Review of the Long-Term Pavement Performance Backcalculation Results—Final Report

PUBLICATION NO. HRT-05-150

FEBRUARY 2006

U.S. Department of Transportation
Federal Highway Administration

Research, Development, and Technology
Turner-Fairbank Highway Research Center
6300 Georgetown Pike
McLean, VA 22101-2296

FOREWORD

This report is a comprehensive review and evaluation of the Long-Term Pavement Performance (LTPP) backcalculation data. In this study, a new approach, called forwardcalculation was developed to determine layered elastic moduli from in situ load-deflection data with procedures and results documented. The entire set of LTPP-computed parameters of backcalculation results was screened using forwardcalculated moduli.

Although users cannot reject any backcalculated modulus value merely because it is outside a reasonable or acceptable range, the forwardcalculated values were, in most cases, more stable on a section-by-section basis than the backcalculated values in the LTPP database. The exception was the portion of the backcalculated database based on slab-on-dense-liquid and slab-on-elastic-solid theory, where the correspondence between the two rigid pavement analysis techniques was excellent and both the backcalculated and forwardcalculated moduli and k-values were very stable.

It is recommended that the backcalculated database be retained as is, with the addition of the complementary forwardcalculated dataset and screening flags, so the database user can decide which method is more suitable to the application.

This report will interest highway agency engineers involved in pavement analysis, design, construction, and deflection data collection, as well as researchers who use LTPP load-deflection data to improve design procedures and standards for constructing and rehabilitating pavements.

Gary L. Henderson
Office of Infrastructure
Research and Development

Notice

Quality Assurance Statement

Technical Report Documentation Page

1. Report No.
FHWA-HRT-05-150

2. Government Accession No.

3. Recipient's Catalog No.

4. Title and Subtitle
Review of the Long-Term Pavement Performance Backcalculation Results—Final Report

5. Report Date
February 2006

6. Performing Organization Code

7. Author(s)
R.N. Stubstad, Y.J. Jiang, M.L. Clevenson, and E.O. Lukanen

8. Performing Organization Report No.

9. Performing Organization Name and Address
Applied Research Associates, Inc.
7184 Troy Hill Drive, Suite N
Elkridge, Maryland 21075-7056

10. Work Unit No. (TRAIS)

11. Contract or Grant No.
DTFH61-02-D-00138

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

14. Sponsoring Agency Code

15. Supplementary Notes
Contracting Officer’s Technical Representative (COTR): Larry Wiser, HRDI
LTPP Data Analysis Contract.

16. Abstract

A new approach to determine layered elastic moduli from in situ load-deflection data was developed. This “forwardcalculation” approach differs from backcalculation in that modulus estimates come directly from the load and deflection data using closed-form formulae rather iteration. The forwardcalculation equations are used for the subgrade and the bound surface course for both flexible and rigid pavement falling weight deflectometer (FWD) data. Intermediate layer moduli are estimated through commonly used modular ratios between adjacent layers.

The entire LTPP set of backcalculated parameters was screened using forwardcalculated moduli. Any assumed or fixed modulus value was left as is and not further screened (e.g., hard bottom). Further, any back- or forwardcalculated values outside a broad range of reasonable values were not further screened, but flagged as unreasonable. Finally, a set of broad range convergence flags (0 = acceptable, 1 = marginal, 2 = questionable, and 3 = unacceptable) were applied to the backcalculated dataset, depending on how closely the pairs of back- and forwardcalculated moduli matched. Since both techniques used identical FWD load-deflection data as input, the moduli derived from each approach should be reasonably close to each other (within a factor of 1.5 to qualify as acceptable, for example).

Although backcalculated values cannot be rejected merely because they are outside a reasonable or acceptable range, the complementary forwardcalculated values were usually more stable on a section-by-section basis. The exception was the portion of the database based on slab-on-dense-liquid or slab-on-elastic-solid theory, where the correspondence between the two approaches was excellent and very stable. Therefore, it is recommended that the backcalculated database be retained as is, with the addition of checks and flags so the database user can choose the best method, depending on the application.

17. Key Words
Pavements, LTPP, FWD, deflection data, elastic modulus, backcalculation, forwardcalculation, screening.

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
97

22. Price

Form DOT F 1700.7 (8-72) **Reproduction of completed page authorized**

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 yard	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 degrees)				
°F	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	°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	35.314	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 degrees)				
°C	Celsius	1.8C+32	Fahrenheit	°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 March 2003)

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

CHAPTER 1. INTRODUCTION

BACKGROUND

The Long-Term Pavement Performance Program (LTPP) has incorporated within its database a set of computed parameter tables. These tables include backcalculated moduli and other related pavement layer data from falling weight deflectometer (FWD) deflections taken before the summer of 1998. Backcalculated data, however, do not exist for all of the pre-1998 data. Some of these data were gathered at joints and other noncontinuous pavement features (where backcalculation is not used), while other data produced results that were already identified as unreliable or out of range.

Deflection data, corresponding backcalculated moduli, or other deflection-based parameters strongly relate to pavement performance, and the premise of mechanistic-empirical design methods is to control stresses and strains as a response to traffic loads. In addition, although many of the available backcalculated moduli certainly appear reasonable, some do not, which has raised some concerns. Based on earlier work where these data have been used, it became desirable to review and screen the backcalculated moduli database to ascertain whether, and to what extent, unreasonable or unlikely values currently exist.

This report documents the procedures and results of a comprehensive review of the LTPP backcalculation results. For this study, only the existing backcalculation data derived for the 1998 or earlier FWD were evaluated. All work was completed under the LTPP Data Analysis Contract (Federal Highway Administration (FHWA) Contract No. DTFH61-02-D-00138).

STUDY OBJECTIVES AND SCOPE

The main objective of this project is to assess and improve the quality of the present and future backcalculated modulus data in the LTPP database. The following are the main activities carried out under this project to meet the primary objective:

1. Provide an assessment of the validity of the LTPP backcalculated modulus parameters that have been derived through the backcalculation process.
2. Develop additional procedures and criteria that can be applied to evaluate the results of backcalculation (whether for LTPP or for other purposes) to ensure that the backcalculated layer parameters are valid.

An additional product from this study is a screening method to assist the analyst in assessing whether the backcalculated moduli obtained, using any backcalculation program, are reasonable. A separate report documents generic draft guidelines for review and evaluation of backcalculated pavement layer parameters.

LTPP DATA SOURCE

The complete LTPP backcalculation and supporting data were requested and received from the FHWA-LTPP customer support center at the beginning of this project. The research team used LTPP Data Release 16.0—July 2003 Upload throughout this project. These data included all available asphalt concrete (AC) and portland cement concrete (PCC) LTPP sections where backcalculation was carried out, including both level E data and nonlevel E data.

REPORT ORGANIZATION

This report is organized into seven chapters, including an introduction, background methods, development of the forwardcalculation methodology, initial evaluation with backcalculation screening results, backcalculation screening methods, summary of the LTPP backcalculation data screening results, and an overall summary with conclusions and recommendations.

This chapter presents a background of the problem, study objectives, LTPP data source, and report organization. Chapter 2 gives a summary of the literature reviewed with an introduction of both the backcalculation and the forwardcalculation techniques. Chapter 3 documents the development of the forwardcalculation methodology that was used in this study, followed by the results of the initial phase I pilot screening results in chapter 4. Chapter 5 outlines the subsequent method for screening the entire LTPP database of the backcalculated computed parameter tables, followed by a summary of the screening results and recommendations for identifying backcalculated data anomalies in chapter 6. Finally, chapter 7 contains a summary, conclusions, and recommendations to complete the report.

Microsoft® Excel spreadsheets have been prepared containing all formulae used in phase I of this study. All forwardcalculation input quantities are totally transparent to those who wish to use the methodology, whether for screening or in rehabilitation design. To this end, four spreadsheets are available—two for asphalt-bound surfaces (using SI and U.S. Customary units) and two for cement-bound surfaces (SI and U.S. Customary). These spreadsheets can be obtained by contacting LTPP Customer Support Services: by phone at 202–493–3035 or by e-mail at ltppinfo@fhwa.dot.gov.

CHAPTER 2. INTRODUCTION TO BACKCALCULATION AND FORWARDCALCULATION METHODS

LITERATURE REVIEW

To review the approach through which backcalculation took place and the load-deflection data were used to create the computed parameter tables of the backcalculated database, two primary references were consulted:

- FHWA, *Backcalculation of Layer Parameters for Long-Term Pavement Performance (LTPP) Test Sections, Volume I: Slab on Elastic Solid and Slab on Dense-Liquid Foundation Analysis of Rigid Pavements,* FHWA-RD-00-086, Washington, DC: FHWA, December 2001.(1)
- FHWA*, Backcalculation of Layer Parameters for LTPP Test Sections—Volume II: Layered Elastic Analysis for Flexible and Rigid Pavements*, FHWA-RD-01-113, Washington, DC: FHWA, December 2001.(2)

These publications describe how backcalculation was calculated for rigid and flexible pavement sections, respectively. After review of these documents, the researchers determined that the described processes used to perform the backcalculation and prescreen the data for outliers were reasonable, though (at least in hindsight) perhaps somewhat imperfect.

The processing of the rigid pavement data appeared to be somewhat more effective than for the flexible pavement data, mainly because rigid pavements were generally divided into only two unknown structural layers, while flexible pavements generally used three, four, and sometimes even five unknown structural layers.

Additionally, the following documents were used, as needed:

- National Cooperative Highway Research Program (NCHRP), *LTPP Data Analysis: Feasibility of Using FWD Deflection Data to Characterize Pavement Construction Quality,* Project 20-50(09): NCHRP Web Document #52, Washington, DC: NCHRP, November 2002. Web address: http://trb.org/news/blurb_detail.asp?id=942.(3)
- FHWA, *Study of LTPP Pavement Deflections*, Project DTFH61-01-P-00144: Unpublished Final Report Submitted to FHWA in September 2001.(4)

These documents were helped to ensure the quality of the FWD load-deflection data and to verify the sensor positions used during FWD testing.

INTRODUCTION TO BACKCALCULATION

Most backcalculation programs, including those used to generate the backcalculated modulus data in the LTPP computed parameter tables, involve numerical integration subroutines that are capable of calculating FWD pavement deflections (and other parameters), given the stiffnesses (or moduli) of the various pavement layers and their thicknesses. If all assumptions are correct, (i.e., each layer is an elastic layer, isotropic and homogeneous, and all other boundary conditions are correct), then it is possible to iterate various combinations of moduli to reach a (virtually) perfect match between the measured and theoretical FWD deflections. In this manner, a solution to the problem of deriving moduli from deflections is obtained.

A serious drawback to this approach is that one or more of the many input assumptions mentioned above may be incorrect and therefore may not apply to the actual pavement system. In spite of this potential drawback, many of the moduli in the database appear to be reasonable and rational, based on common engineering sense and a working knowledge of pavement materials.

INTRODUCTION TO FORWARDCALCULATION

Forwardcalculation techniques were developed and used for the pilot study to generate moduli that are independent of the backcalculated values so they can be used for comparison to screen the backcalculated moduli in the database. This approach is based on the premise that two substantially different approaches to calculated layered elastic parameters from the same deflection data should produce at least somewhat similar moduli given that either approach is credible.

Forwardcalculation involves using certain portions of the FWD deflection basin to derive an apparent modulus or stiffness of the subgrade and/or the bound surface course, using closed-form as opposed to iterative solutions. The deflections measured at larger distances from the load mainly determine the subgrade modulus, while the surface course modulus is mainly a function of the near-load deflections and/or the radius of curvature of the deflection basin. Including the center deflection reading, which in effect is a reflection of the overall pavement system stiffness also enhances both of these forwardcalculation approaches.

The advantages of forwardcalculation are as follows:

1. Since the subgrade and bound surface course stiffnesses obtained are not dependent on the other moduli within the pavement system, as is the case with backcalculation, each problem provides a unique solution.
2. Forwardcalculation is easy to understand and use, whereas backcalculation is presently more of an art than a science. Anyone can perform forwardcalculation, while backcalculation requires expert engineering judgment along with the art of running the iterative program of choice. For backcalculation, the art is in the evaluation of the reasonableness of the results and selection of the model and other input parameters.
3. The forwardcalculation techniques developed for this project produce considerably less scatter in the data (for the same layer and test section) than do backcalculation techniques.

Nothing in pavement analysis comes without its own unique drawbacks. As such, these drawbacks are not limited to backcalculation alone, for example:

1. Since the subgrade and surface course stiffnesses are calculated independently, in combination the values obtained may or may not be reasonable with respect to the total center deflection.
2. To obtain a third, intermediate layer stiffness (if present), such as a granular base, analysts could then assume that the surface and subgrade stiffnesses are correct and then fit the center deflection to the remaining unknown stiffness of, for example, a base course layer. This approach suffers from the same drawback as backcalculation—the layer’s modulus depends on another layer’s, or layers’, analysis results.
3. It is also possible to use a ratio between the subgrade modulus calculated through forwardcalculation and apply the modular ratio relationship for unbound base materials. Certainly, there is no assurance that this method is correct; however, the test of reasonableness is best applied to the results.

4. Since this method produces approximate values (particularly for the base or intermediate layer/s), these results should only be used as layer modulus *estimates*, for example, for screening or quality assurance/quality control (QA/QC) purposes.

In the following sections, the method used in forwardcalculation is described, followed by a section with the screening results from phase I (modified during phase II) of this study that compares the backcalculated (computed) parameters in the database to the forwardcalculated values for the 18 trial sections evaluated in the pilot study.

CHAPTER 3. FORWARDCALCULATION METHODOLOGY

BACKGROUND AND PREVIOUS DEVELOPMENTS

Closed-form solutions for determining select layered-elastic properties of pavement systems have been used extensively in the past.

In 1884, Boussinesq developed a set of closed-form equations for a semi-infinite, linear elastic median half-space, including the modulus of elasticity of the median, based on a point load. Subsequent study has shown that the apparent or composite subgrade modulus derived from any FWD sensor at offset "r" can be calculated from the equation in Figure 1:(5)

$$E_{o,r} = (0.84 \bullet a^2 \bullet \sigma_o) / (d_r \bullet r)$$

Figure 1. Equation. Composite subgrade modulus at an offset.

where: $E_{o,r}$ = Surface or composite modulus of the subgrade beneath the sensor used
a = Radius of FWD loading plate
σ_o = (Peak) pressure of FWD impact load under loading plate
d_r = (Peak) FWD deflection reading at offset distance r
and r = Distance of deflection reading d_r from center of loading plate

The suggested constant of 0.84 assumes that Poisson's ratio is 0.4 (from the calculation $1-\mu^2$). If d_r is a reasonably large distance from the edge of the loading plate, the load can be assumed a point load, so the plate pressure distribution does not matter. Furthermore, small changes in Poisson's ratio have only a minimal impact on this equation.

Subsequent developments have allowed the use of the shape of the deflection basin to estimate various layered elastic (or slab-on-dense-liquid) moduli from FWD deflection readings.

CENTERLINE SUBGRADE MODULUS BASED ON THE HOGG MODEL

One method to ascertain the approximate subgrade stiffness, or elastic modulus, directly under an imposed surface load is the Hogg model. The Hogg model is based on a hypothetical two-layer system consisting of a relatively thin plate on an elastic foundation. The method in effect simplifies the typical multilayered elastic system with an equivalent two-layer stiff-layer-on-elastic foundation model. Depending on the choice of values along the deflection basin used to calculate subgrade stiffness, the tendency exists to either over- or underestimate the subgrade modulus. The Hogg model uses the deflection at the center of the load and one of the offset deflections. Hogg showed that the offset distance where the deflection is approximately one-half of that under the center of the load plate was effective at removing estimation bias. His calculations consider variations in pavement thickness and the ratio of pavement stiffness to subgrade stiffness, since the distance to where the deflection is one-half of the deflection under the load plate is controlled by these factors.

The underlying model development for a finite subgrade was first published in 1944.(6) The implementation of the model used in this study was published in 1983.(7) The equations are as follows:

$$E_0 = I\frac{(1+\mu_0)(3-4\mu_0)}{2(1-\mu_0)}\left(\frac{S_0}{S}\right)\left(\frac{p}{\Delta_0 l}\right)$$

Figure 2. Equation. Hogg subgrade modulus.

$$r_{50} = r\frac{(1/\alpha)^{1/\beta} - B}{\left[\frac{1}{\alpha}\left(\frac{\Delta_0}{\Delta_r}-1\right)\right]^{1/\beta} - B}$$

Figure 3. Equation. Offset distance where deflection is half of center deflection.

$$l = y_0\frac{r_{50}}{2} + \left[(y_0 r_{50})^2 - 4mar_{50}\right]^{\frac{1}{2}}$$

if $\frac{a}{l} < 0.2$, then $l = (y_0 - 0.2m)r_{50}$

Figure 4. Equation. Characteristic length of deflection basin.

$$\left(\frac{S_0}{S}\right) = 1 - \overline{m}\left(\frac{a}{l} - 0.2\right)$$

if $\frac{a}{l} < 0.2$, then $\left(\frac{S_0}{S}\right) = 1.0$

Figure 5. Equation. Theoretical point load stiffness/pavement stiffness ratio.

where:

E_0 = Subgrade modulus
μ_0 = Poisson's ratio for subgrade
S_0 = Theoretical point load stiffness
S = Pavement stiffness = p/Δ_0 (area loading)
p = Applied load
Δ_0 = Deflection at center of load plate
Δ_r = Deflection at offset distance r
r = Distance from center of load plate
r_{50} = Offset distance where $\Delta_r/\Delta_0 = 0.5$
l = Characteristic length
h = Thickness of subgrade
I = Influence factor—see Table 1
α = Curve fitting coefficient—see Table 1
β = Curve fitting coefficient—see Table 1
B = Curve fitting coefficient—see Table 1
y_0 = Characteristic length coefficient—see Table 1
m = Characteristic length coefficient—see Table 1
$\overline{m}$ = Stiffness ratio coefficient—see Table 1

Wiseman (7) described the implementation of the Hogg model using three cases. One is for an infinite elastic foundation, and the other two cases are for a finite elastic layer with an effective thickness that is assumed to be approximately 10 times the characteristic length, *l*. The two finite thickness cases are for fixed Poisson's ratios of 0.4 and 0.5, respectively. Figure 1 shows the various constants used for the three versions of the Hogg model.

Table 1. Hogg model coefficients.

	Hogg model case		***I***	***II***	***III***
	Depth to hard bottom	***h/l***	**10**	**10**	**Infinite**
Eqn.	Poisson's ratio	μ_0	0.50	0.40	All Values
2	Influence factor	I	0.1614	0.1689	0.1925
3	Range Δ_r/Δ_0		> 0.70	> 0.43	All Values
	$r_{50}=f(\Delta_r/\Delta_0)$	α	0.4065	0.3804	0.3210
		β	1.6890	1.8246	1.7117
		B	0	0	0
	Range Δ_r/Δ_0		< 0.70	< 0.43	
	$r_{50}=f(\Delta_r/\Delta_0)$	α	2.6947E-3	4.3795E-4	
		β	4.5663	4.9903	
		B	2	3	
4	$l=f(r_{50},a)$	y_0	0.642	0.603	0.527
		m	0.125	0.108	0.098
5	$(S/S_0)=f(a/l)$	$\overline{m}$	0.219	0.208	0.185

Case *II* of the Hogg model, used for the past 15 years, has been found to be reasonably stable on a wide variety of pavement types and locations, tending toward high correlation with backcalculated subgrade moduli but with significantly lower (and more conservative) results than the corresponding backcalculated values. This difference is because of apparent or actual subgrade nonlinearity (effectively, stress-softening) and/or a finite depth of subgrade (as calculated by Case *II*) to a semirigid bottom layer of subgrade material.

In addition, less variation is indicated between FWD test points when the Hogg model of forwardcalculation is used, as compared to virtually any backcalculation approach. This phenomenon is examined in the subgrade screening results in chapter 4.

Both as a screening tool and to derive relatively accurate, in situ subgrade stiffnesses, the Hogg model is effective and very easy to use compared to others and thus Case *II* is the recommended method to calculate subgrade moduli in forwardcalculation.

BOUND SURFACE COURSE MODULUS BASED ON THE AREA METHOD

A viable method to determine the apparent surface course stiffness of the upper-most bound layer(s), under an imposed surface load is called the AREA (or quasi-radius of curvature) approach.

This approach was first introduced in NCHRP Study 20-50(09), *LTPP Data Analysis: Feasibility of Using FWD Deflection Data to Characterize Pavement Construction Quality*.[3] More recently, the equations originally suggested have been updated and calibrated for AC and PCC pavement surfaces.

For both pavement types, the radius of curvature method is based on the AREA concept (a deflection basin curvature index) and the overall composite modulus of the entire pavement structure, E_o, as the equation in Figure 6 shows.

$$E_o = (1.5 \bullet a \bullet \sigma_o) / d_o$$

Figure 6. Equation. Composite modulus under FWD load plate.

where: E_o= Composite modulus of the entire pavement system beneath the load plate
a = Radius of FWD load plate
σ_o= (Peak) pressure of FWD impact load under the load plate
and d_o= (Peak) center FWD deflection reading

The equation in Figure 6 has been extensively used over the past three to four decades. A 1987 textbook by P. Ullidtz(5) gives an excellent introduction to this approach.

Figure 6 is the most commonly used version of this equation. In theory, it is based on an evenly distributed and uniform FWD load and a Poisson's ratio of 0.5. Generally, Poisson's ratio will be less than 0.5 (usually thought to be between 0.15 and 0.20 for PCC layers and between 0.3 and 0.5 for most other pavement materials), while the distribution of the load under the FWD plate will not be exactly uniform (rather it will be somewhat nonuniform because of the rigidity of the loading plate). These two offsetting factors have resulted in the widely used and straightforward 1.5 times composite modulus formula, which was therefore chosen to develop the forwardcalculation spreadsheets.

AREA, used for rigid pavements in this study, and as reported by AASHTO in 1993, is calculated as:(8)

$$A_{36} = 6 * [1 + 2(d_{12}/d_0) + 2(d_{24}/d_0) + (d_{36}/d_0)]$$

Figure 7. Equation. 914-millimeter (mm) (36-inch) AREA equation for rigid pavements.

where: A_{36} = AREA beneath the first 914 mm (36 inches) of the deflection basin
d_0 = FWD deflection measured at the center of the FWD load plate
d_{12} = FWD deflection measured 305 mm (12 inches) from the center of the plate
d_{24} = FWD deflection measured 610 mm (24 inches) from the center of the plate
and d_{36} = FWD deflection measured 914 mm (36 inches) from the center of the plate

When calculating AREA$_{36}$, the diameter of the loading plate must be between 300 mm (11.8 inches) and 305 mm (12 inches). An AREA$_{36}$ calculation of 36 is achieved if all four deflection readings, at the 0-, 305-, 610-, and 914-mm (0-, 12-, 24-, and 36-inch) offsets are identical, which is equivalent to an infinitely stiff upper layer.

While the equation in Figure 7 has been found to be well suited for rigid pavements with a large radius of curvature, flexible pavements generally have a much smaller radius of curvature (i.e., a steeper deflection basin). Accordingly, for AC pavements a new version of the AREA concept based on FWD sensors placed at 0-, 203-, and 305-mm (0-, 8-, and 12-inch) offsets was derived:

$$A_{12} = 2 * [2 + 3(d_8/d_0) + (d_{12}/d_0)]$$

Figure 8. Equation. 305-mm (12-inch) AREA equation for flexible pavements.

where: A_{12} = AREA beneath the first 305 mm (12 inches) of the deflection basin
d_0 = FWD deflection measured at the center of the FWD load plate
d_8 = FWD deflection measured 203 mm (8 inches) from the center of the plate
and d_{12} = FWD deflection measured 305 mm (12 inches) from the center of the plate

An $AREA_{12}$ calculation of 12 is achieved if all three deflection readings, at the 0-, 203-, and 305-mm (0-, 8-, and 12-inch) offsets, are identical, which is equivalent to an infinitely stiff upper layer (never very close to this value for flexible pavements, however).

A series of calculations were made for AC and PCC pavement types to see what the AREA term becomes if *all* layers in a multilayered elastic system have identical stiffnesses or moduli (and Poisson's ratios). This can be calculated using, for example, the CHEVRON, CHEVLAY2, ELSYM5, or BISAR multilayered elastic programs (CHEVLAY2 was used in this case). It turns out that, no matter which modulus value is selected, as long as all of the layers are assigned the same identical modulus of elasticity, the $AREA_{36}$ term is always equal to 11.04 for rigid pavements (assuming no bedrock) and $AREA_{12}$ is always equal to 6.85 if bedrock is assumed for flexible pavements. (Note: The $AREA_{12}$ calculation for identical moduli with no bedrock = 6.91, close in value.) The reason that bedrock was assumed for AC and not PCC pavements is that FWD deflection readings generally reflect the presence of an underlying stiff layer for flexible pavements, but not for rigid pavements. Using either approach, however, the resulting calculations for upper layer pavement stiffness will be nearly the same, whether or not bedrock is assumed.

The minimum AREA values of 11.04 and 6.85 for the 914-mm (36-inch) and 305-mm (12-inch) areas, respectively, are important in the following equations because they can now be used to ascertain whether the upper layer has a significantly higher stiffness than the underlying layer(s), and to what extent this increase affects the stiffness of the upper, bound pavement layers. For example, if the $AREA_{36}$ term is much larger than 11.04, then the concrete layer is appreciably stiffer than the underlying (unbound) layer(s). The value 11.04 is therefore used in Figure 9, while Figure 10 can be considered as a radius of curvature stiffness index, based on the stiffness of the bound upper layer(s) compared to the composite stiffness of the underlying unbound layers.

The calculation of E_o was previously explained in connection with the presentation of Figure 6, as a composite, effective stiffness of *all* the layers under the FWD loading plate. If these two terms are combined so that the boundary conditions are correct and the logic of the two AREA concepts are followed for PCC and AC pavements, the following equations result:

$$AF_{PCC} = [(k_2 - 1) / \{k_2 - (AREA_{36} / k_1)\}]^{1.79}$$

Figure 9. Equation. AREA factor for rigid pavements.

where: AF_{PCC} = AREA factor, i.e., the improvement in AREA from 11.04 to the 1.79 power
k_1 = 11.04 (the AREA when the stiffness of the concrete layer is the same as the lower layers)
k_2 = 3.262 (maximum possible improvement in AREA = 36 / 11.037)

$$AF_{AC} = [(k_2 - 1) / \{k_2 - (AREA_{12} / k_1)\}]^{1.35}$$

Figure 10. Equation. AREA factor for flexible pavements.

where: AF_{AC}= AREA factor, i.e., the improvement in AREA to the 1.35 power
k_1 = 6.85 (the AREA when the stiffness of the asphalt layer is the same as the lower layers)
k_2 = 1.752 (maximum possible improvement in AREA = 12 / 6.85)

$$E_{PCC} = [E_o * AF_{PCC} * k_3^{(1/AFpcc)}] / k_3^{2.38}$$

Figure 11. Equation. Stiffness or modulus of the upper PCC layer.

$$E_{AC} = [E_o * AF_{AC} * k_3^{(1/AFac)}] / k_3^{2}$$

Figure 12. Equation. Stiffness or modulus of the upper AC layer.

where: E_{PCC}= Stiffness or modulus of the upper PCC (bound) layer(s)
E_{AC} = Stiffness or modulus of the upper AC (bound) layer(s)
E_o= As defined by Figure 6
AF = As defined by Figure 9 for PCC or Figure 10 for AC
k_3 = Thickness ratio of upper layer thickness / load plate diameter = $h_1 / (2*a)$
and a= Radius of the FWD load plate

Both Figure 11 and Figure 12 have been calibrated using a large number of trial CHEVLAY2 runs, and they work very well for typical pavement materials and moduli ratios. However, this approach is empirical rather than totally rigorous or scientific. Thus this method can be used effectively to approximate the relative stiffness of the upper (bound) layer(s) in a pavement cross section for QC, comparative, or routine testing and analysis.

The advantage of using the equations in Figure 9 through Figure 12 or similar equations developed elsewhere is that forwardcalculation techniques, together with commonly used deflection-based quantities (such as AREA), can be combined. Only the composite modulus or stiffness of the pavement system, the AREA, and the pavement thickness normalized to the diameter of the loading plate are needed to calculate the relative stiffness of the bound upper layer(s) of pavement.

INTERMEDIATE LAYER MODULUS CALCULATIONS

Forwardcalculation techniques, as discussed in chapter 3, for the subgrade and bound surface courses, can in turn be used in a pseudobackcalculation manner to derive the approximate stiffness of the intermediate layer, or layers, situated between the subgrade and bound surface course. Alternatively, the modulus relationship developed by Dorman and Metcalf between two adjacent layers of unbound materials can be used.(9) This method computes the base modulus as shown by Figure 13:

$$E_{Base} = 0.2 \bullet h_2^{0.45} \bullet E_{Sub}$$

Figure 13. Equation. Modulus of the unbound base layer using the Dorman and Metcalf relationship.

where: E_{Base} = Dorman and Metcalf base modulus, MPa
h_2 = Thickness of the intermediate base layer, mm
and E_{Sub} = Subgrade modulus, MPa

Some philosophical issues exist with this quasi-backcalculation approach. The most important is that the calculations of the surface course modulus and the centerline subgrade modulus, as outlined in chapter 3, are virtually independent of one another and usually use different deflection sensors (except the center deflection) to derive the appropriate forwardcalculated values. Thus, when the center deflection is once again used to close the multilayered system by matching up the total center deflection with the pair of surface course and subgrade modulus values, the base course modulus so derived will be the least reliable of the three.

Accordingly, the trial data used in phase I for the 15 flexible sections chosen for the pilot study were a matrix of forward- and backcalculated values shown in Table 2. For PCC sections, only the surface course and the subgrade were forwardcalculated by the two-layer variable method used in the backcalculation process from the LTPP database.

Table 2. Moduli used for screening of LTPP database values.

Layer	First Method	Second Method
Asphalt Layer(s)	$AREA_{12}$ modulus	$AREA_{12}$ modulus
Base Layer(s)	Pseudobackcalculated	Dorman & Metcalf—from Hogg subgrade
Subgrade Layer	Case *II* Hogg modulus	Case *II* Hogg modulus

In summary, using forwardcalculated modulus data is not intended to replace backcalculation or any other form of modulus of elasticity measurements. Forwardcalculation, like all other methods of determining apparent, in situ stiffnesses or moduli merely gives the engineer estimates of these values. The only question is: How realistic are such estimates for pavement evaluation or design?

Accordingly, forwardcalculation is designed for routine FWD-based project use and for screening purposes for moduli derived using other methods, especially backcalculation. The present study attempts to determine which of the backcalculated modulus values in the LTPP database—which are also estimates—are *reasonable*, since two distinctly different methods of deriving stiffnesses or moduli from the same FWD load-deflection data should not produce vastly dissimilar results.

CHAPTER 4. INITIAL LTPP BACKCALCULATION DATA SCREENING RESULTS

OVERVIEW

During the development phase of the project (phase I), the researchers selected 18 LTPP pilot sections to evaluate and verify the forwardcalculation methodology. Although only these pilot test sections (albeit with a wide variety of layer thicknesses and test locations) were screened for comparison purposes, this selection still resulted in a large number of data pairs and, accordingly, an adequate sampling of the large volume of data in the LTPP database. Many data points resulted because each individual FWD test point (each with up to four FWD drop heights using multiple drops) provided independently calculated values using both back- and forwardcalculation techniques. Thus, each of the fifteen 152.4-meter (m) (500-foot (ft)) -long flexible sections contains around 500 comparable pairs of moduli. In addition, each 152.4-m (500-ft) rigid section contains somewhat fewer moduli—around 80 comparable pairs of data for the 3 rigid sections screened.

ORGANIZATION OF DATA

For the phase I study, the researchers picked representative but diverse test sections from the appropriate data tables. In all, 15 flexible and 3 rigid sections were selected for review and the development of the screening techniques that were eventually used during phase II. The 18 sections all contained backcalculated data for most or all of the FWD test points along each of the test sections, and they were selected based on diverse layer thicknesses, geographic location, and test dates. Both General Pavement Studies (GPS) and Specific Pavement Studies (SPS) sections were used to further ensure a wide range of input values.

The data were imported from the appropriate LTPP data tables into various Microsoft™ Excel spreadsheets for further processing. Parallel columns of data, both backcalculated and forwardcalculated (described below), were arranged for ease of postprocessing and comparisons of related stiffnesses, or moduli.

The following LTPP sections and dates of FWD tests comprised the 18 trial datasets:

- 04-0114 17 February 1994 (flexible SPS).
- 04-0117 7 January 1998 (flexible SPS).
- 04-0221 8 February 1994 (rigid SPS).
- 04-1003 26 February 1992 (flexible GPS).
- 05-3011 15 June 1993 (rigid GPS).
- 12-1370 14 December 1989 (flexible GPS).
- 12-9054 26 September 1989 (flexible GPS).
- 13-4111 16 September 1992 (flexible GPS).
- 16-1021 13 August 1991 (flexible GPS).
- 20-1005 20 February 1992 (flexible GPS).
- 23-1001 24 April 1995 (flexible GPS).
- 31-0120 3 August 1995 (flexible SPS).

- 31-0121 10 June 1997 (flexible SPS).
- 32-1020 14 September 1994 (flexible GPS).
- 35-1003 26 April 1995 (flexible GPS).
- 35-1005 18 April 1994 (flexible GPS).
- 36-1011 16 August 1993 (flexible GPS).
- 48-4143 24 July 1990 (rigid GPS).

For the phase I preliminary analyses, these data were processed and analyzed as described in the following sections.

CHECK FOR ERRORS OR ANOMALIES IN THE BACKCALCULATION PROCESS

At the outset of phase I, the scope of work assumed that the level E backcalculated values present in the database, for both rigid and flexible pavements, at a minimum, matched the measured deflection basin, i.e., within a reasonable root mean square (RMS) value. Accordingly, spot checks were made on a few of the deflection basins to see whether the same set of moduli could be obtained using the same backcalculation program (MODCOMP). Even if these results were not exactly the same, another approach was to determine whether the RMS values in the level E database were the same as those that could be derived by using the backcalculated values in the database to forwardcalculate a new RMS value.

Although the RMS value comparisons were within reason, they were not identical. It was also not possible, in all cases, to obtain the same set of backcalculated values by rerunning the FWD data through MODCOMP. Nevertheless, the differences could well be attributed to how the backcalculation program was run (e.g., user-controlled inputs) or to rounding differences that cannot be precisely reproduced.

Based on the LTPP sections checked and a general review of the results, the researchers determined that the data in the existing level E database are acceptable insofar as the backcalculated moduli can be used to recalculate a deflection basin and an RMS value that are within reason. Accordingly, the existing backcalculated database was screened as originally proposed in the original scope of work.

SUBGRADE SCREENING RESULTS

Figure 14 shows a log-log plot of all flexible test points analyzed using forwardcalculation techniques versus the backcalculated values for the same test points and drop heights. This graph shows that the two methods of analysis correlate well for most of the data. However, the overall correlation is not very good (the r-squared value = 0.39). A careful review of Figure 14 reveals that a number of outliers caused the low r-squared value and that these outliers are primarily caused by backcalculated values that do not follow the trend. (Using a log-log scale makes the graph look better than a linear plot and regression analysis would.)

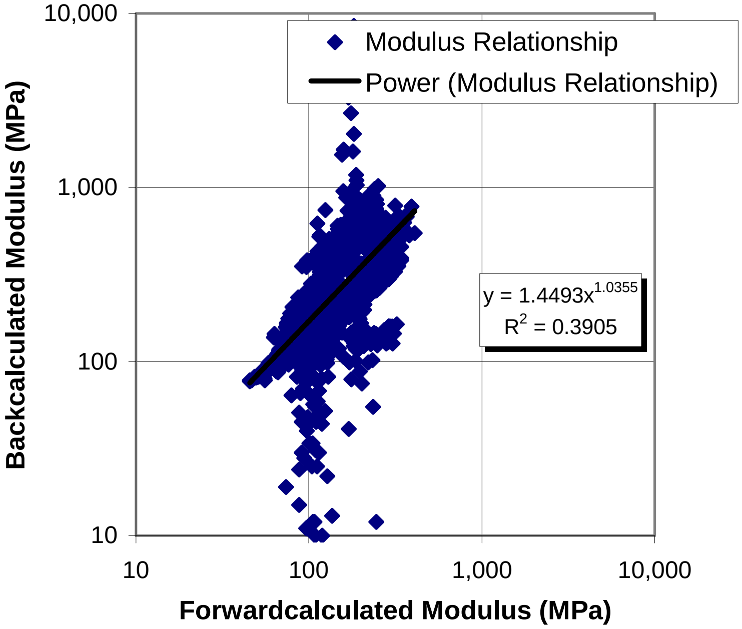


Figure 14. Graph. Back- versus forwardcalculated subgrade moduli for 15 trial LTPP flexible sections.

Another way to view the data is to examine the overall nationwide averages and the variability of each set of values.

Certainly, variability in subgrade moduli is to be expected. Examining at least 15 varying subgrade soils spread across several states and regions with obvious differences causes differences, while spatial variability also exists within any given 152.4-m (500-ft) test section. On the other hand, both the averages and the overall variability for each method should be similar, since they are all based on the same FWD test data, the same sections, and the same test points. Table 3 summarizes the basic statistics for the two analysis methods.

Table 3. Statistics for back- and forwardcalculated subgrade moduli for 15 trial flexible sections.

Statistic	Hogg Subgrade	Backcalculated Subgrade
Median (MPa*)	129	236
Average (MPa)	150	320
Std. Dev. (MPa)	68	493
COV (%)	46	154

*1 megapascal (MPa) = 145 pounds per square inch (psi)

Based on the overall results shown in Table 3, it is apparent that the Hogg forwardcalculation model indicates a smaller variability in subgrade stiffness (coefficient of variation (COV) = 46%) compared to the backcalculation method (COV = 154%). Some of the subgrade layers used during backcalculation (when more than one layer was classified as a subgrade material) were not included in this pilot analysis. The subgrade layers that were not included were the ones with the poorest relationship to forwardcalculation and with the highest variability (see also Figure 20 in chapter 4). Also the median value is probably more indicative of a true average than the averages (arithmetic means), which are increased by the high and implausible modulus values in the backcalculated database.

It appears that the nationwide variability of subgrade materials, expressed as COV, should be in the 40 to 60 percent range. The nationwide standard deviation for backcalculation was even larger than the average value found, which is not feasible and confirms again that some backcalculated values were implausibly high.

By comparison, the average P46 laboratory moduli reported for LTPP's fine-grained soils was 71 MPa (around 55% of the forwardcalculated median). Meanwhile, the COV in moduli for the same nationwide soil samples was 45 percent—see, for example, *LTPP Data Analysis: Variations in Pavement Design Inputs* (10). This NCHRP research indicates that the distribution of forwardcalculated subgrade moduli is similar to the distribution of the LTPP P46 laboratory test moduli.

The 45 percent COV for subgrade materials found through an independent means therefore adds credence to the Hogg model COV of 46 percent found during Phase I of this study. The difference between the forwardcalculated Hogg modulus and the laboratory-associated P46 modulus is probably because the subgrade, when tested in situ by the FWD, is covered and well-confined by a pavement system, while the laboratory P46 tests are conducted directly on elements of the subgrade, whether disturbed or not, with or without soil suction, etc.

One level of identifying suspect backcalculated subgrade moduli using the forwardcalculated values could be to limit the divergence of the two approaches to a factor of two. Using this factor of two as an example, if the subgrade modulus from forwardcalculation = 80 MPa (11,600 psi), then the acceptable (unflagged) range of the backcalculated values would be 40–160 MPa (5,800–23,200 psi). Out of the 15 flexible section set of trial data, some 30% of the backcalculated values were not within this acceptable range.

For the concrete sections, all 132 backcalculated subgrade moduli were within a factor of 1.5 below or above the minimum and maximum of the forwardcalculated values. Figure 15 shows that the values were always above so for PCC sections, none of the phase I backcalculated subgrade moduli appear to be candidates for flagging. Figure 15 also shows that the Hogg model produces lower subgrade modulus values, probably because these values represent the apparent (estimated) subgrade modulus under the load, with an effective depth to a rigid layer, whereas the backcalculation approach did not use such an assumption.

Since the spread in back- and forwardcalculated subgrade moduli under concrete pavements was smaller than in the case of the other values compared in the phase I pilot study, these values were plotted in arithmetic form in Figure 15—which still resulted in a surprisingly good r-squared value of 0.84.

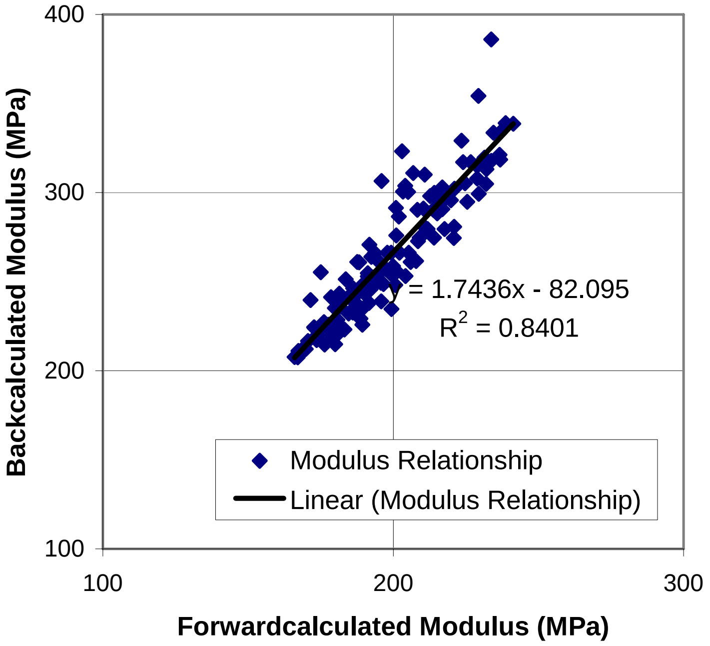


Figure 15. Graph. Back- versus forwardcalculated subgrade moduli for three trial LTPP rigid sections.

SURFACE COURSE SCREENING RESULTS

Figure 16 shows a log-log plot of all flexible layer test points analyzed using forwardcalculation techniques introduced in chapter 3 versus the backcalculated values for the same test points and drop heights. This graph shows that the overall values track quite well; the correlation is good, with an r-squared of 0.67 for the back- versus forwardcalculated moduli.

Although there is a reasonable correlation between the back- versus forwardcalculated AC moduli, as shown in Figure 16, this graph (and others that follow) reveals two or more simultaneous trends. In this instance, out of the 15 asphaltic test sections, most of the points north of the best-fit regression line were from two Florida sites while most of the points south of the line were from two Nebraska sites. Table 4 (Florida) and Table 5 (Nebraska) show the average moduli (all layers) for these four sites using the two methods of analysis.

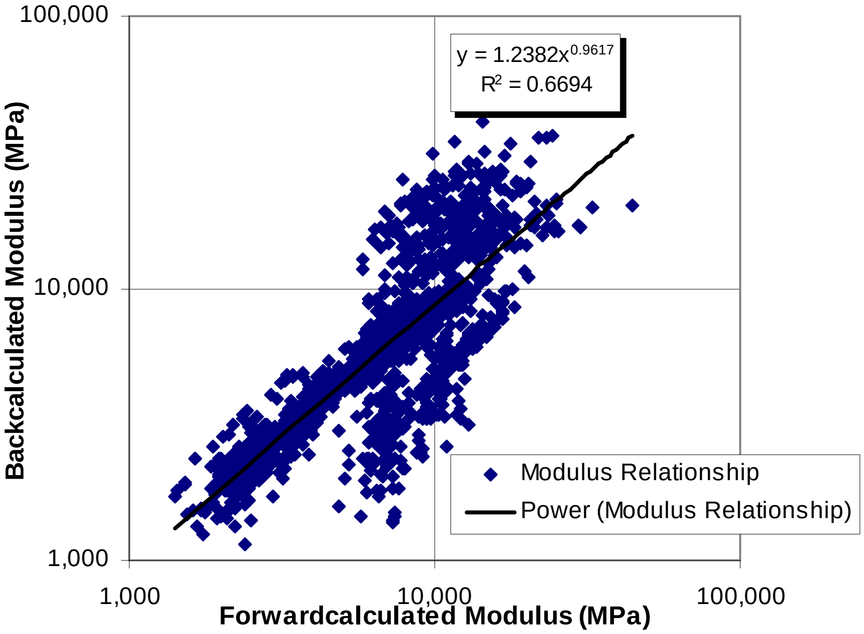
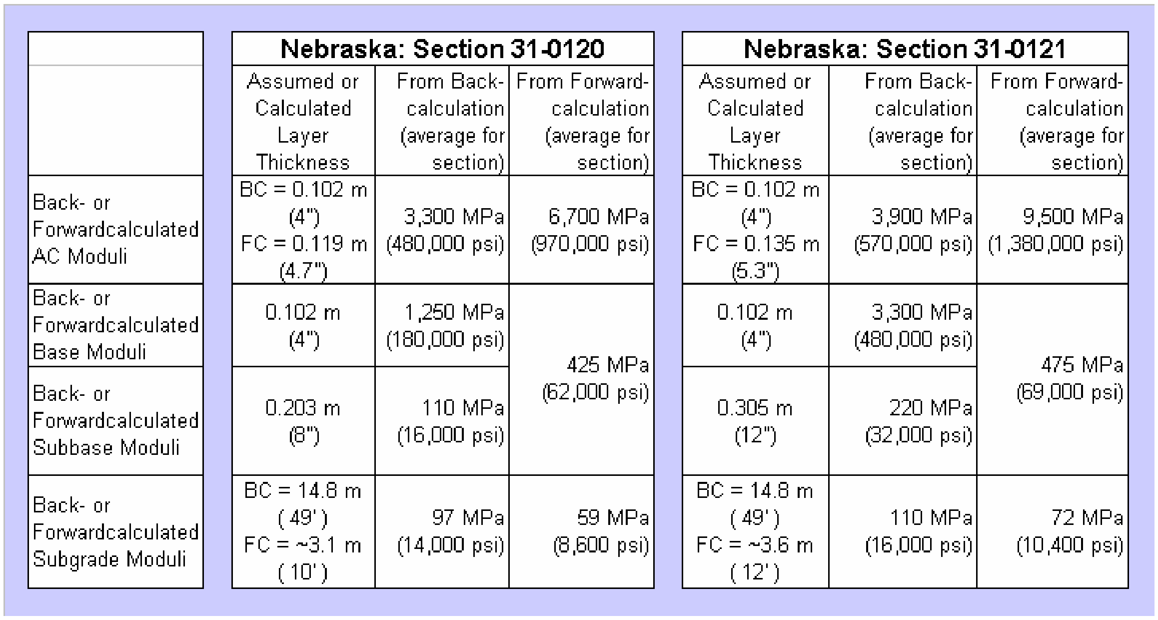


Figure 16. Graph. Back- versus forwardcalculated asphalt layer moduli for 15 trial LTPP flexible sections.

Table 4. Back- and forwardcalculated moduli for two trial Florida sections.

	Florida: Section 12-1370			Florida: Section 12-9054		
	Assumed or Calculated Layer Thickness	From Back-calculation (average for section)	From Forward-calculation (average for section)	Assumed or Calculated Layer Thickness	From Back-calculation (average for section)	From Forward-calculation (average for section)
Back- or Forwardcalculated AC Moduli	0.043 m (1.7")	19,000 MPa (2,800,00 psi)	9,750 MPa (1,400,000 psi)	0.064 m (2.5")	12,500 MPa (1,800,00 psi)	6,050 MPa (880,000 psi)
Back- or Forwardcalculated Base Moduli	0.272 m (10.7")	237 MPa (34,000 psi)	300 MPa (43,500 psi)	0.254 m (10")	79 MPa (11,500 psi)	290 MPa (42,000 psi)
Back- or Forwardcalculated Subbase Moduli	0.376 m (14.8")	85 MPa (12,000 psi)		0.305 m (12")	14,000 MPa (2,000,000 psi)	
Back- or Forwardcalculated Subgrade Moduli	BC = 3.04 m (10') FC = ~1.7 m (5.5')	1,370 MPa (198,500 psi)	100 MPa (14,500 psi)	BC = Semi-infinite FC = ~1.6 m (5.4')	215 MPa (31,000 psi)	117 MPa (17,000 psi)

Table 5. Back- and forwardcalculated moduli for two trial Nebraska sections.



	Nebraska: Section 31-0120			Nebraska: Section 31-0121		
	Assumed or Calculated Layer Thickness	From Back-calculation (average for section)	From Forward-calculation (average for section)	Assumed or Calculated Layer Thickness	From Back-calculation (average for section)	From Forward-calculation (average for section)
Back- or Forwardcalculated AC Moduli	BC = 0.102 m (4") FC = 0.119 m (4.7")	3,300 MPa (480,000 psi)	6,700 MPa (970,000 psi)	BC = 0.102 m (4") FC = 0.135 m (5.3")	3,900 MPa (570,000 psi)	9,500 MPa (1,380,000 psi)
Back- or Forwardcalculated Base Moduli	0.102 m (4")	1,250 MPa (180,000 psi)	425 MPa (62,000 psi)	0.102 m (4")	3,300 MPa (480,000 psi)	475 MPa (69,000 psi)
Back- or Forwardcalculated Subbase Moduli	0.203 m (8")	110 MPa (16,000 psi)		0.305 m (12")	220 MPa (32,000 psi)	
Back- or Forwardcalculated Subgrade Moduli	BC = 14.8 m (49') FC = ~3.1 m (10')	97 MPa (14,000 psi)	59 MPa (8,600 psi)	BC = 14.8 m (49') FC = ~3.6 m (12')	110 MPa (16,000 psi)	72 MPa (10,400 psi)

Results in Table 4 and Table 5 above show two primary factors involved in these discrepancies. The first was that the two Florida sections shown in Table 4 had a very thin layer of asphalt concrete (64 mm (2.5 inches) or less), which is not well suited for backcalculation. In contrast, the forwardcalculation results for these two sections appear reasonable.

The second and probably the most important overall factor that caused the relatively large discrepancies between back- and forwardcalculated values for these four sections was the so-called compensating layer effect that often results from an iterative backcalculation routine. The compensating layer effect is a result of backcalculating the modulus of successive layers from the subgrade up, which has a tendency to compensate for even relatively small errors in the layer or layers below by alternately over- and underestimating the modulus of each successive layer in the pavement system. The compensating layer effect is especially pronounced for Florida section 12-9054, where the subbase layer (actually a compacted fine-grained soil) results in an unrealistically high modulus (14,000 MPa (2,000,000 psi)), followed upwards by a base layer (well-compacted limerock) with an unrealistically low modulus of 80 MPa (11,600 psi). This layer, in turn, is followed by an unrealistically high modulus (at that test site) for the hot mixed asphalt surface course of some 12,500 MPa (1,800,000 psi). Meanwhile, forwardcalculation results in a subgrade modulus of approximately upper 3 m (10 ft) of material of 120 MPa (17,000 psi), followed by a combined base and subbase layer of 300 MPa (42,000 psi). Finally, forwardcalculation indicates a modulus for the asphalt layer of around 6,000 MPa (880,000 psi), resulting in asphalt moduli points north of the best-fit line for all sections shown in Figure 16.

The materials used in Florida section 12-1370 were identical (see modulus comparison in Table 4, although the compensating layer effect is different, with too high a subgrade modulus for the upper 3 m (10 ft) of subgrade from backcalculation.

The opposite effect in the asphaltic surface course is evident for the Nebraska sections shown in Table 5, although to a lesser degree, with seemingly reasonable backcalculated subgrade and subbase moduli, but very high base course moduli, especially for section 31-0121. Because of the compensating layer effect, lower surface course moduli result from backcalculation than from forwardcalculation (see values in Table 5). In both of these sections, the subbase was a crushed stone, the base was a permeable asphalt treated base, and the surface course was dense graded asphalt concrete.

As was shown with the subgrade moduli screening results in chapter 4, another way to examine these data is to consider the overall nationwide averages and the variability associated with each set of values. With the asphalt layer, the averages and variability associated with the same set of test sections and the time of FWD test should be similar.

Table 6 summarizes the basic statistics for both the backcalculated and forwardcalculated ($AREA_{12}$) analysis methods.

Table 6. Statistics for back- and forwardcalculated surface course moduli for flexible sections.

Statistic	$AREA_{12}$ Asphalt Layer	Backcalculated Asphalt Layer
Median (MPa*)	7,164	5,730
Average (MPa)	7,704	7,448
Std. Dev. (MPa)	4,316	5,850
COV (%)	56	79

*1 megapascal (MPa) = 145 pounds per square inch (psi)

Based on the overall results shown in Table 6, both methods produce essentially the same average AC modulus, approximately 7,500 MPa (1,100,000 psi). While these modulus levels appear higher than normal for asphalt concrete, in fact these results are reasonable medians and averages, since the data included both high, medium, and low AC mat temperatures from FWD tests conducted at all seasons except when the subgrade was frozen. Furthermore, the coefficient of variation associated with each analysis procedure appears plausible (56 and 79 percent for forward- and backcalculation, respectively), although once again the forwardcalculation method appears somewhat more stable. The 15-section nationwide forwardcalculated COV is greater for AC than for subgrade materials, probably because of the temperature-sensitive, viscoelastic properties of asphalt-bound materials as opposed to unbound subgrade materials, which are generally not viscoelastic.

One of the 15 flexible sections analyzed had two surface course layers that were used in backcalculation. The extra or second-layer plots are described in the extra layer results section. Since these were not indicative of the overall trend, they are not included in Figure 16 or the statistics shown above.

In screening the backcalculated results, if a criterion of a factor of two (times or divided by) were used, then some 15 percent of the backcalculated asphalt concrete moduli would be flagged as out-of-range; if the factor is changed to 1.5, then 24 percent would be out-of-range, and so on. The use of several levels of flagging was eventually adopted and recommended for the LTPP backcalculated database (see chapter 5).

Figure 17 shows a log-log plot of all rigid test points analyzed using the checking for errors or anomalies screening method versus the backcalculated values for the same test points and drop heights. Two backcalculated values are shown because two methods were used in the backcalculation process: slab-on-dense-liquid (DL) foundation and slab-on-elastic-solid (ES) foundation. In both cases, the r-squared values are somewhat poorer than with asphalt concrete (r-squared = 0.61 and 0.70 for the ES and DL cases, respectively). However, this result is to be expected, since the range of values encountered for AC is greater than for PCC because of the viscoelastic nature of asphalt-bound materials.

Using screening criteria, for example, where the backcalculated values should be within a factor of 1.5 times, or divided by 1.5, the corresponding forwardcalculated values, only 18 out of 124 PCC moduli (or 14.5 percent of the total) would be considered out-of-range (reduced to 8 out of 124, or 6.5 percent, if a flagging factor of 2 is used).

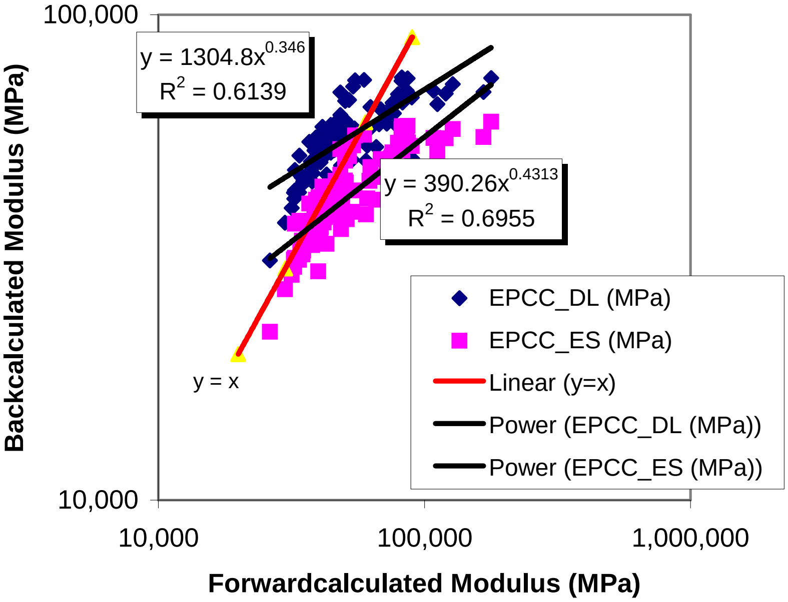


Figure 17. Graph. Back- versus forwardcalculated concrete layer moduli for three trial LTPP rigid sections.

Table 7 summarizes the basic statistics for both the backcalculated and forwardcalculated (AREA_{36}) rigid pavement analysis methods.

Table 7. Statistics for back- and forwardcalculated PCC moduli for rigid sections.

Statistic	Forward-calculated PCC modulus	Backcalculated EPCC_ES	Backcalculated EPCC_DL
Average (MPa*)	54218	42351	55973
Std. Dev. (MPa)	24774	7849	8755
COV (%)	46	19	16

*1 megapascal (MPa) = 145 pounds per square inch (psi)

The averages are very similar between the forwardcalculated model and the backcalculated DL model, while the backcalculated ES model is somewhat lower.

The coefficients of variation were 16, 19, and 46 percent for the backcalculated DL model, ES model, and forwardcalculated $AREA_{36}$ model, respectively. The forwardcalculation model results in a COV that appears too high when compared to both backcalculation models in the LTPP computed parameter database. Yet it is still possible that the forwardcalculation model used in this study is better able to reveal significant differences between low- and high-strength concrete mixes than either backcalculation model. This trend was discovered during an NCHRP project.(3)

INTERMEDIATE (BASE) COURSE SCREENING RESULTS

As stated in chapter 3, backcalculation of the intermediate layer, or layers, between a subgrade and a bound surface course is the most tenuous and uncertain of all. This situation is true whether the analyst starts with both of the upper and lower layers as through forwardcalculation or with the subgrade alone, as is generally done through backcalculation. To reiterate this point, *any* errors in the process leading up to the base course calculation of stiffness or modulus, however slight they may be, will lead to much larger and offsetting errors in the base layer(s) if a closed-loop solution is sought. (A closed-loop solution is one where the sum of the vertical strains under the FWD test load in all underlying pavement layers is equal to the load from the measured center deflection.) In backcalculation, this phenomenon is known as the compensating layer effect, which will influence the pseudobackcalculation routine developed for the intermediate layer after forwardcalculation of the upper and lower layers, even if to a lesser degree. If the Dorman and Metcalf equation is used, this drawback will not apply since the intermediate layer is simply calculated as a ratio of the subgrade modulus (as a function of the thickness of this layer).

Figure 18 shows a log-log plot of all flexible test points analyzed using the pseudo-backcalculation screening approach versus the backcalculated values for the same test points and drop heights.

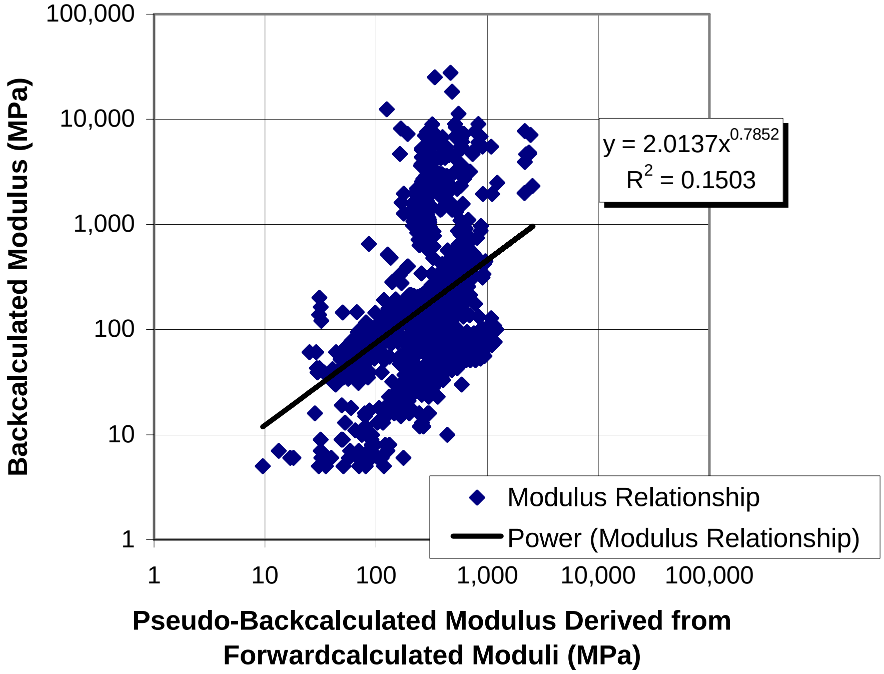


Figure 18. Graph. Back- versus forward-based base layer moduli for 15 flexible LTPP sections.

Figure 18 shows virtually no relationship between the two sets of values. The backcalculation routine chosen to create the computed parameter data tables has evidently fixed the minimum possible base course modulus at 5 or 6 MPa (~750 psi), while the pseudobackcalculation/forwardcalculation-based approaches used a maximum possible base course modulus of some 2,500 MPa (360,000 psi). Obviously, both of these values are outside of typical ranges for granular or unbound base courses. As Figure 18 shows, the correlation between the forwardcalculation-based method and backcalculation only yields an r-squared value of 0.15. Meanwhile, both approaches suffer from excessive variability, with the pseudobackcalculation approach having a COV of 66 percent and backcalculation having a COV of 272 percent (see Table 8). This anomaly presents a problem because COV levels should be similar to those found for unbound (and generally even more inconsistent) subgrade materials.

Table 8. Statistics for backcalculated and pseudobackcalculated base course moduli for flexible sections.

Statistic	E(2) based on forwardcalculated surface course and subgrade moduli	E(2) from backcalculation database
Median (MPa*)	306	148
Average (MPa)	361	565
Std. Dev. (MPa)	238	1,538
COV (%)	66	272

*1 megapascal (MPa) = 145 pounds per square inch (psi)

As Table 8 shows, the average and median intermediate layer moduli derived through either approach appear reasonable, with the possible exception of the median backcalculated value (approximately 150 MPa (~20,000 psi)), which is too low.

Of the 15 flexible sections analyzed, 4 had 2 base course layers that were used in backcalculation. The extra, or second-value, plots are discussed below.

These high variability trends were indicative of the two methods throughout the entire FWD load-deflection database and the backcalculated tables. Therefore, the researchers felt it more realistic to use the ratio published by Dorman and Metcalf to estimate the intermediate layer modulus.(9) This approach assumes that a well-constructed unbound subbase or base course will realize an increase in modulus over and above that of the subgrade by a factor that is only dependent on the thickness of the intermediate layer or layers. This ratio is considered valid for intermediate layer thicknesses between 50 and 600 mm (2 and 24 inches), resulting in ratios from 1.16 for a 50-mm (2-inch) layer and 3.56 for a 600-mm (24-inch) layer.

Using the same 15 flexible section dataset, and considering the fact that 6 of these 15 sections had intermediate layers that were classified in the LTPP database basically as "improved subgrade," Table 9 shows the remaining 9 section statistics.

Table 9. Statistics for base course moduli from backcalculation and from forwardcalculation using Dorman and Metcalf's equation for nine trial flexible sections.

Statistic	E(2) using Dorman and Metcalf ratio to forwardcalculated subgrade moduli	E(2) from backcalculation database
Median (MPa*)	313	247
Average (MPa)	361	921
Std. Dev. (MPa)	142	1,991
COV (%)	39	216

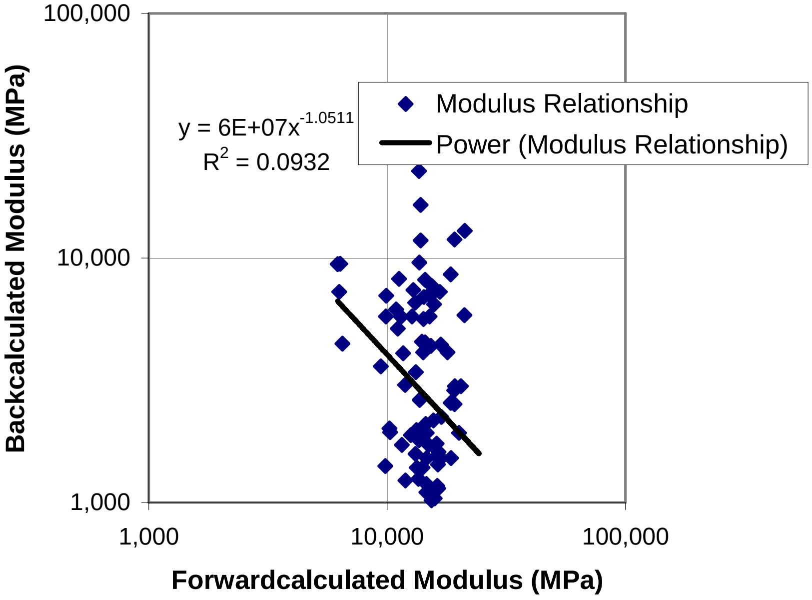
*1 megapascal (MPa) = 145 pounds per square inch (psi)

The researchers concluded that the median and average base or subbase moduli from Dorman and Metcalf's relationship were far more realistic (310–360 MPa (45,000–50,000 psi)) as screening values, as was the reasonable nationwide COV of 39 percent (see Table 9). By contrast, the COV using the pseudobackcalculation procedure was 66 percent (see Table 8). The median base course modulus from backcalculation (250 MPa (35,000 psi)) also appears reasonable, but certainly not the backcalculated average of 921 MPa (135,000 psi) or the COV of 216 percent gained using this method (see Table 9).

Accordingly, the Dorman and Metcalf relationship was used for phase II to screen the entire database. For PCC sections, only two back- or forwardcalculated values were derived, one for the subgrade and one for the rigid upper layer or layers.

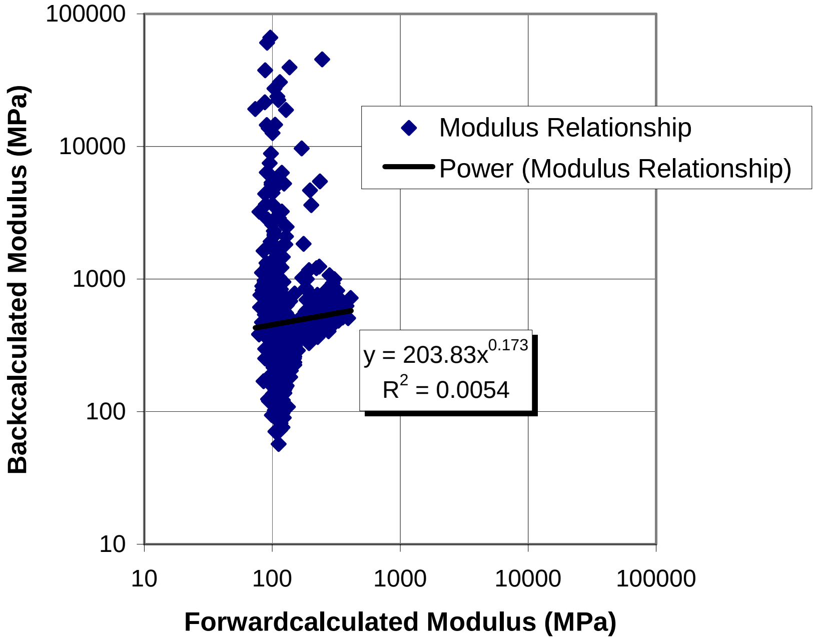
EXTRA LAYER RESULTS FROM BACKCALCULATION

This section shows the extra layers used in backcalculation for the phase I trial database, over and above the two or three layers calculated through forwardcalculation. These situations occurred when the MODCOMP backcalculation program used more than three layers (plus any assumed rigid bottom) when generating the computed parameter file of backcalculated values.



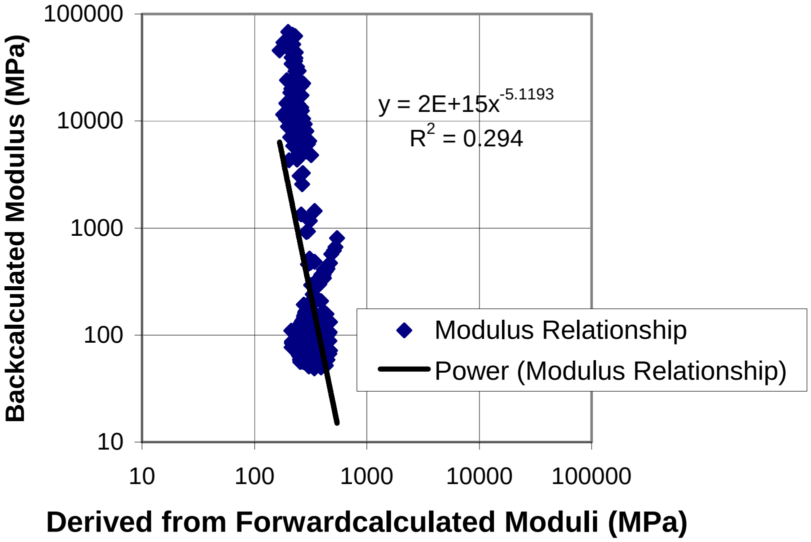
y (the y axis—the backcalculated modulus) = 6 times 10 to the 7th power (6E+07) times x (the axis—the forwardcalculated modulus) raised to the -1.0511 power; R^2 (the coefficient of determination) = 0.0932

Figure 19. Graph. Back- versus forwardcalculated asphalt layer moduli for one trial LTPP flexible section with two upper (bound) layers.



R^2 = the coefficient of determination

Figure 20. Graph. Back- versus forwardcalculated subgrade moduli for five trial LTPP flexible sections with two subgrade (lower unbound) layers.



y (the y axis—the backcalculated modulus) = 2 times 10 to the 15th power (2E+15) times x (the axis—the forwardcalculated modulus) raised to the -5.1193 power; R^2 (the coefficient of determination) = 0.294

Figure 21. Graph. Back- versus forwardcalculated base course moduli for four trial LTPP flexible sections with two intermediate layers.

In the three figures above, two of the three exhibit correlations that regress in the wrong direction. The r-squared values indicate an extremely poor fit, whatever the direction of the best-fit line. Accordingly, it would appear that backcalculation, or any other available method, is not very good at deriving stiffnesses or moduli for more than three unknown structural layers (plus a rigid layer at-depth, if any).

CHOICE OF SCREENING LIMITS AND CODES

Based on the analyses carried out during phase I, the following screening limits were developed. Table 10 shows these limits with a generic description of each.

Table 10. Flagging codes suggested for screening of the backcalculated LTPP database tables.

Generic description of the correspondence between back- and forwardcalculated moduli	Suggested correspondence codes (flags)	Ratio between the forwardcalculated and backcalculated modulus values
Acceptable	0	2/3 ≤ Ratio ≤ 1.5
Marginal	1	1/2 ≤ Ratio ≤ 2 (and not code 0)
Questionable	2	1/3 ≤ Ratio ≤ 3 (and not codes 0 or 1)
Unacceptable	3	Ratio < 1/3 or Ratio > 3

In the selection of a fairly broad range of values that are acceptable as far as the backcalculated LTPP computed parameter tables are concerned, researchers found that neither back- nor forwardcalculation offers any certain or unequivocal ground truth of in situ moduli. Both methods, using distinctly different assumptions and theory, arrive at approximations (at best) of in situ modulus values in a layered elastic system consisting of two or more layers. Therefore, it is certainly acceptable if these two different approaches produced moduli within a factor of 1.5 times or divided by each other, for the same layer and test point. In such cases, it is impossible to claim that one is correct while the other is incorrect, because no known ground truth exists. The only valid conclusion is that each value, within an acceptable range of each other, is therefore reasonable or acceptable, provided as well that each lies within a reasonable range for the materials it represents (see also chapter 5 and Table 14).

The same logic was used to arrive at the generic terms marginal, questionable, and unacceptable, as outlined in Table 10. For example, it was unacceptable if records occurred from the two dissimilar methods of analysis, although using exactly the same FWD input data, resulted in a layer modulus more than a factor of three times or divided by each other. In such cases, either one of the two values is reasonable or both are unreasonable. The key screening steps in chapter 5 discuss in more detail how these and the other cases of back- versus forwardcalculation discrepancies delineated in Table 10 were handled.

CHAPTER 5. LTPP BACKCALCULATION DATABASE SCREENING METHODOLOGY

LTPP DATA SOURCE USED IN THIS STUDY

The complete computed parameter tables of backcalculated pavement layer data plus the supporting tables (Release 16.0—July 2003 Upload) were used and screened in this study.

LTPP Data Tables Used

The following tables from the LTPP database were used in either computing the forwardcalculated moduli or screening the backcalculation values:

- EXPERIMENT_SECTION—Stores current experiment information that is driven by maintenance and rehabilitation (M and R) activities.
- TST_L05B—Table containing section representative layer thickness and descriptions for all constructions.
- MON_DEFL_FLX_BAKCAL_BASIN—Deflection basin parameters used for the pavement backcalculation computations using MODCOMP v4.2 computer program.
- MON_DEFL_FLX_BAKCAL_LAYER—Layer structure and material inputs for the pavement backcalculation computations using MODCOMP v4.2 computer program.
- MON_DEFL_FLX_BAKCAL_POINT—Interpreted results of backcalculated elastic layer moduli from FWD measurements for flexible and rigid pavement structures using MODCOMP v4.2 computer program.
- MON_DEFL_FLX_BAKCAL_SECT—Summary of results presented in MON_DEFL_FLX_BAKCAL_POINT by section and test date. Results in MON_DEFL_FLX_BAKCAL_POINT with greater than 2 percent ERROR_RMSE were excluded from summary statistics.
- MON_DEFL_FLX_NMODEL_POINT—Interpreted results of nonlinear backcalculated from FWD measurements for flexible and rigid pavement structures using MODCOMP v4.2 computer program.
- MON_DEFL_FLX_NMODEL_SECT—Summary of results presented in MON_DEFL_FLX_NMODEL_POINT by section and test date. Results in MON_DEFL_FLX_NMODEL_POINT with greater than 2 percent ERROR_RMSE were excluded from summary statistics.
- MON_DEFL_FWDCHECK_CMNTS—Comments generated during use of FWDCHECK for basic analysis of the deflection data (not part of the backcalculation process, but listed here as a possible information source even though it is only partially populated).

- MON_DEFL_LOC_INFO—Test point specific condition data for Dynatest FWD.
- MON_DEFL_MASTER—FWD data collection general site measurement information.
- MON_DEFL_RGD_BAKCAL_BASIN—Deflection basin parameters used in backcalculation of rigid pavement structures.
- MON_DEFL_RGD_BAKCAL_LAYER—Pavement structure input parameters used in the backcalculation of elastic layer moduli and pavement structural material properties.
- MON_DEFL_RGD_BAKCAL_POINT—Interpreted elastic layer moduli and pavement structural material properties from backcalculation and direct computations of FWD measurements of rigid pavement structures using version 2.2 of ERESBACK.
- MON_DEFL_RGD_BAKCAL_SECT—Test section statistics for interpreted elastic layer moduli and pavement structural material properties from backcalculation and direct computations of FWD measurements for rigid pavement structures for each measurement pass.

LTPP Backcalculation Tables Screened

All the LTPP tables containing backcalculated moduli were screened using the forwardcalculated values. Table 11 gives a list of these tables, as well as the number of records contained and screened in each computed parameter table in the LTPP database.

Table 11. LTPP backcalculation tables and number of records screened.

Name of Backcalculation Table for Screening	Number of Data Records	Number of Records Screened	% Records Screened
MON_DEFL_FLX_BAKCAL_POINT	1,645,615	1,088,679	66.2%
MON_DEFL_FLX_BAKCAL_SECT	44,544	25,564	57.4%
MON_DEFL_FLX_NMODEL_POINT	181,051	130,805	72.2%
MON_DEFL_FLX_NMODEL_SECT	3,852	2,754	71.5%
MON_DEFL_RGD_BAKCAL_POINT	37,246	36,989	99.3%
MON_DEFL_RGD_BAKCAL_SECT	1,189	1,183	99.5%

The first four lines of Table 11 are the MODCOMP data records, while the last two lines are the two-layer rigid pavement data using the dense liquid and elastic solid methodology. Almost all of the unscreened data from Table 11 resulted from the use of a rigid or stiff layer at some depth in the flexible section data tables (for both the flexible and some of the rigid section data) created by MODCOMP or an assumed layer modulus for any other structural layer when MODCOMP was used. These moduli were assumed, or fixed, and were therefore not screened.

In addition, with data migration and other issues, the records in tables *_BAKCAL_LAYER, *_BAKCAL_BASIN, and *_BAKCAL_POINT are no longer directly connectable with one another. Since data from these tables (plus TST_L05B and others) were used in the screening process, a very limited number (for example, <1 percent of the total number of records in the rigid backcalculated data tables from the last two lines of Table 11) of records that could not be connected were left unscreened.

Since the completion of the backcalculation project (in 1999), the LTPP program underwent a major change in the way the CONSTRUCTION_NO field is assigned. As a result, the CONSTRUCTION_NO values in the backcalculation tables do not directly correlate with the CONSTRUCTION_NO values in other key LTPP tables such as the EXPERIMENT_SECTION and TST_L05B tables. For this study, the forwardcalculation method used the deflection basins in the MON_DEFL_FLX_BAKCAL_BASIN table and the MON_DEFL_RGD_BAKCAL_BASIN table (which use the former CONSTRUCTION_NO assignments) while using the pavement structure data (material type and layer thicknesses) from the TST_L05B table (which uses the current CONSTRUCTION_NO assignments). To ensure the proper connection of the corresponding records, the following fields were compared to ensure the proper assignment of the CONSTRUCTION_NO values: EXPERIMENT_SECTION.CN_ASSIGN_DATE, MON_DEFL_FLX_BAKCAL_LAYER.CN_REF_DATE, and MON_DEFL_RGD_BAKCAL _LAYER.CN_REF_DATE. This process was successful in almost all cases, as indicated above.

KEY STEPS FOR SCREENING THE LTPP BACKCALCULATION DATA

The following steps were taken to screen backcalculated moduli:

1. Obtain the FWD deflection basin data.
2. Determine the forwardcalculation layer structures.
3. Conduct forwardcalculation for each basin with layer structure identified.
4. Compute section level summary statistics of forwardcalculation parameters.
5. Correspond (connect) the forwardcalculated moduli with the backcalculated moduli.
6. Screen the backcalculated moduli using the corresponding forwardcalculated moduli.

Each step is discussed in detail below.

Step 1. Obtain the FWD Deflection Basins for Forwardcalculation

The objective of this study was to screen the backcalculated moduli in the LTPP database and use the same deflection basins that were used to derive these backcalculated moduli. As a result, the deflection basins from the tables MON_DEFL_FLX_BAKCAL_BASIN and MON_DEFL_RGD _BAKCAL_BASIN were extracted and subsequently used in the forwardcalculation computations.

Step 2. Determine the Pavement Layer Structures for Forwardcalculation

As presented in chapter 4, elastic moduli for up to three layers are forwardcalculated for each deflection basin. Then the pavement systems were divided or combined into a two- or three-layer structure, as follows:

1. Surface (bound) layer (AC or PCC).
2. Base layer (unbound or granular).
3. Subgrade; depth to apparent stiff layer calculated from the deflection basin.

For rigid pavements, the uppermost base layer below the PCC slab was considered the base layer.

For flexible pavements, the layer system is more complex, and more than three layers were used in backcalculation for many flexible pavement sections. The researchers applied engineering judgment to assign each of the backcalculation layers to correspond to a forwardcalculation layer, according to the scheme shown in Table 12.

Step 3. Conduct Forwardcalculation

Forwardcalculation is carried out using the method discussed in chapter 3 for each of the two or three forwardcalculation layers (i.e., the bound surface course, base if present, and subgrade).

A small percentage of the FWD load-deflection data has been associated with nonstandard sensor positions. These nonstandard positions were adjusted to their actual positions before applying the forwardcalculation procedures.

Table 13 gives an outline of the deflection data where nonstandard sensor positions were considered, provided there were any backcalculated data in the database associated with these data (seldom the case).

Table 12. Assignment of backcalculated layers for forwardcalculation of flexible pavements.

Layer Structure Information from the TST_L05B or Backcalculation Tables				Assigned Forwardcalculated Layer
Layer Description	**Layer Type**	**LTPP Code**	**Material Type**	
Overlay	AC	1	Hot mixed, hot laid AC, dense graded	Asphalt concrete layer
Overlay	AC	13	Recycled AC, hot laid, central plant mix	Asphalt concrete layer
Overlay	AC	16	Recycled AC, heater scarification/recompaction	Asphalt concrete layer
Seal Coat	AC	20	Other	Asphalt concrete layer
Seal Coat	AC	71	Chip seal	Asphalt concrete layer
Seal Coat	AC	72	Slurry seal	Asphalt concrete layer
Seal Coat	AC	73	Fog seal	Asphalt concrete layer
Seal Coat	AC	82	Sand seal	Asphalt concrete layer
AC Layer Below Surface (Binder Course)	AC	1	Hot mixed, hot laid AC, dense graded	Asphalt concrete layer
AC Layer Below Surface (Binder Course)	AC	13	Recycled AC, hot laid, central plant mix	Asphalt concrete layer
Base Layer	AC	319	HMAC	Asphalt concrete layer
Base Layer	AC	321	Asphalt treated mixture	Asphalt concrete layer
Interlayer	AC	71	Chip seal	Asphalt concrete layer
Interlayer	AC	75	Nonwoven geotextile	Asphalt concrete layer
Interlayer	AC	77	Stress absorbing membrane interlayer	Asphalt concrete layer
Interlayer	AC	78	Dense graded asphalt concrete interlayer	Asphalt concrete layer
Friction Course	AC	2	Hot mixed, hot laid AC, open graded	Asphalt concrete layer

Table 12. Assignment of backcalculated layers for forwardcalculation of flexible pavements—*Continued*

Friction Course	AC	71	Chip seal	Asphalt concrete layer
Surface Treatment	AC	9	Plant mix (emulsified asphalt) material, cold laid	Asphalt concrete layer
Surface Treatment	AC	11	Single surface treatment	Asphalt concrete layer
Surface Treatment	AC	71	Chip seal	Asphalt concrete layer
Surface Treatment	AC	82	Sand seal	Asphalt concrete layer
Interlayer	EF	74	Woven geotextile	Subgrade
Interlayer	EF	75	Nonwoven geotextile	Subgrade
Base Layer	GB	302	Gravel (uncrushed)	Granular base layer
Base Layer	GB	303	Crushed stone	Granular base layer
Base Layer	GB	304	Crushed gravel	Granular base layer
Base Layer	GB	306	Sand	Granular base layer
Base Layer	GB	309	Fine-grained soils	Granular base layer
Base Layer	GB	310	Other (specify if possible)	Granular base layer
Base Layer	GB	337	Limerock, caliche	Granular base layer
Base Layer	GB	307	Soil-aggregate mixture (predominantly fine-grained)	Subgrade
Base Layer	GB	308	Soil-aggregate mixture (predominantly coarse-grained)	Subgrade
Subbase Layer	GB	308	Soil-aggregate mixture (predominantly coarse-grained)	Subgrade
Subbase Layer	GS	302	Gravel (uncrushed)	Granular base layer
Subbase Layer	GS	303	Crushed stone	Granular base layer
Subbase Layer	GS	304	Crushed gravel	Granular base layer
Base Layer	GS	308	Soil-aggregate mixture (predominantly coarse-grained)	Subgrade
Subbase Layer	GS	306	Sand	Subgrade
Subbase Layer	GS	307	Soil-aggregate mixture (predominantly fine-grained)	Subgrade
Subbase Layer	GS	308	Soil-aggregate mixture (predominantly coarse-grained)	Subgrade
Subbase Layer	GS	309	Fine-grained soils	Subgrade
Subbase Layer	GS	310	Other (specify if possible)	Subgrade
Subbase Layer	GS	338	Lime-treated soil	Subgrade

Table 12. Assignment of backcalculated layers for forwardcalculation of flexible pavements—*Continued*

Embankment Layer	GS	102	Fine-grained soils: lean inorganic clay	Subgrade
Embankment Layer	GS	131	Fine-grained soils: silty clay	Subgrade
Base Layer	TB	319	HMAC	Asphalt concrete layer
Base Layer	TB	320	Sand asphalt	Asphalt concrete layer
Base Layer	TB	321	Asphalt treated mixture	Asphalt concrete layer
Base Layer	TB	324	Dense graded, cold laid, mixed in place	Asphalt concrete layer
Base Layer	TB	328	Recycled asphalt concrete, plant mix, hot laid	Asphalt concrete layer
Base Layer	TB	334	Lean concrete	Asphalt concrete layer
Base Layer	TB	325	Open graded, hot laid, central plant mix	Granular base layer
Base Layer	TB	327	Open graded, cold laid, mixed in place	Granular base layer
Base Layer	TB	331	Cement aggregate mixture	Granular base layer
Base Layer	TB	350	Other	Granular base layer
Base Layer	TB	333	Cement-treated soil	Subgrade
Base Layer	TB	339	Soil cement	Subgrade
Base Layer	TB	340	Pozzolanic-aggregate mixture	Subgrade
AC Layer Below Surface (Binder Course)	TS	1	Hot mixed, hot laid AC, dense graded	Asphalt concrete layer
Subbase Layer	TS	320	Sand asphalt	Asphalt concrete layer
Subbase Layer	TS	325	Open graded, hot laid, central plant mix	Granular base layer
Subbase Layer	TS	331	Cement aggregate mixture	Granular base layer
Subbase Layer	TS	338	Lime-treated soil	Subgrade
Subbase Layer	TS	339	Soil cement	Subgrade

Table 13. FWD- and time-specific sensor positioning anomalies in the LTPP database.

Region & FWD S/N	Dates Affected (inclusive)	Actual Sensor Positions (inches)	Approx. # of Test Dates
Reg. 1–s/n129	3 Nov ’95→14 Apr ’96	0, 8, 12, 18, 24, 36 & 48	21
Reg. 1–s/n129	15 Apr ’97→21 May ’97	0, 8, 12, 18, 24, 36 & 48	12
Reg. 2–s/n061*	4 Aug ’89→10 Aug ’89	0, 8, 12, 24, 30.5, 48 & 72	4
Reg. 2–s/n130	25 Aug ’94→7 Sep ’94	0, 8, 12, 18, 36, 48 & 60	16
Reg. 3–s/n075	17 Jan ’90→22 Jan ’90	0, 8, 12, 18, 30, 42 & 66	4
Reg. 3–s/n132	29 Jul ’96→25 Oct ’96	0, 8, 12, 18, 24, 36 & 48	29
Reg. 4–s/n061*	<26 Feb ’89→8 Sep ’89	0, 8, 12, 24, 30.5, 48 & 72	97
Reg. 4–s/n061	17 Jul ’95→31 Oct ’95	0, 8, 12, 18, 24, 36 & 48	65
Reg. 4–s/n131	<24 May ’ 94→30 Apr ’96	0, 8, 12, 18, 24, 36 & 48	191
Reg.4–s/n131$_{10}$	16 Dec ’97→20 Jan ’98	0, 8, 18, 24, 36, 48 & 60	≥ 8

* Same FWD and overlapping dates—LTPP field tests conducted in two different LTPP Regions.

Step 4. Compute Section Level Summary Statistics of Forwardcalculated Parameters

For the section level data, to identify and remove outliers for a given section (and test date), the researchers used the so-called interquartile range (IQR) as outlined below.

Pavement engineers typically use two standard deviations as criteria for identifying outliers. The shortcoming of this approach is that neither the population mean nor the population standard deviation is available when evaluating the data for outliers. Instead, the sample mean and sample standard deviation are generally used, without consideration of the actual distribution. This technique introduces a bias in identifying the outliers when using the two standard deviation approach because outliers are (incorrectly) included in the computation of the sample mean and the sample standard deviation. In addition, the section standard deviation on an arithmetic basis is often large enough to compute negative values on the low end of the section level modulus range. This calculation results in elimination of few (if any) of the unreasonably low values and only eliminates the unreasonably high values. The nonnormal and asymmetric distribution of the modulus data usually causes this problem. In fact, the distribution of moduli generally is closer to a log-normal distribution than an arithmetic normal distribution.

To overcome these difficulties, the IQR method has been used to identify and remove outliers in the computed point-by-point moduli for each section (and date of test).(11) The following provides specifics of this method:

$$IQR = Q_3 - Q_1$$

Figure 22. Equation. Interquartile range.

where: Q_1 = 25th quartile of the logs of the moduli
and Q_3 = 75th quartile of the logs of the moduli

Outliers are defined as values that are outside the range: (Q_1 - 1.5 * IQR, Q_3 + 1.5 * IQR).

Data points that were outside of the above range were identified as outliers and not used to calculate the section means from forwardcalculation.

Step 5. Correspond the Forwardcalculated Moduli with the Backcalculated Moduli

After all forwardcalculation is completed, the forwardcalculated moduli were paired with the backcalculated moduli using their section IDs, according to table 12.

Step 6. Screen the Backcalculated Moduli Using the Corresponding Forwardcalculated Moduli

The LTPP database of backcalculated moduli was screened. This screening took place using the following sequential steps:

1. ***The modulus values in the backcalculation tables that were assumed or held constant were not screened***—Since these values are presumably a good educated guess at the actual in situ stiffness, they were not screened and accordingly were left as is in the database with an appropriate flag.
2. ***Reasonableness screening***—Various pavement materials are commonly associated with typical or reasonable moduli, depending on the material type and other factors. Assuming the backcalculated value was not fixed, a wide range of feasible modulus values was assigned to the various material types, and any value outside of these rather liberal ranges could then be called into question, whether the method of determining the modulus is back- or forwardcalculation. Table 14 lists these values. During screening of the database, also including the newly created forwardcalculated values, these limits were applied *before* applying the remaining criteria. In other words, if a given modulus calculation was outside of the broad ranges indicated in Table 14, then it was either flagged in the case of the existing tables or noted in the case of forwardcalculated values, and then not used in further screening routines.
3. ***Correspondence screening using forwardcalculated values*** – Provided the data did not become flagged during Steps 1 or 2 of the screening process, each backcalculated value was then compared to the corresponding forwardcalculated value. If the backcalculated modulus was within a factor of 1.5 of the forwardcalculated value, then it was assumed to be "acceptable" and not recommended for flagging (except through the use of a "0," see Table 15) in the database. If it was outside of this reasonable range (1.5 times the forwardcalculated value or the forwardcalculated value divided by 1.5), then the flags shown in

Table 15 were used to indicate that the existing value in the database was “suspect.” These flagging codes were used for both the “point” data tables and the “section” data tables.

Table 14. Reasonable ranges for various pavement layers in the LTPP database.

	LTPP Code	Reasonable Range			
		MPa		psi	
		min	max	min	Max
Base Materials					
Asphalt-Treated Mixture, not Permeable Asphalt-Treated Base (PATB)	321	700	25,000	101,500	3,625,000
Gravel, Uncrushed	302	50	750	7,250	108,750
Crushed Stone	303	100	1,500	14,500	217,500
Crushed Gravel	304	75	1,000	10,875	145,000
Sand	306	40	500	5,800	72,500
Soil-Aggregate Mixture (predominantly fine-grained)	307	50	700	7,250	101,500
Soil-Aggregate Mixture (predominantly coarse-grained)	308	60	800	8,700	116,000
Fine Grained Soil or Base	309	35	450	5,100	65,000
Hot-Mixed AC	319	700	25,000	101,500	3,625,000
Sand Asphalt	320	700	25,000	101,500	3,625,000
Dense-Graded, Cold-Laid, Central Plant Mix AC	323	700	25,000	101,500	3,625,000
Open-Graded, Hot Laid, Central Plant Mix AC	325	350	3,500	50,750	507,500
Cement Aggregate Mixture	331	2,000	20,000	290,000	2,900,000
Econocrete	332	3,500	35,000	507,500	5,075,000
Lean Concrete	334	4,500	45,000	652,500	6,525,000
Soil Cement	339	1,000	7,000	145,000	1,015,000
Open-Graded, Cold Laid, In-Place Mix AC	327	200	3,000	29,000	435,000
Limerock; Caliche	337	150	1,500	21,750	217,500
Other—Treated Base (TB)	350	400	8,000	58,000	1,160,000
Bound Surface Courses					
Concrete Surface (uncracked)		10,000	70,000	1,450,000	10,150,000
AC Surface (>0 ^{O}C–<45 ^{O}C, not alligatored)		700	25,000	101,500	3,625,000
Unbound Subgrades					
Any unbound type		15	650	2,175	94,250

Table 15. Flagging codes used to screen the backcalculated LTPP database.

Description of the correspondence between the forwardcalculated and the backcalculated modulus values	Correspondence code values (flags)	Ratio between the forwardcalculated and backcalculated modulus values
Acceptable	0	2/3 ≤ Ratio ≤ 1.5
Marginal	1	1/2 ≤ Ratio ≤ 2 (& not code 0)
Questionable	2	1/3 ≤ Ratio ≤ 3 (& not codes 0 or 1)
Unacceptable	3	Ratio < 1/3 or Ratio > 3

Incorporation of the Screening Results into the LTPP Database

All applicable flags associated with the backcalculated moduli in the LTPP computed parameter database will be submitted to FHWA, including all records where the backcalculated values were assumed (fixed) or not reasonable. All remaining data will be submitted with an appropriate correspondence flag (i.e., 0, 1, 2, or 3—see Table 15) to be incorporated into the existing backcalculation data tables, as outlined above.

In addition, tables of all forwardcalculated moduli, both at the point and section levels, will be given to FHWA as candidates for incorporation into the LTPP database as computed parameters. These data will also include the “reasonableness flag” where applicable.

CHAPTER 6. LTPP BACKCALCULATION DATABASE SCREENING RESULTS

This chapter gives a summary and discussion of the screening results of the LTPP backcalculation database. Backcalculation data at all LTPP record levels (A to E) were screened. Level E data versus other levels' (A to D) backcalculation data are compared first. Screening results of the flexible pavement systems are then provided, followed by the screening results of the rigid pavement systems using various backcalculation procedures or models. Finally, screening results of the section average values are presented.

LEVEL E AND OTHER LEVELS OF DATA QUALITY

In the past, LTPP generally released only those data that had passed to level E in the database. In the case of FWD data, the status of level E was principally assigned when the LTPP data tables were complete in other regards, the quality or correctness of the FWD data notwithstanding. Figure 23 is an example of a level E data analysis for the subgrade layer(s) using a linear-elastic model from MODCOMP compared to the forwardcalculation approach using the Hogg model as delineated in the previous sections. Figure 24, meanwhile, is the same set of subgrade charts, but for all levels of subgrade data in the flexible pavement system database.

For all pie chart figures in this chapter, the slices are shown in clockwise order, starting with the "not assumed"/"acceptable"/"reasonable" slice, which always faces right.

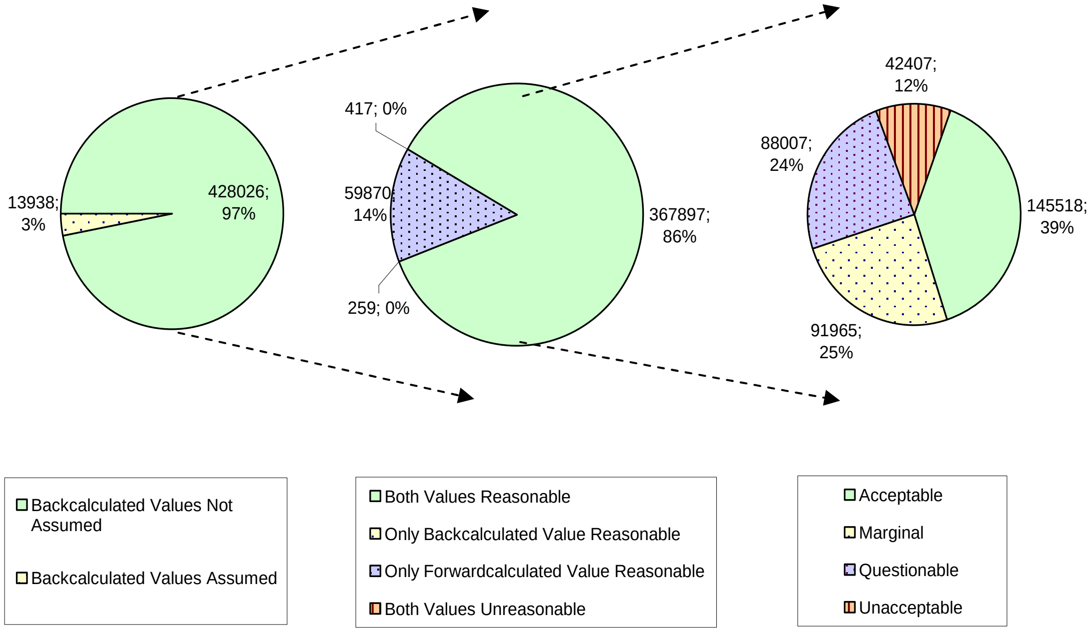


Figure 23. Charts. Screening results of the elastic moduli of the subgrade for all flexible sections in the MON_DEFL_FLX_BAKCALC_POINT table based on the linear elastic model (the level E records only).

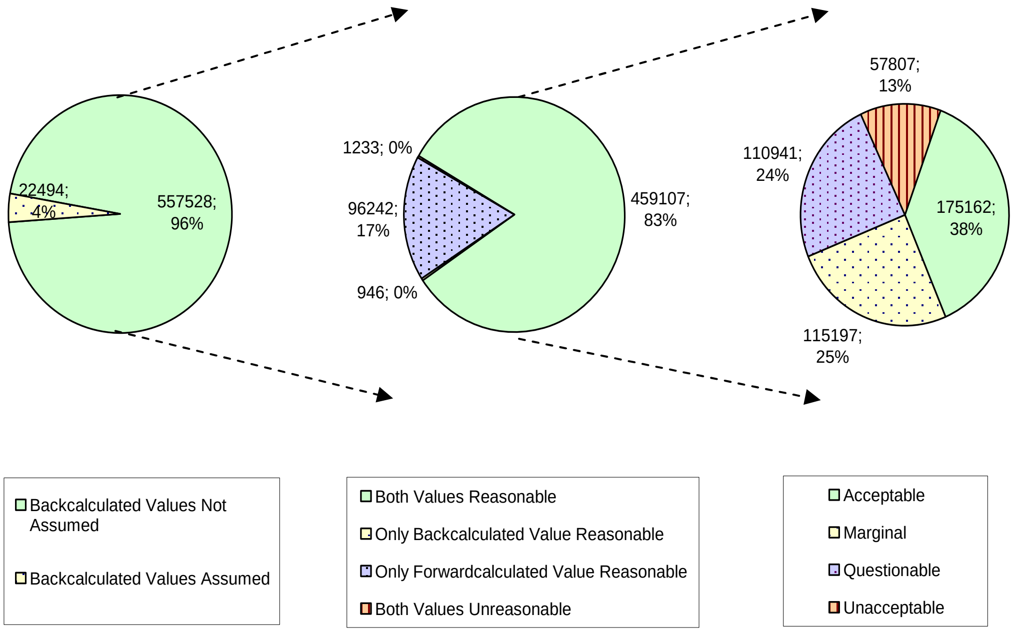


Figure 24. Charts. Screening results of elastic moduli of the subgrade for all the flexible sections in the MON_DEFL_FLX_BAKCALC_POINT table based on the linear elastic model (contains both level E and nonlevel E records).

Comparing the pie charts in Figure 23 and Figure 24 shows no appreciable difference in the results. The level E data consist of about 442,000 records, of which 3 percent were assumed, or fixed. Of the remaining 97 percent, 86 percent of these were reasonable, meaning they were within the broad limits shown in Table 14 for subgrade materials (15–650 MPa (2,000–95,000 psi). By contrast, the entire data set consisted of some 580,000 records, with 96 percent not assumed, and 83 percent of these were reasonable—not much different from the level E data. Finally, in the case of the level E data, 39 percent will not be assigned any outlier flag, or a flag of “0.” For the entire data set, the corresponding percentage for a flag of “0” is 38 percent. (A flag of “0” means that the backcalculated modulus is within a factor of 1.5 times or divided by the forwardcalculated subgrade modulus value.)

In almost all other instances, the differences between level E data and all the data were negligible. Therefore, in the following sections, results of screening the entire database will be reported without breaking out the level E data as a separate subcategory of these data.

SCREENING OF THE FLEXIBLE PAVEMENT BACKCALCULATION PARAMETERS—LINEAR ELASTIC MODEL

This section deals with the portion of the database that comprises asphalt (flexible) pavements where the MODCOMP backcalculation program was used to populate the current LTPP computed parameter data table, using a linear elastic model.(2)

The entire set of backcalculated asphalt surface course moduli consists of more than 200,000 records. Only 1 percent used an assumed value for backcalculation purposes (see Figure 25, left pie chart).

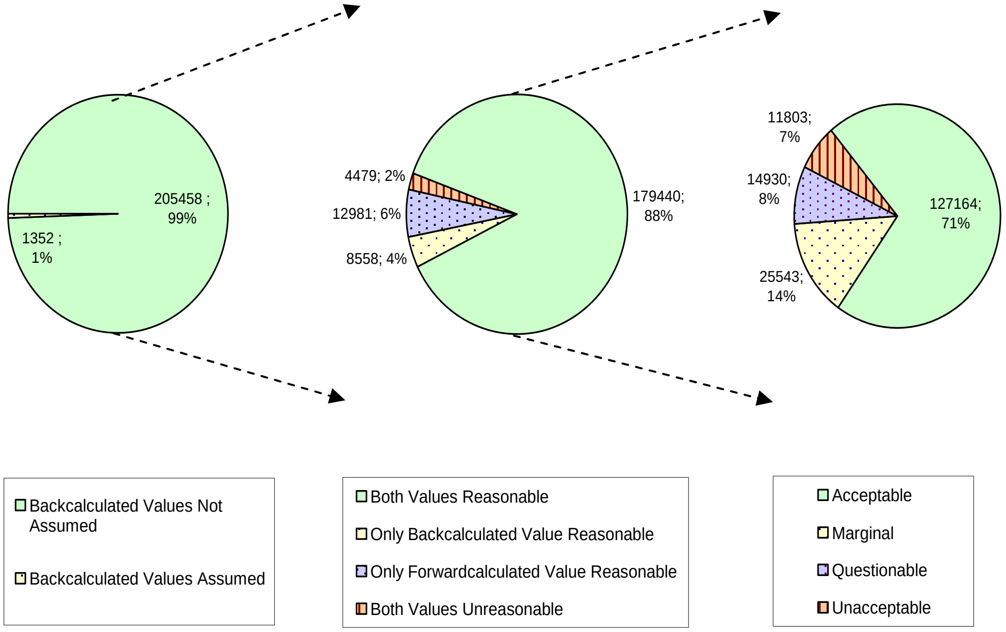


Figure 25. Charts. Screening results of elastic moduli of the asphalt concrete layer for the flexible sections in the MON_DEFL_FLX_BAKCALC_POINT table based on the linear elastic model.

Of the 99 percent of moduli that were not assumed, both backcalculated and forwardcalculated values were reasonable in 88 percent of the remaining records, meaning the estimated moduli were within a very broad range for asphalt-bound surface layers of 700–25,000 MPa (100,000–3,600,000 psi) in these records. The reason for such a broad range is that asphalt concrete surfaces are viscoelastic and influenced by seasonal temperatures, which in the case of LTPP ranged from well below freezing to over 50 °C (122 °F). Both values were outside of this broad range in only 2 percent of all nonassumed records (see Figure 25, middle pie chart).

Of the above 88 percent, the right-hand pie chart in Figure 25 shows that 71 percent were acceptable, again meaning that the forwardcalculated values were within a factor of 1.5 times or 2/3 of the backcalculated value (see Table 15). In addition, 14 percent of the backcalculated values were marginal, 8 percent were questionable, and 7 percent were unacceptable. Table 15 explains these terms in detail.

Figure 26 shows the subgrade charts for the flexible pavement, linear elastic set of data.

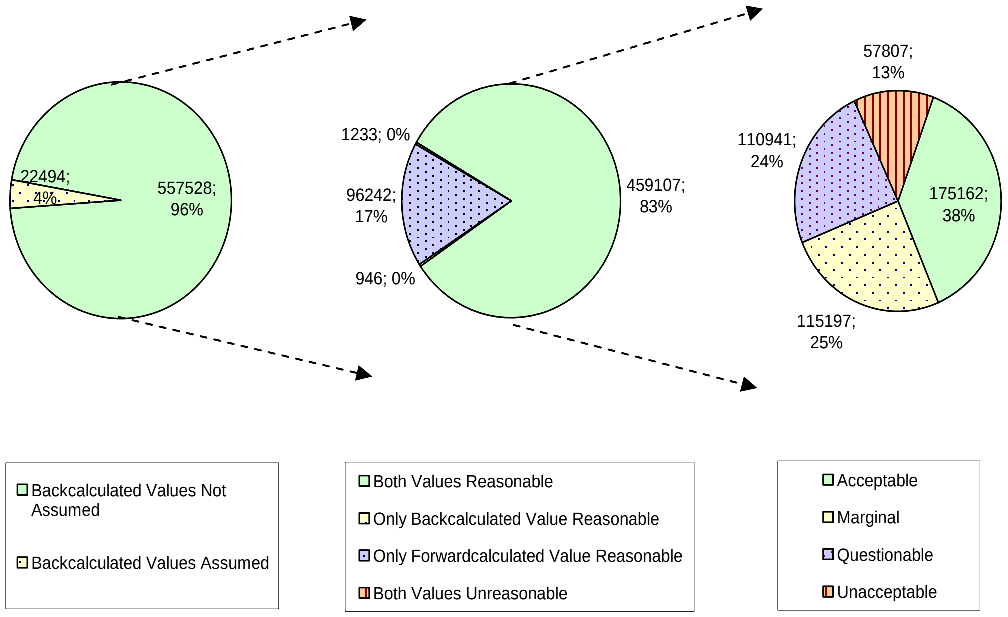


Figure 26. Charts. Screening results of elastic moduli of the subgrade for the flexible sections in the MON_DEFL_FLX_BAKCALC_POINT table based on the linear elastic model.

In this case, the number of records is about 2.5 times greater than for the surface course layer, because the MODCOMP program generally divides the subgrade into two or more layers. In addition, many records have a subgrade modulus listed but not a bound layer modulus, probably because of problems in the backcalculation process, which starts with the determination of the subgrade modulus based on one of the outermost sensors.

The Hogg model handles the subgrade as a single effective layer, under the load and to a finite depth (to hard bottom or the appearance of a hard bottom).

Because the Hogg forwardcalculation model, on average, calculates a subgrade modulus around half that of the linear elastic backcalculation model, the percentage of acceptable moduli is much lower than that associated with the asphalt surface course (38 percent versus 71 percent). This phenomenon is mainly because the backcalculation model uses the outer sensor deflections to calculate the subgrade response characteristics, while the Hogg model uses the center deflection and the shape of the entire deflection basin to arrive at an effective subgrade modulus under the load. For pavement performance and design applications, the Hogg model is the more conservative and realistic. This difference is one reason why the older AASHTO design guides recommend dividing the subgrade modulus by three for a more conservative pavement design.

Figure 27 shows plots of the intermediate or unbound base course moduli (linear model).

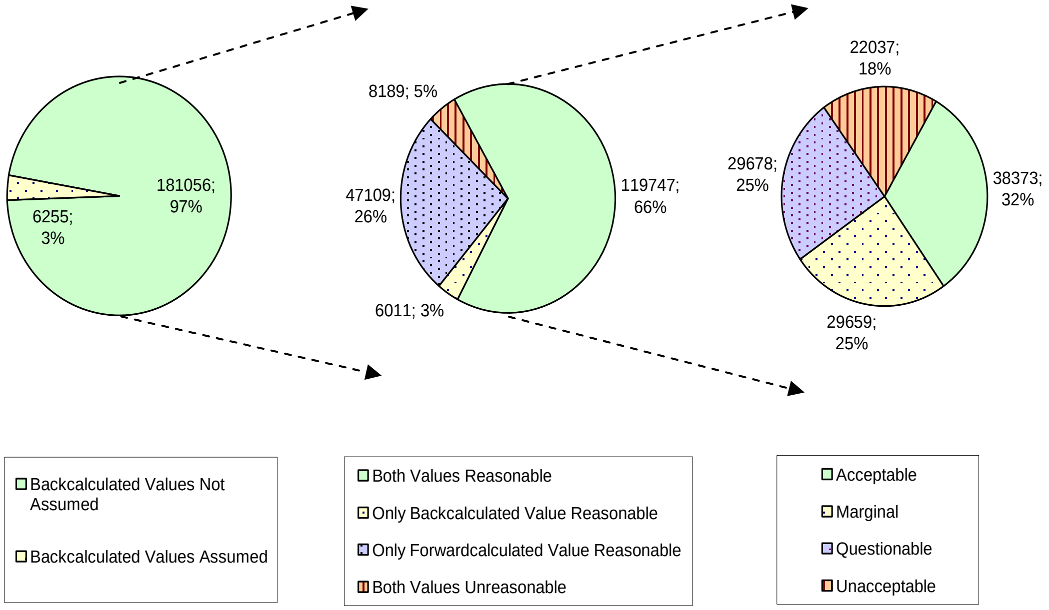


Figure 27. Charts. Screening results of elastic moduli of the base layer for the flexible sections in the MON_DEFL_FLX_BAKCALC_POINT table based on the linear elastic model.

The middle chart in Figure 27 indicates that only about 70 percent of the backcalculated base course moduli were within the rather broad limits set forth in Table 14. Furthermore, of the 66 percent of records where both values were reasonable, only 32 percent of the records involved were acceptable by Table 15 definitions. Also, 18 percent of the backcalculated intermediate layer data were unacceptable (i.e., different by more than a factor of 3). Clearly, the base course is the most difficult to backcalculate with any consistency.

SCREENING OF THE FLEXIBLE PAVEMENT BACKCALCULATION PARAMETERS—NONLINEAR ELASTIC MODEL

This section deals with the portion of the database that comprises asphalt (flexible) pavements and where the MODCOMP backcalculation program was used to populate the current LTPP-computed parameter data table using a nonlinear elastic model.

While the linear elastic dataset of backcalculated asphalt surface course moduli consists of some 200,000 records, the nonlinear elastic dataset only contains 37,000 records, covering essentially the same data for the same structural layer. Evidently, the nonlinear feature of the MODCOMP program was only used when beneficial to do so (see Figure 25 and Figure 28, left pie charts).

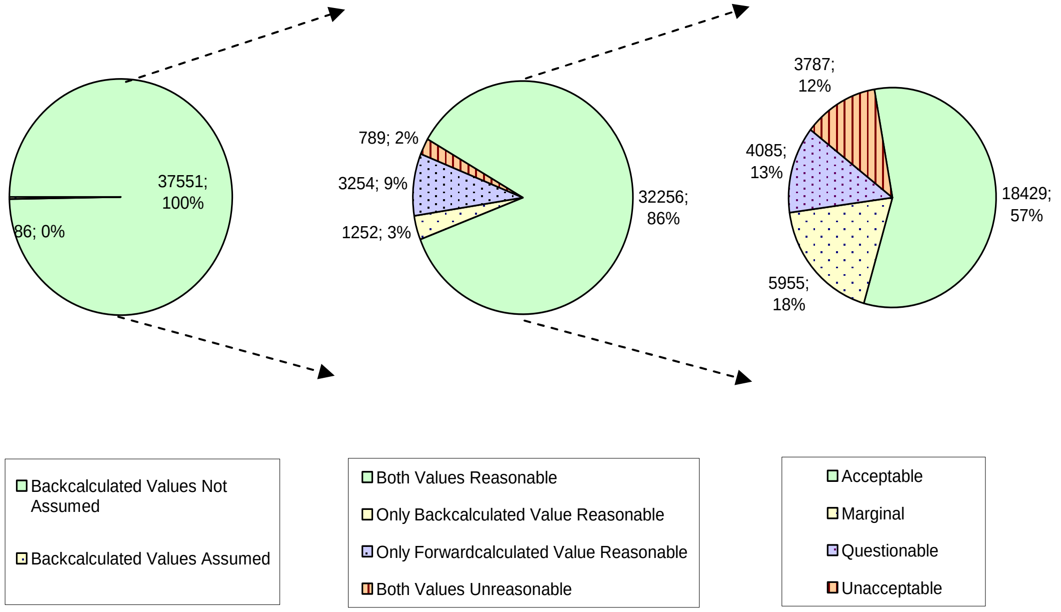


Figure 28. Charts. Screening results of elastic moduli of the asphalt concrete layer for the flexible sections in the MON_DEFL_FLX_ NMODEL_POINT table based on the nonlinear elastic model.

There was not a great deal of difference between the linear elastic and nonlinear elastic model results. If anything, the correspondence between forwardcalculation and backcalculation is slightly poorer with the nonlinear model. For example, 57 percent of the AC modulus values were acceptable (see right pie chart in Figure 28), whereas 71 percent were acceptable using the linear elastic model (see Figure 25).

These counterintuitive results are not necessarily because the materials were truly linear elastic, but rather because the use of any backcalculation program is highly user-dependent, requiring engineering skill and knowledge to model the pavement to get reasonable results. Such results were not possible with the LTPP data because it was processed in batch mode, so attention to each individual test point (record) was not feasible.

Figure 29 shows plots of the intermediate (unbound) base course moduli using the nonlinear model.

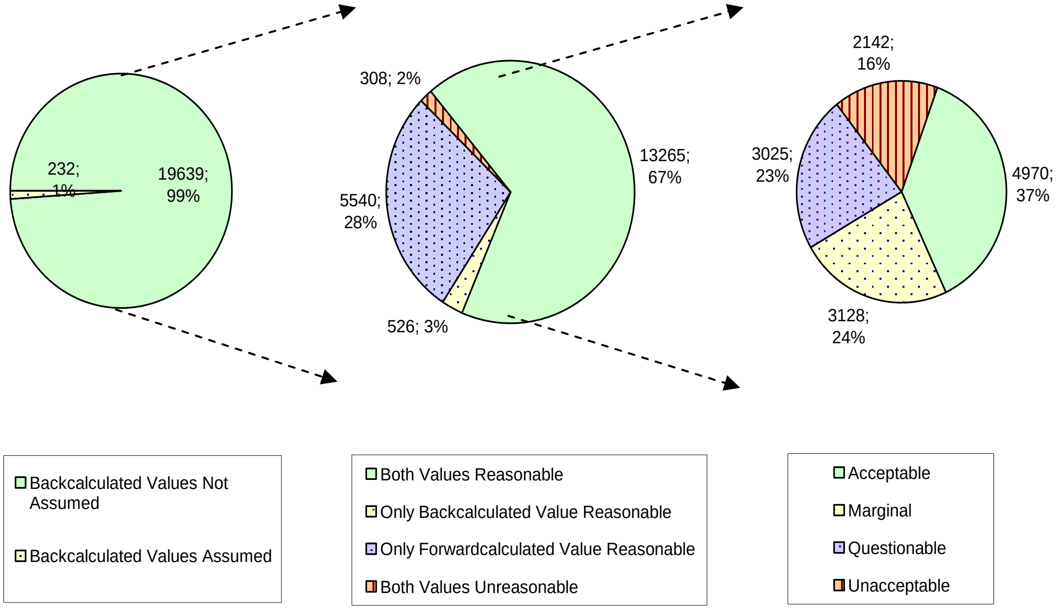


Figure 29. Charts. Screening results of elastic moduli of the base layer for the flexible sections in the MON_DEFL_FLX_ NMODEL_POINT table based on the nonlinear elastic model.

The three plots in Figure 29 once again don’t show a great deal of difference in their comparison to forwardcalculated values, between the base moduli derived though linear (Figure 27) and nonlinear (Figure 29) backcalculation. In spite of an attempt to improve the large variability associated with backcalculated base course moduli, the batch mode of nonlinear backcalculation did not help a great deal.

Figure 30 shows the subgrade charts for the nonlinear elastic flexible pavement set of data.

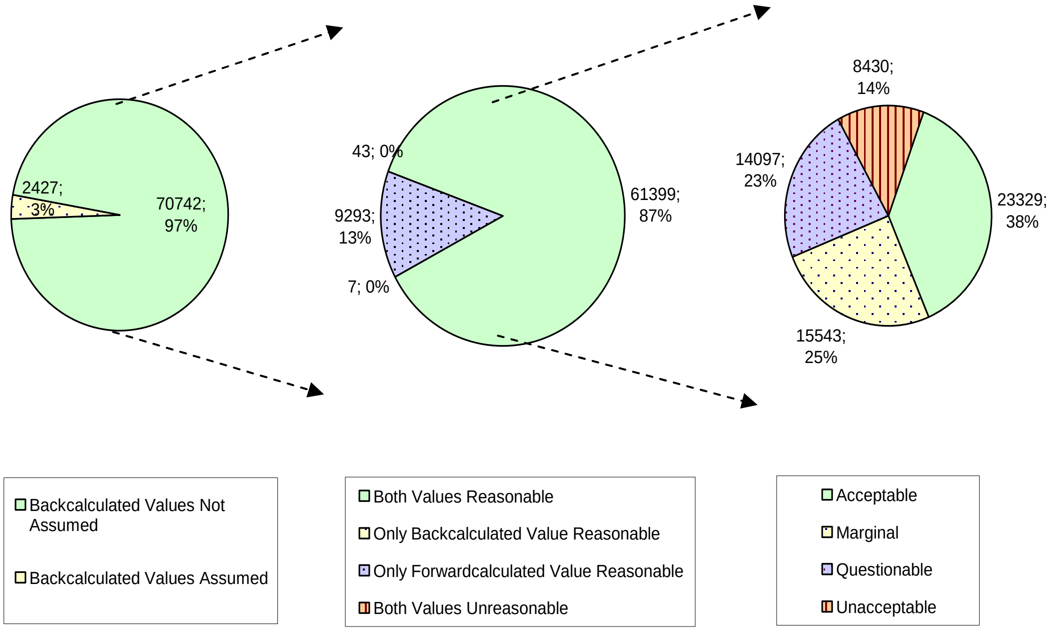


Figure 30. Charts. Screening results of elastic moduli of the subgrade for the flexible sections in the MON_DEFL_FLX_ NMODEL_POINT table based on the nonlinear elastic model.

In the case of the subgrade, for all practical purposes, no difference exists between the linear and nonlinear elastic analysis methods (see Figure 26 and Figure 30). Evidently, in spite of using the nonlinear model on about 15 percent of available FWD load-deflection records, backcalculation still results in subgrade moduli that are much higher than the Hogg model calculations (or ELMOD, for example), because of the differences in how nonlinearity is handled by the three methods.

It is possible to use the MODCOMP program and model the nonlinearity of the subgrade (or the upper portion of the subgrade) in another manner, which can result in lower subgrade moduli in many cases. Once again, however, this technique was not possible because of the need for careful attention on a case-by-case basis to material properties, nonlinear models, and material coefficients in the various LTPP test sections.

ADAPTATION OF FORWARDCALCULATION TECHNIQUE FOR LTPP RIGID PAVEMENT SECTIONS

This section deals with the criteria used to adapt the forwardcalculation routines to the backcalculation database.

Since forwardcalculation is designed to calculate only two modulus values directly (the bound surface course and the subgrade), it is necessary to use relationships between one of these layers and the base course, whether bound or unbound. Additionally, since one of the methods used to generate the backcalculated tables in the LTPP database involved a choice between a 100 percent bonded and a 100 percent unbonded condition between the PCC slab and the base course, it was also necessary to develop a method for forwardcalculation that would consider these two different input assumptions.

As discussed previously, only the PCC surface course and the subgrade moduli are forwardcalculated, essentially ignoring the effect of the base layer. Therefore, the computed E_{PCC} actually reflects the effect of both the upper PCC layer and the underlying base layer. In other words, E_{PCC} is an *apparent* modulus of these two upper layers, and needs to be divided into two parts, especially when a bound base layer is involved: the actual modulus of the PCC layer and the calculated modulus of the base. In these cases, E_{PCC} is called $E_{pcc,app.}$, which is the apparent modulus of the PCC layer alone as influenced by the base.

The method used to divide the calculated $E_{pcc,app.}$-value is adopted from Khazanovich, et al.(1) The upper PCC surface layer and the base layer may be bonded or unbonded and are assumed to act as plates. Thus, no through-the-thickness compression is assumed. The details of this method are given below for an unbonded and bonded condition between the PCC slab and the base, respectively.

For the unbonded case, the PCC slab modulus is computed from the equation in Figure 31.

$$E_1 = \frac{h_1^3}{h_1^3 + \beta h_2^3} E_{pcc,app}$$

Figure 31. Equation. PCC slab modulus—100 percent unbonded case.

For the bonded case, the PCC slab modulus is computed from the equation in Figure 32.

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

Figure 32. Equation. PCC slab modulus—100 percent bonded case.

where:

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

Figure 33. Equation. Layer thickness relationship—both cases.

and:

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

Figure 34. Equation. Modular ratio β—both cases.

and:

$E_{pcc,app.}$ = Apparent modulus of the PCC layer, assuming no base course effect
E_1 = Modulus of upper plate, i.e., the PCC layer
E_2 = Modulus of lower plate, i.e., the base layer
h_1 = Thickness of upper plate, i.e., the PCC slab
h_2 = Thickness of lower plate, i.e., the base layer

The procedures presented above require the modular ratio as an input parameter. Engineering judgment should determine this ratio. It is assumed that if the ratio is assigned within reasonable limits, the PCC modulus results (= E_1) are insensitive to the ratio. Table 16 presents the recommended modular ratios (β) of the calculated PCC and base moduli for each type of base layer. It should be noted that β from Figure 34 is defined as a ratio of base to PCC moduli. This equation creates stability for the case of a weak base (i.e., when β approaches 0). Therefore, the ratios from Table 16 should be inverted before using them in the procedure described above.

Given the values for β and for the actual plate thicknesses, h_1 and h_2, the equations in Figure 31 and Figure 32 may be used with the forwardcalculated $E_{pcc,app.}$-value to yield E_1 and E_2 for the two upper layers.

Identify Interface Condition Between the PCC Slab and the Base Layer(s)

For the point-by-point forwardcalculated moduli, modulus values were calculated for both the unbonded and the bonded cases. These values can be used to screen the corresponding unbonded and bonded values in the backcalculation tables.

For the section mean modulus, the bond condition between the PCC slab and the base is given in the backcalculation table as a bond index, as estimated by Khazanovich, et al.(1) The same bond index was adopted for the forwardcalculation moduli to select either the unbonded or the bonded values for the section database.

Table 16. Back- and forwardcalculated modulus ratios for E_{PCC} / E_{Base}.

LTPP Code	Base Type	Ratio $\beta^{*}=1/\beta$
1	Hot-mixed, hot-laid 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

Table 16. Back- and forwardcalculated modulus ratios for E_{PCC} /E_{Base}—*Continued*

308	Soil-aggregate mixture (predominantly coarse grained)	250
319	Hot-mixed AC	15
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 PCC	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 fly ash	150
353	Treatment: lime and cement fly ash	150
354	Treated: PCC	50
355	Treatment: bitumen (includes all classes of bitumen and asphalt treatments)	100
700	AC	15
730	PCC	1

SCREENING OF THE RIGID PAVEMENT BACKCALCULATION PARAMETERS—LINEAR ELASTIC MODEL

The same linear elastic backcalculation program (MODCOMP) used to populate the backcalculated flexible pavement system data was also used to backcalculate interior slab layered elastic moduli.

Since the forwardcalculation routines developed to screen the LTPP backcalculated database were designed to operate in two modes—one with and one without bond between the PCC and base layers—the summary charts shown in this section are divided into two parts. One of these compares the forwardcalculated values assuming 100 percent bond between layers and the other, assuming 100 percent slip between the concrete surface layer and the base.

Figure 35 summarizes the screening results for forwardcalculated PCC moduli based on 100 percent bond between the concrete slab and the base, while Figure 36 is based on forwardcalculated values based on 100 percent slip between the two upper layers.

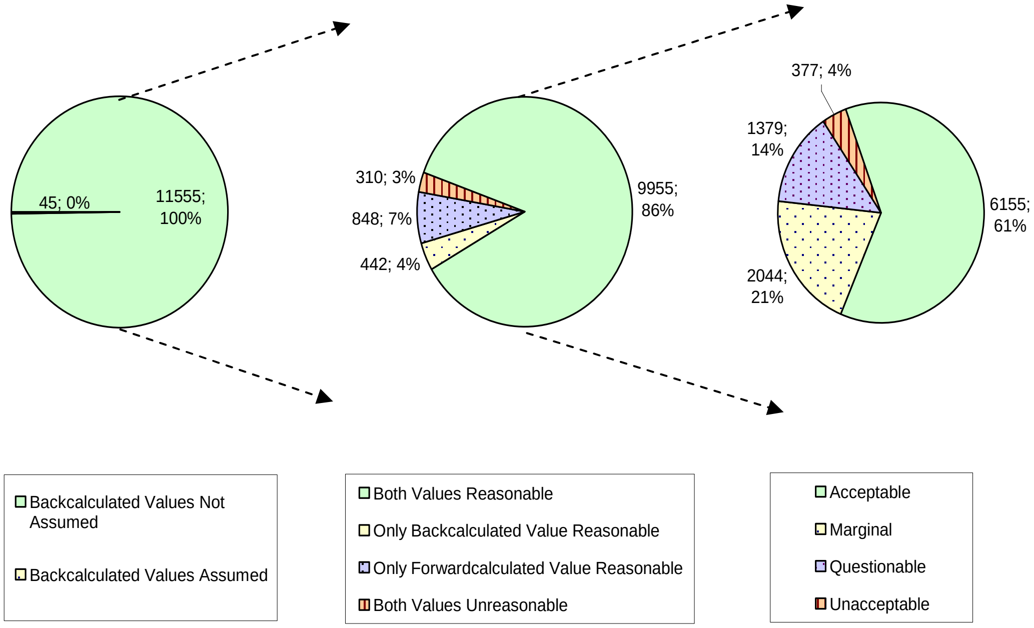


Figure 35. Charts. Screening results of elastic moduli of the interior concrete slab for the rigid sections in the MON_DEFL_FLX_BAKCALC_POINT table based on the linear elastic model for backcalculation and a bonded condition between the slab and base for forwardcalculation.

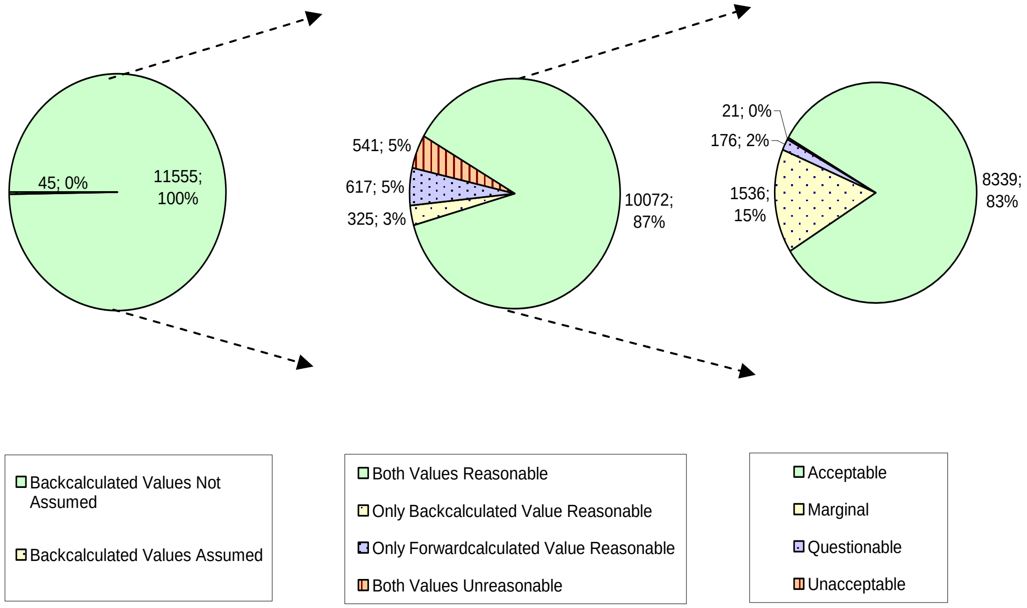


Figure 36. Charts. Screening results of elastic moduli of the interior concrete slab for the rigid sections in the MON_DEFL_FLX_BAKCALC_POINT table based on the linear elastic model for backcalculation and an unbonded condition between the slab and base for forwardcalculation.

Similarly, Figure 37 depicts the screening results for forwardcalculated base course moduli based on 100 percent bond between the concrete surface and the base, while Figure 38 reflects the forwardcalculated moduli based on 100 percent slip between the two upper layers.

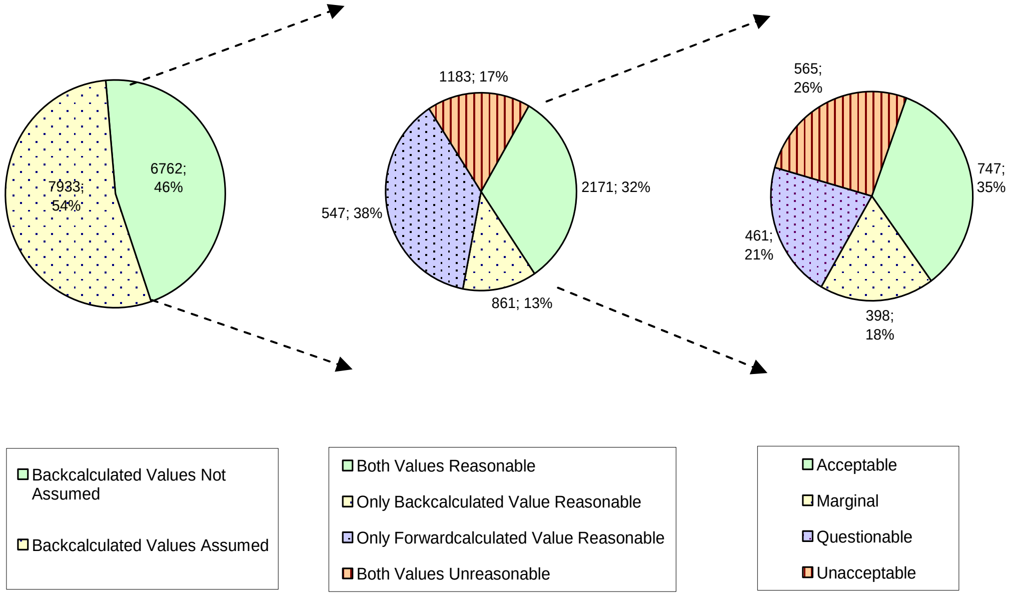


Figure 37. Charts. Screening results of elastic moduli of the base layer for the rigid sections in the MON_DEFL_FLX_BAKCALC_POINT table based on the linear elastic model for backcalculation and a bonded condition between the concrete slab and base layer for forwardcalculation.

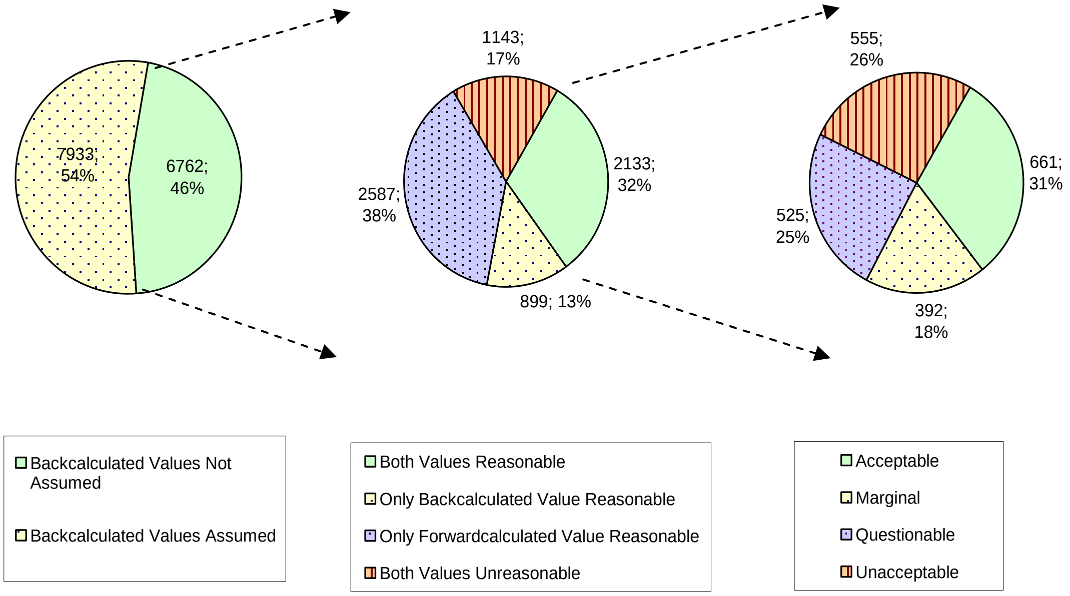


Figure 38. Charts. Screening results of elastic moduli of the base layer for the rigid sections in the MON_DEFL_FLX_BAKCALC_POINT table based on the linear elastic model for backcalculation and an unbonded condition between the concrete slab and base layer for forwardcalculation.

The four preceding figures do not show a great deal of difference in the charts comparing the forwardcalculated values with slip between the concrete and the base and the cases with no slip to backcalculated moduli. These values are not because there isn't any difference in the two; rather, the acceptance and flagging criteria for the backcalculated tables is rather broad, as for example having to be more than a factor of 1.5 different before any flag (1, 2, or 3) is applied.

In the case of the backcalculated PCC modulus, the 100 percent slip criterion used in forwardcalculation resulted in a somewhat better comparison: 83 percent versus 61 percent of the remaining values (see right pie charts in Figure 36 and Figure 35, respectively). Conversely, in the case of the base course moduli, the use of the 100 percent bonded criterion results in a slightly better comparison: 35 percent versus 31 percent—see Figure 37 and Figure 38, respectively.

Figure 39 shows the comparison of the screening results for forwardcalculated subgrade moduli based on the Hogg model versus backcalculated subgrade moduli using MODCOMP. Since the Hogg model uses a direct (closed form) solution that is not dependent on the moduli of the overlying layers, no difference occurs whether there is 100 percent slip or 100 percent bond between the surface and the base course.

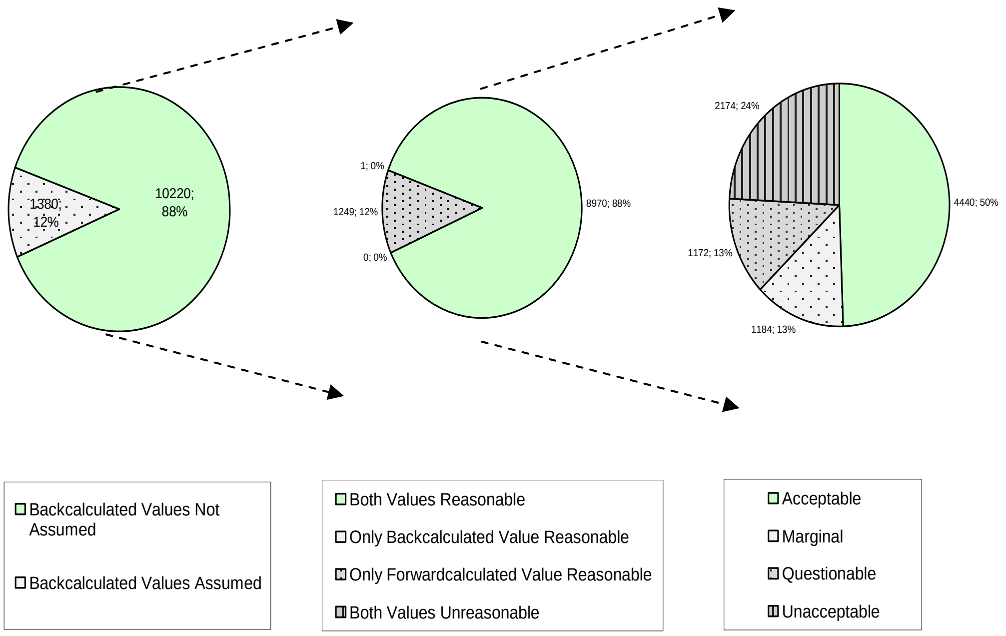


Figure 39. Charts. Screening results of elastic moduli of the subgrade for the rigid sections in the MON_DEFL_FLX_BAKCALC_POINT table based on the linear elastic model.

There is some improvement in the backcalculated table of subgrade moduli for rigid sections compared to the table for flexible sections. For the rigid sections, 50 percent of the sections were within a factor of 1.5 of the forwardcalculated subgrade moduli, while in the flexible case only 31 percent of the values were within the same factor of 1.5.

SCREENING OF THE RIGID PAVEMENT BACKCALCULATION PARAMETERS—SLAB-ON-ELASTIC-SOLID ANALYSIS

Another method used to populate the table of backcalculated moduli in the LTPP database was the theory of a concrete slab on an elastic solid foundation. The method used was developed specifically for the LTPP FWD database and the rigid pavements within that database.(1) Using this approach, two different backcalculation methods can be employed: bonded and unbonded condition between the concrete slab and the base.

Figure 40 and Figure 41 show the screening results for this portion of the database, for the concrete layer with a bonded and unbound condition between the slab and the base. Figure 42 and Figure 43 show the corresponding base course charts for the elastic solid model set of data.

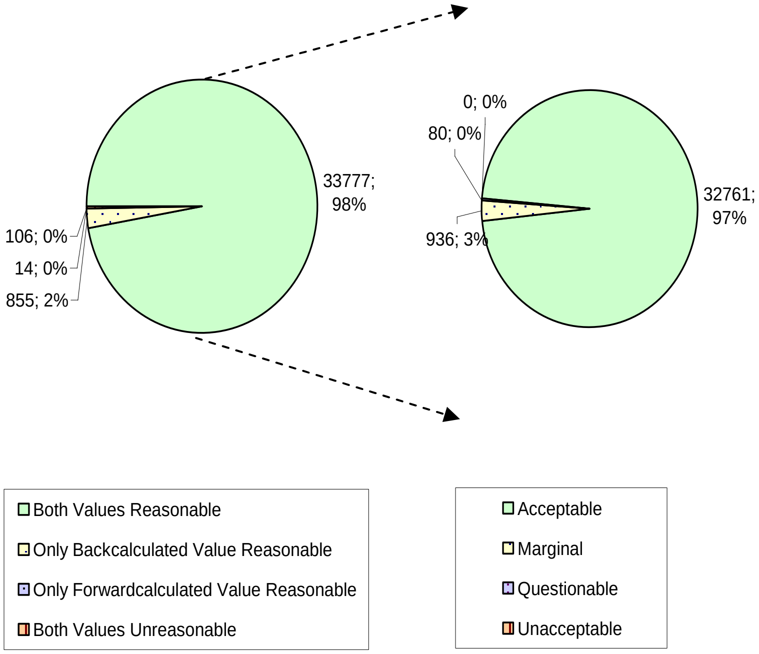


Figure 40. Charts. Screening results of elastic moduli of the PCC slab for the rigid sections in the MON_DEFL_RGD_BAKCALC_POINT table using the elastic solid model for backcalculation and assuming bonded condition between the slab and the base for back- and forwardcalculation.

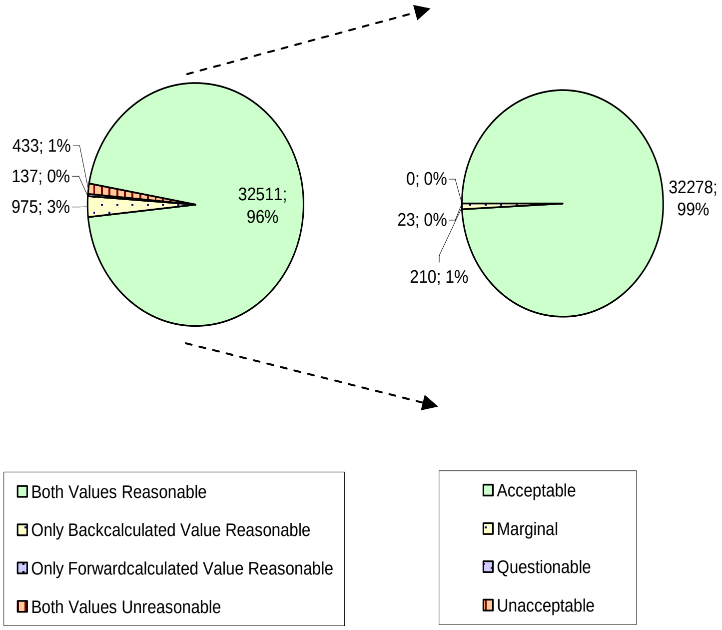


Figure 41. Charts. Screening results of elastic moduli of the PCC slab for the rigid sections in the MON_DEFL_RGD_BAKCALC_POINT table using the elastic solid model for backcalculation and assuming unbonded condition between the slab and the base for back- and forwardcalculation.

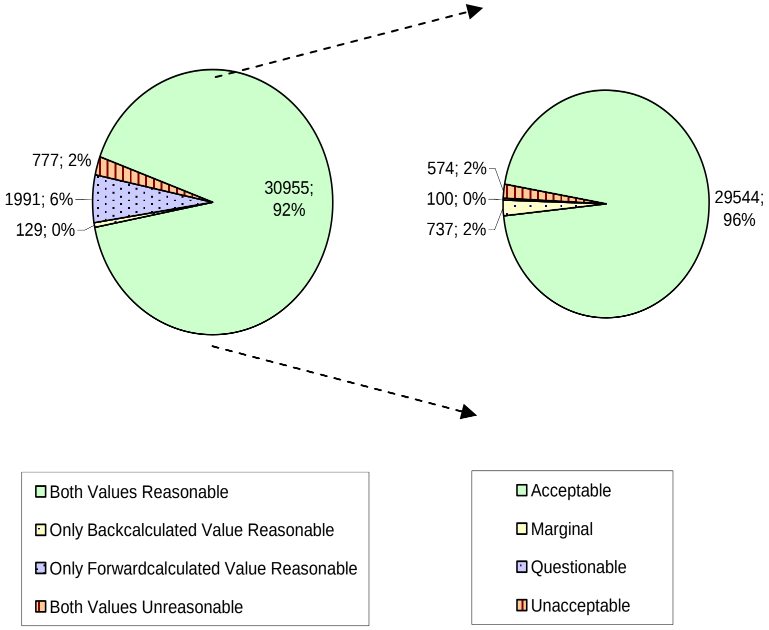


Figure 42. Charts. Screening results of elastic moduli of the base layer for the rigid sections in the MON_DEFL_RGD_BAKCALC_POINT table using the elastic solid model for backcalculation and assuming bonded condition between the slab and the base for back- and forwardcalculation.

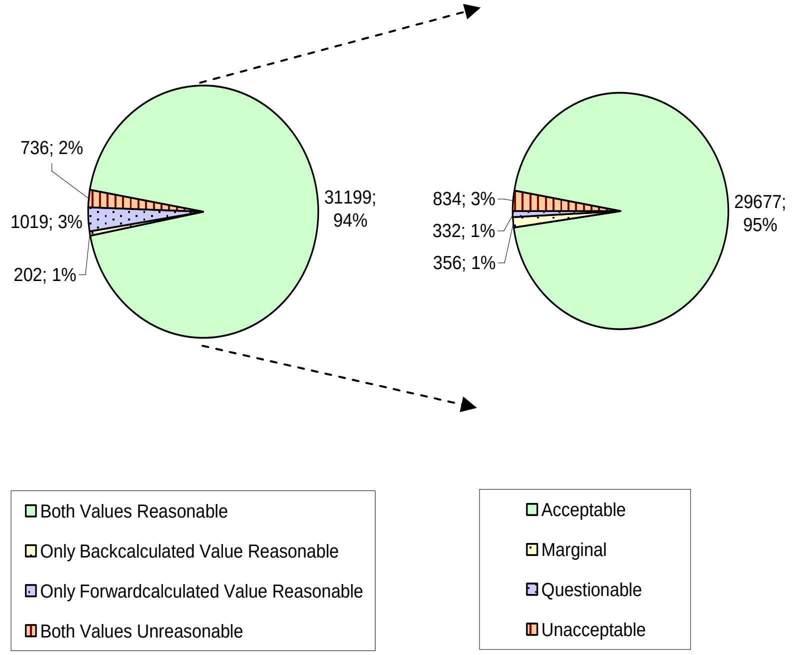


Figure 43. Charts. Screening results of elastic moduli of the base layer for the rigid sections in the MON_DEFL_RGD_BAKCALC_POINT table using the elastic solid model for backcalculation and assuming unbonded condition between the slab and the base for back- and forwardcalculation.

As Figure 40 and Figure 41 show, the correspondence between the reasonable range forwardcalculated and backcalculated concrete modulus is excellent, both for the bonded and unbonded cases (97 and 99 percent, respectively). This correlation is mainly because the backcalculation method used, which was essentially a two-layer system with fixed ratios between the concrete surface and base courses, was also used in forwardcalculation of rigid pavement systems. In the forwardcalculation procedure, the same ratios, as a function of the base course type, were used to calculate the base course modulus. It is believed that this approach to both back- and forwardcalculation is much more tenable—and realistic.

Accordingly, the base course moduli comparison between back- and forwardcalculation was also very good. Of all reasonable values, at least 95 percent were within a factor 67 to 150 percent of the forwardcalculated modulus (see Figure 42 and Figure 43).

Figure 44 shows the subgrade modulus charts for the elastic solid backcalculation method.

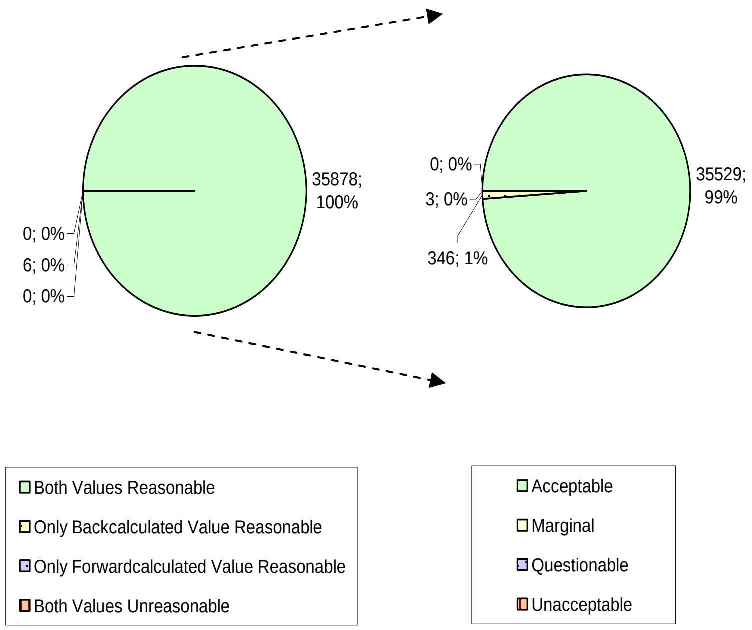


Figure 44. Charts. Screening results of elastic moduli of the subgrade for the rigid sections in the MON_DEFL_RGD_BAKCALC_POINT table using the elastic solid model for backcalculation.

Once again, the correspondence between back- and forwardcalculation of the subgrade was excellent (see Figure 44). In fact, the subgrade modulus relationship is the best of all, with close to 100 percent of the values in the backcalculated database (i.e., the elastic solid model) being in the reasonable range and 99 percent of these being within a factor of 1.5 of the forwardcalculated moduli from the Hogg model.

SCREENING OF THE RIGID PAVEMENT BACKCALCULATION PARAMETERS—SLAB-ON-DENSE-LIQUID ANALYSIS

The last approach used for backcalculating the moduli of rigid pavement layers is based on the theory of a slab on dense liquid, which also was originally developed by Westergaard. This approach is explained in full in the same reference as the slab-on-dense-liquid model.(1) Similar to the elastic solid model, two different backcalculation methods were used, a bonded and an unbonded condition between the concrete slab and the base layer.

Figure 45 and Figure 46 show the screening results for this portion of the database, for the concrete layer, for a bonded and unbonded condition between the slab and the base. Figure 47 and Figure 48 show the corresponding base course charts for the dense-liquid model set of data.

These four figures show that the correspondence between back- and forwardcalculation is also excellent for the dense liquid model of backcalculation, compared to forwardcalculation. Nevertheless, the percentages that were within of 67 to 150 percent (2/3 to 3/2) of the forwardcalculated values were lower than for the elastic solid model. Most of these values were around 90 percent with no flag identified, for both a bonded and an unbonded condition between the concrete slab and the base course.

The slightly better results associated with the elastic solid model are not surprising, since the forwardcalculation formulae for a concrete layer were developed using elastic layer theory, not Westergaard's equations.

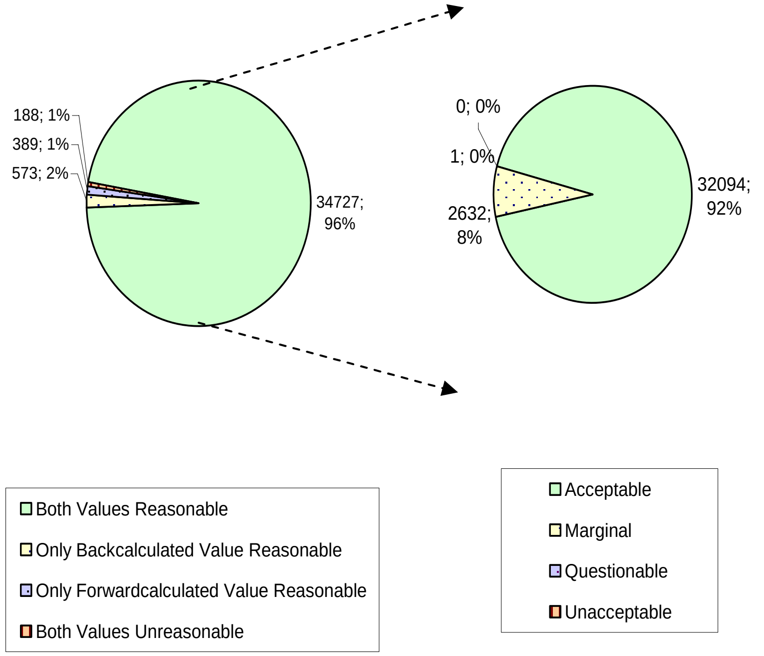


Figure 45. Charts. Screening results of elastic moduli of the PCC slab for the rigid sections in the MON_DEFL_RGD_BAKCALC_POINT table using the dense liquid model for backcalculation and assuming bonded condition between the slab and the base for back- and forwardcalculation.

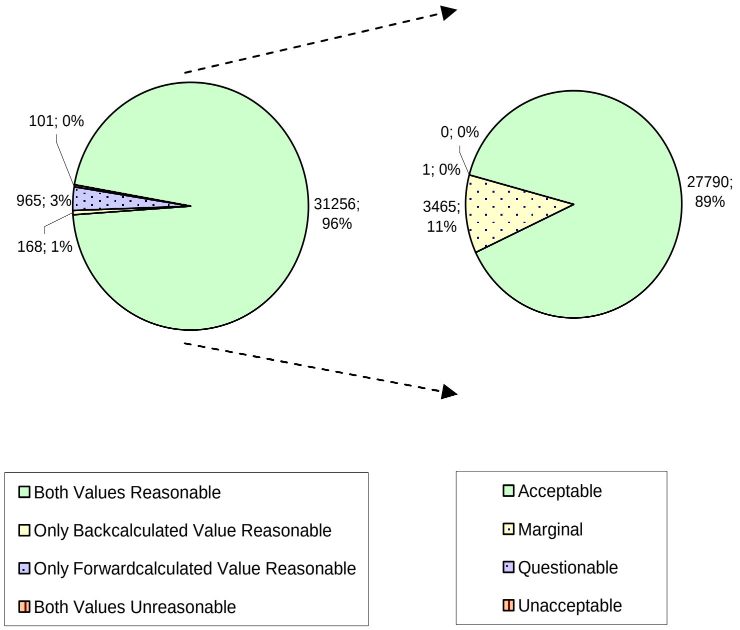


Figure 46. Charts. Screening results of elastic moduli of the PCC slab for the rigid sections in the MON_DEFL_RGD_BAKCALC_POINT table using the dense liquid model for backcalculation and assuming unbonded condition between the slab and the base for back- and forwardcalculation.

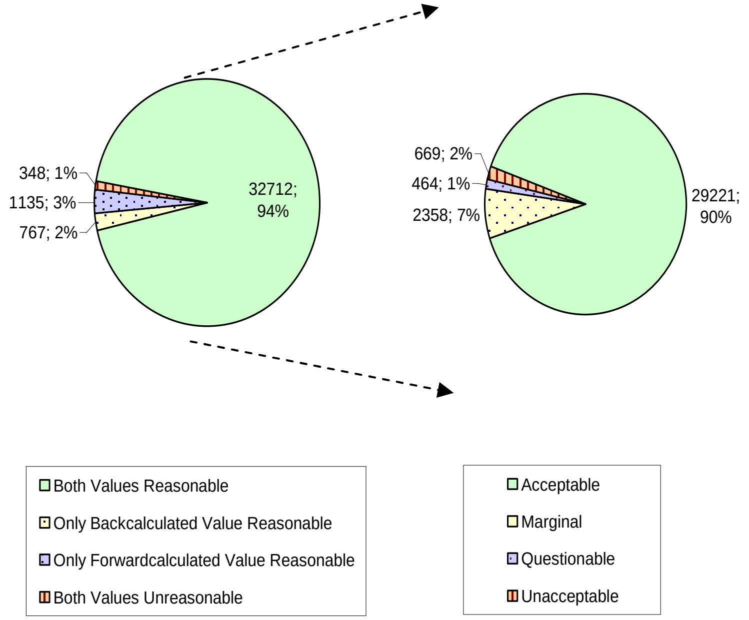


Figure 47. Charts. Screening results of elastic moduli of the base layer for the rigid sections in the MON_DEFL_RGD_BAKCALC_POINT table using the dense-liquid model for backcalculation and assuming bonded condition between the slab and the base for back- and forwardcalculation.

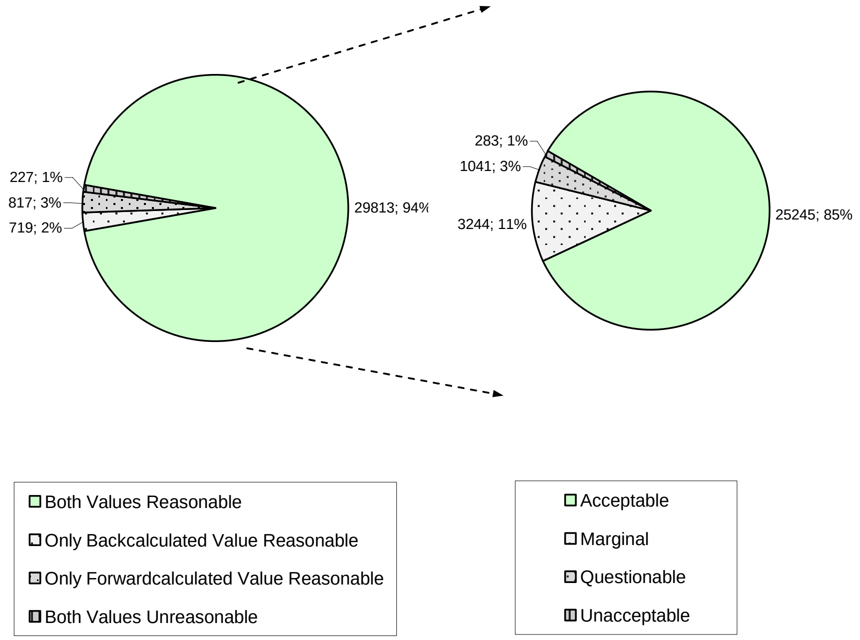


Figure 48. Charts. Screening results of elastic moduli of the base layer for the rigid sections in the MON_DEFL_RGD_BAKCALC_POINT table using the dense-liquid model for backcalculation and assuming unbonded condition between the slab and the base for back- and forwardcalculation.

When the dense-liquid model is used, the subgrade is not characterized by a modulus of elasticity, but rather by a k-value. Accordingly, the k-value in the case of forwardcalculation was derived using the same relationship developed when the dense-liquid and elastic-solid models were developed. Since this relationship is empirical and has inconsistent units, the E-value must be in MPa while the k-value is in kPa/mm.

$$k\text{-}value = 0.296 \times E_{subgrade} \; [R^2 = 0.87]$$

Figure 49. Equation. Subgrade k-value.

and:

$k\text{-}value$ = Subgrade modulus of reaction, k-value, kPa/mm
$E_{subgrade}$ = Subgrade modulus of elasticity, MPa

Figure 50 shows the subgrade k-value charts for the dense-liquid backcalculation method.

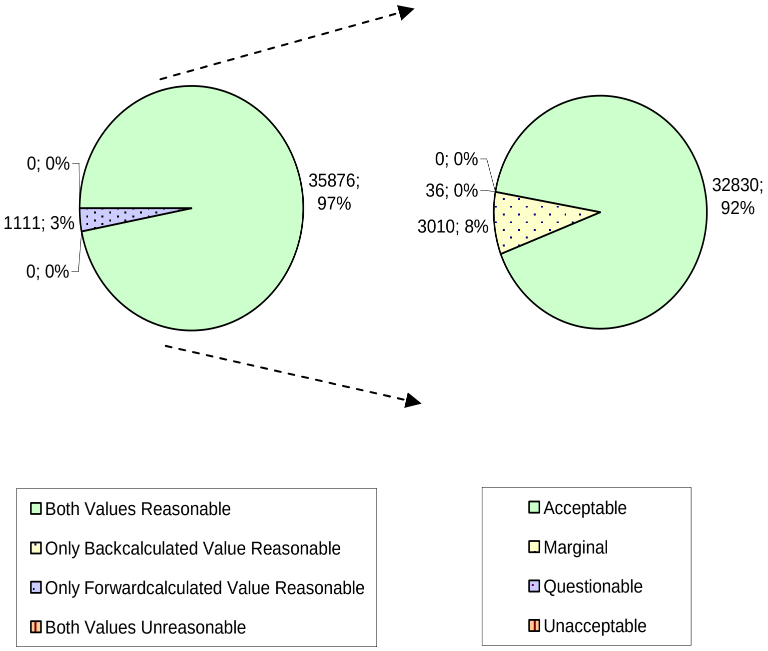


Figure 50. Charts. Screening results of the subgrade k-values for the rigid sections in the MON_DEFL_RGD_BAKCALC_POINT table using the dense-liquid model for backcalculation.

Again, the correspondence between the two methods of calculating the k-value of the subgrade under a concrete slab is very good, although somewhat poorer than with the elastic solid model versus forwardcalculation. In this case, 92 percent of all reasonable values were within 67 to 150 percent of the forwardcalculated k-value.

SCREENING OF THE SECTION AVERAGE BACKCALCULATED DATABASE

In addition to the point tables, the LTPP database also consists of section backcalculated data tables, designed to represent LTPP pavement section average moduli rather than point-by-point moduli as were screened in the preceding subsections. Each LTPP section was typically 152 m (500 ft) in length.

The existing section average data in the LTPP database were derived by first calculating the arithmetic average and standard deviation of the moduli for a given layer for each pavement section. Next, all data lying outside of two standard deviations were eliminated, and a new average was calculated based on the remaining moduli after elimination of outliers. One of the problems with this approach is that the data typically are not normally distributed on an arithmetic scale, but rather much closer to a log normal distribution. Accordingly, more often than not—especially when more than two unknown structural layers were backcalculated—the two standard deviation approach did not eliminate the very low modulus values, since two standard deviations downwards on an arithmetic scale often resulted in negative moduli. Accordingly, many higher-than-reasonable values were (correctly) eliminated while the lower-than-reasonable values were (incorrectly) retained from the section average. Accordingly, this procedure often introduces a bias (on the low side) into the section averages.

To rectify this discrepancy, the forwardcalculated values were treated as follows: The logarithms of all point data from a given section and structural layer were tabulated. Next, the IQR was calculated on these data, as Moore and McCabe describe in chapter 5.(11) Outliers then were identified as those values outside the range of (Q1 - 1.5 * IQR, Q3 + 1.5 * IQR). Finally, the average of the remaining (unexcluded) moduli was calculated, which is the section average modulus for a given layer.

Figure 51 and Figure 52 show examples of a section data table from back- and forwardcalculation as compared to the equivalent example from the point data table. Figure 51 represents the results for screening of the base course layer(s) in the point data table from MODCOMP (linear elastic model) for the flexible pavement database. (This figure is the same as Figure 27.) Figure 52 shows the corresponding section data, screened using the same criteria as for the point data according to the above-outlined procedure. There is little percentage difference between the two figures, although a small improvement occurs from the point to the section level in the backcalculated tables.

Figure 53 and Figure 54 show another example of the difference between the point and section data tables for the subgrade k-value in the rigid section LTPP database, based on the dense-liquid model of backcalculation. In this example, a small improvement occurs in the correspondence between back- and forwardcalculation from the point level to the section level. This pattern was, in general, the case for other layers and backcalculation methods.

All charts associated with the section database are presented in appendix A.

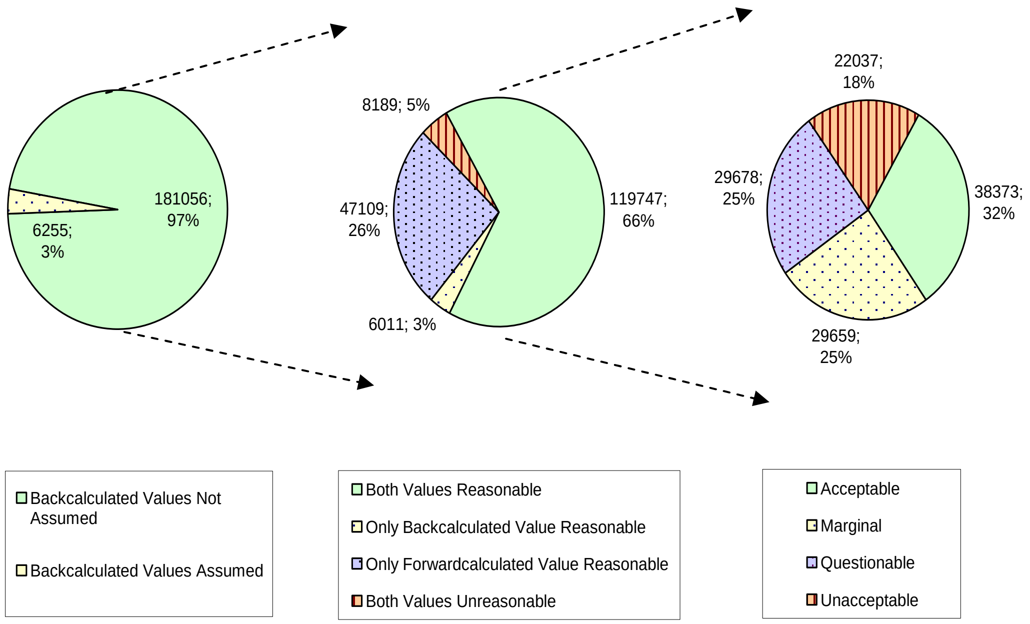


Figure 51. Charts. Screening results of elastic moduli of the point base layer for the flexible sections in the MON_DEFL_FLX_BAKCALC_POINT table based on the linear-elastic model.

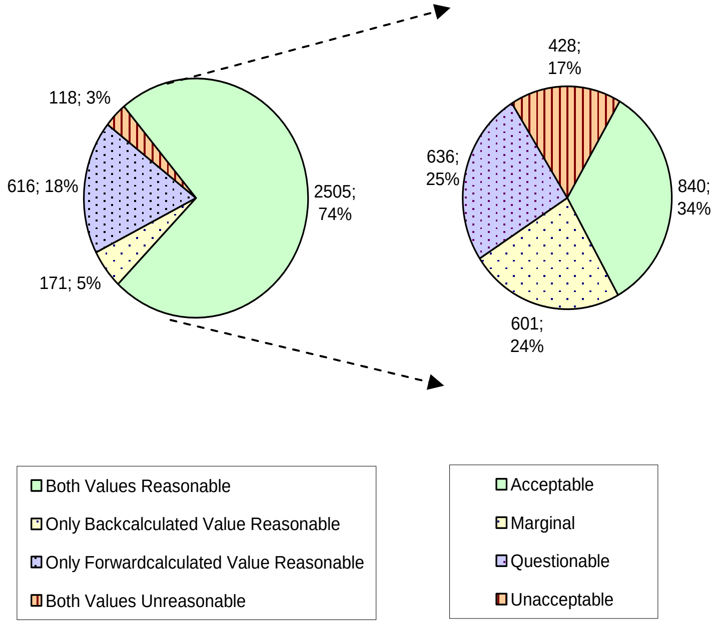


Figure 52. Charts. Screening results of elastic moduli of the section base layer for the flexible sections in the MON_DEFL_FLX_BAKCALC_SECT table based on the linear-elastic model.

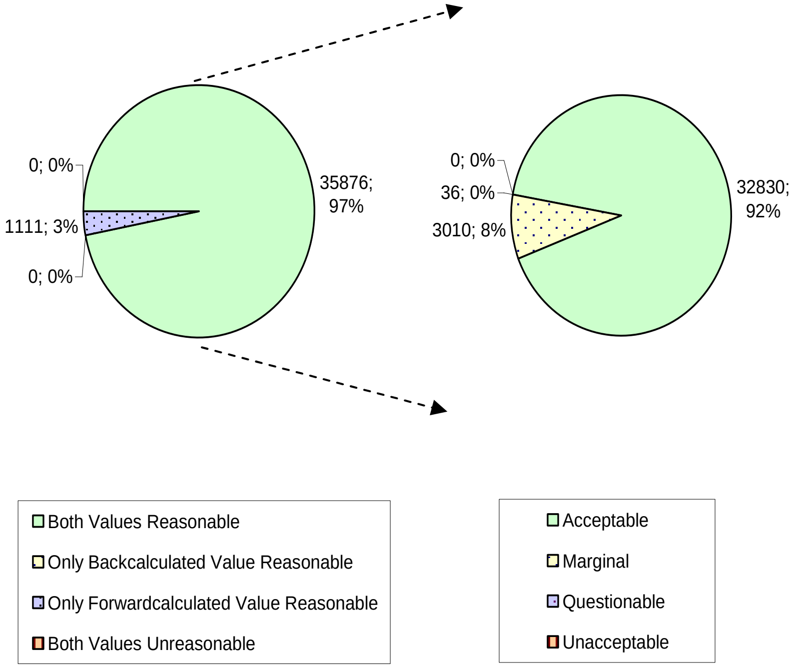


Figure 53. Charts. Screening results of the subgrade point k-value table for the rigid sections in the MON_DEFL_RGD_BAKCALC_POINT table using the dense-liquid model for backcalculation.

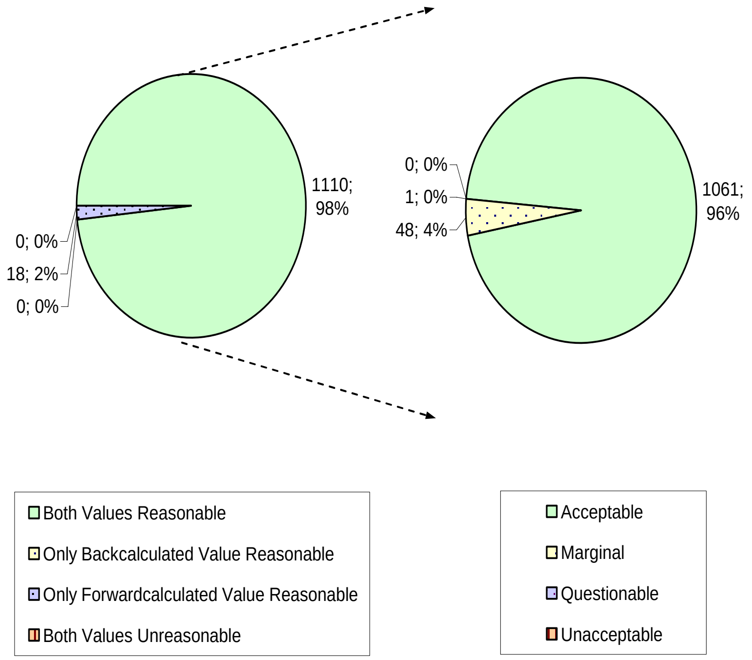


Figure 54. Charts. Screening results of the subgrade section k-value table for the rigid sections in the MON_DEFL_RGD_BAKCALC_SECT table using the dense-liquid model for backcalculation.

CHAPTER 7. SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

SUMMARY

This report presents the results of a study that uses forwardcalculation techniques to screen the backcalculated computed parameter files in the LTPP database. The two different forwardcalculation techniques developed appear to produce reasonable results, both for screening and for estimates of moduli—one for the subgrade and one for the bound surface course layer. In addition, for flexible pavements a relationship developed by Dorman and Metcalf was used for estimates of the modulus of the unbound base course(s). For rigid pavements, a set of ratios relating the modulus of the concrete layer to the base layer was used, very similar to the method in part of the LTPP database covering backcalculation of rigid pavement systems.

The entire set of computed parameter tables of backcalculated pavement layer data was screened with appropriate forwardcalculated moduli. These data cover all available AC and PCC sections where backcalculation was carried out, including both level E and nonlevel E (Release 16.0—All QC Levels, July 2003 Upload). These computations were divided into two parts: a layered-elastic backcalculation approach using the MODCOMP computer program and a backcalculation approach developed specifically for rigid pavement systems using slab-on-dense-liquid and slab-on-elastic solid theory.

Some percentage of the backcalculated flexible pavement layered elastic moduli in the LTPP database derived from MODCOMP were assumed, or fixed, based on engineering judgment and to facilitate the backcalculation process. These values were not screened, but rather left unchanged as they exist in the existing tables with an associated “Y” flag. An even larger percentage of the backcalculated (and some of the forwardcalculated) data were considered to be not within a reasonable range according to the values presented in Table 14. For easy reference, this table is reproduced in this section as Table 17. Records containing moduli outside of the ranges shown in Table 17 were not further screened. Instead, they were flagged (using an “N” data cell, as appropriate) as not reasonable. All remaining records were then screened using the corresponding forwardcalculated moduli. Four different correspondence flags associated with each screened data record have been designated (see Table 15):

0 = Acceptable: The backcalculated value is within a factor of 1.5 of the forwardcalculated value.

1 = Marginal: The backcalculated value is within a factor of 2.0 of the forwardcalculated value (not 0).

2 = Questionable: The backcalculated value is within a factor of 3.0 of the forwardcalculated value (not 0 or 1).

3 = Unacceptable: The backcalculated value is greater than 3 times or less than ⅓ times the forwardcalculated value.

Table 17. Reasonable ranges for various pavement layers in the LTPP database (same as Table 14).

	LTPP Code	Reasonable Range			
		MPa		psi	
		min	max	min	Max
Base Materials					
Asphalt-Treated Mixture, not Permeable Asphalt-Treated Base (PATB)	321	700	25,000	101,500	3,625,000
Gravel, Uncrushed	302	50	750	7,250	108,750
Crushed Stone	303	100	1,500	14,500	217,500
Crushed Gravel	304	75	1,000	10,875	145,000
Sand	306	40	500	5,800	72,500
Soil-Aggregate Mixture (predominantly fine grained)	307	50	700	7,250	101,500
Soil-Aggregate Mixture (predominantly coarse grained)	308	60	800	8,700	116,000
Fine Grained Soil or Base	309	35	450	5,100	65,000
Hot-Mixed AC	319	700	25,000	101,500	3,625,000
Sand Asphalt	320	700	25,000	101,500	3,625,000
Dense-Graded, Cold-Laid, Central Plant Mix AC	323	700	25,000	101,500	3,625,000
Open-Graded, Hot-Laid, Central Plant Mix AC	325	350	3,500	50,750	507,500
Cement-Aggregate Mixture	331	2,000	20,000	290,000	2,900,000
Econocrete	332	3,500	35,000	507,500	5,075,000
Lean Concrete	334	4,500	45,000	652,500	6,525,000
Soil Cement	339	1,000	7,000	145,000	1,015,000
Open-Graded, Cold-Laid, In-Place Mix AC	327	200	3,000	29,000	435,000
Limerock; Caliche	337	150	1,500	21,750	217,500
Other—Treated Base (TB)	350	400	8,000	58,000	1,160,000
Bound Surface Courses					
Concrete Surface (uncracked)		10,000	70,000	1,450,000	10,150,000
AC Surface (>0 ^{O}C–<45 ^{O}C, not alligatored)		700	25,000	101,500	3,625,000
Unbound Subgrades					
Any unbound type		15	650	2,175	94,250

Evaluation of the Rigid Pavement Backcalculated Data Derived from Slab-on-Dense-Liquid and Slab-on-Elastic-Solid Foundation Models

By and large, the screening process produced a set of excellent relationships for the rigid pavement data, essentially based on two-layer slab-on-elastic-solid and slab-on-dense-liquid models, modified as mentioned above for the base layer by using appropriate ratio-based formulas. For all structural layers, nearly 95 percent of all records screened were labeled with a flag of “0,” or acceptable, while most of the few remaining nonzero flags were “1,” or marginal.

Evaluation of the Backcalculated Data Derived from Layered Elastic Analysis

For the flexible pavement data and for the rigid pavement data using layered elastic theory (all generated through the MODCOMP backcalculation program), the screening process produced some data tables with fairly good agreement between the two analysis methods and many tables with relatively poor agreement between the back- and forwardcalculated moduli.

By way of background, for backcalculation involving more than two unknown layers, in most backcalculation programs, the modulus values are effectively derived from the bottom up. This factor is also true for the MODCOMP program. As a result, when a small error occurs in the lowest unknown layer—the subgrade—the compensating layer effect will inevitably occur, by alternately under- and over-estimating the moduli of the succeeding (overlying) layers. In these cases, by the time the fourth or fifth layer from the bottom is adjusted through the iteration process—the bound surface course—the necessary compensation for an incorrect subgrade modulus has taken place and a reasonable result has generally been obtained in spite of alternating too-high and too-low results in the intermediate layers beneath the surface course. The compensating layer effect appears to be mainly associated with distressed pavements that usually do not follow the rules and assumptions made of linear or even nonlinear layered elastic theory. On the other hand, with homogeneous, undistressed, and well-defined pavement structures, backcalculation often appears to work quite well. This observation is especially true for interior slab concrete tests—although only when a two-unknown layer system is used (plus a hard layer at some depth, if present).

Accordingly, the backcalculated asphalt and concrete surface course moduli using MODCOMP resulted in the best correspondence to the forwardcalculated moduli of all layers analyzed. For the asphalt moduli, better than 70 percent of the correspondence screened values (for both the point- and the section-data) were acceptable (flag = 0). For the concrete moduli at the point data level using MODCOMP, better than 60 percent of the screened data using a bonded condition in forwardcalculation were acceptable (flag = 0), while more than 80 percent of these data were acceptable assuming an unbonded condition between the PCC surface and the base course, when compared to the forwardcalculated values for rigid pavements. At the section level for the concrete modulus derived from MODCOMP, better than 90 percent of the backcalculated screened data were acceptable, with a correspondence flag of “0.”

For the subgrade layer, the correspondence between back- and forwardcalculated moduli using MODCOMP (both linear and nonlinear) was somewhat poorer than with the asphalt layer. However, these results are principally from the methodology, not the correctness (or lack thereof) of each method. Forwardcalculation uses the center deflection and the shape of the deflection bowl to characterize the subgrade stiffness under the load plate to a finite depth, as defined by the shape of the deflection bowl. Backcalculation uses one or more of the outer geophones to characterize the subgrade stiffness at that particular distance from the load, assuming it will also have the same stiffness under the load plate. Often this does not appear to be the case—hence, the compensating layer effect. In other instances, in particular with concrete or a very stiff AC pavements, a horizontally constant subgrade modulus appears to be a more reasonable assumption.

Consequently, only about 40 percent of the correspondence screened records for flexible pavement subgrades were classified as acceptable (flag = 0). The results of screening the subgrade section tables as well as the nonlinear version of MODCOMP were similar. On the other hand, most of the bias between the two methods was in the same direction—the backcalculated subgrade moduli from MODCOMP were generally higher than those from forwardcalculation. For the concrete sections, the correspondence between the two approaches was somewhat better, with about 50 percent of these being classified as acceptable, with a correspondence flag = 0. In all unacceptable cases, MODCOMP versus forwardcalculation produced divergent results that were about equally divided between marginal, questionable, and unacceptable (flag = 1, 2, or 3, respectively).

For the base layer using the MODCOMP backcalculation program, many of the backcalculated moduli (and some of the forwardcalculated moduli from the use of the Dorman and Metcalf relationship) were not reasonable according to the broad ranges given in Table 17. Of the remaining values that were screened using the correspondence flags, only between 30 and 40 percent of the data resulted in an acceptable flag of "0," with the remainder once again divided more or less evenly among marginal, questionable, and unacceptable (corresponding flags = 1, 2, or 3, respectively).

The Microsoft® Excel spreadsheets containing all formulae used in phase I of this study have been provided to FHWA, so all forwardcalculation input quantities are totally transparent to those who wish to use the methodology, whether for screening or in rehabilitation design. To this end, four spreadsheets are available—two for asphalt-bound surfaces (using SI and U.S. Customary units) and two for cement-bound surfaces (SI and U.S. Customary). These spreadsheets can be obtained by contacting LTPP Customer Support Services: by phone at 202– 493–3035 or by e-mail at ltppinfo@fhwa.dot.gov. A publication entitled *Guidelines for Review and Evaluation of Backcalculation Results* (FHWA-HRT-05-152) is also available from FHWA for those wishing to use these spreadsheets.

CONCLUSIONS

This report presents the results of a study that used forwardcalculation techniques to screen the entire set of backcalculated computed parameter results in the LTPP database. Two parallel computed parameter data sets now exist: one existing set resulting from backcalculation and one newly created set resulting from forwardcalculation, for the same LTPP sections and using the same FWD input data. This choice does not mean that one method or the other is strictly right or wrong. They are, however, in many instances different.

As this report shows, backcalculation is more of an art than a science, although it is certainly rigorous and scientific in the sense that it can use the entire deflection basin to fairly accurately match up the theoretical and actual measured deflections with backcalculated modulus values. The user, however, must be aware of its limitations and assumptions, such as linear-elasticity, homogeneity, isotropic behavior, in addition to the assumption of being horizontally identical in stiffness for each structural layer beneath the width of the deflection basin, especially if a linear-elastic model is chosen for backcalculation. A skilled backcalculation analyst can deal with these potential shortfalls quite well by skillfully modeling the pavement system and by dealing with apparent or actual nonlinearity in a variety of ways.

For example, the analyst can assign a semirigid layer at some depth where the deflection basin suggests a possible stiff layer or bedrock, similar to how the Hogg model in forwardcalculation defines a depth to an apparent stiff layer, whether there actually is a very stiff layer or bedrock or not at that depth. Adjacent structural layers may also be combined to backcalculate an unknown layer modulus that would otherwise not influence the deflection basin enough to enable the derivation of a modulus value for a relatively thin structural layer. In other cases, a single, relatively thick pavement layer can be separated into two layers in the input file to characterize the apparent difference in material response as a function of depth within the pavement.

What would be most satisfying and give considerably more credibility to both backcalculated and forwardcalculated results is if they are both reasonable and correspond to one another (within reason) with a flag of "0" (i.e., within a factor of 1.5 of one another). For in situ layered-elastic properties of pavement systems, this level of correspondence can be considered reasonable and generally satisfactory for engineering purposes. When this correlation occurs, it can be maintained that the input assumptions for either approach were essentially correct and that either set of moduli may be used with confidence,.

But what should be done when the correspondence flags between back- and forwardcalculation are 1, 2, or 3 (i.e., greater than a factor of 1.5 different from one another)? This situation means that both values are within a reasonable range according to Table 17 and are neither fixed nor assumed. It probably also means that the theoretical assumptions of one or the other, or both, methods are incorrect—or the method of choice is not being used wisely or correctly. Although forwardcalculation produced more stable results, globally, than the three- or more-layer backcalculation approach (using MODCOMP), backcalculated values cannot be categorically rejected, because they do offer a theoretically correct solution to a specific FWD deflection basin, however implausible they may appear. Accordingly, some of these cases may well be implausible, but there is still a possibility—however remote—that the values are in fact more or less correct, given the nature of in situ pavement materials and the often bizarre behavior of these materials under a load and under the influence of ever-changing environmental and other site-specific factors.

Now, however, the LTPP database user can be forewarned by the various flags and data quality checks as outlined in this report and assess whether to accept the values present in the existing backcalculated database (or the forwardcalculated parallel database), depending on the intended evaluation purpose.

In conclusion, the slab-on-elastic-solid or slab-on-dense-liquid models for backcalculation offer excellent correspondence with the rigid pavement forwardcalculation techniques, with very few values being labeled unreasonable. Accordingly, in the vast majority of cases, either (or both) may be used with a good degree of confidence.

RECOMMENDATIONS

Existing LTPP Backcalculation Data—Flagging and Addition of Forwardcalculation Data

As a remedial measure, it is recommended that the current LTPP backcalculated tables be retained as is, although with the various checks and flags added as outlined in this report. It is also recommended that the forwardcalculated values be appended to the computed parameter data tables, so that an LTPP database user can compare the two sets of values obtained from the same deflection basin. When these pairs of values pass both the reasonableness test and the acceptable (correspondence flag) test, then either (or both) may then be used with a greater degree of confidence than one or the other as a stand-alone value.

Future Analysis of the LTPP FWD Deflection Data—Conduct both Back- and Forwardcalculation

To date, only a limited percentage of the total volume of FWD load-deflection data have been processed through either back- or forwardcalculation. As this report documents, no single truth exists to determine or quantify actual in situ layered elastic moduli. The results obtained through backcalculation depend at least as much on how the program of choice is used than on the actual mechanics of how the program functions. Although forwardcalculation produces a unique set of values, these values are approximations, not cast-in-stone truth or baseline values. However, these approximations can certainly be used to guide the backcalculation program user to see if he/she is in the ballpark with answers obtained through any chosen method of load-deflection data analysis.

As a QA measure, it is further recommended that the entire FWD load-deflection database, where back- or forwardcalculation can be carried out, be reanalyzed in the case of the previously analyzed MODCOMP data along with the unanalyzed post-1998 data. Furthermore, since LTPP is a research project, it is not recommended that only one solution be offered as new or improved LTPP computed parameters, but rather two or more different solutions be provided to the LTPP database user. Forward- and backcalculation programs with different theoretical assumptions (for example, by comparing MODCOMP and forwardcalculation results) should be employed so that the LTPP database user can compare the values obtained for the same layer, test point, and test section.

Especially in the case of layered elastic backcalculation of three or more unknown layers, it is very important that each test section be handled on an individual basis by an experienced and savvy user of the selected backcalculation program. Even for an experienced analyst, this process will take some time, since each LTPP section should be carefully reviewed for discrepancies between the program's input assumptions and actual deflection behavior. If MODCOMP (or any other backcalculation program) is selected for a second round of LTPP deflection data analysis, much more time will be necessary than for a typical batch processing of load-deflection data. For any layered elastic analysis using backcalculation, forwardcalculation as outlined herein may be used as a comparison and, if desired, to seed the backcalculation routine selected, as long as the forwardcalculated values are well within the reasonable ranges in Table 17. This table may be changed and updated as appropriate, for example by narrowing the range of reasonable asphalt layer moduli as a function of pavement temperature (if available), if new in situ modulus information is forthcoming about any of the materials listed in the table. Seeding with forwardcalculated values may well positively affect the backcalculated solutions, providing a more reasonable starting point for a good deflection basin fit and a more believable set of moduli in the output.

It will not be necessary to reanalyze or rescreen the back- or forwardcalculated values in the slab-on-elastic-solid or slab-on-dense-liquid database, since these two different approaches produced very similar results. It is recommended that experienced analysts carry out the same two approaches on the remaining rigid pavement data measured at interior slab locations using slab-on-dense-liquid and slab-on-elastic-solid theory for backcalculation.

Selection of Future LTPP FWD Data Analysis Tools—Backcalculation and Forwardcalculation

It is recommended that a second round of LTPP FWD deflection data analysis consist of the following steps:

- **Forwardcalculation of all LTPP sections**—Use the methods as outlined in this report.
- **Backcalculation of the LTPP rigid pavement sections**—Use slab-on-elastic-solid or slab-on-dense-liquid foundation analysis, as developed under the previous LTPP backcalculation project (FHWA-RD-01-113).
- **Backcalculation of the LTPP flexible pavement sections**—Use a sound and user-friendly layered elastic backcalculation analysis program and seed values from forwardcalculation (provided these values are within reasonable ranges).

Recommended Actions to Improve Future Backcalculation Results

In the future, the forwardcalculated values can be used in the following ways to improve the backcalculation results:

- The forwardcalculated values (if they are within a reasonable range) should be used to "seed" most backcalculation routines to assist in arriving at more reasonable and accurate backcalculated modulus values.

- When a "flag" arises for any reason (reasonable ranges, large discrepancies with forwardcalculation, etc.), at the discretion of the analyst backcalculation can be modified and repeated to minimize these differences and/or mitigate the compensating layer effect, thereby improving the backcalculated database while leaving the forwardcalculated results in the database as well.

Notes on a Viable Alternative to Classic Multilayered Elastic Backcalculation

This section is based primarily on the knowledge and experience of the investigators of this task order, not an evaluation outcome of the project.

As an alternative to classic, multilayered backcalculation (e.g., MODCOMP, MODULUS, EVERCALC, etc.), some LTPP database processing time could be saved by using the proprietary ELMOD program, which is easier for a hands-off batch mode. This technique would still provide LTPP database users with the results of two different approaches using two methods (backcalculation with ELMOD and forwardcalculation as developed for this project) that are similar in some respects and dissimilar in others. The current version of ELMOD offers the user two internal processing engines—one using a deflection basin matching routine similar to traditional backcalculation and the other using the radius of curvature method, which is similar to the forwardcalculation routine for bound surface layers presented in this report. Based on our experience with ELMOD, the latter is more stable, and therefore more believable, because in many cases, layered elastic pavement systems (especially distressed pavement sections) generally do not follow the classical laws of homogeneity, isotropic properties, and horizontally constant moduli. Accordingly, both ELMOD approaches should be batch-processed so as to provide the LTPP database user with three comparable solutions—two from ELMOD and one from forwardcalculation. Traditional backcalculation (for example, using MODCOMP again) could also be added as a fourth set of values, as long as they are carried out more carefully and thoroughly than before, as mentioned previously.

The suggestion to consider the use of ELMOD, above, does not necessarily mean that ELMOD is better or more accurate than MODCOMP, EVERCALC, or MODULUS, etc. All of these traditional programs—as well as ELMOD and the forwardcalculation techniques presented in this report—produce approximations of in situ modulus values, at best. When using elastic layered theory on the vast quantity of LTPP data, ELMOD as a backcalculation engine would be both less costly and more efficient than most other backcalculation approaches known to the research team.

There may well be a public domain or other alternative to ELMOD, but the research team is not familiar with such an alternative. As far as is known, ELMOD is the only program that will both run deflection basin matching and radius of curvature or a similar method in one package.

APPENDIX A

This appendix consists of charts showing the screening results of the section average backcalculation data.

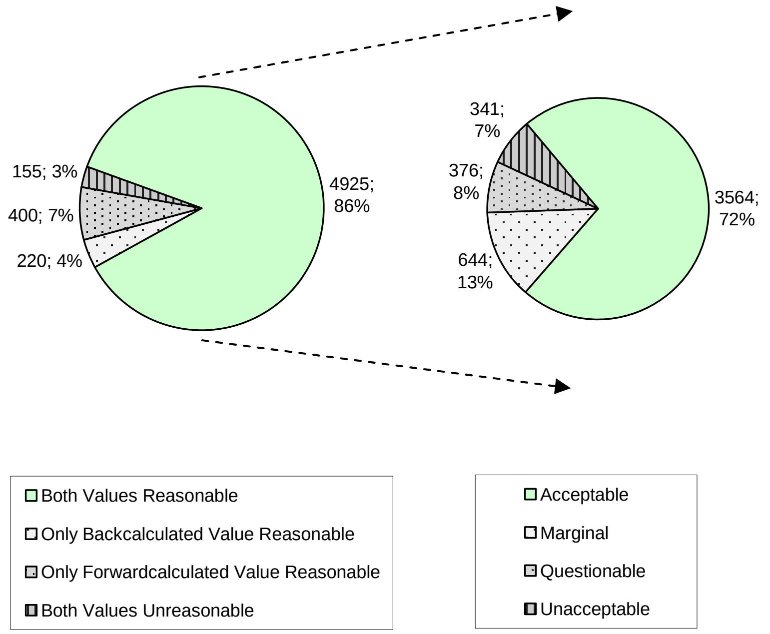


Figure 55. Charts. Screening results of section average elastic moduli of the asphalt concrete layer for the flexible sections in the MON_DEFL_FLX_BAKCALC_SECT table based on the linear elastic model.

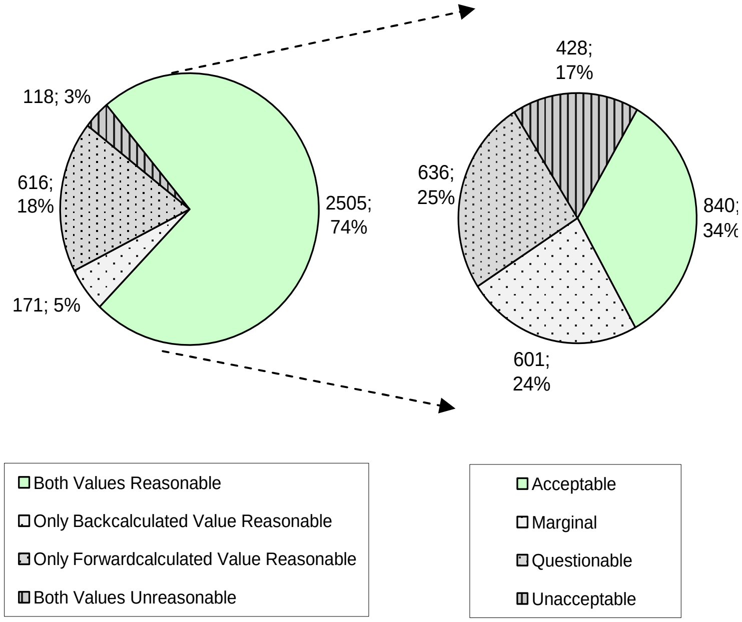


Figure 56. Charts. Screening results of section average elastic moduli of the base layer for the flexible sections in the MON_DEFL_FLX_BAKCALC_SECT table based on the linear elastic model.

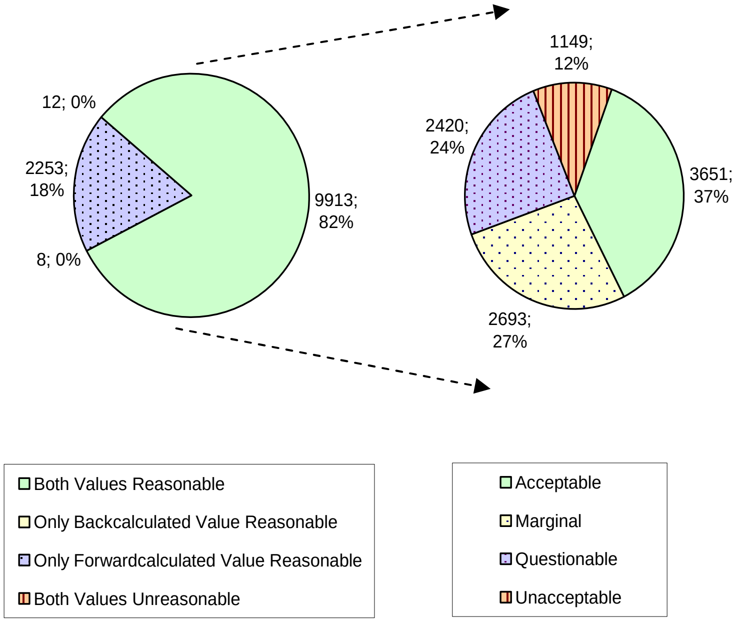


Figure 57. Charts. Screening results of section average elastic moduli of the subgrade for the flexible sections in the MON_DEFL_FLX_BAKCALC_SECT table based on the linear elastic model.

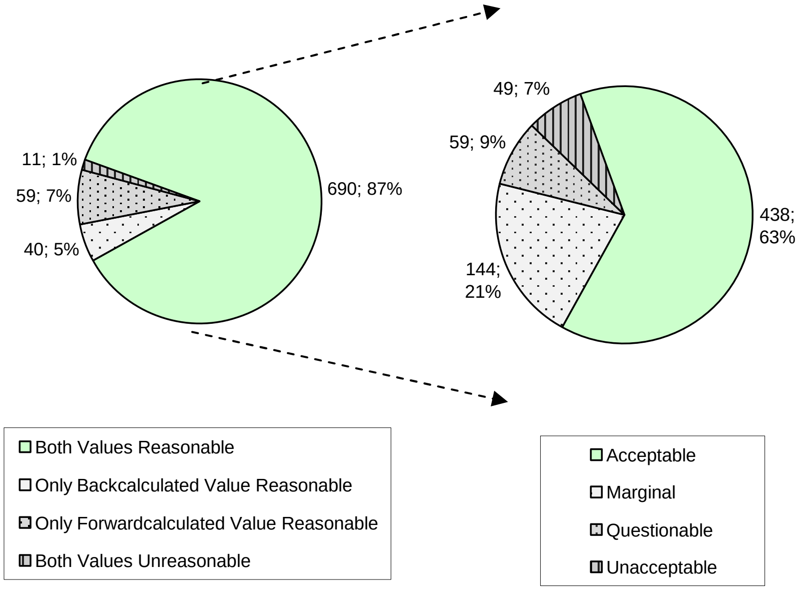


Figure 58. Charts. Screening results of section average elastic moduli of the asphalt concrete layer for the flexible sections in the MON_DEFL_FLX_BAKCALC_SECT table based on the nonlinear elastic model.

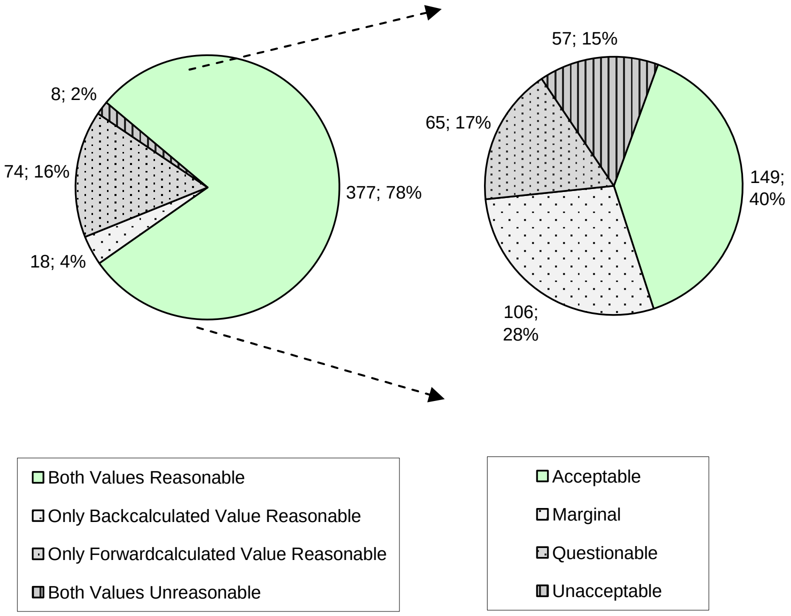


Figure 59. Charts. Screening results of the section average elastic moduli of the base layer for the flexible sections in the MON_DEFL_FLX_BAKCALC_SECT table based on the nonlinear elastic model.

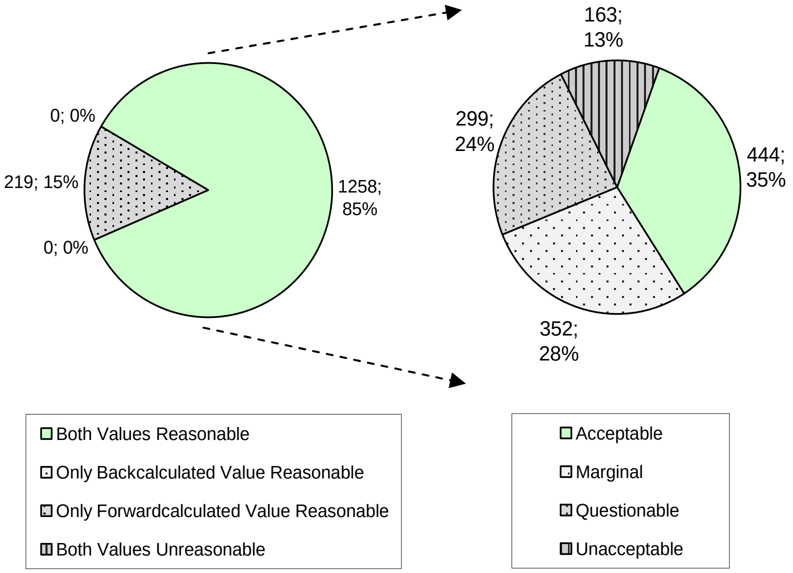


Figure 60. Charts. Screening results of the section average elastic moduli of the subgrade for the flexible sections in the MON_DEFL_FLX_BAKCALC_SECT table based on the nonlinear elastic model.

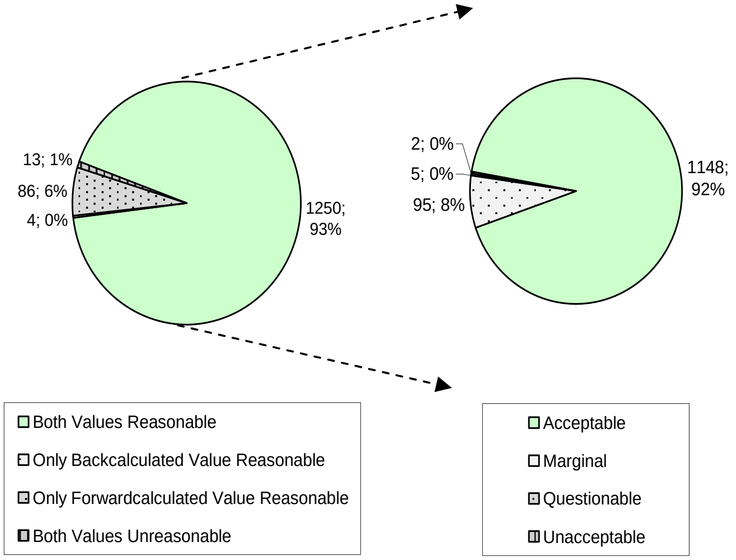


Figure 61. Charts. Screening results of the section average elastic moduli of the PCC slab for the rigid sections in the MON_DEFL_FLX_BAKCALC_SECT table based on the linear elastic model using MODCOMP.

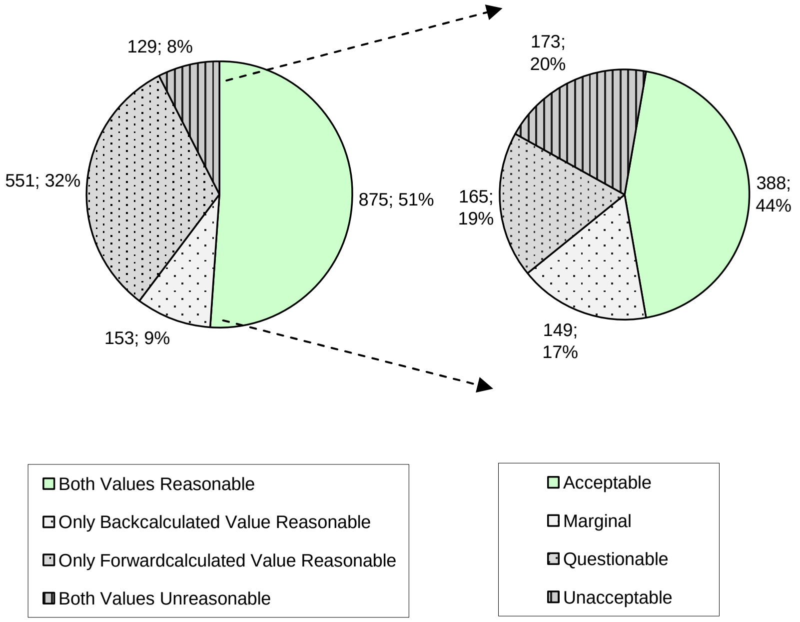


Figure 62. Charts. Screening results of the section average elastic moduli of the base layer for the rigid sections in the MON_DEFL_FLX_BAKCALC_SECT table based on the linear elastic model using MODCOMP.

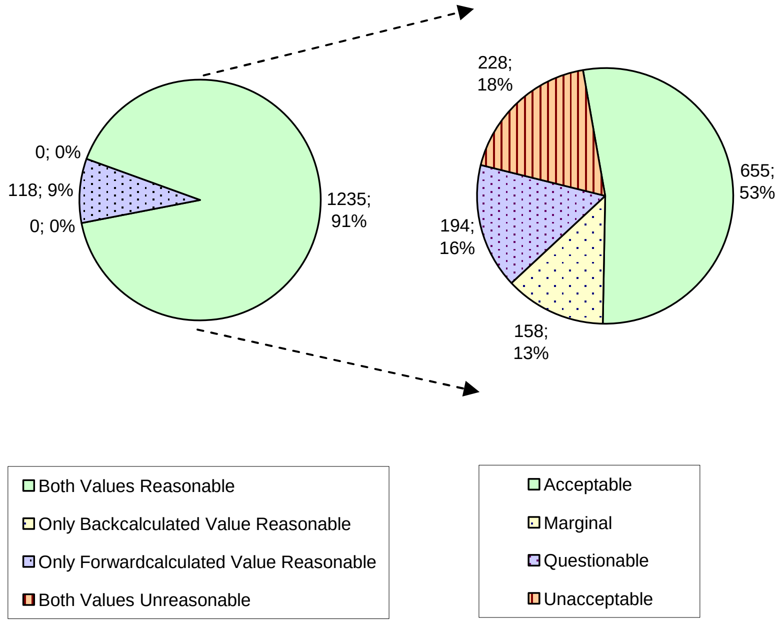


Figure 63. Charts. Screening results of the section average elastic moduli of the subgrade for the rigid sections in the MON_DEFL_FLX_BAKCALC_SECT table based on the linear elastic model using MODCOMP.

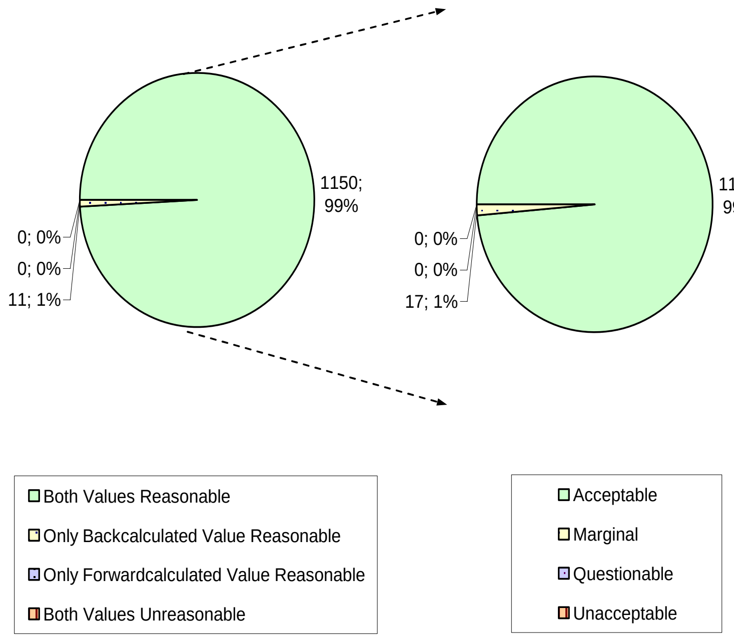


Figure 64. Charts. Screening results of the section average elastic moduli of the PCC slab for the rigid sections in the MON_DEFL_RGD_BAKCALC_SECT table based on the slab-on-elastic-solid model.

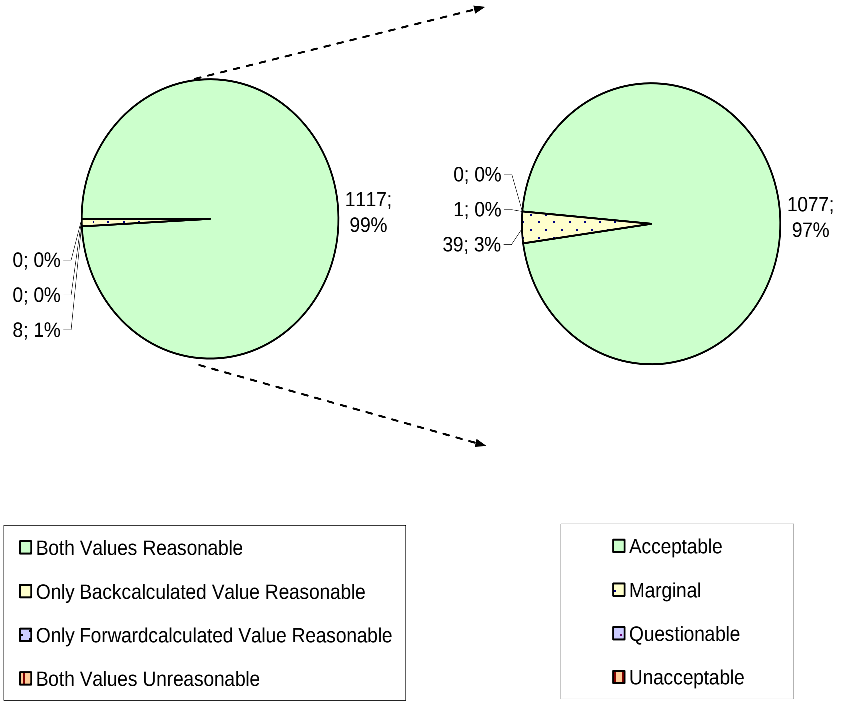


Figure 65. Charts. Screening results of the section average elastic moduli of the PCC slab for the rigid sections in the MON_DEFL_RGD_BAKCALC_SECT table based on the slab-on-dense-liquid model.

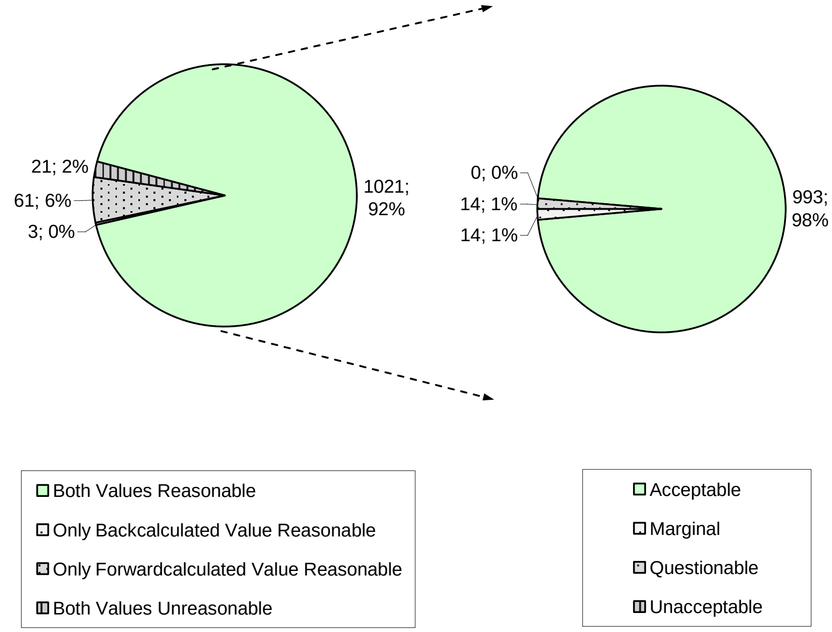


Figure 66. Charts. Screening results of the section average elastic moduli of the base layer for the rigid sections in the MON_DEFL_RGD_BAKCALC_SECT table based on the slab-on-elastic-solid model.

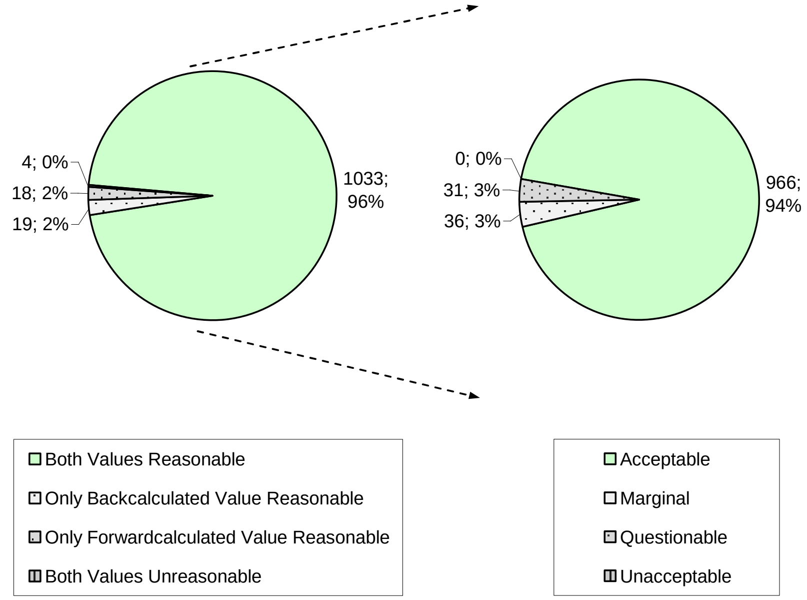


Figure 67. Charts. Screening results of the section average elastic moduli of the base layer for the rigid sections in the MON_DEFL_RGD_BAKCALC_SECT table based on the slab-on-dense-liquid model.

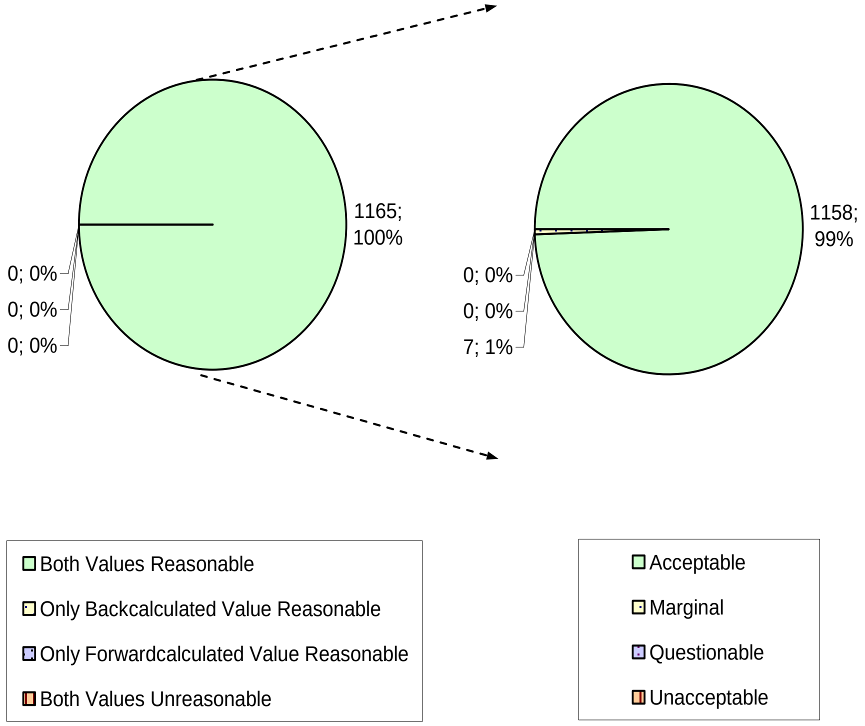


Figure 68. Charts. Screening results of the section average elastic moduli of the subgrade for the rigid sections in the MON_DEFL_RGD_BAKCALC_SECT table based on the slab-on-elastic-solid model.

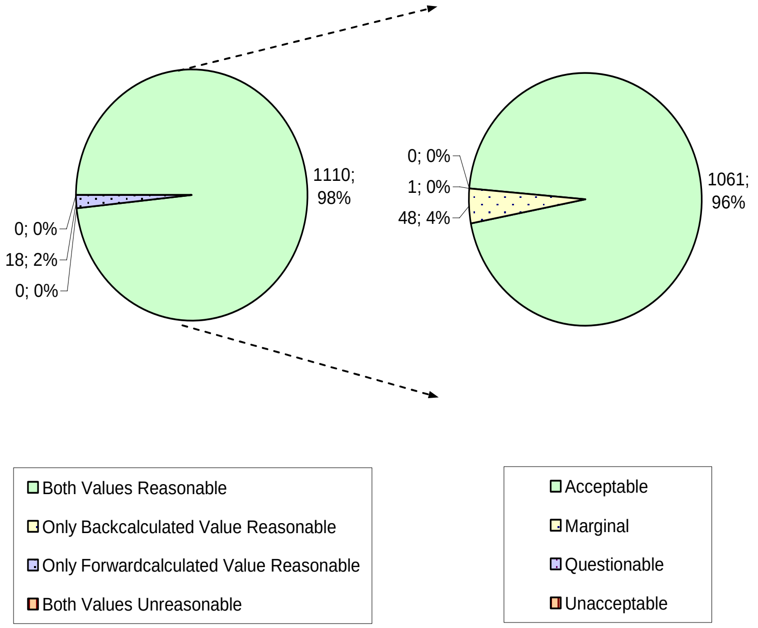


Figure 69. Charts. Screening results of the section average k-values of the subgrade for the rigid sections in the MON_DEFL_RGD_BAKCALC_SECTtable based on the slab-on-dense-liquid model.

REFERENCES

1. Khazanovich, L., S.D. Tayabji, and M.I. Darter, *Backcalculation of Layer Parameters for Long-Term Pavement Performance (LTPP) Test Sections, Volume I: Slab on Elastic Solid and Slab on Dense-Liquid Foundation Analysis of Rigid Pavements,* FHWA-RD-00-086, Washington, DC, Federal Highway Administration, December 2001.

2. Von Quintus, H.L., and A.L. Simpson, *Backcalculation of Layer Parameters for LTPP Test Sections—Volume II: Layered Elastic Analysis for Flexible and Rigid Pavements,* FHWA-RD-01-113, Washington, DC, Federal Highway Administration, October 2002.

3. National Cooperative Highway Research Program, *LTPP Data Analysis: Feasibility of Using FWD Deflection Data to Characterize Pavement Construction Quality,* Project 20-50(09): NCHRP Web Document #52 (http://trb.org/news/blurb_detail.asp?id=942), Washington, DC, National Cooperative Highway Research Program, November 2002.

4. Federal Highway Administration, *Study of LTPP Pavement Deflections,* Project DTFH61-01-P-00144, unpublished final report submitted to FHWA in September 2001.

5. Ullidtz, P., *Pavement Analysis,* The Technical University of Denmark, Elsevier, 1987.

6. Hogg, A.H.A., "Equilibrium of a Thin Plate on an Elastic Foundation of Finite Depth," *Philosophical Magazine*, volume 35 (243), 1944, pp. 265–276.

7. Wiseman, G., and J. Greenstein, "Comparison of Methods of Determining Pavement Parameters from Deflection Bowl Measurements," *Proceedings of the 7th Asian Regional Conference on Soil Mechanics and Foundation Engineering*, 1983, pp. 158–165.

8. American Association of State Highway and Transportation Officials, *AASHTO Guide for Design of Pavement Structures,* Washington, DC: AASHTO, 1993.

9. Dorman, G.M., and C.T. Metcalf, "Design Curves for Flexible Pavements Based on Layered System Theory," *Highway Research Record No. 1188*, Washington, DC, National Academy Press, 1965, pp. 69–84.

10. National Cooperative Highway Research Program, *LTPP Data Analysis: Variations in Pavement Design Inputs,* NCHRP Web Document #48 (http://trb.org/news/blurb_detail.asp?id=742), Washington, DC, National Cooperative Highway Research Program, July 2002.

11. Moore, D.S., and McCabe, G.P., *Introduction to the Practice of Statistics*, 5th Edition, W.H. Freeman, New York, 2005.