent backcalculated values for both subgrade and concrete layers.

Minnesota Section 274040 exhibited lower backcalculated values in the end of spring and early summer (June 1994, April–May 1996) and much higher backcalculated values for winter and early spring months. Freezing subgrades resulted not only in higher subgrade moduli, but also in increased backcalculated PCC moduli. This increase is much higher than can be expected by an increase in bending stiffness of the constructed layers due to frozen base and upper subgrade. However, the dynamic nature of FWD testing may explain this discrepancy. Therefore, accounting for dynamic effects in backcalculation may significantly increase reliability.

Tables 12 and 13 present coefficients of variation in mean backcalculated parameters from the first FWD passes for the SMP LTPP sections for DL and ES models, respectively. It can be observed that variability is higher than that observed for GPS sections. This may be due to more frequent testing and, therefore, better ability to catch the spring thaw with SMP testing. It is also clear that, for the majority of the sections, variability in backcalculated results from different FWD passes in one day may be significantly higher than seasonal variability. This suggests that

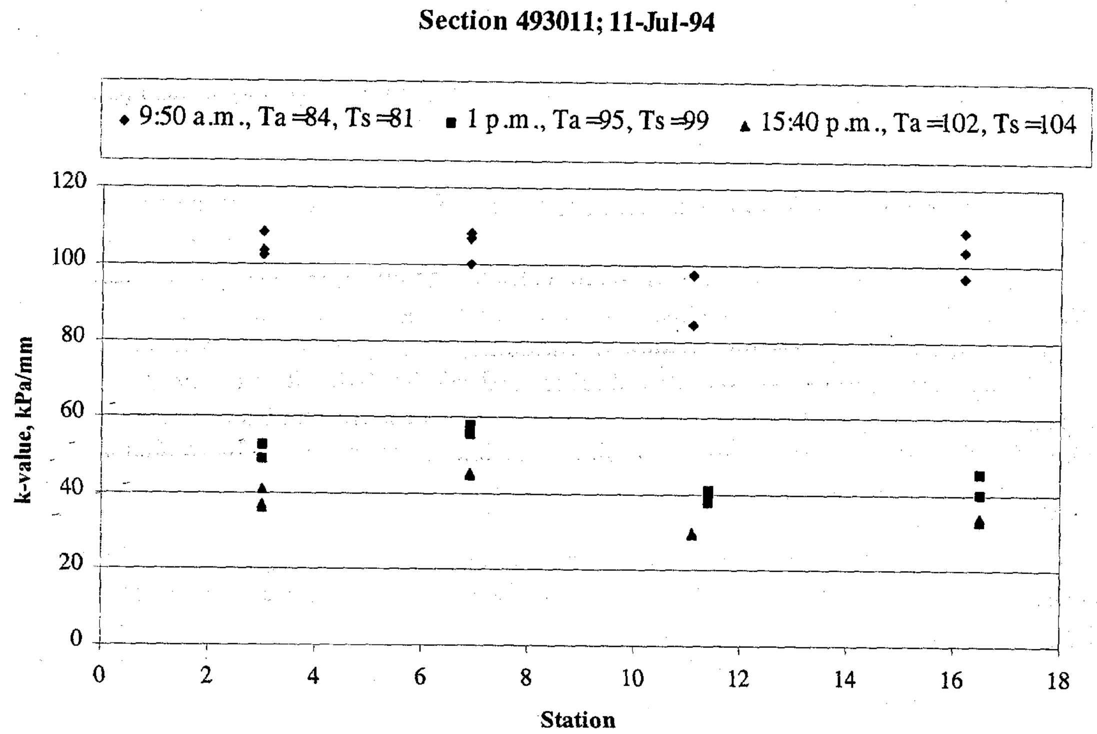


Figure 71. Daily variation in backcalculated k-value, section 493011 (July 1994).

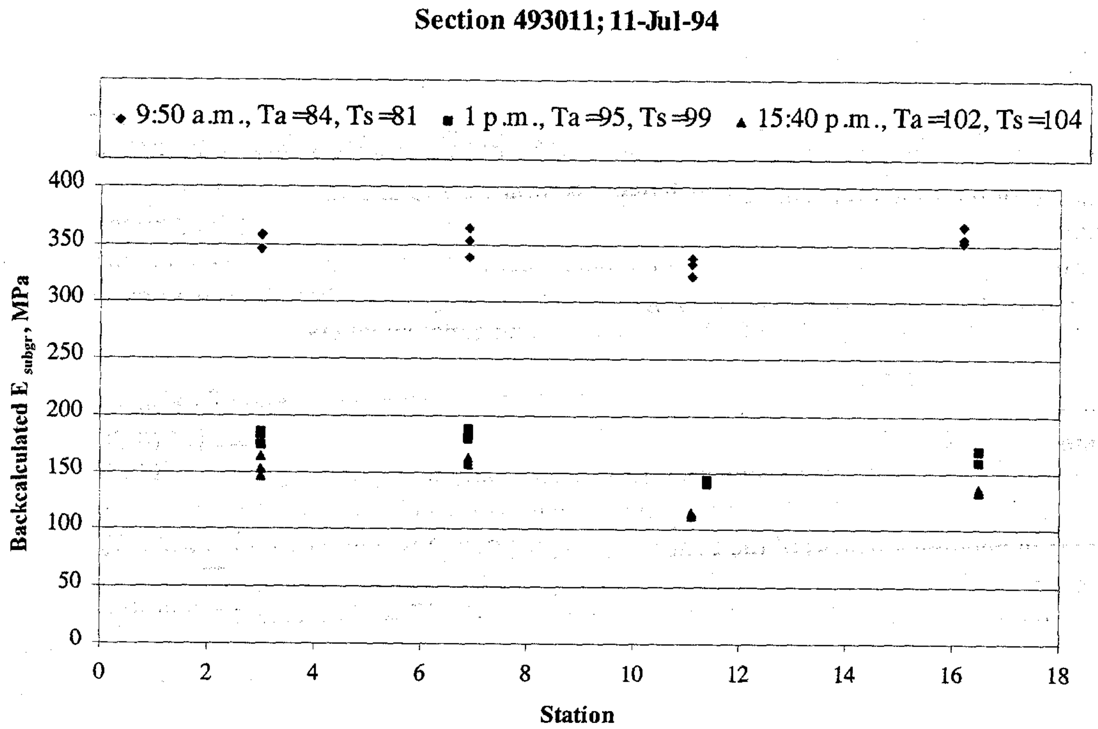


Figure 72. Daily variation in backcalculated subgrade modulus of elasticity, section 493011 (July 1994).

Section 493011; 11-Jul-94

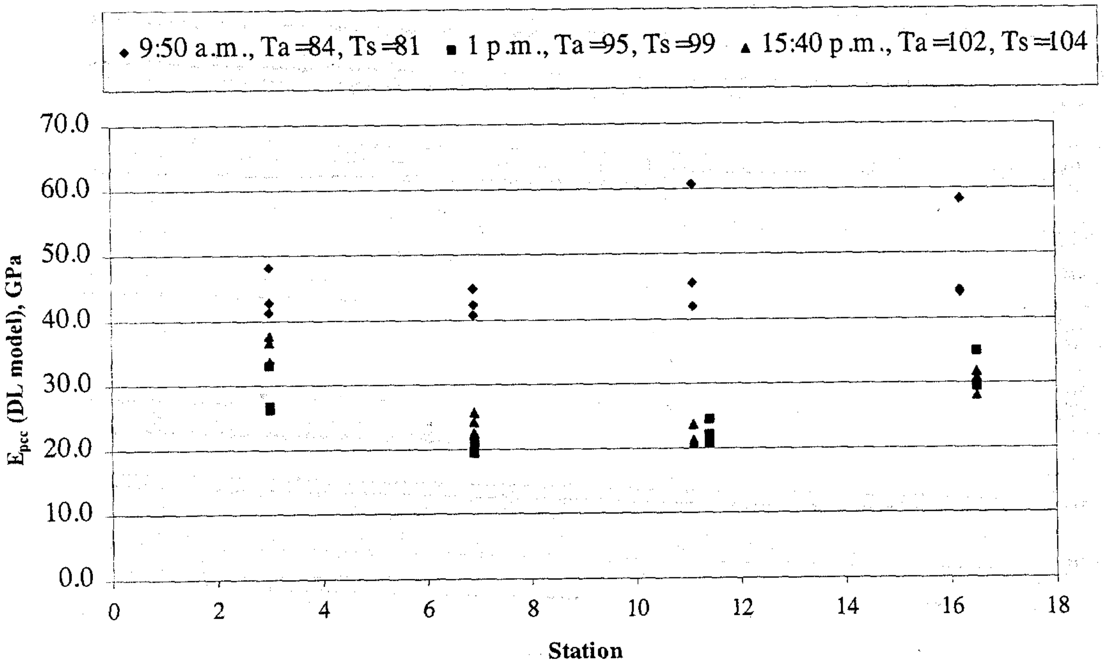


Figure 73. Daily variation in backcalculated PCC modulus of elasticity (DL model), section 493011 (July 1994).

Section 493011; 11-Jul-94

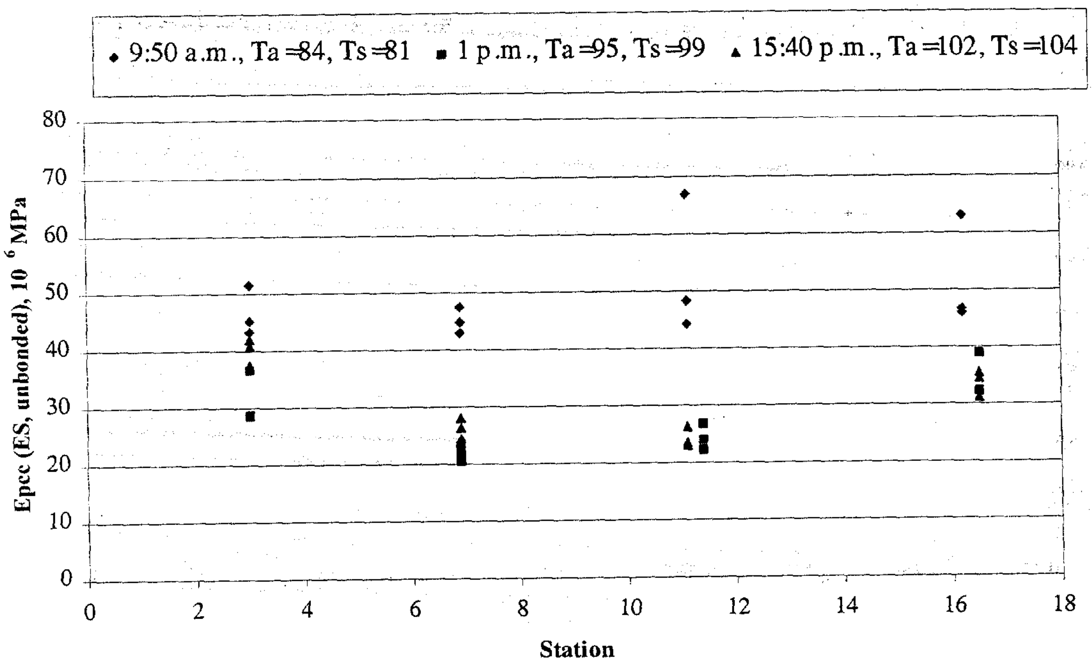


Figure 74. Daily variation in backcalculated PCC modulus of elasticity (ES model), section 493011 (July 1994).

Section 274040; 31-Mar-94

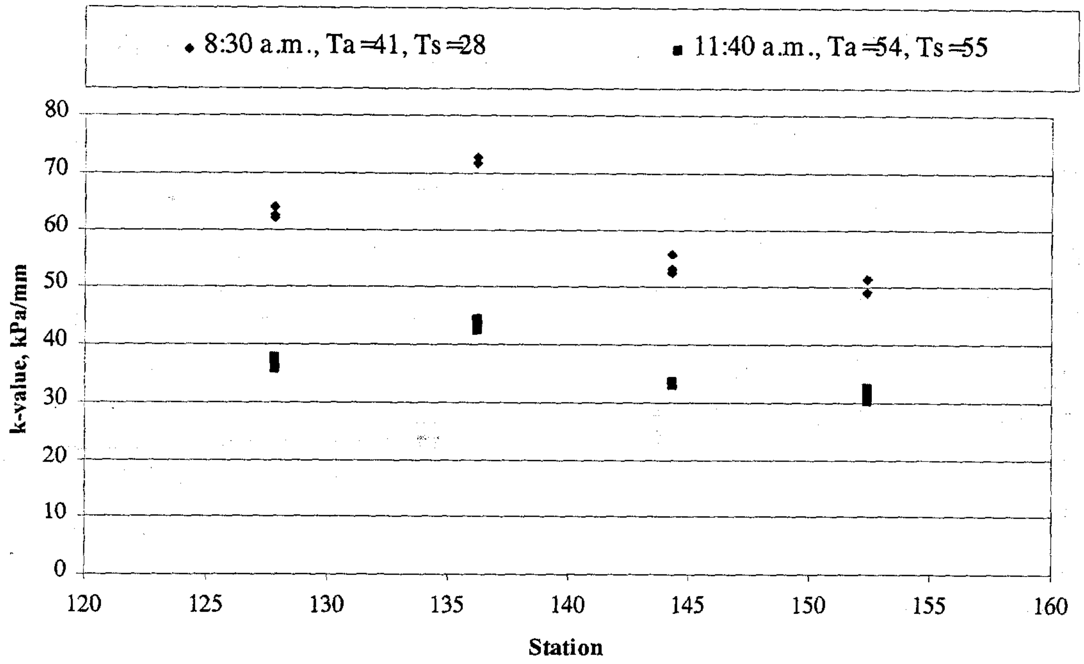


Figure 75. Daily variation in backcalculated k-value, section 274040 (March 1994).

Section 274040; 31-Mar-94

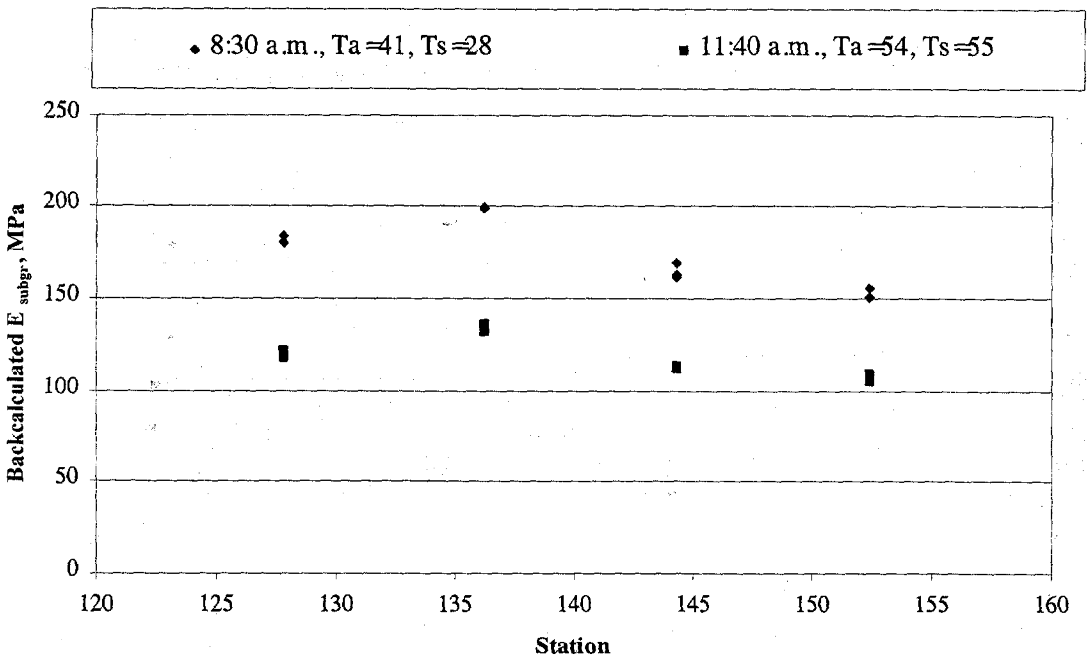


Figure 76. Daily variation in backcalculated subgrade modulus of elasticity, section 274040 (March 1994).

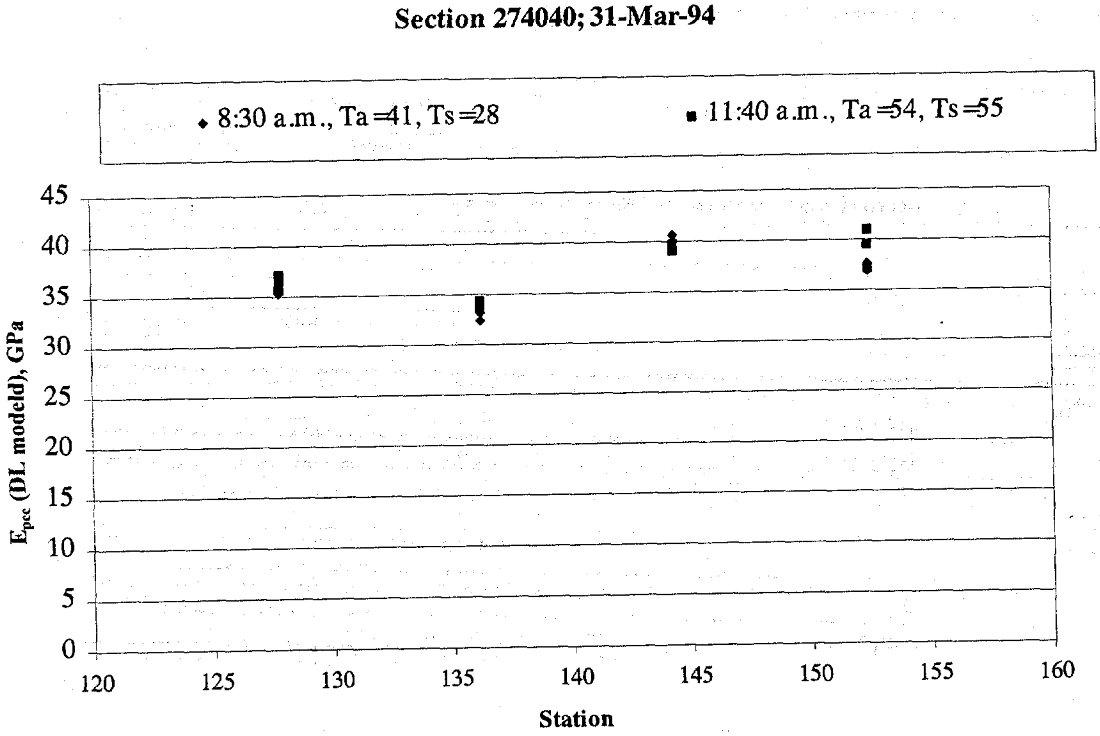


Figure 77. Daily variation in backcalculated PCC modulus of elasticity (DL model), section 274040 (March 1994).

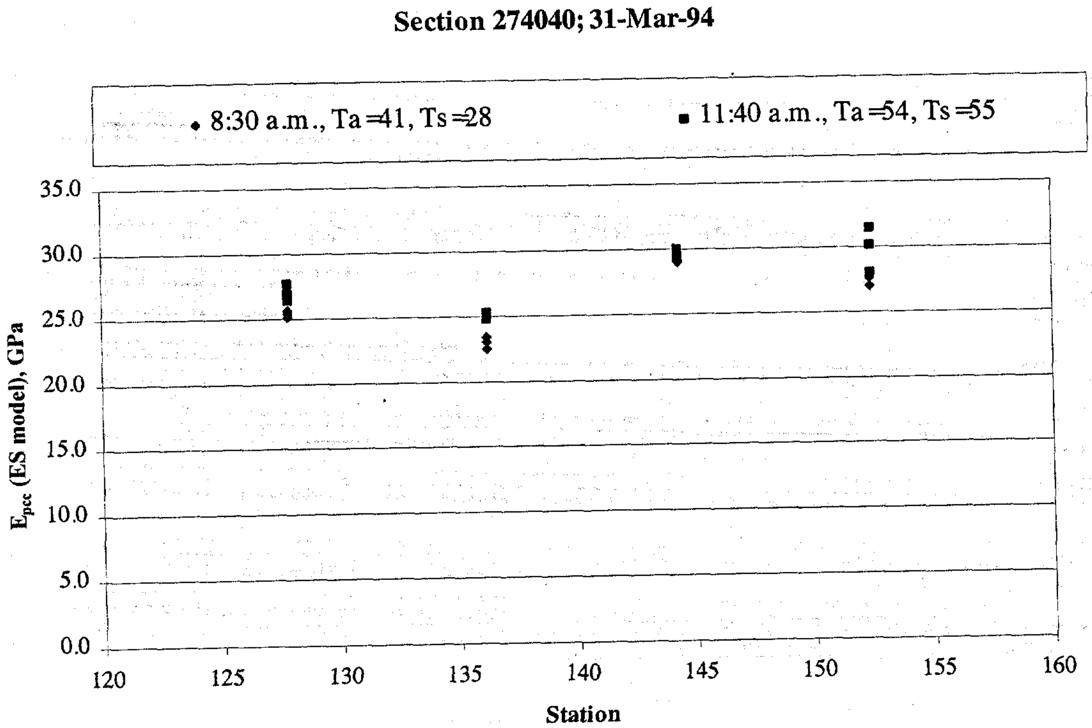


Figure 78. Daily variation in backcalculated PCC modulus of elasticity (ES model), section 274040 (March 1994).

Table 10. Coefficients of variation of the mean values of backcalculated parameters from the same day of testing (DL model).

State	Section	k-Value		Radius of Relative Stiffness		PCC Modulus of Elasticity	
		Mean	Max	Mean	Max	Mean	Max
Arizona	040215	0.200	0.485	0.045	0.071	0.101	0.232
California	063042	0.084	0.221	0.045	0.136	0.120	0.293
Georgia	133019	0.412	0.694	0.076	0.135	0.140	0.239
Indiana	183002	0.063	0.063	0.005	0.009	0.040	0.053
Kansas	204054	0.036	0.085	0.008	0.019	0.008	0.017
Minnesota	274040	0.081	0.374	0.020	0.096	0.016	0.045
Nebraska	313018	0.140	0.207	0.023	0.043	0.157	0.235
New York	364018	0.111	0.228	0.022	0.058	0.038	0.095
North Carolina	370201	0.061	0.183	0.024	0.037	0.082	0.152
Pennsylvania	421606	0.102	0.215	0.022	0.055	0.043	0.074
Texas	484142	0.107	0.193	0.021	0.046	0.076	0.231
Texas	484143	0.099	1.503	0.072	1.188	0.099	1.437
Utah	493011	0.183	0.560	0.027	0.086	0.219	0.614
Washington	533813	0.135	0.537	0.024	0.098	0.055	0.169
Manitoba	833802	0.052	0.213	0.014	0.060	0.047	0.146
Quebec	893015	0.076	0.200	0.030	0.080	0.090	0.249

Table 11. Coefficients of variation of the mean values of backcalculated parameters from the same day of testing (ES model).

State	Section	Subgrade Modulus of Elasticity		Radius of Relative Stiffness		PCC Modulus of Elasticity	
		Mean	Max	Mean	Max	Mean	Max
Arizona	040215	0.169	0.417	0.052	0.080	0.103	0.213
California	063042	0.061	0.122	0.050	0.150	0.122	0.322
Georgia	133019	0.359	0.588	0.092	0.155	0.114	0.171
Indiana	183002	0.058	0.061	0.006	0.010	0.038	0.051
Kansas	204054	0.033	0.073	0.010	0.023	0.005	0.010
Minnesota	274040	0.062	0.293	0.021	0.112	0.020	0.047
Nebraska	313018	0.139	0.215	0.025	0.044	0.158	0.234
New York	364018	0.095	0.188	0.026	0.065	0.035	0.065
North Carolina	370201	0.059	0.195	0.025	0.049	0.073	0.153
Pennsylvania	421606	0.075	0.120	0.020	0.040	0.048	0.077
Texas	484142	0.091	0.231	0.020	0.052	0.065	0.189
Texas	484143	0.017	0.064	0.014	0.033	0.032	0.068
Utah	493011	0.193	0.517	0.029	0.077	0.210	0.583
Washington	533813	0.115	0.444	0.026	0.111	0.055	0.155
Manitoba	833802	0.043	0.200	0.015	0.070	0.047	0.139
Quebec	893015	0.058	0.208	0.029	0.047	0.087	0.249

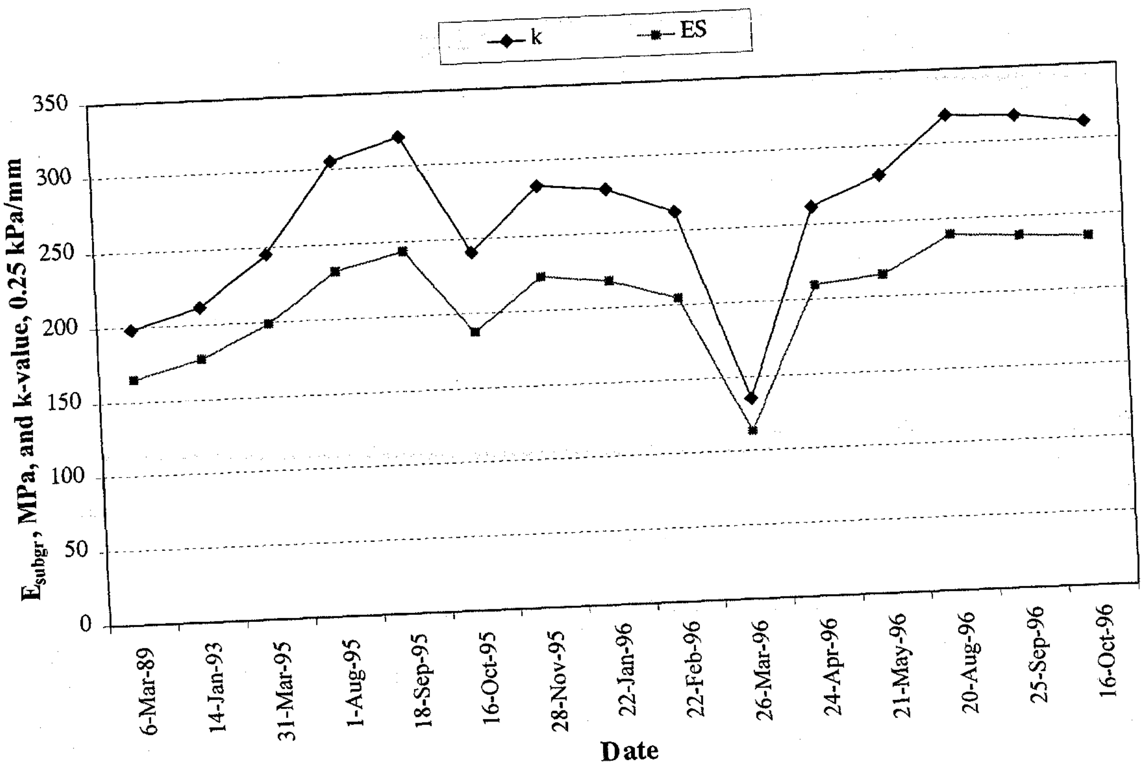


Figure 79. Seasonal variation in backcalculated subgrade moduli, section 133019.

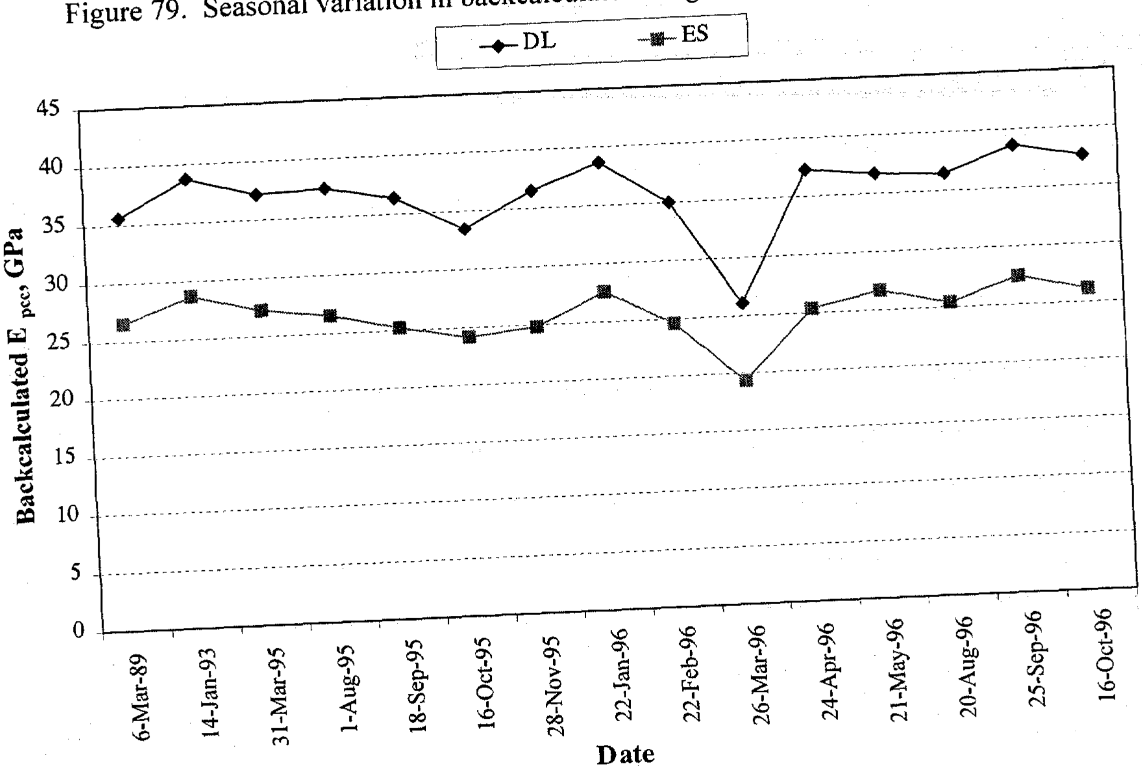


Figure 80. Seasonal variation in backcalculated PCC modulus of elasticity, section 133019.

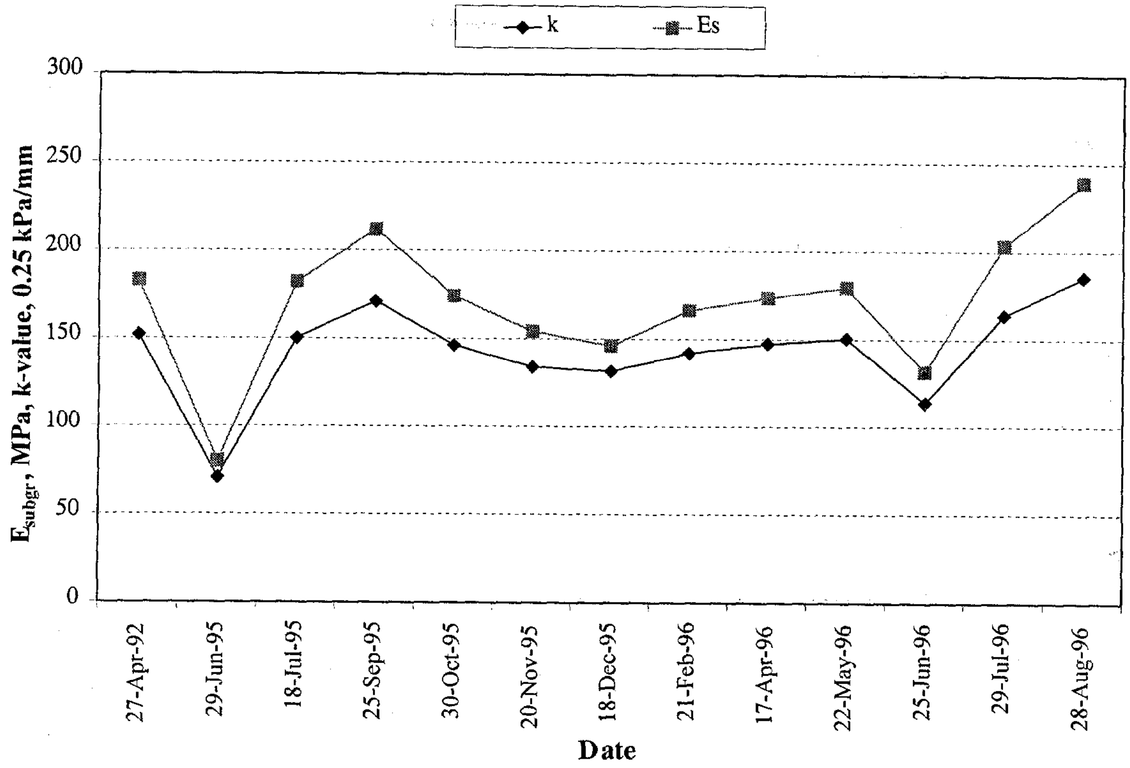


Figure 81. Seasonal variation in backcalculated subgrade moduli, section 533813.

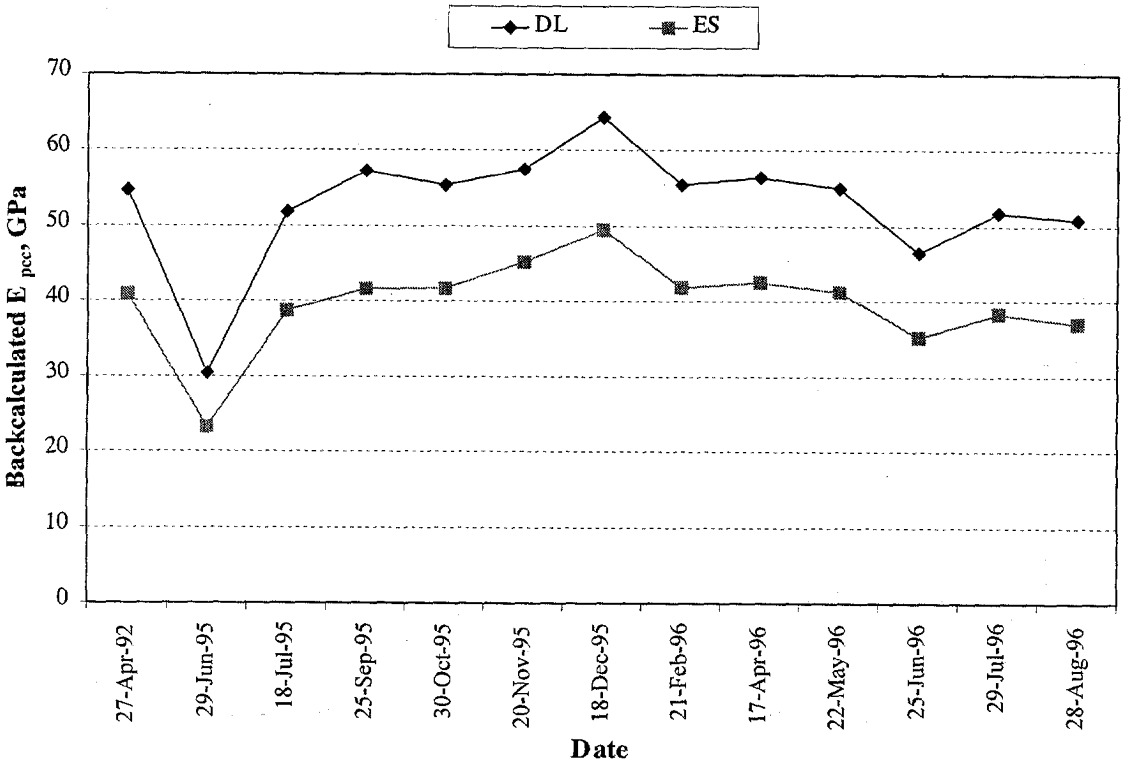


Figure 82. Seasonal variation in backcalculated PCC modulus of elasticity, section 533813.

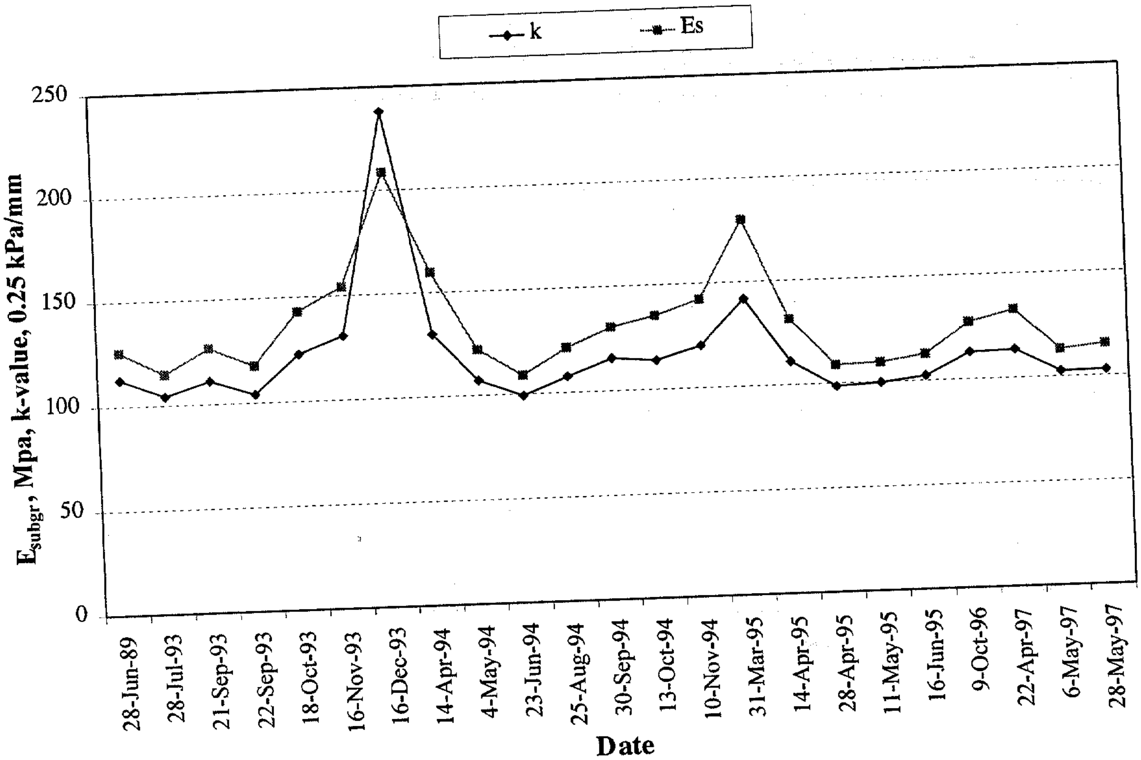


Figure 83. Seasonal variation in backcalculated subgrade moduli, section 274040.

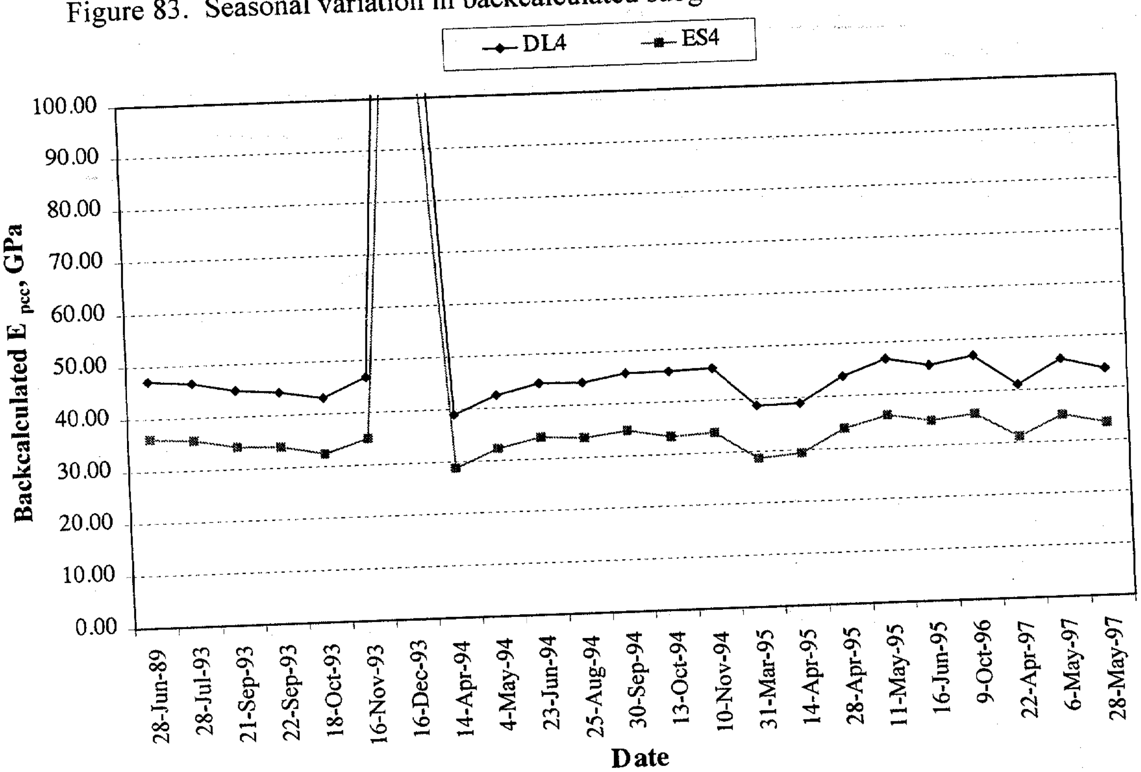


Figure 84. Seasonal variation in backcalculated PCC modulus of elasticity, section 274040.

Table 12. Coefficients of variation of the mean values of backcalculated parameters from first FWD passes (DL model).

State	Section	k-Value	PCC Modulus of Elasticity	Radius of Relative Stiffness
Arizona	040215	0.125	0.057	0.138
California	063042	0.125	0.077	0.204
Georgia	133019	0.199	0.040	0.091
Indiana	183002	0.113	0.039	0.072
Kansas	204054	0.085	0.031	0.093
Minnesota	274040	0.386	0.089	0.531
Nebraska	313018	0.214	0.071	0.122
New York	364018	0.177	0.027	0.124
North Carolina	370201	0.210	0.061	0.080
North Carolina	370205	0.204	0.051	0.120
North Carolina	370208	0.110	0.024	0.128
North Carolina	370212	0.045	0.045	0.132
Pennsylvania	421606	0.191	0.051	0.087
Texas	484142	0.099	0.051	0.118
Texas	484143	0.079	0.032	0.056
Utah	493011	0.156	0.044	0.161
Washington	533813	0.236	0.054	0.167
Manitoba	833802	0.652	0.151	0.801
Quebec	893015	0.357	0.095	0.546

Table 13. Coefficients of variation of the mean values of backcalculated parameters from first FWD passes (ES model).

State	Section	Subgrade Modulus of Elasticity	PCC Modulus of Elasticity	Radius of Relative Stiffness
Arizona	040215	0.093	0.064	0.150
California	063042	0.087	0.087	0.230
Georgia	133019	0.173	0.052	0.088
Indiana	183002	0.088	0.045	0.079
Kansas	204054	0.080	0.041	0.104
Minnesota	274040	0.287	0.099	0.588
Nebraska	313018	0.125	0.075	0.128
New York	364018	0.163	0.028	0.112
North Carolina	370201	0.172	0.072	0.091
North Carolina	370212	0.181	0.063	0.068
Pennsylvania	421606	0.125	0.063	0.154
Texas	484142	0.054	0.049	0.127
Texas	484143	0.096	0.042	0.080
Utah	493011	0.066	0.059	0.128
Washington	533813	0.055	0.034	0.061
Manitoba	833802	0.140	0.046	0.149
Quebec	893015	0.208	0.063	0.175

it is important to conduct FWD basin testing early in the morning to reduce variability in backcalculated values.

Backcalculation Analysis Results

A summary of the backcalculation analysis results for the SMP sections is given in the LTPP IMS table MON_DEFL_RGD_BAKCAL_SECT. The results are presented in terms of the mean values, minimum values, maximum values, and standard deviations of the following parameters:

DL Model

- k-value (modulus of subgrade reaction).
- E_{PCC} (modulus of elasticity of the PCC slab).
- E_{base} (modulus of elasticity of the base layer).

ES Model

- E_{subgr} (modulus of elasticity of the subgrade).
- E_{PCC} (modulus of elasticity of the PCC slab).
- E_{base} (modulus of elasticity of the base layer).

CHAPTER 5. LIMITATIONS OF CURRENT BACKCALCULATION PROCEDURES

Although backcalculated parameters determined in this study were found to be realistic for the majority of the LTPP rigid pavement sections, this study also identified some limitations of the current backcalculation procedures for rigid pavements. It was noted that backcalculated values may vary significantly due to factors such as temperature at the time of testing, slab curling conditions, time of day of the testing, bonding conditions, and time of year of the testing. Current rigid pavement backcalculation technology is inappropriate to adequately address all these aspects. The LTPP database, however, provides an excellent opportunity to conduct an in-depth study of these factors.

This chapter summarizes observed problems with rigid pavement backcalculation and discusses research needed to address the problems.

Comparison of Backcalculated and Laboratory PCC Moduli

It is commonly believed that the backcalculated E_{PCC} is approximately equal to the static E_{PCC}. However, only limited information on comparison of these parameters is available. Darter et al. reported that the mean value of backcalculated elastic modulus for three American Association of State Highway and Transportation Officials (AASHTO) Road Test Loop1 sections was approximately equal to the elastic modulus obtained from dynamic tests on beam samples.(1) However, the scatter was too wide to make any definite conclusions.

Analysis of backcalculated concrete moduli was beyond the scope of the previous LTPP study.(2) In this study, a comparison of backcalculated moduli of elasticity of concrete versus elastic moduli obtained from the cores was performed for GPS-3 sections. Only a weak correlation between these moduli is observed. Figure 85 presents backcalculated moduli versus laboratory moduli for LTPP sections with an aggregate base. These sections were selected to eliminate the effect of a stiff stabilized base on the results of backcalculation. However, even for these sections, the correlation between backcalculated and laboratory moduli is not strong.

Many factors may contribute to this discrepancy. The choice of subgrade model, the effect of temperature curling, and dynamic effects significantly affect the results of backcalculation. In addition, the laboratory testing was performed on only a few samples taken beyond the ends of the section where deflections were measured. Proper accounting for these factors should close the gap between backcalculated and laboratory moduli.

Slab Curling Correction

Discussion of the results of backcalculation for SMP sections identified the need for development of slab curling correction factors. Several SMP sections exhibited significant reduction in backcalculated subgrade moduli from morning to midday testing. Also, backcalculated PCC moduli appeared to depend on the time of day of the testing. Development of appropriate correction factors should be of high priority for the following reasons:

- It is not always possible to conduct FWD testing in the early morning when thermal gradients are usually very low.

- FWD testing of GPS sections may be conducted under different temperature conditions. In this case, backcalculated parameters in the beginning of the section are not comparable with the backcalculated parameters at the end of the section. This is possibly why in several cases, reduction in backcalculated subgrade moduli at the end of the section is observed.

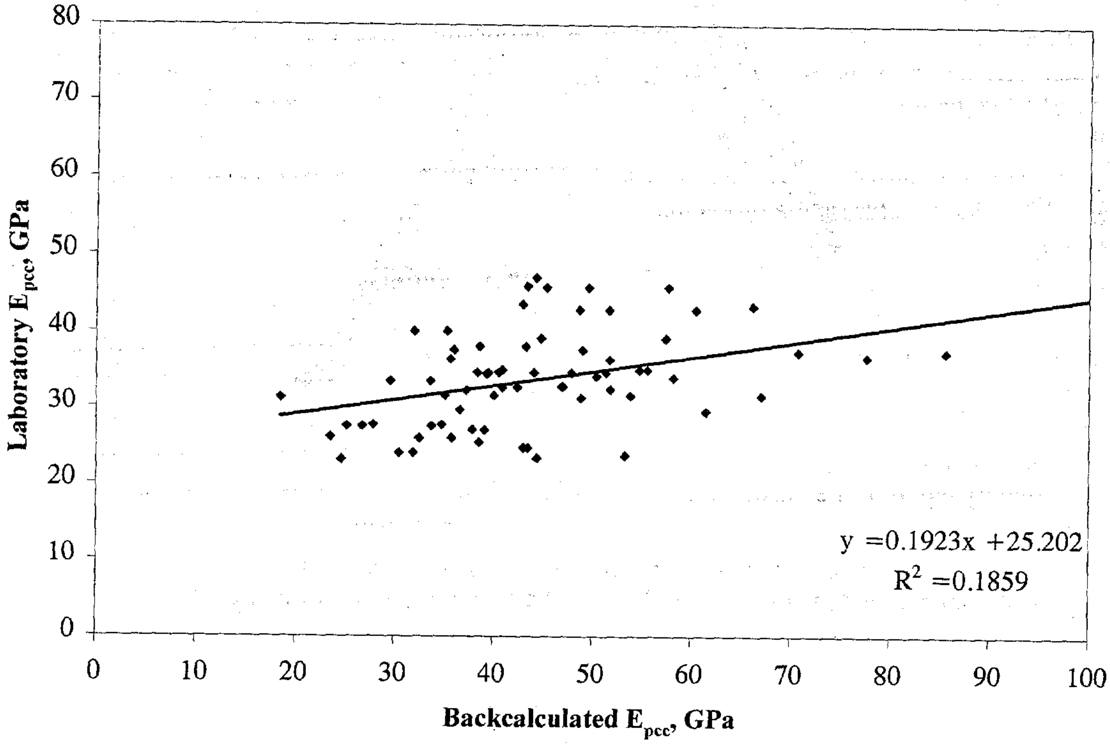


Figure 85. Comparison of backcalculated and laboratory concrete moduli of elasticity.

Dynamic Interpretation of FWD Test Results

Analysis of backcalculated PCC moduli shows significant variations in this parameter from different test dates for some sections. One of the possible explanations of this effect is that the current backcalculation procedures for rigid pavements assume quasi-static pavement behavior during FWD testing (see figure 86). Field test data indicate, however, that this assumption may not be valid. If the pavement would behave quasi-statically, the peak of the applied load would occur at exactly the same time as the peaks of the sensor deflections. Figure 87 presents a typical load and deflection time history during FWD testing. This figure shows a significant lag between the peak of the applied load and among the peaks of the sensor deflections.

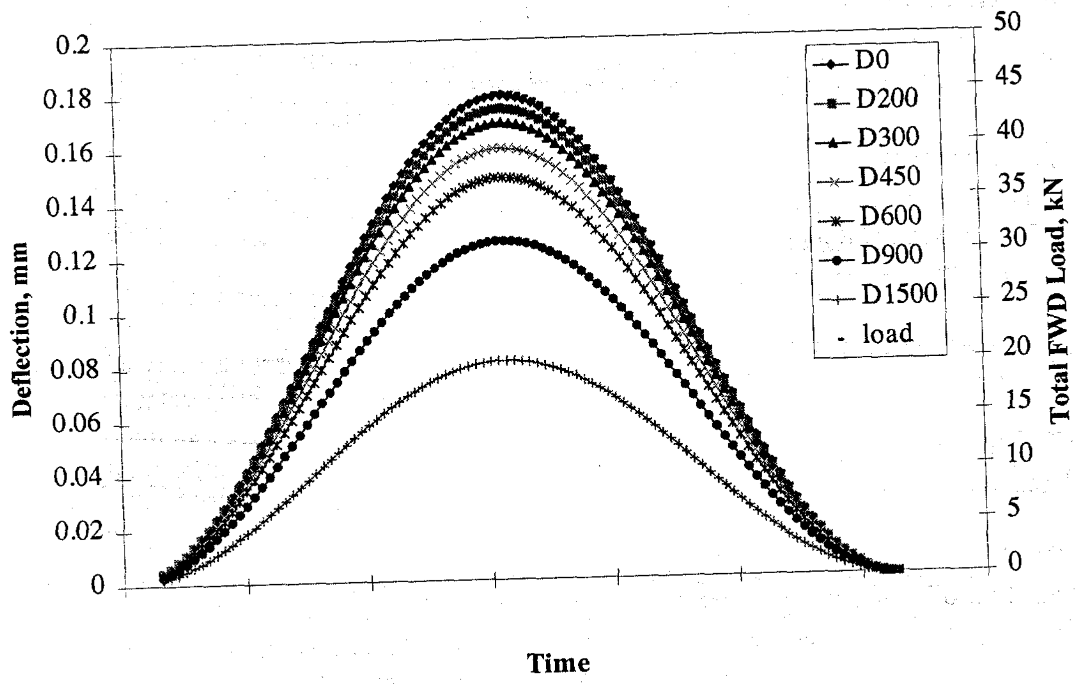


Figure 86. Quasi-static pavement responses to FWD loading.

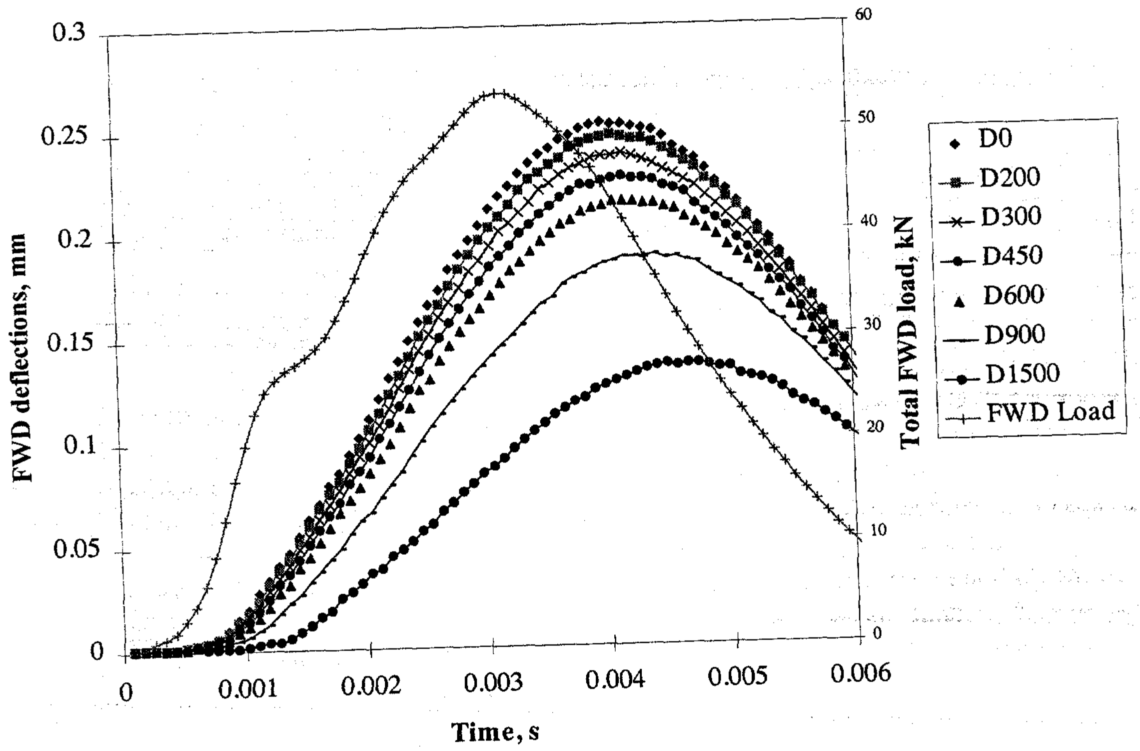


Figure 87. Measured pavement responses to FWD loading.

In this study, Westergaards's solution for the interior loading of a slab-on-grade was generalized for a case of dynamic loading. The following nondimentional parameter, m*, affecting dynamic response of a PCC slab was identified:

$$m^* = \frac{m}{k}\left(\frac{2\pi}{T}\right)^2 \tag{51}$$

where

m	=	mass of the unit area of the plate and the movable portion of subgrade
T	=	duration of the applied FWD load
k	=	coefficient of subgrade reaction

A closed form analytical solution for determining deflection time history from FWDtype loading was developed. A numerical evaluation of that solution has been facilitated by development of a computer program. The execution time per backcalculation on a PC is only a fraction of a second. In the future, this solution can serve as a basis for development of an efficient dynamic backcalculation procedure for rigid pavements.

To investigate the importance of pavement inertia, the dynamic behavior of a slab-on-grade was simulated. The following slab parameters were assumed: E = 34.5 GPa; $\mu = 0.15$; h = 225 mm; k = 27.1 kPa/mm. The nondimensional mass, m^*, was varied from 0 (quasi-static behavior) to 10. The FWD load was modeled as a load uniformly distributed over a circle with a radius equal to 150 mm. The following time history was assumed:

$$g(t^*) = 1 - \cos(t^*) \tag{52}$$

where t* is the nondimensional time defined as:

$$t^* = 2\pi \frac{t}{T} \tag{53}$$

Figures 88 to 90 present solutions for m* equal to 1, 4, and 10, respectively. If the nondimensional deflection m* is equal to 0 (quasi-static loading; see figure 86), then the peak of the applied load coincides in time with the peaks of all sensor deflections. With an increase in m*, the lag between the load peak and the deflection peaks increases, and this increase is higher for the outer sensors.

Dynamic Effects on Results of Backcalculation

The maximum applied load deflections were used as input parameters to the conventional static backcalculation procedure. Figure 91 presents the ratio between backcalculated E and k and actual E and k with respect to m^*. One can see that backcalculated moduli (from a conventional backcalculation procedure) are higher than actual plate elastic moduli, and an increase in m^* increases discrepancy between backcalculated and actual moduli of elasticity. Although backcalculated k-values are much lower than those used in forward calculation, they are less sensitive to m^*. Since the "actual" k-value of subgrade is not known anyway, one may assume that this discrepancy is accounted for by converting k_{dyn} into k_{static}.

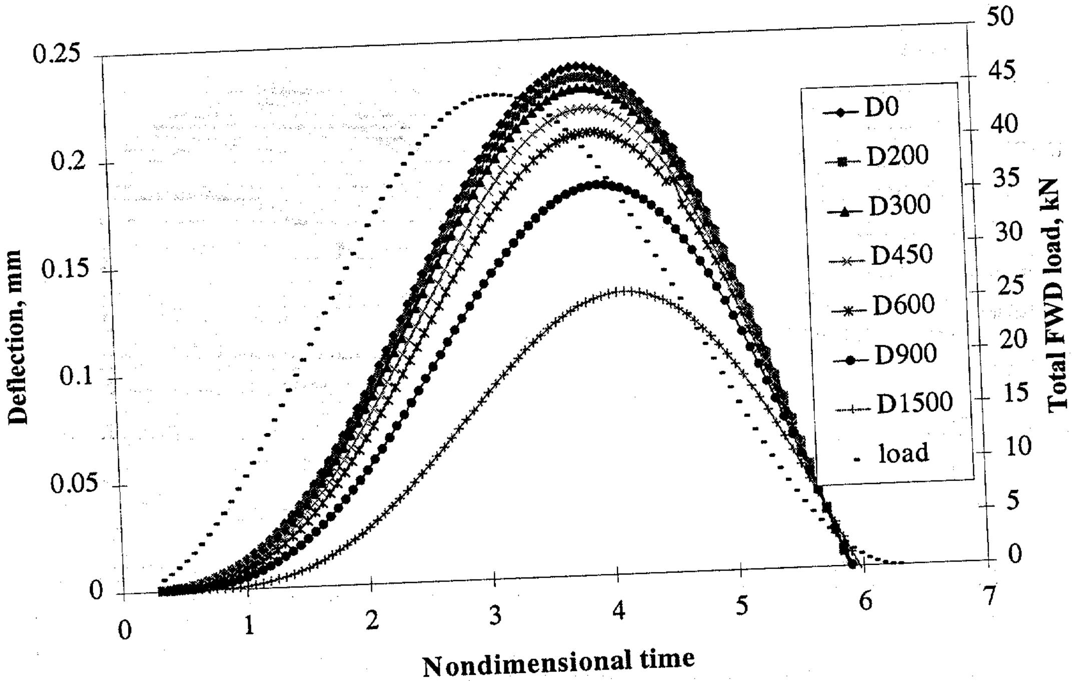


Figure 88. Effect of pavement inertia on FWD sensor deflections, m*=1.

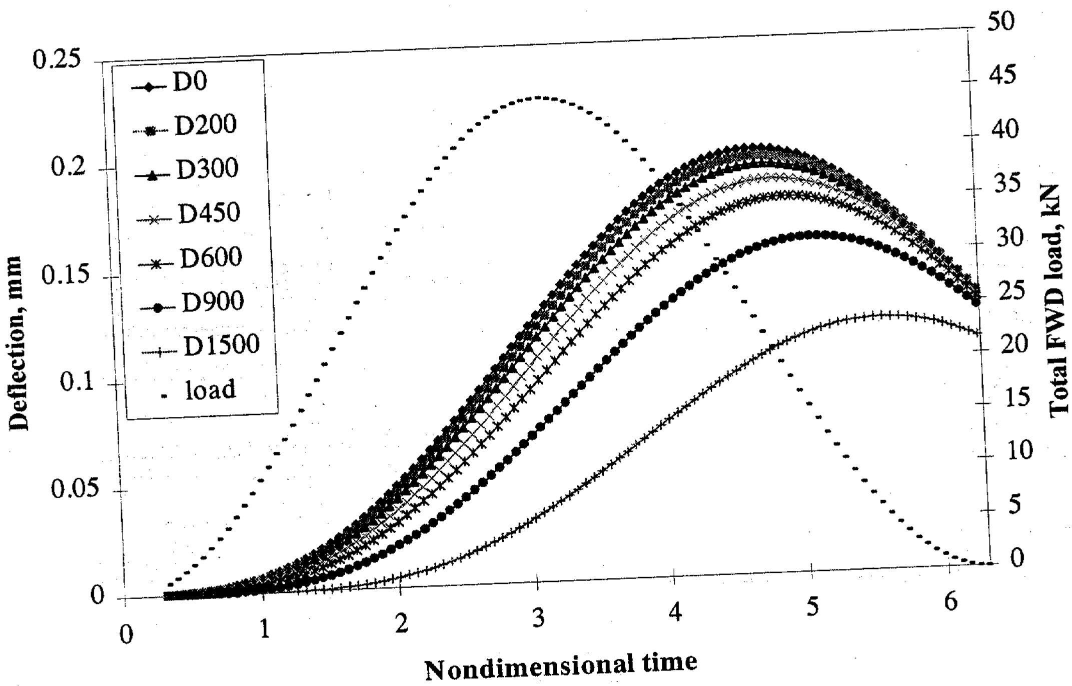


Figure 89. Effect of pavement inertia on FWD sensor deflections, m*=4.

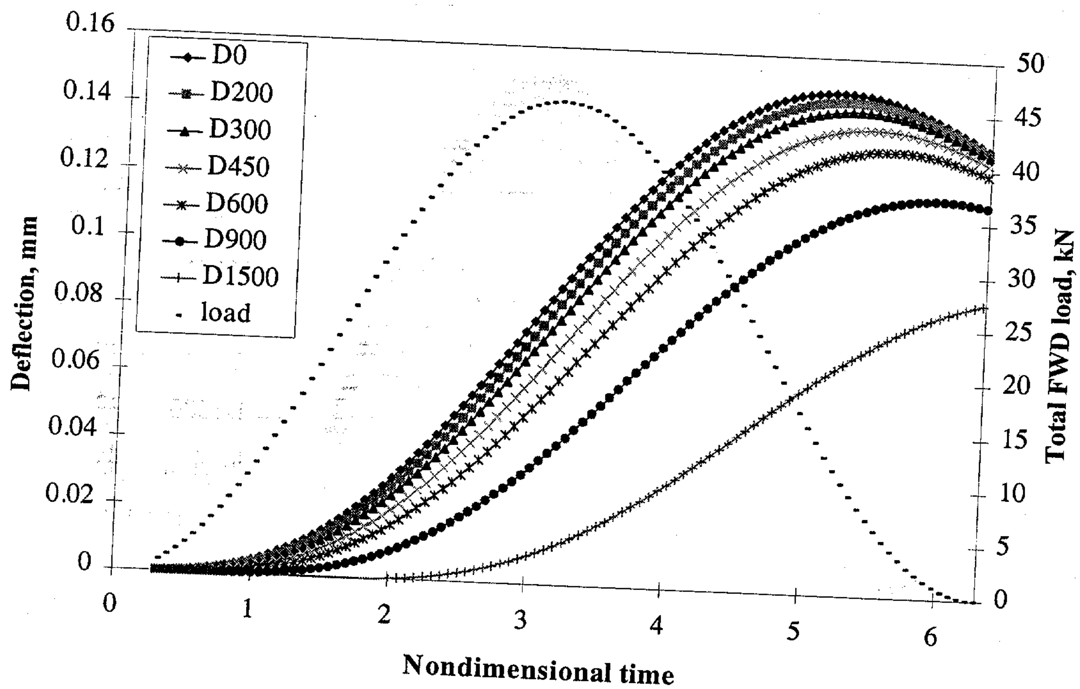


Figure 90. Effect of pavement inertia on FWD sensor deflections, m*=10.

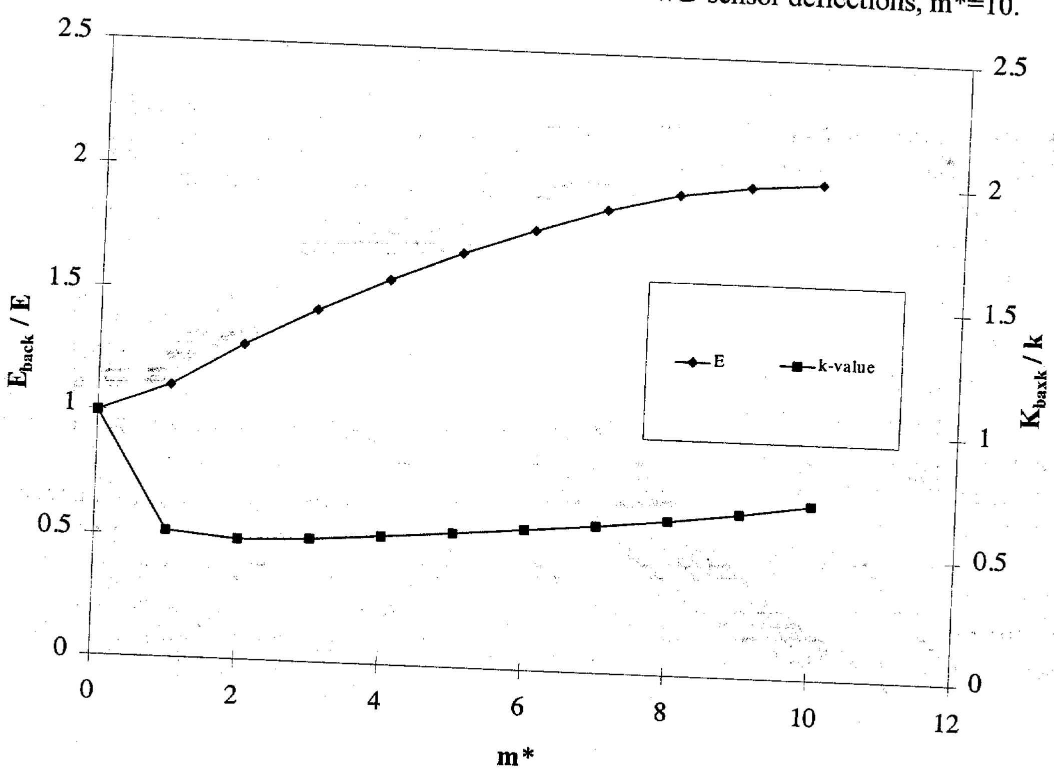


Figure 91. Effect of pavement inertia on the results of backcalculation.

To further investigate the importance of the inertia effect on the results of backcalculation, it is necessary to estimate the nondimensional mass, m*, for a typical rigid pavement. The inertia of the pavement system, m, comes from the inertia of the concrete slab and subgrade, and these inertia are additive, therefore:

$$m = m_{sl} + m_{subgr} \tag{54}$$

where

m_{sl} = mass of a unit area of concrete slab
m_{subgr} = mass of a unit area of subgrade moved by FWD load

Therefore,

$$m^* = m^*_{sl} + m^*_{subgr} \tag{55}$$

The parameter m_{subgr} is not known and should be determined from backcalculation. It is of interest, however, to estimate m^*_{sl} to check if it has a reasonable value to explain dynamic effects. Indeed,

$$m_{sl}^* = \gamma \frac{h_{sl}}{k} \left(\frac{2\pi}{T} \right)^2 \tag{56}$$

where

γ = density of concrete

Assuming that the slab is 225 mm thick with a density equal to 0.027 N/cm^3, the k-value is equal to 27.1 kPa/mm, and the duration of impulse is equal to 0.025 s, m^* is equal to 1.28. Therefore, for this set of parameters, the influence of the inertial properties of the concrete layer significantly affects the results of backcalculation. Addition of the subgrade inertia makes the dynamic effects even more pronounced.

Variation in the pavement inertia due to effects of temperature and moisture on the base and subgrade layers may explain seasonal variation in backcalculated elastic parameters. If a PCC pavement is tested at the same location at different times of the year, it is reasonable to suggest that the backcalculated subgrade elastic properties will show significant changes, but the backcalculated elastic properties of the concrete will be similar. However, use of the conventional static backcalculation procedures may lead to surprising results. It was observed in this study that several SMP rigid pavement sections located in a cold climate exhibited much higher PCC moduli of elasticity in the winter than in the rest of the year. The fact that the frozen subgrade increases the flexural stiffness of the pavement (reflected in the higher backcalculated PCC modulus) explains only a part of the discrepancy. Therefore, it is reasonable to suggest that the remaining part of the difference came from the increase in the mass of the plate moved by the FWD load.

This discussion leads to the following conclusions:

1. Dynamic effects can significantly affects the measured deflections.

2. The mass of the subgrade moved by the impulse affects backcalculated moduli.
3. The variability in backcalculated moduli from one test to another may be explained by dynamic behavior of rigid pavements under FWD loading.
4. An efficient backcalculation procedure may be developed. This solution may use the results of static backcalculation and correct it using a correction factor obtained from the analysis of lags between deflection peaks.

CHAPTER 6. SUMMARY AND RECOMMENDATIONS FOR CONTINUED RESEARCH

The analyses reported in this document were intended to calculate elastic layer properties (the coefficients and exponents of the constitutive equation) from deflection measurements and recommend representative elastic parameters for each section for inclusion in the LTPP IMS database. This report presented a discussion on the selection of the backcalculation methodology and results of the backcalculation for GPS, SPS, and SMP rigid pavement sections. The following are highlights of the study:

- The Best Fit method was selected as the primary backcalculation method for the LTPP rigid pavement sections for both DL and ES subgrade models.
- Four sensors (0, 305, 610, and 914 mm) were used for rigid pavement backcalculation.
- A computer program that includes pre-processor, backcalculation, and post-processor modules was developed and utilized for backcalculation of GPS, SPS, and SMP rigid pavement sections.
- In the majority of the cases, reasonable backcalculated values were obtained for the PCC slab, a variety of base types, and many different subgrades.
- Strong correlation was found between backcalculated parameters using DL and ES subgrade models.
- It was found that temperature curling during a day has a profound effect on the results of backcalculation. Therefore, it is important to conduct FWD basin testing early in the morning when temperature gradients are low to reduce variability in backcalculated values.
- Poor correlation was found between backcalculated and laboratory elastic moduli of concrete.
- A large proportion of unstabilized or stabilized base courses were modeled as bonded to the PCC slabs to produce reasonable backcalculated material moduli (center slab backcalculation).

The next logical step should be to improve the backcalculation procedure for rigid pavements to address the problems identified in this study. Following are the most urgent needs:

- Develop PCC slab temperature curling correction factors for the results of backcalculation.
- Develop correction factors accounting for dynamic behavior of rigid pavements under FWD loading and verify them using LTPP deflection history data.
- Adjust backcalculated parameters obtained in this study using the correction factors for temperature curling and dynamic behavior.

These additional studies will significantly improve the reliability of backcalculated parameters, narrow the gap between backcalculated and laboratory determined PCC moduli, and significantly improve our understanding of rigid pavement behavior.

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APPENDIX A. TYPICAL RESULTS OF BACKCALCULATION FOR PCC LTPP GPS SECTIONS

This appendix consists of two sections: a brief description of the presentation of the results followed by typical backcalculation analysis.

The first item of the section analysis report for each section is an information table. The first set of information is drawn from IMS table TST_L05B. It contains the following data items:

Section Number: This is a 6-digit number, the first two digits of which refer to the SHRP LTPP-assigned state ID. The last four digits correspond to the SHRP section ID.

State: This field contains the name of the state to which the section belongs.

Layer Information: The thicknesses of each layer along with a description of layer type is presented under headings Layer 1, Layer 2, etc. As in the IMS database, the layers are numbered starting from the subgrade layer to the topmost layer in the section. For example, consider a pavement section comprising PCC, base, and subgrade layers. Here, Layer 1 would correspond to the subgrade, Layer 2 is the base, and Layer 3 is the PCC.

The second set of information in the table, presented under the heading Backcalculation System, is drawn from the table MON_DEFL_RGD_BAKCAL_LAYER. It contains the following data items:

Layer Information: The final pavement profile selected to perform the backcalculation analysis is presented under headings Layer 1 and Layer 2. Subgrade layer information is not included.

Ratio: This refers to the modulus ratio of the PCC and the base layers (E_{PCC}/E_{base}), a numerical value included in the MON_DEFL_RGD_BAKCAL_LAYER table.

The relevant PCC backcalculation data are presented in plots for each parameter as discussed later. Because the subgrade is modeled both as dense liquid and elastic solid, two analyses are performed for each pavement section. Four graphs are plotted for each case showing the variation of the PCC modulus, base modulus, the radius of relative stiffness, and the subgrade parameter (either the k-value or the elastic modulus) for each point of the section.

The paragraphs below contain brief information regarding the section plots.

Section Number

The section number for each plot is located above all other entries in the legend. A sample plot legend is included in figure 92 for clarity.

Filled Versus Hollow Legends

The plots present data of interest obtained from FWD tests over several visits to the site. Each visit is indicated by a unique legend entry. For example in figure 92, the data for the test performed on 31-Aug-89 is identified with a square point, whereas the data for the test performed on 16-Apr-93 is identified using a triangular point, etc. Further, any symbol of a given shape could either be filled or empty, as shown in figure 92. A filled legend indicates that the data point was used in computing the mean value of the quantity it represents (PCC modulus, base modulus, k-value, etc.). An empty legend indicates that the data point has been excluded from the computation of the mean. This may occur due to test type, the error predicted for that quantity exceeds the tolerance, or it does not fall within twice the standard deviation.

Representation of the Mean Value

The recommended mean value for a data set is represented by a line through the data under consideration, as well as by a numerical value in the legend box located at the right top corner of each plot (see figure 92). The numerical value shown will have the same units as the individual points. The mean value for any given test date is placed immediately below the symbol designation for that particular test date, as shown in figure 92.

It is possible, in some cases, that the mean value is not plotted on the figures for certain data sets. This is because no mean value recommendation was made. Figure 92 illustrates one such instance, the 16-Apr-90 test date.

Indication of Bonded and Unbonded PCC-Base Interface

The suffix "b" or "u" is attached to the legend date text to represent either a bonded PCC and base layer interface or an unbonded interface, respectively.

High Cut-off Limit

The data range shown for the graphs are those that have been determined to be the "allowable" range for that particular example. The dense-liquid modulus of subgrade reaction, k, may range from 0 to 200 kPa/mm, for example. Data points lying along the y = "max" line of any plot might carry a value that is either y = "max" or greater. For example, any k greater than 200 kPa/mm will plot as 200 kPa/mm.

Blank Output Charts

It may occur that the analysis procedure prints out a blank figure with a message that a quantity has not been backcalculated. This message indicates that the backcalculation procedure does not calculate moduli of elasticity either because there was no thickness information available or there was an unbonded PCC overlay present in the system.

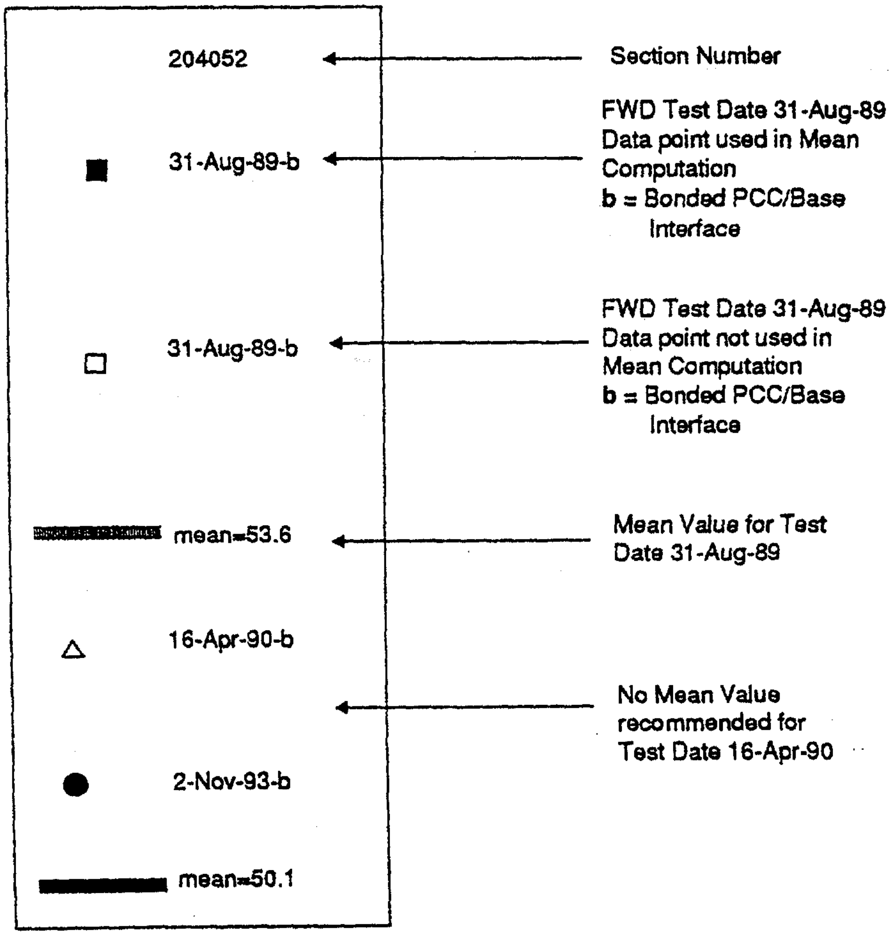

Figure 92. Typical data plot legend.

Example 1

Section: 013998
State: Alabama
Layer 5: Portland Cement Concrete (CRCP)
Thickness: 208 mm
Layer 4: Soil Cement
Thickness: 145 mm
Layer 3: Fine-grained Soils
Thickness: 152 mm
Layer 2: Lime-Treated Soil
Thickness: 152 mm
Layer 1: Coarse-grained soil: silty sand
Thickness: NA

Backcalculation system:
Layer 1: Thickness 208 mm
Layer 2: Thickness 145 mm; Ratio = 10

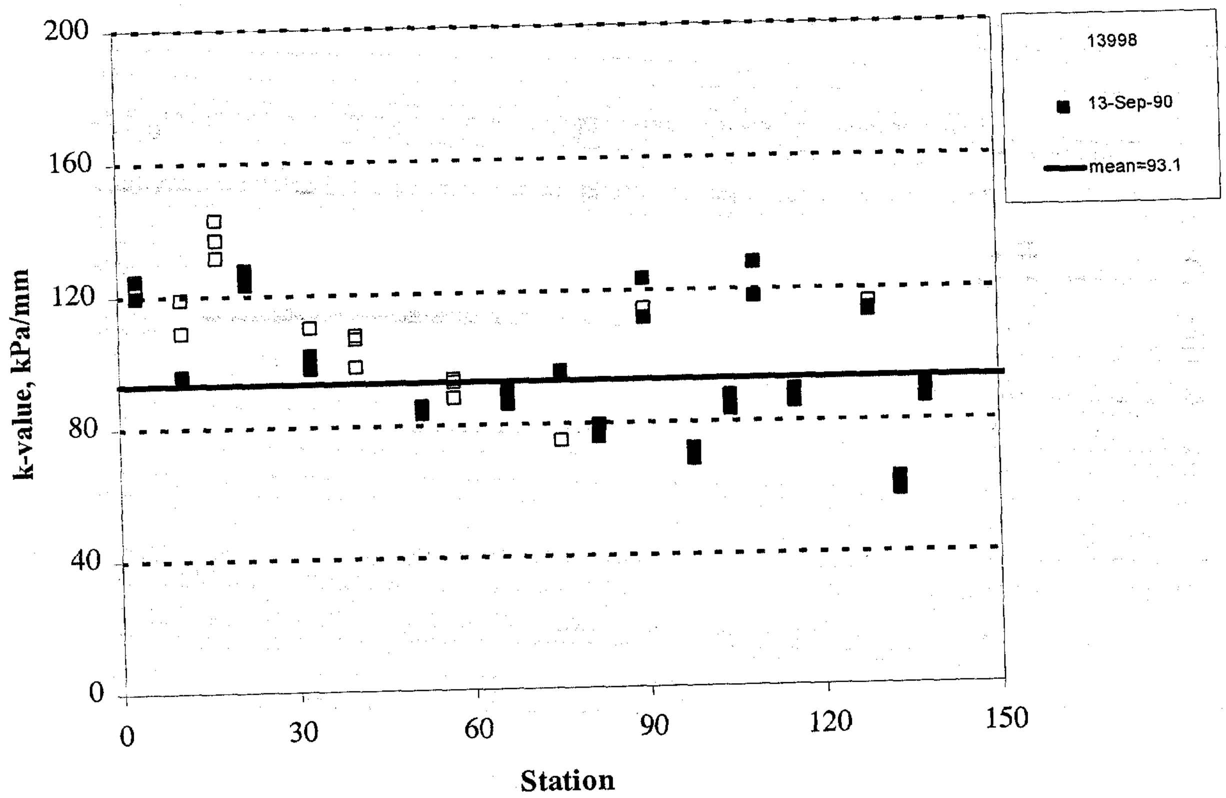

Figure 93. Backcalculated k-values for section 013998.

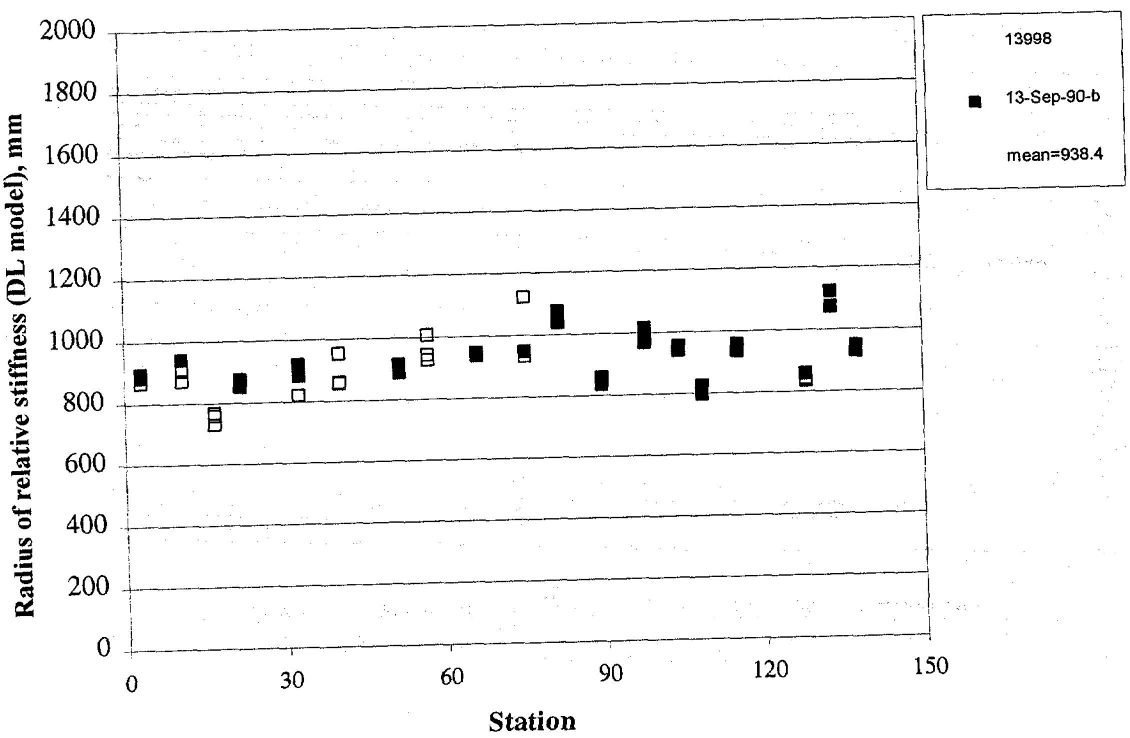

Figure 94. Backcalculated radius of relative stiffness (DL model) for section 013998.

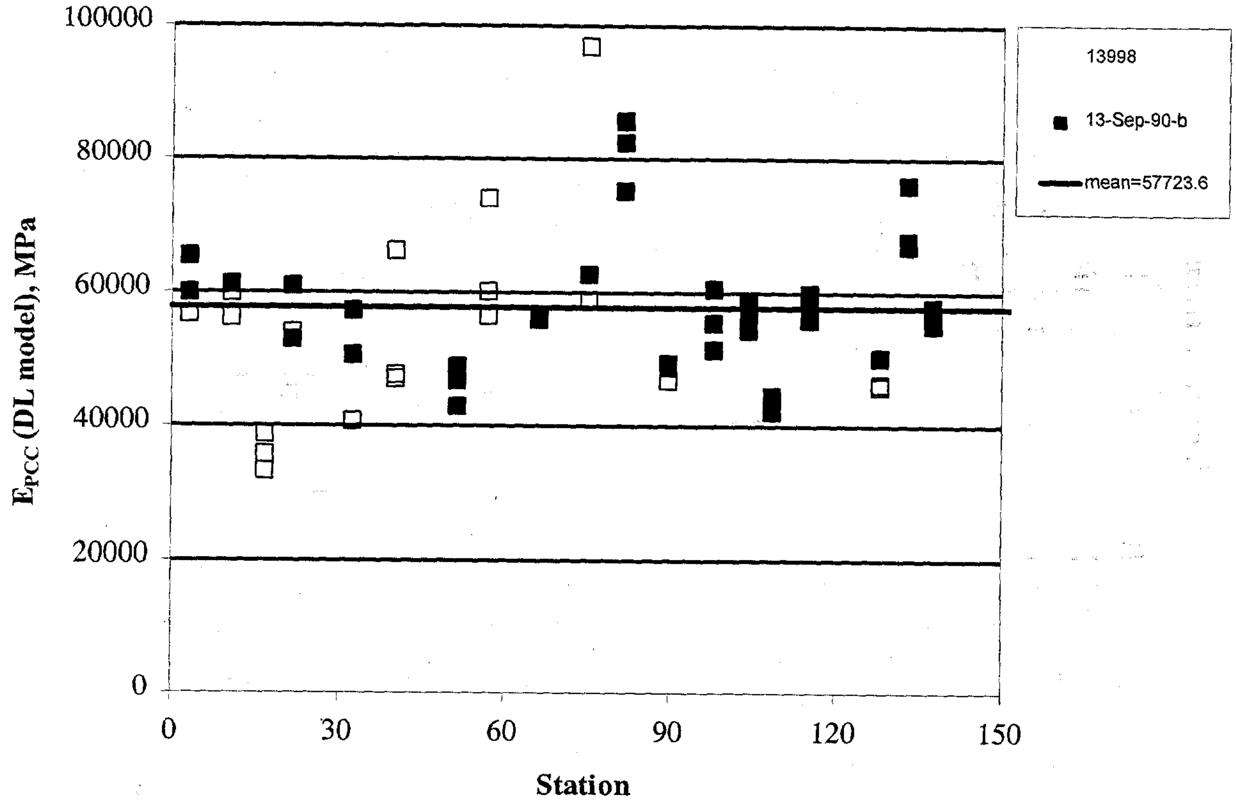

Figure 95. Backcalculated PCC elastic modulus (DL model) for section 013998.

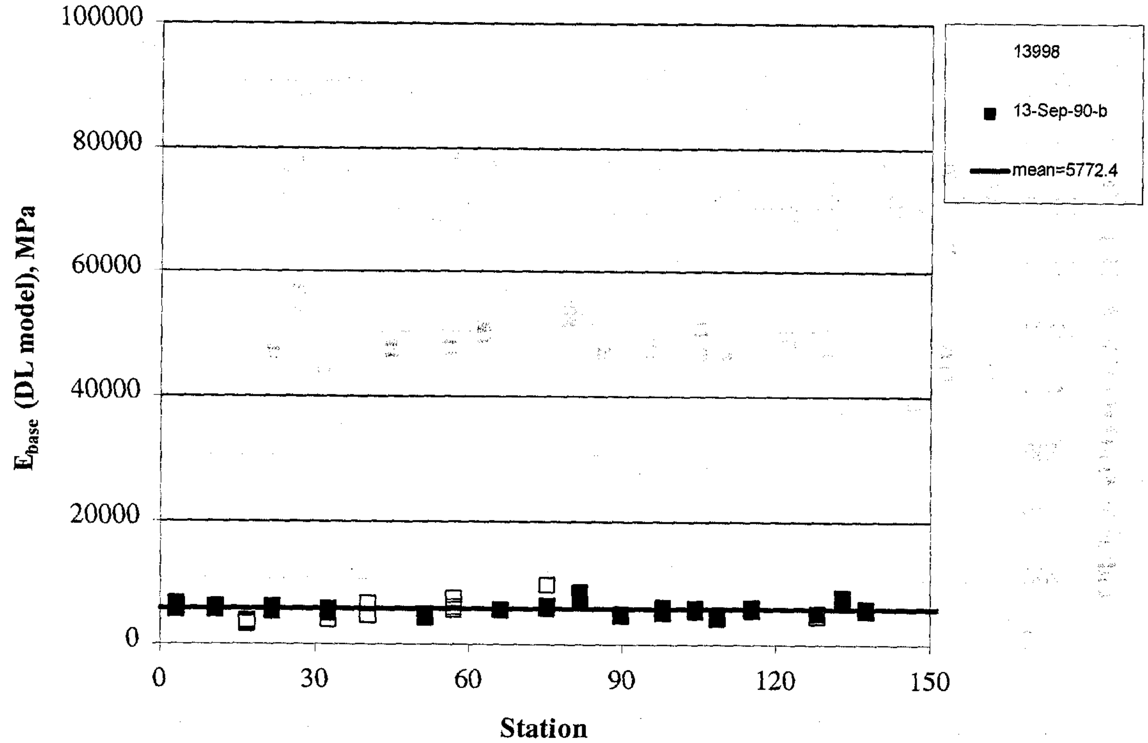

Figure 96. Backcalculated elastic modulus of base (DL model) for section 013998.

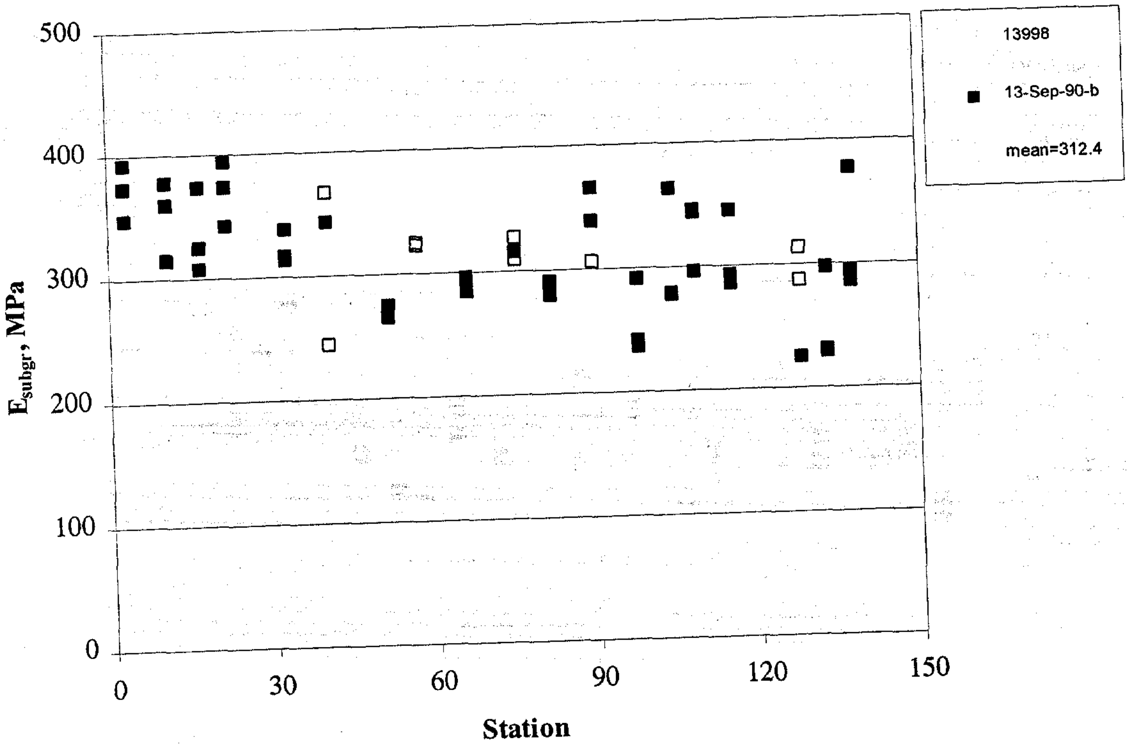

Figure 97. Backcalculated modulus of elasticity of subgrade for section 013998.

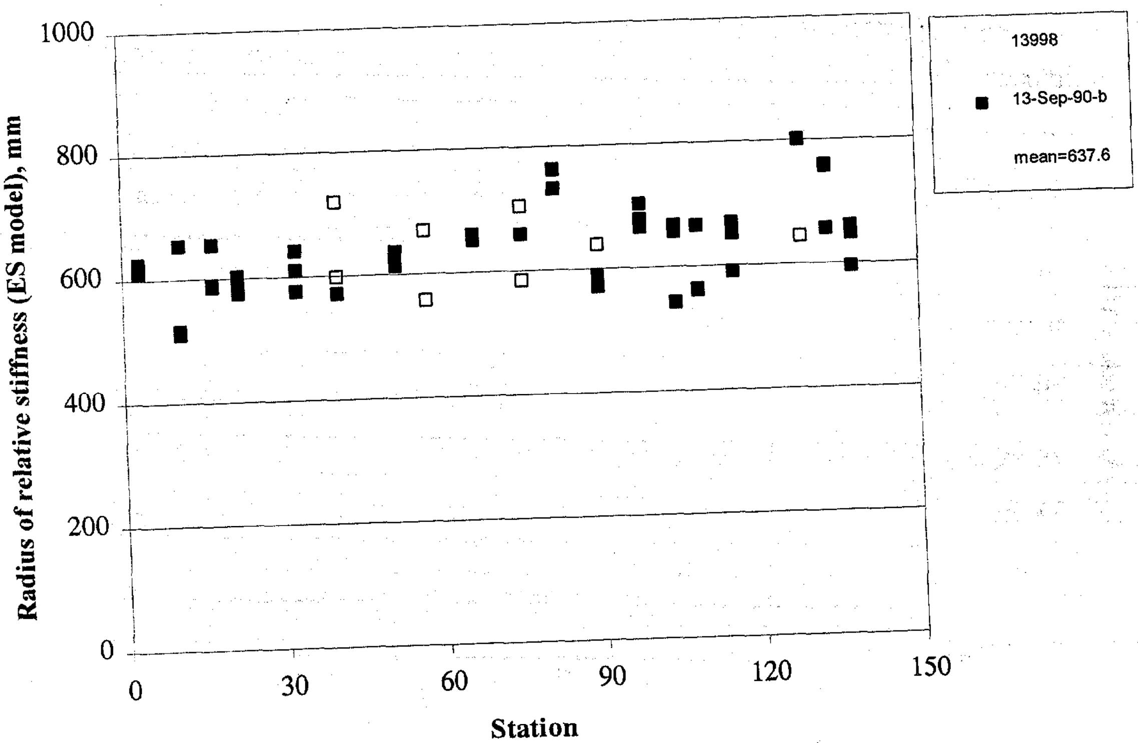

Figure 98. Backcalculated radius of relative stiffness (ES model) for section 013998.

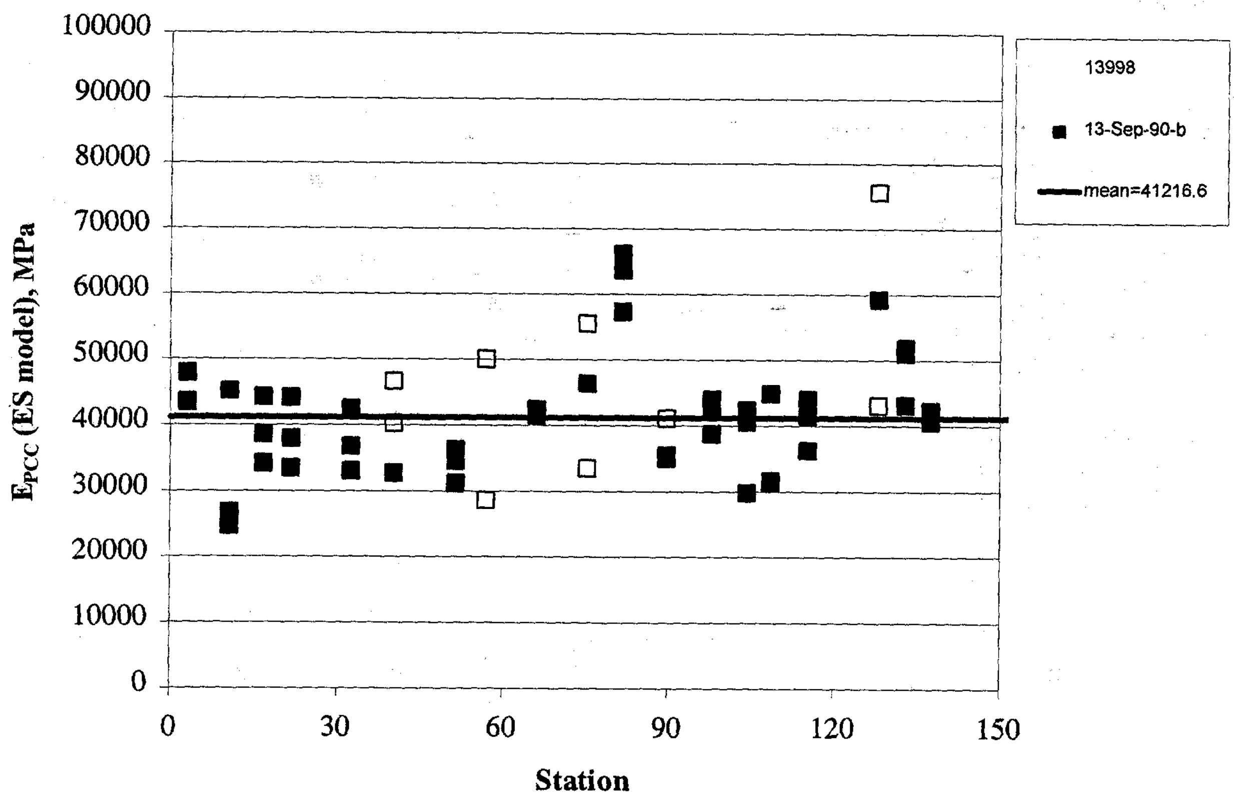

Figure 99. Backcalculated PCC elastic modulus (ES model) for section 013998.

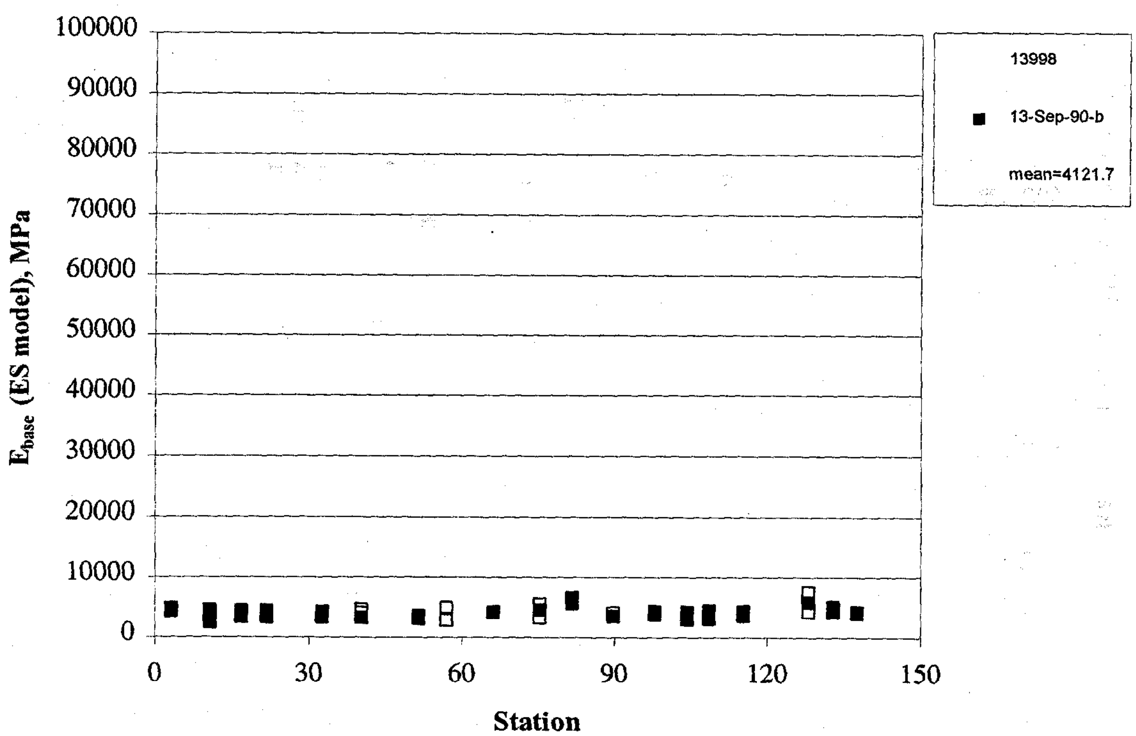

Figure 100. Backcalculated elastic modulus of base (ES model) for section 013998.

Example 2

Section: 015008
State: Alabama
Layer 4: Portland Cement Concrete (CRCP)
Thickness: 234 mm
Layer 3: HMAC
Thickness: 155 mm
Layer 2: Crushed Stone
Thickness: 198 mm
Layer 1: Coarse-grained soil: silty sand
Thickness: NA

Backcalculation system:
Layer 1: Thickness 234 mm
Layer 2: Thickness 155 mm; Ratio = 15

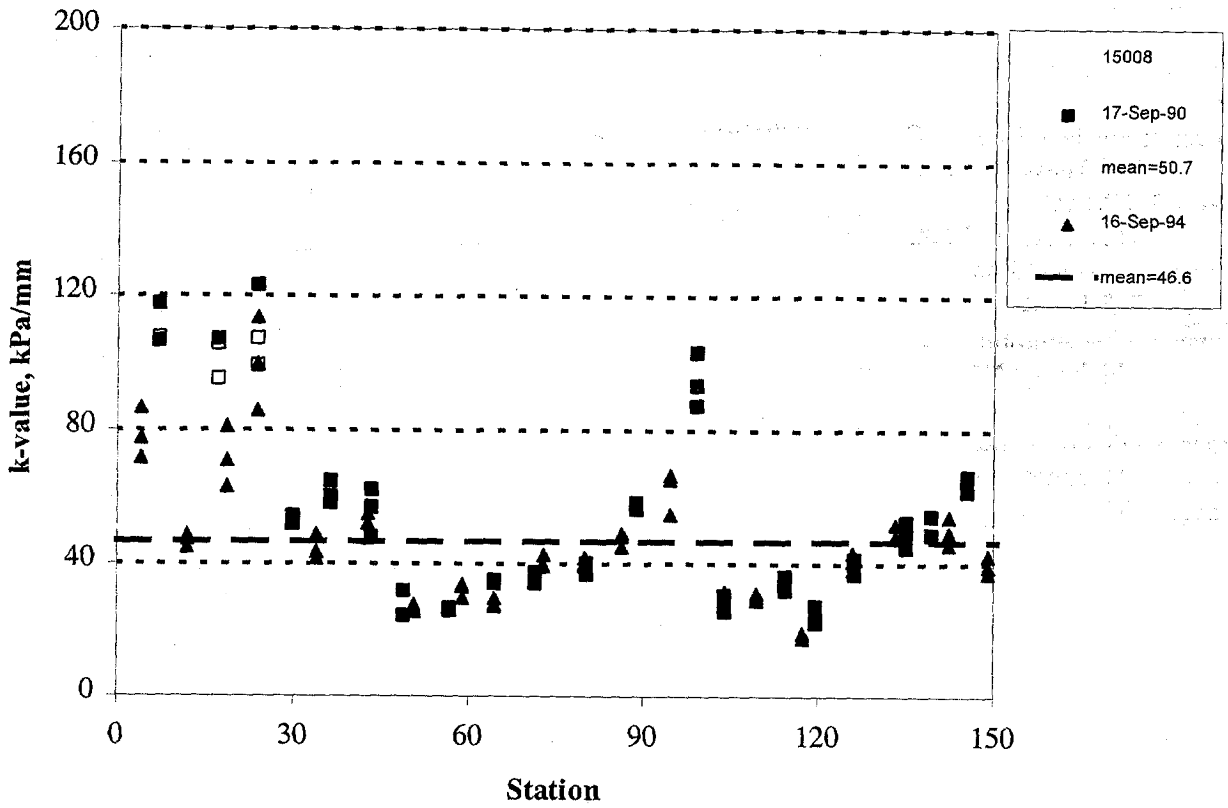

Figure 101. Backcalculated k-values for section 015008.

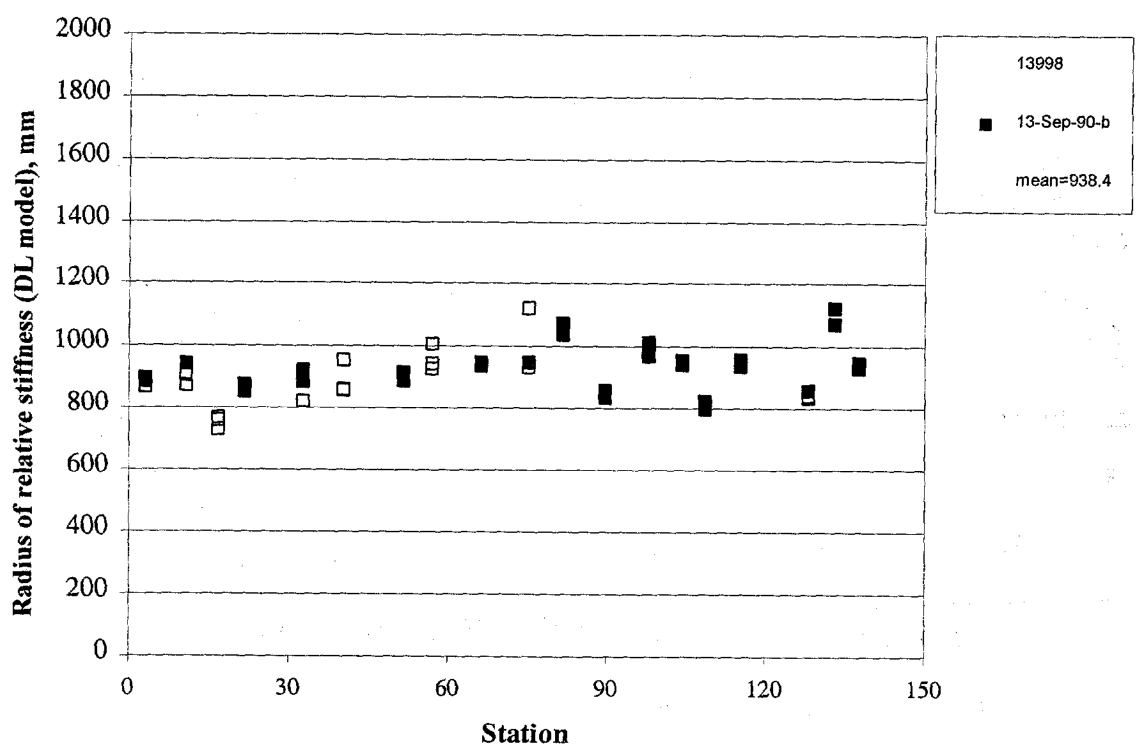

Figure 102. Backcalculated radius of relative stiffness (DL model) for section 015008.

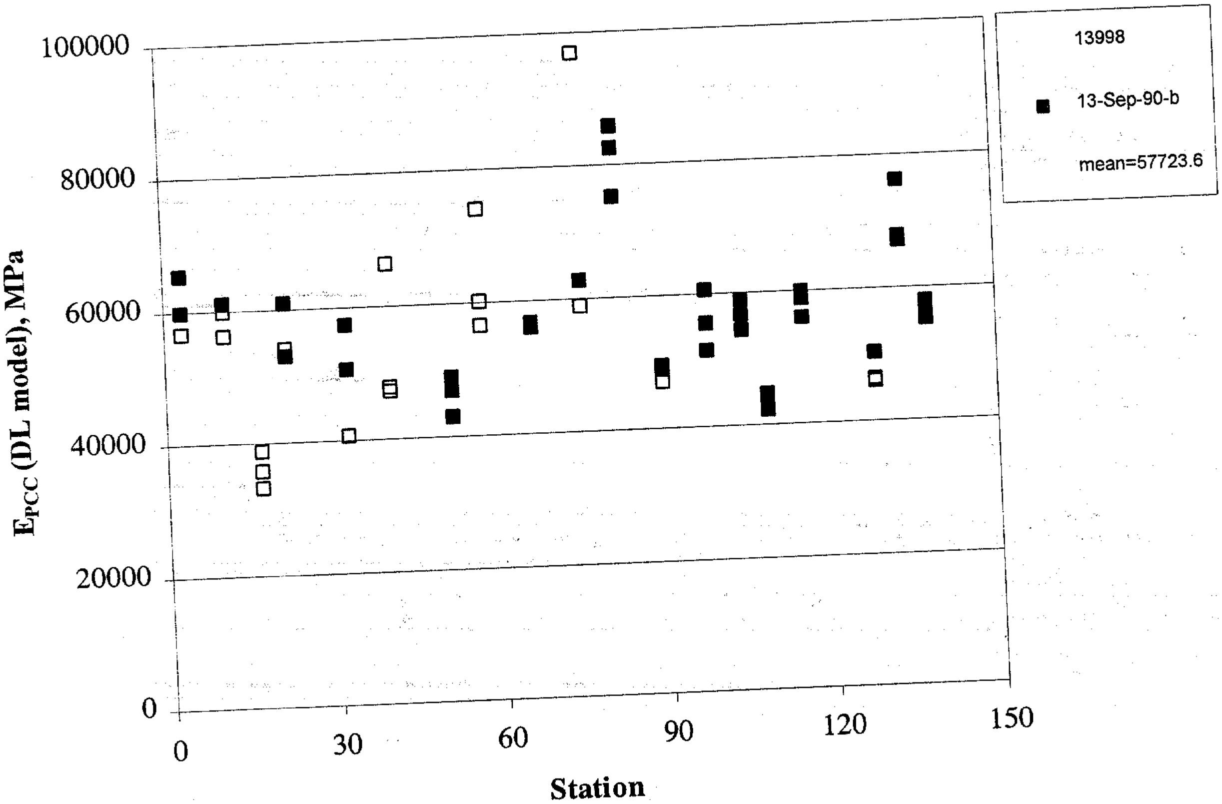

Figure 103. Backcalculated PCC elastic modulus (DL model) for section 015008.

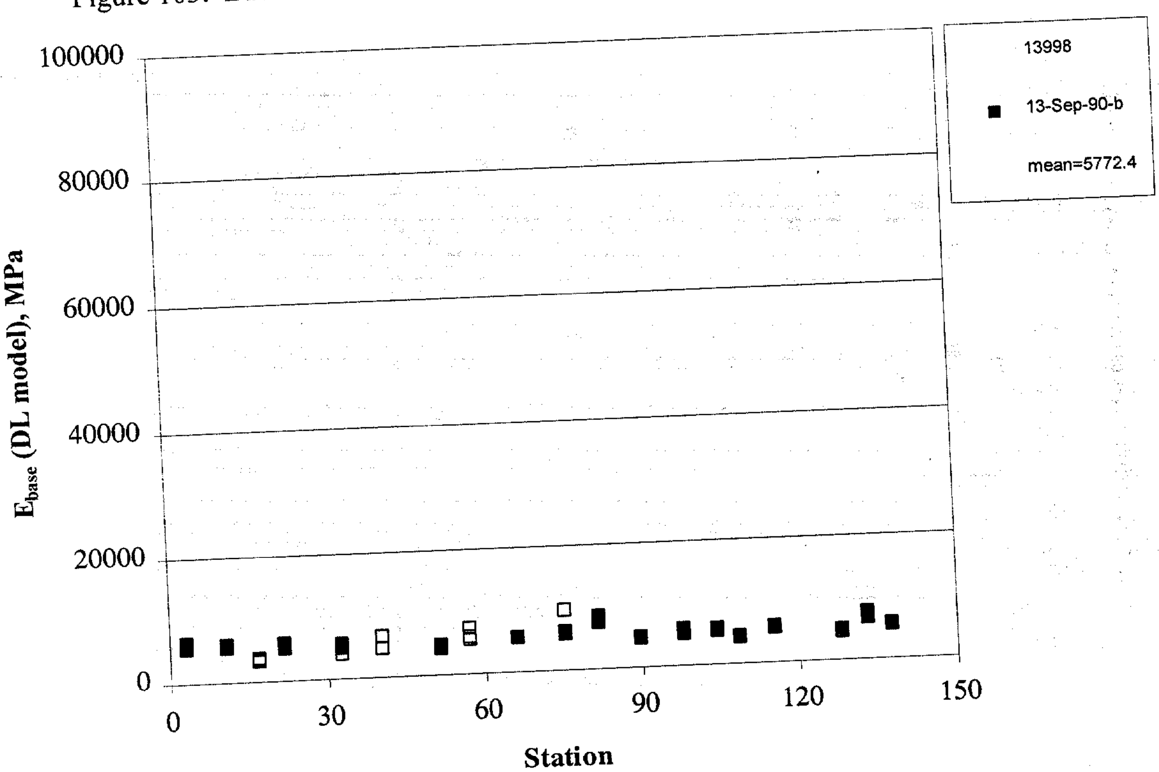

Figure 104. Backcalculated elastic modulus of base (DL model) for section 015008.

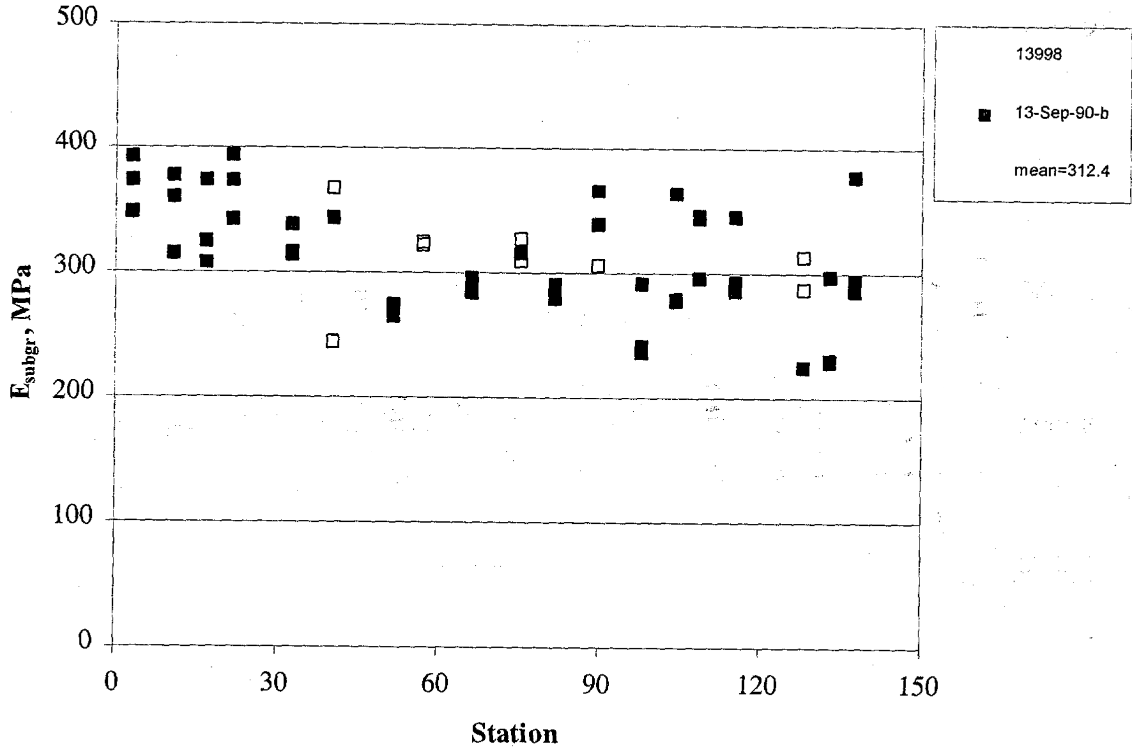

Figure 105. Backcalculated modulus of elasticity of subgrade for section 015008.

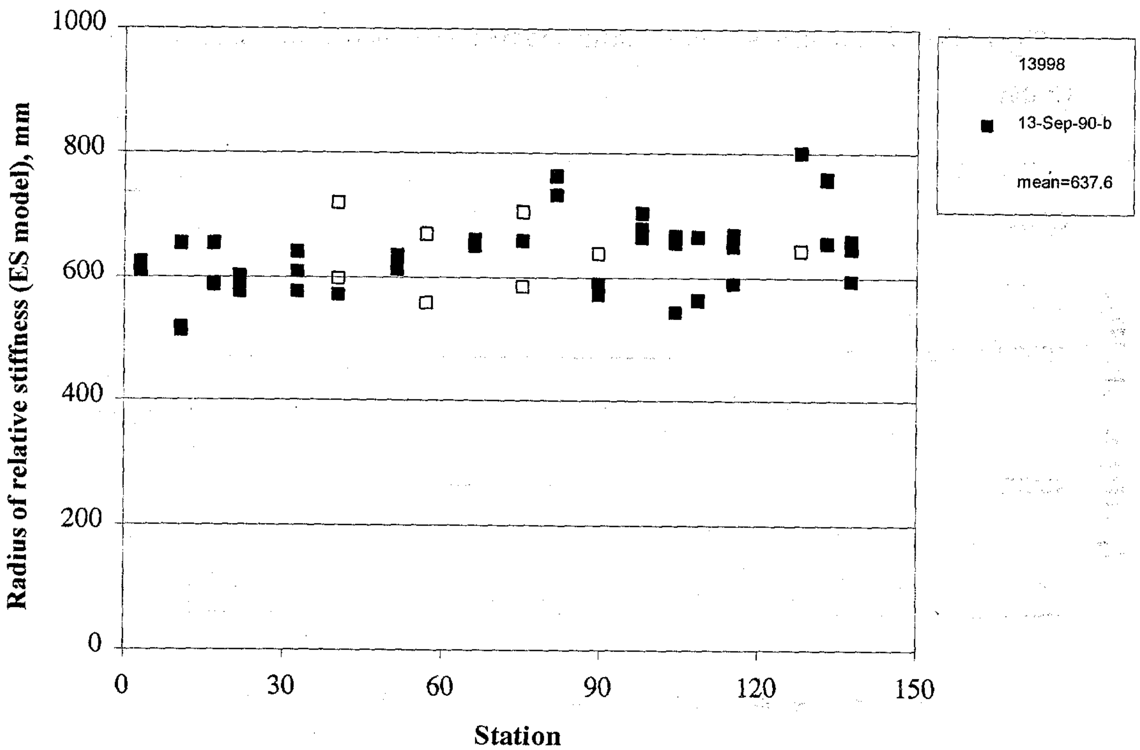

Figure 106. Backcalculated radius of relative stiffness (ES model) for section 015008.

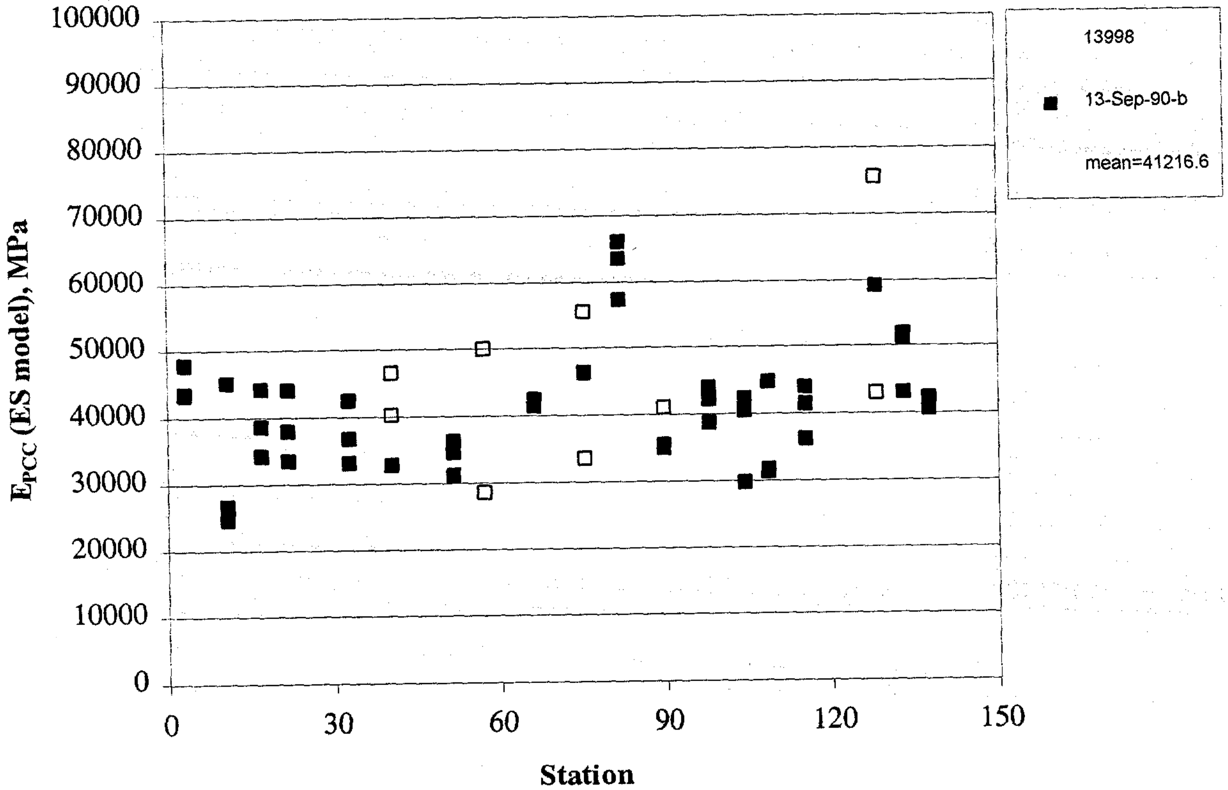

Figure 107. Backcalculated PCC elastic modulus (ES model) for section 015008.

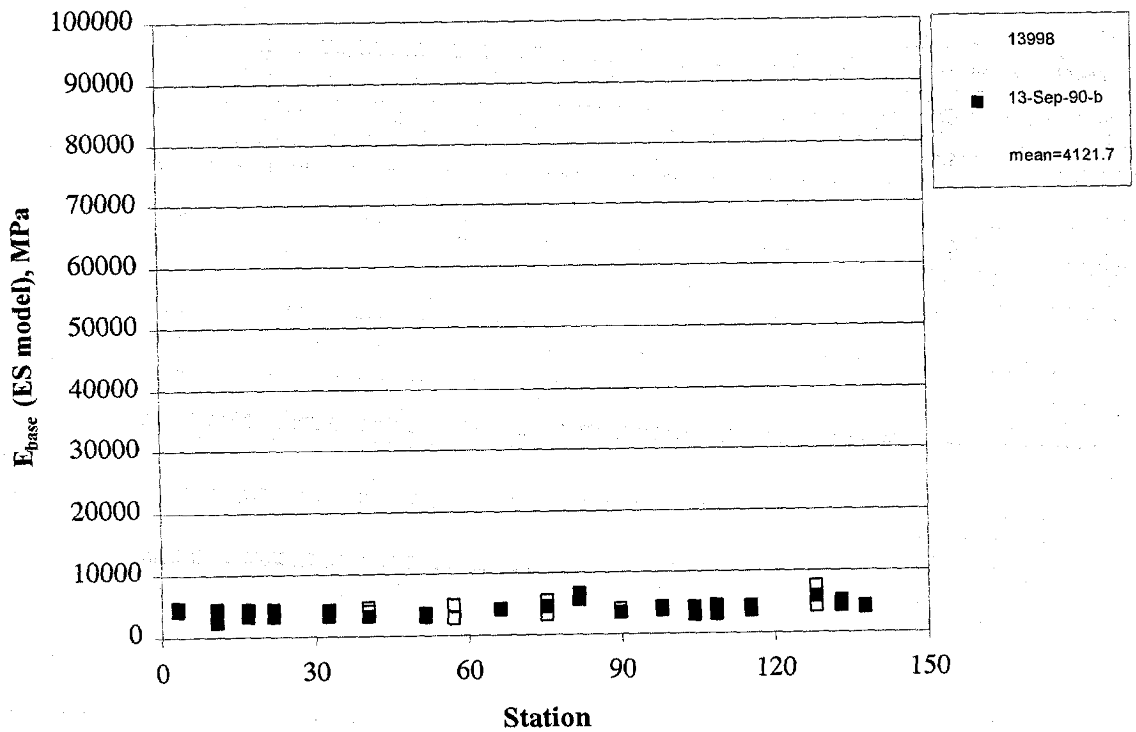

Figure 108. Backcalculated elastic modulus of base (ES model) for section 015008.

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