Long-Term Pavement Performance Program Determination of In-Place Elastic Layer Modulus: Backcalculation Methodology and Procedures

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LTPP™

FOREWORD

The Long-Term Pavement Performance (LTPP) database includes deflection basins measured on thousands of test sections across the United States. These deflection data were used to backcalculate the elastic layer modulus of both flexible and rigid pavements. This report documents the tools, data analyses, backcalculation and forward calculation packages, and procedures used to calculate the in-place elastic layer modulus of the LTPP test sections. It summarizes the backcalculated elastic layered modulus of both new and rehabilitated flexible and rigid pavements in the LTPP program and demonstrates their use in day-to-day practice for pavement design, rehabilitation, and management. Many agencies have used the LTPP deflection data for calibrating mechanistic-empirical distress transfer functions, including those in the *Mechanistic-Empirical Pavement Design Guide*.[1]

An important outcome presented in this report is the documentation of methods and procedures for calculating in-place elastic layer modulus, including the pre- and post-processing tools so the results can be recreated by others to make the process less user-dependent. In addition, the elastic modulus computed parameter tables included in the LTPP database (Standard Data Release 27.0 released in 2013) are defined and explained in this report so agencies can use these results in multiple areas.[2] This final report is intended for use by pavement researchers as well as by practicing engineers involved in rehabilitation design and management of agencies' pavements.

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Director, Office of Infrastructure
Research and Development

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16. Abstract

Deflection data have been measured at periodic intervals with a falling weight deflectometer on all rigid, flexible, semi-rigid, and rehabilitated pavement test sections included in the Long-Term Pavement Performance (LTPP) program. A common use of deflection data is to backcalculate in-place layered elastic modulus values. The Federal Highway Administration sponsored earlier studies to backcalculate elastic layer modulus values from deflection basins measured on all LTPP test sections and included those computed values in the LTPP database.[3–5] While the earlier studies focus on the use of nonlinear methods and were considered to have minimal success, Some of the methods used have advanced within the past decade. As such, there was a need to revisit the methods used to improve on the results.

This report summarizes all activities completed to backcalculate the elastic layered modulus from deflection basins measured on all test sections included in the LTPP program. Specifically, the report documents the tools, data analyses, backcalculation and forward calculation packages, and procedures used to calculate, on a production basis, the in-place elastic layer modulus of the LTPP test sections. Multiple packages (including BAKFAA, EVERCALC©, MICHBACK©, MODULUS, MODCOMP©, and the area and best fit methods) were considered and evaluated for estimating layered elastic modulus values on a production basis. (See references 6–10.) The methods used in production for backcalculating elastic layer moduli include a combination of EVERCALC© and MODCOMP© for all types of pavements and the best fit method for rigid pavements. The methods and procedures, including the pre- and post-processing tools, have been automated so the results can be recreated by others not directly involved in development of the tools and procedures. The report also summarizes the results from the production runs to calculate the elastic layered modulus of flexible and rigid pavements (new construction and rehabilitation) as well as demonstrate the application and use of the results.

17. Key Words Backcalculation, Deflection data, Elastic modulus, EVERCALC©, Falling weight deflectometer, Long-Term Pavement Performance, LTPP, MODCOMP©, MODTAG©, Modulus, *Mechanistic-Empirical Pavement Design Guide*, Pavement evaluation	18. Distribution Statement No restrictions. This document is available to the public through the National Technical Information Service, Springfield, VA 22161. http://www.ntis.gov

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SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square 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)		
^oF	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	^oC
		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)		
^oC	Celsius	1.8C+32	Fahrenheit	^oF
		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)

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LIST OF ACRONYMS AND SYMBOLS

AASHTO	American Association of State Highway and Transportation Officials
AC	asphalt concrete
ANN	artificial neural network
ATB	asphalt-treated base
CPT	computed parameter table
CRCP	continuously reinforced concrete pavement
FHWA	Federal Highway Administration
FWD	falling weight deflectometer
GB	granular base
GPR	ground-penetrating radar
GPS	General Pavement Studies
GS	granular subbase
HMA	hot mix asphalt
JPCP	jointed plain concrete pavement
JRCP	jointed reinforced concrete pavement
LTE	load transfer efficiency
LTPP	Long-Term Pavement Performance
MEPDG	*Mechanistic-Empirical Pavement Design Guide*
PCC	portland cement concrete
RAP	reclaimed asphalt pavement
RMSE	root mean squared error
SDR	Standard Data Release
SHRP	Strategic Highway Research Program
SLIC	Sensor Location Independent Check
SMP	Seasonal Monitoring Program
SPS	Specific Pavement Studies
SS	subgrade soil
TB	treated base
TS	treated subgrade

CHAPTER 1. INTRODUCTION

BACKGROUND

Deflection data have been measured at periodic intervals with a falling weight deflectometer (FWD) on all rigid, flexible, and composite pavement test sections included in the Long-Term Pavement Performance (LTPP) program. These data or deflection basins have been measured to determine the load-response properties of the pavement structure and subgrade. Currently, there are 16,364 FWD testing days and more than 2,400 test sections in the LTPP database.

Deflections are measured approximately every 2 years for sections included in Specific Pavement Studies (SPS) experiments and every 5 years for sections included in General Pavement Studies (GPS) experiments. There are 64 test sections included in the LTPP Seasonal Monitoring Program (SMP), and deflection data were measured every month for 1 to 2 years for these sites. The SMP sites were used to determine the change in structural properties throughout the year and how changes in moisture and temperature affect the in-place structural response properties.

A common use of deflection data is to backcalculate in-place layered elastic modulus values. Layered elastic modulus values and how the values change over time are used as inputs for estimating remaining life and deciding on an appropriate rehabilitation and design strategy. In addition, many agencies have used the LTPP deflection data for use in calibrating mechanistic-empirical distress transfer functions, including those in the *Mechanistic-Empirical Pavement Design Guide* (MEPDG).(1)

The Federal Highway Administration (FHWA) sponsored earlier studies to backcalculate elastic layer modulus values from deflection basins and included these computed values in the LTPP database. (See references 3, 4, 11, and 12.) Some of the methods used in the earlier studies, however, have been advanced within the past decade. In addition, the amount of deflection data in the LTPP database has increased substantially, especially for the SPS sites. As such, FHWA sponsored a follow-up project to revisit the methods used in the first round of backcalculation and to calculate the elastic layered modulus values for the deflection data that did not exist during the first round of backcalculation.[1]

PROJECT OBJECTIVE

The objective of this study was to select one or more methods to determine the in-place elastic layered modulus from deflection basin measurements for the LTPP test sections and execute those methods for all flexible, rigid, and composite pavement sections included in the LTPP program. These backcalculated elastic layer modulus values, simulated pavement structures for each LTPP test section, and related parameters were integrated into the computed parameter tables (CPTs) of the LTPP database. The project was divided into the following two phases:

[1]In this report, "backcalculation packages" refers to both forward calculation and backcalculation software programs for estimating the in-place layered elastic modulus values from deflection basin data.

- **Phase I:** Phase I included selecting methods and demonstrating those methods and associated pre- and post-processing tools for estimating in-place elastic layered modulus values.[2] As part of phase I, the recommended procedures to be used in the next phase were demonstrated through a series of case studies.[3]

- **Phase II:** Phase II included executing the methods selected from phase I and backcalculating the elastic layered modulus from deflection basin data stored in the LTPP data for the simulated flexible, rigid, composite, and rehabilitated pavement structures. This phase also included uploading the calculated values and associated parameters into a set of CPTs in the LTPP database.

SCOPE OF REPORT AND ORGANIZATION

This report is divided into seven chapters, including this introductory chapter, as follows:

- Chapter 2 describes the process used to select candidate backcalculation methodologies and programs. It summarizes the work completed under phase I of this project.

- Chapter 3 summarizes the case studies that were used to select the backcalculation methods and develop the pre- and post-processing utility tools as well as the automated procedure.

- Chapter 4 provides an overview of the backcalculation process. This includes the rules of simulation, deflection data evaluation to identify problem basins, and acceptance criteria used to judge and interpret the results of the backcalculation process.

- Chapter 5 summarizes the results from the backcalculation process and the data included in the computed parameter database. It also identifies the evaluation factors used to judge the results of test sections that had moderate to high errors and were excluded from the statistical summaries in the CPTs.

- Chapter 6 includes examples to demonstrate application of the backcalculated elastic layered modulus results.

- Chapter 7 summaries the findings and recommendations from this project.

This report also contains three appendices that provide detailed information on the computed parameter database, the tools and macros written to facilitate the entry of required data, and the backcalculation process so that similar results can be obtained by others not directly involved in this project.

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[2]The project team reviewed multiple methods to determine the in-place elastic layered modulus values, and the results were reported to FHWA in an unpublished technical memorandum, the contents of which are summarized in this report.

[3]The project team reported the phase I results to FHWA in an unpublished interim report. The contents of the interim report are summarized in this report.

CHAPTER 2. BACKCALCULATION METHODOLOGY AND PACKAGES

This chapter summarizes the activities completed in phase I of this project.(13) It describes how specific backcalculation packages were selected as candidates to determine the elastic layer modulus values for all test sections included in the LTPP program.

TYPES OF BACKCALCULATION METHODS

There are many programs and methods that can be used to estimate the in-place elastic modulus values of pavement structural layers from deflection basins. Hou developed one of the first solutions for backcalculation of elastic layer modulus values of more than two layers.(13) Hou's approach is to search for the set of layer modulus values that minimize the sum of the squared differences between the calculated and measured deflections. Many backcalculation software programs use this general approach, matching measured deflections to deflections calculated with multilayer elastic theory.

The types of backcalculation methods can be grouped into five generalized categories, which are summarized in the following sections.

Iterative Search Methods

The iterative search method is based on the backcalculation program making repeated calls to an elastic layer subroutine to match the measured to calculated deflections for program-selected or derived layer moduli. The iteration process stops when the measured and calculated deflections are within a tolerance level or when the maximum number of iterations is reached. The user sets the tolerance and maximum number of iterations.

Lytton and Anderson provided a detailed description of two algorithms included in this category of programs.(15,16) The iterative search method involves selecting an initial set of layer modulus values. These modulus values are used to compute surface deflections, which are compared to the measured deflections. The assumed modulus values are adjusted, and the process is repeated until the calculated deflections match the measured deflections within a specified tolerance. Many backcalculation packages use this method, especially those that are used for production and research purposes.

EVERCALC© and MODCOMP© are two programs that fall within this category.(7,9) The MODCOMP© software package was used in the first round of backcalculation for all pavements.(4) Both EVERCALC© and MODCOMP© were selected for this study to backcalculate the elastic layer modulus for all of the LTPP sections.

Database Search Methods

Backcalculation by database search involves searching a database of calculated deflection basins generated for varying modulus values for specific pavement structure to find the calculated deflection basin that best matches the measured deflection basin. Database backcalculation programs work by generating a database of deflection basins for a matrix of elastic layer modulus values and either fixed layer thicknesses or a matrix of thicknesses and then searching the database for the deflection basin that most closely matches the measured basin.

The database search-based programs include MODULUS, COMDEF, and DBCONPAS, which were all developed about the same time. (See references 16–21 and 8.)

Equivalent Thickness Methods

Odemark presented an equivalent thickness method for analyzing deflections.[22] The equivalent thickness approach reduces a multilayer elastic system to an equivalent system with fewer layers (generally three or less) for which a solution is easily obtainable. Equivalent thickness-based methods use either the iterative or database search methods in finding a calculated deflection basin for a set of layer moduli that best match the measured basin.

Examples of equivalent thickness-based backcalculation programs include those developed by Ullidtz and by Lytton and Michalak.[23–25] Ullidtz's program, Evaluation of Layer Moduli and Overlay Design (ELMOD©), is widely used since it is distributed by Dynatest® as part of a software package offered to purchasers of the Dynatest FWDs. ELMOD© is a proprietary software package.

Forward Calculation Methods or Closed-Form Solutions

Some methods use specific points of the measured deflection basin to directly calculate the modulus of limited layers. These methods are referred to as "forward" calculation methods and provide a unique solution for each deflection basin. The forward calculation method or closed-form solution was used during the first round of modulus determination for LTPP.[3]

Most of the closed-form solution methods are limited to three or fewer layers (including the subgrade or foundation)—a major disadvantage of these methods. This limitation makes individual layers with anomalies or defects difficult to identify because it requires use of the equivalent stiffness concept. More importantly, the error can be large between the measured and calculated deflections for the sensors excluded from the calculation process.

The Hogg model is an example of closed-form solutions for flexible pavements.[26] The area and best fit methods are a deviation from the elastic layer theory approach commonly used for flexible pavements. The area-based procedure for backcalculating the *k*-value from deflections for rigid pavement analyses was developed in the 1980s and enhanced in the 1990s. (See references 27–32.) The best fit method was used in the first round of backcalculation for rigid pavement structures and was also selected for use for this study.

Other Methods

Other methods that have been recently developed include the use of artificial neural networks (ANNs), genetic algorithms, and dynamic backcalculation methods.

ANNs

DIPLOBACK is an example of one backcalculation package that uses ANN.[33] Software packages that use ANNs to complete the backcalculation in terms of pattern recognition similar to the procedure established by Lytton and Michalak through the SEARCH program.[25] Some researchers have developed neural network models using a large synthetic database generated from routine finite element analysis software programs, such as ILLI-SLAB for rigid pavements and ILLI-PAVE for flexible pavements. (See references 34–40.) Most ANN methods are confined to a small infra-space of pavements, and site features and are not used routinely by practitioners.

Genetic Algorithms

Multiple programs have been developed based on genetic algorithms. Zhang et al. developed a modified genetic algorithm called MGABPLM in 1998, which is based on the Homotopy method.[41] This category of backcalculation has been used very infrequently and only for research purposes.

Dynamic Analysis Methods

Dynamic analysis methods require the use of FWD deflection-time histories using frequency and time-domain solutions. DYNABACK-F is a program based on dynamic analyses.[42] This category of backcalculation packages is complex, requires a lot of data, and as such, is only used by a small group within the industry for research purposes.

Summary

Practitioners commonly use iterative and database search backcalculation packages for research, pavement evaluation, and rehabilitation design. Unfortunately, none of the programs that fall in these categories result in a unique set of modulus values for a specific pavement structure. Multiple combinations of elastic layer modulus values with similar errors can exist. This non-uniqueness of solutions is the major reason for debate on which method is the better one and which set of layer modulus values is the correct one. The closed form solution package ELMOD© is widely used, but it is a proprietary program. Moreover, a closed form solution (unique set of layer modulus values) does not necessarily imply a correct or accurate solution.

CANDIDATE BACKCALCULATION PROGRAMS

Many published documents have included a literature review and comparison of backcalculation methods. This section includes a brief review of the findings from other studies related to the selection and use of candidate backcalculation programs. It also identifies factors that can have a significant impact on the results and how those items can be handled as part of executing large batch files for production backcalculation.

Comparison of Backcalculation Programs

Rada et al. published a comparison of the features of several computer programs for backcalculation.[43] More recently, a European study tabulated the features of 20 different computer programs used for backcalculation.[44] Most backcalculation programs rely on an elastic layer program to calculate surface deflections and use the iterative or database search methods.

Von Quintus and Killingsworth used multiple software packages to backcalculate layer modulus from the same deflection basin data for selected LTPP test sections.[45–47] The following programs were included in this study:

- MODULUS 4.2.[8]
- MODCOMP3© and MODCOMP3.6©.
- WESDEF.
- WESNET.
- MICHBACK 1.0©.[10]
- FWD-DYN.

These programs were evaluated on the basis of technical merit, functionality, and data processing compatibility using 18 test sections located in the LTPP southern region. Von Quintus and Killingsworth concluded that one software package should be used because of the large differences found between many of the programs.

Von Quintus and Simpson followed up with a similar study for selecting a package to backcalculate elastic layer modulus values for the deflection basins measured on the approach and leave ends of each LTPP test section.[4] The approach and leave ends were used because many cores were extracted from these locations for layer thickness determination after the first round of deflection basin measurements. Von Quintus and Simpson compared multiple packages using the following five evaluation factors:

- Accuracy of the program.
- Operational characteristics.
- Ease of use of the program.
- Stability of the program.
- Probability of success.

They recommended the use of MODCOMP4.0© for backcalculating elastic layer moduli.

Generally, nearly all previous studies recommended one method over others, recommended multiple methods, or determined that all methods compared produced similar results. The following list summarizes the results from a few other projects that compared backcalculation programs:

- Gergis conducted a comparison of ELMOD©, MODULUS, EVERCALC©, MODCOMP©, and WESDEF and recommended EVERCALC© for routine research use.(48)

- Al-Suhaibani et al. compared six backcalculation programs (CHEVDEF, ELSDEF, FDEDD1, WESDEF, SEARCH, and BISDEF©) and reported that CHEVDEF and ELSDEF produced more reliable results than the others.(49)

- Zhou et al. compared EVERCALC©, WESDEF, and MODULUS and reported that the results from all three packages were basically the same.(49) This finding was in direct contrast to the finding by Von Quintus and Killingsworth.(45)

The first backcalculation study sponsored by FHWA for flexible pavements used the software package MODCOMP4.0© for consistency of results between linear and nonlinear solutions.(4) MODCOMP4.0© was also used for rigid pavements along with a forward calculation procedure developed by Khazanovich.(3) MODCOMP4.0© was selected over EVERCALC©, MODULUS, and other programs because of its capability and versatility to consider different constitutive equations for unbound layers and soils. This same finding was reached in backcalculating layer elastic modulus values for multiple local calibration and commercial projects.(51)

Many agencies have backcalculated layer modulus values for the LTPP test sections located within their agency. States in which layer modulus values have been backcalculated from LTPP FWD deflection data include Arizona, Colorado, Michigan, Mississippi, Missouri, Montana, Ohio, Texas, Utah, Washington, Wisconsin, and Wyoming. EVERCALC©, MODULUS, and ELMOD© have been used most extensively for backcalculating in-place elastic layer modulus values used in the local calibration studies. However, MODCOMP© and MICHBACK© have also been used by selected agencies.(10) The MODCOMP© program was used to generate in-place layer modulus values for the global calibration effort of the MEPDG.(52)

FHWA sponsored two more recent studies related to the use of FWD deflection data and backcalculation of layer modulus data (Smith et al. and Rada et al.).(53,5) These two studies and reports are referred to throughout this report as the Smith and Rada studies.(53,5) Both studies include a review of FWD deflection data and backcalculation software packages for estimating in-place modulus values. The Smith study includes a more extensive review of backcalculation methods for both rigid and flexible pavements, while the Rada study was prepared using a complete set of deflection data from the LTPP SPS-1 experiment. These literature reviews also documented the programs that are being used by different agencies for rehabilitation, evaluation, and forensic investigations. Knowing the programs that agencies are using is important so that the results will be readily useable to as many agencies as possible.

While both the Smith and Rada studies provide a comparison of backcalculation programs, the Smith study includes a more detailed comparison of selected backcalculation packages.(53,5)

Both of these studies used case studies from the LTPP program to evaluate and compare the results from different software packages. The summaries included in the Smith study and the earlier backcalculation projects provide an excellent comparison of the different software packages. The Rada study uses the MODULUS and MODCOMP© software packages and found that the MODULUS program resulted in many more acceptable solutions.(5) The Smith study documented the use of the MODCMOP, MICHBACK©, and EVERCALC© programs and found varying results.(53) The EVERCALC© program, however, consistently resulted in lower error terms.

Results from the two literature reviews confirmed the summary of available backcalculation programs that have already been summarized in the existing literature. Hall also completed a similar unpublished literature review of deflection data and backcalculation methods. Hall's review included international projects and software packages that are available from outside the United States. These summaries and others list and compare the following:

- The maximum number of sensors considered by the software package.
- The maximum number of layers that can be backcalculated depending on the number of sensors.
- Nonlinear and linear capabilities and the type of constitutive equations considered by the software package.
- Convergence scheme.
- Advantages and disadvantages of the program in relation to its application with the MEPDG software.
- Support services for the software.
- Operational properties and physical features of the software.

In summary, many of the backcalculation procedures are similar, but the results can be different due to assumptions, iteration technique, backcalculation, or forward calculation schemes used within the programs. Some of these methods, such as MODCOMP© and EVERCALC©, also have the capability to estimate the elastic layer modulus values and coefficients of nonlinear constitutive relationships (stress-sensitivity properties). Specifically, these methods can be grouped in those with different constitutive models for describing the behavior between load and deflection or stress and strain: linear, quasi-nonlinear, and nonlinear backcalculated modulus values. Regardless, results from the backcalculation packages have been debated and questioned since their development in the mid-1970s. There is no consensus on the best procedure or the one providing the most reliable and accurate results.

Ground Truth Regarding Backcalculated Modulus Values

The deflection-based elastic moduli represent composite values and do not result in a unique set of elastic layer moduli. It is challenging to determine which set of elastic layer moduli represents the real values and which backcalculation package consistently results in those values. The following list contains some points that must be considered in explaining any discrepancy between the modulus values determined through different techniques and in defining an acceptable set of elastic layer moduli:

- The field-derived elastic modulus is an equivalent value for multiple layers of similar materials that can have substantial differences in how a material responds to load (see figure 1 and figure 2), while the laboratory-measured dynamic or resilient modulus is a specific value for one mixture or material. The five arrows included in figure 1 designate the individual layers or lifts included in the asphalt concrete core.

- The field-derived elastic modulus is an equivalent value that includes the effects of any cracking or fatigue damage in the bound layers, while the laboratory-measured value is an intact specimen, either cored from the pavement or compacted in the laboratory.

- Multiple combinations of field-derived elastic modulus values can result from a deflection basin, as there is no unique combination of layer modulus values, while a unique modulus value is obtained in the laboratory for each test specimen based on the specific testing conditions.

- The resulting backcalculated elastic modulus value is dependent on the allowable error between the computed and measured deflection basins, while the resulting laboratory-measured dynamic or resilient modulus value is dependent on the precision and bias of the test procedure.

- The resulting backcalculated elastic modulus value is subject to compensating errors (increasing and decreasing modulus values of adjacent layers), boundary conditions, and stress conditions, while there is no compensating error effect in the laboratory-measured dynamic or resilient modulus values.

As an example, five asphalt concrete layers or lifts are shown in figure 1. These five individual layers result in different dynamic moduli. The upper three layers are less than 2 inches each, which are too thin for backcalculating the elastic moduli from deflection basins. The backcalculation process would combine all layers into one hot mix asphalt (HMA) layer for which an equivalent or composite elastic modulus would be determined from the deflection basins. One main issue is that these structures, which are typical, increase the variance between the laboratory measured and backcalculated modulus values. Some procedures combine the laboratory measured values into an equivalent modulus using the equivalent modulus concept.

It is difficult, if not impossible, to determine the ground truth values because of the simplifying assumptions used in all backcalculation programs. More importantly, there is significant debate within the pavement engineering community of what constitutes ground truth. Thus, the software packages that result in values consistent with the perceived realistic values and results between multiple programs were used in selecting the candidate packages to be used in the case studies as well as for the production runs.

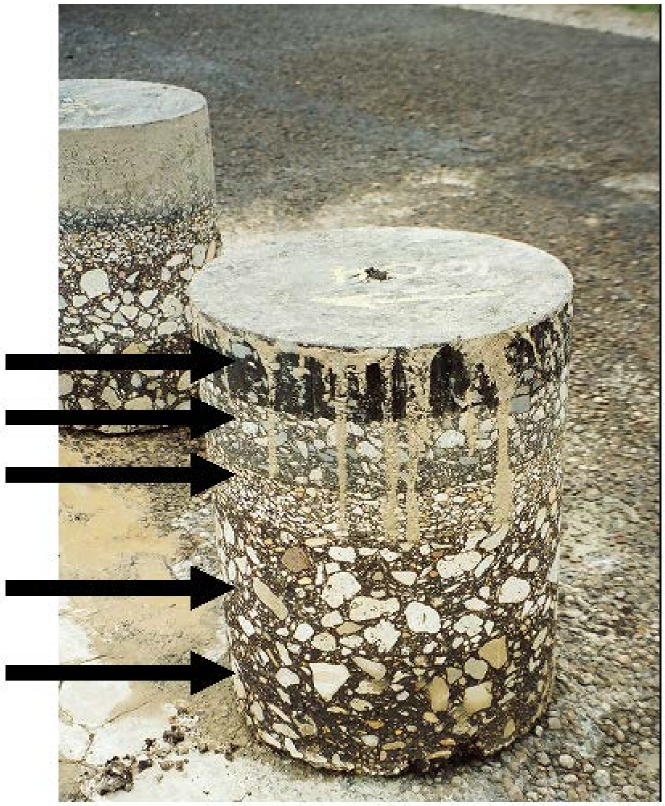


Figure 1. Photo. Core recovered from an LTPP test section used to equate laboratory-measured modulus values to backcalculated elastic modulus values (Texas SPS-5 section).

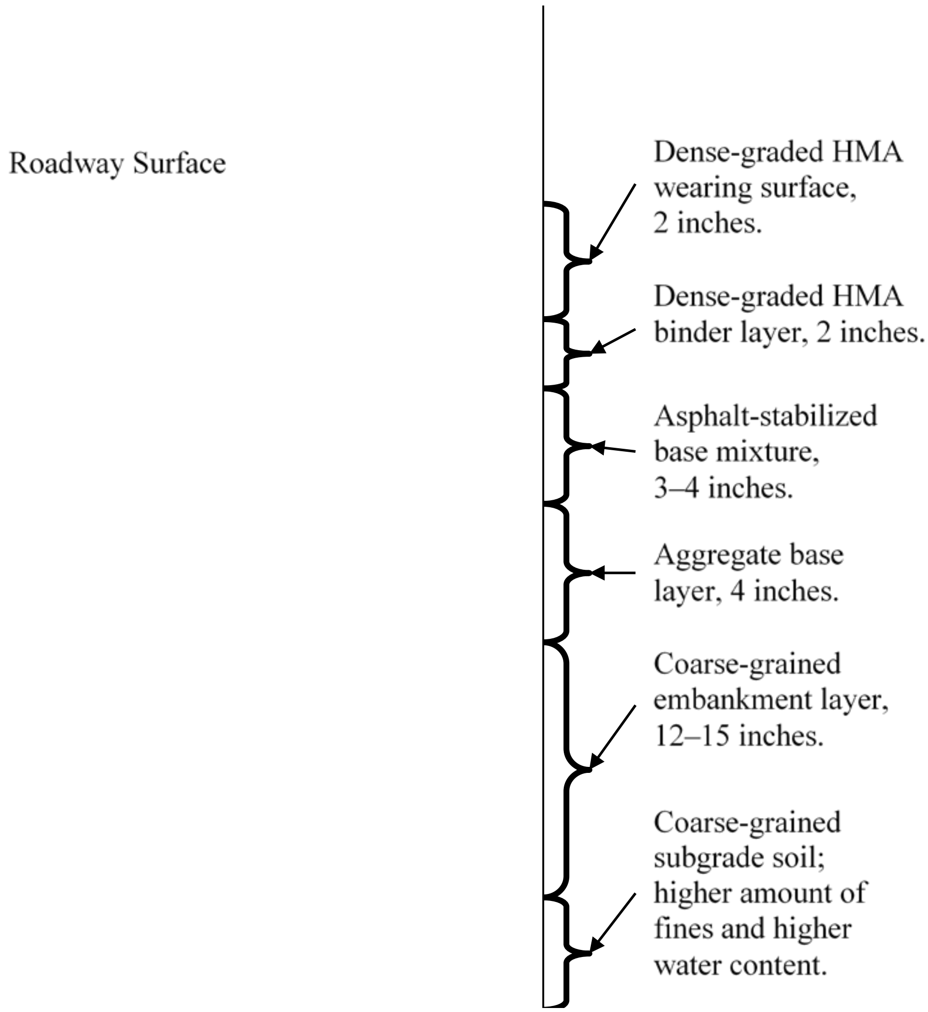


Figure 2. Photo. Cross-section of the pavement layers exposed during a forensic investigation to measure the rutting within individual pavement layers (Arizona SPS-1 section).

Factors Considered in Selecting Candidate Programs

The following factors were considered in selecting candidate programs for use in the case studies:

- **Probability of success in matching measured to calculated deflection basins**: This was a difficult factor to consider between software programs because the real in-place modulus values were unknown, and the lowest error or difference between the measured and calculated deflection basins did not necessarily mean the layer modulus values were more correct than another set with a slightly higher error. Different error terms are used by different backcalculation programs which represent different values. The root mean squared error (RMSE) term was used in comparing the candidate programs. It was assumed that a "good" match between the calculated and measured deflection basins (low RMSE) is a reasonable estimate of the in-place values.

- **Applicability to diverse pavement structures and layer conditions**: If possible, the same program should be applicable and used for all pavement types included in the LTPP database. These include thin and thick HMA pavements; HMA overlays of flexible, rigid, rubblized, and recycled layered pavements; jointed plain concrete pavement (JPCP), jointed reinforced concrete pavement (JRCP), continuously reinforced concrete pavement (CRCP), and portland cement concrete (PCC) overlays of rigid pavements. It is a possibility that the same package might not be applicable for all pavement types. Results from the case studies included in the demonstration did result in the use of a primary and a secondary package.

- **Capability to execute large batch files**: From a production standpoint, this was an important requirement. Any package without the capability to execute large batch files was excluded from further consideration for making the production runs.

- **Maximum number of layers for which the layer modulus values can be determined from the deflection basins**: The maximum number of five layers was used in the backcalculation process, including a bedrock layer when present. A backcalculation study sponsored by FWHA in 1997 included determining the modulus of HMA layers with stripping, foundation layers below and above the water table depth, and selected stabilized layers.(46)

- **Software package is available in the public domain**: This factor takes into account the ease with which other agencies may procure the same software. It is important for future use to backcalculate layer moduli as more deflection basins are added to the LTPP database so it can be used by other agencies to backcalculate modulus values for their own roadway segments to be consistent with LTPP, if desired.

- **Soundness of the technical approach used in the backcalculation algorithm and its relevance to the MEPDG procedures**: Results from the backcalculation process need to be applicable for use in the MEPDG because many agencies are using or are planning to use the MEPDG for pavement design.(1)

- **Speed of convergence**: Speed of convergence of the software package to determine the set of layer modulus values is important for large production runs. In addition, the iteration process for convergence can be a consideration for the production runs. Speed of convergence is a preferred feature in a program but is not considered a critical factor. Accuracy and lack of bias are more salient features.

Six programs were selected for use in the case studies for calculating layer stiffness properties from deflection basins on a production basis. The selection of these six programs was based on the results and recommendations from published documents and, to a minor degree, on the experience of the authors. Table 1 summarizes the features of the six packages selected for use in the case studies.

Table 1. Backcalculation software packages used in the case studies.

Feature of Package[a]	Backcalculation Software Packages/Methods					
	BAKFAA[6]	**EVERCALC©[7]**	**MICHBACK©[10]**	**MODCOMP©[9]**	**MODULUS[8]**	**Area Method[b]**
Backcalculation method	Iterative	Iterative (optimization)	Raphson-Newton	Iterative	Database (optimization)	Closed form solution
Convergence scheme	Sum of squares of absolute error	Sum of absolute error	Least squares	Relative deflection error at sensors	Sum of relative squared error	N/A
Non-linear analysis capability	No	Yes, limited	No	Yes	No	No
Visual image of basin convergence	Yes	Yes	No	No	No	N/A
Pavement type specific	Rigid and flexible	Rigid, flexible, and composite	Flexible and composite	Rigid, flexible, and composite	Flexible	Rigid and composite
Forward response calculation method	Multilayer elastic theory	Multilayer elastic theory	Multilayer elastic theory	Multilayer elastic theory	Multilayer elastic theory	Closed form solution
Ability to fix modulus	Yes	Yes	Yes	Yes	Yes	No
Maximum number of Layers	5	5	3	5	4	2
Layer interface analysis[c]	Variable	Fixed	Fixed	Fixed	Fixed	Fixed

N/A = Not applicable.
[a]Forward calculation methods used to determine seed values for the backcalculation procedures are not listed in this table.
[b]The best fit method was evaluated simultaneously, and the differences in the computed values as well as the feasibility to automate the procedure were evaluated. In addition, the forward calculation spreadsheets prepared using the Hogg model were used.[26]
[c]The layer interface condition was selected to be consistent with the field distress development.

STANDARDIZATION OF BACKCALCULATION PROCESS

The first version of ASTMD 5858-96(2015), *Standard Guide for Calculating In Situ Equivalent Elastic Moduli of Pavement Materials Using Layered Elastic Theory*, was published in 1996 and last updated in 2008.(54) This guide presents the concepts for backcalculating pavement layer elastic modulus values from measured deflections using elastic layer theory. The guide does not address adjustments for load level, frequency, temperature, or seasonal variation. Since the backcalculation guidance provided in ASTM D5858-96 is based on elastic layer theory, it is applicable to flexible pavements and only to a limited extent to rigid pavements (i.e., interior loading and slab size/stiffness ratios less than 8). Neither ASTM International nor the American Association of State Highway and Transportation Officials (AASHTO) has approved further standards or guidance. As such, ASTM D5858-96 was followed in backcalculating elastic layer moduli.

CHAPTER 3. CASE STUDIES

The purpose of the case studies conducted in phase I of this project were twofold: (1) select the forward and/or backcalculation methods from the candidates identified in chapter 2 and (2) provide direction for automating the backcalculation process by establishing the decisionmaking criteria in evaluating the results. In addition, results from the case studies were used to confirm the rules of simulation in establishing the pavement structure on an automated basis.

LTPP TEST SECTIONS SELECTED FOR CASE STUDIES

Test sections from the LTPP SPS and SMP experiments were selected because deflection basins for these experiments were measured at shorter time intervals than for the GPS experiments. Six case studies were used to compare and evaluate the candidate backcalculation and forward calculation programs and to demonstrate the different pre- and post-processing tools to be used for the production runs. The LTPP projects selected for the case studies are listed in table 2. The reasons for selecting these sites are as follows:

- Two of the case studies are LTPP SMP sites. The reason for selecting these seasonal sites was to estimate the variation in elastic modulus values over temperature and other seasonal changes as determined from deflection basins. One of the seasonal sites included in the demonstration is a rigid pavement (Utah 49-3011), and the other is a flexible pavement (Georgia 13-1005).

- Three case studies represent newly constructed pavements—two new construction flexible pavements from the SPS-1 experiment (Iowa and Wisconsin) and one new construction rigid pavement from the SPS-2 experiment (North Carolina). These projects were selected to include a wide range of layer thicknesses and materials for both pavement types.

- Two case studies represent rehabilitated or overlaid pavements—one from the SPS-5 experiment (rehabilitated flexible pavements) and one from the SPS-6 experiment (rehabilitated rigid pavements). The sections selected are from the Mississippi SPS-5 project to include varying HMA overlay mixtures (virgin and recycled asphalt pavement mixes) and layer thicknesses, while sections were selected from the Oklahoma SPS-6 project to include varying types of treatments to the existing PCC slabs.

Table 2. LTPP test sections used for the case studies.

Pavement Type	New Construction Sites	Rehabilitation Sites	SMP Sites
Rigid	North Carolina SPS-2: all sections	Oklahoma SPS-6 intact and rubblized sections	49-3011 (Utah)
Flexible	Wisconsin SPS-1 sections 0113, 0116, and 0119; Iowa SPS-1 sections 0101, 0106, and 0109	Mississippi SPS-5 control, virgin, and recycled asphalt pavement sections	13-1005 (Georgia)

COMPARISON OF RESULTS FROM CANDIDATE BACKCALCULATION PROGRAMS

This section provides a brief comparison of the results between the candidate backcalculation software packages in terms of the evaluation factors set forth in chapter 2. The BAKFAA and MICHBACK© programs were dropped from further consideration because of issues encountered in executing large batch files for the first few case study sites.[10] For the other four programs, three criteria were used in judging the acceptability of the results from the candidate forward and backcalculation methods: RMSE values, magnitude of the moduli, and comparison to laboratory-measured modulus values.

Deflection Basin Matching—RMSE

Figure 3 summarizes and compares the average RMSE values resulting from the backcalculation of layer moduli at each test section and day of testing. As shown, MODTAG© consistently had lower RMSE values, while MODULUS consistently had higher RMSEs.[1(55)] Many of the MODTAG© RMSE values were less than 1 percent. EVERCALC© and MODTAG© also had a higher percentage of stations with less than 2 percent RMSE. Based on the RMSE values, MODTAG© and EVERCALC© consistently resulted in a closer match between the measured and calculated deflection basins. The MODULUS program exhibited higher RMSE values in almost all cases for the two conditions: assuming the presence and absence of an apparent rigid layer or bedrock.

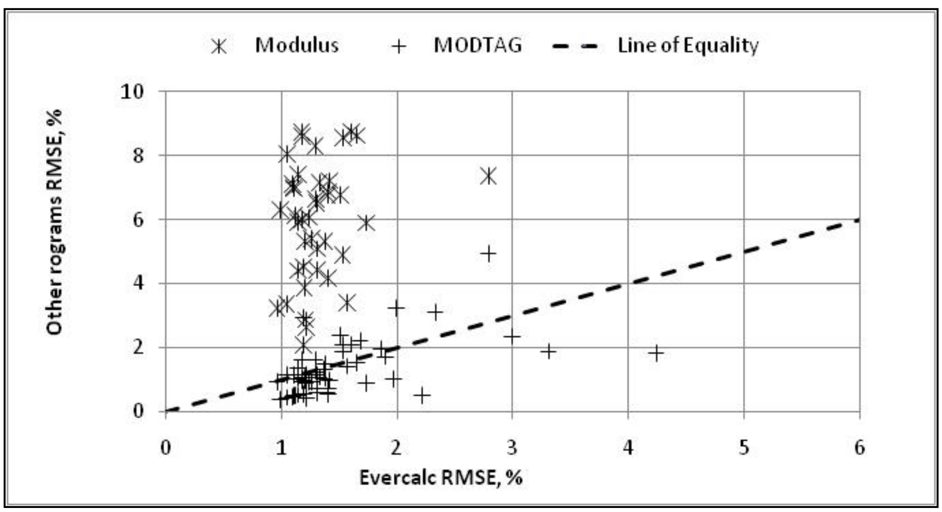


Figure 3. Graph. Comparison of RMSE values between backcalculation programs for flexible pavement sections comparing MODULUS, MODTAG©, and EVERCALC©.

Figure 4 summarizes and compares the average RMSEs from the best fit forward calculation method and EVERCALC©. As shown, the RMSEs from the best fit method were significantly higher than from the EVERCALC© program. This observation is in line with the authors' experience from other projects with using the forward calculation equations based on the Hogg

[1]MODTAG© includes various data subroutines for evaluating the deflection basin data and uses MODCOMP© for the backcalculation process. MODTAG© was used in the comparison of the programs within the first phase of the project. However, MODCOMP6© was used for the production or batch runs under the second phase of the project.

model for flexible pavements—the forward calculation program resulted in sets of layer moduli with significantly higher RMSE values than the backcalculation program.(26)

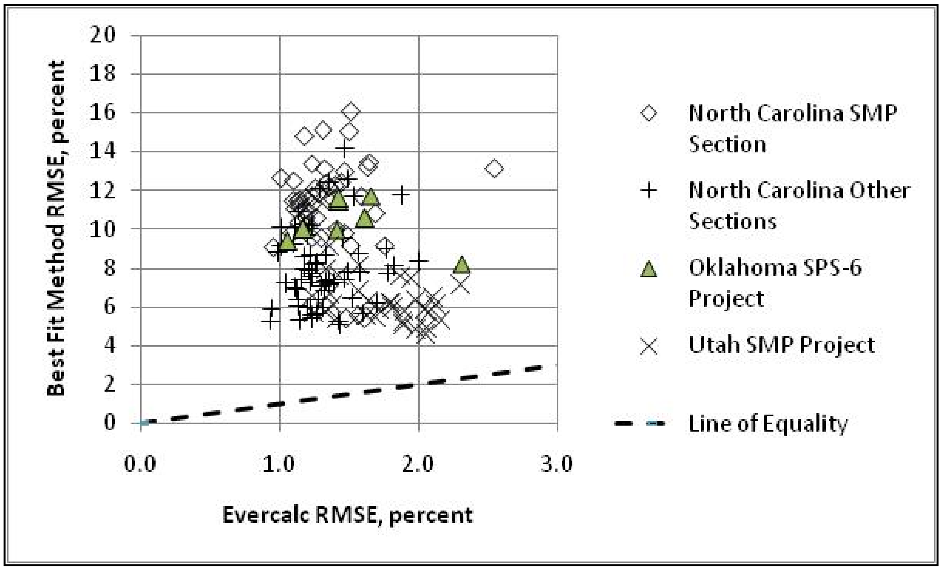


Figure 4. Graph. Comparison of RMSE values between backcalculation programs for rigid pavement sections comparing best fit method and EVERCALC©.

Distribution of Elastic Moduli

The range of default elastic modulus values included in the MEPDG was used to define the initial acceptable range of elastic modulus values for comparing the results between different programs for different materials and soils.(1) The percentage of values within the acceptable range of moduli with RMSE less than 2 percent is summarized in the interim report for this project.(13) EVERCALC© exhibited a higher percentage of stations for which moduli were calculated within the typical range for the specific material in question. Backcalculated layer moduli for individual stations were outside the acceptable range of values, but the averages and majority of stations were within the range of typical values.

The distribution of resulting layer moduli for each layer during a day's testing can be used to investigate the reasonableness of the results. Figure 5 shows the distribution of results for the crushed stone base material at the Georgia 13-1005 site, which exhibits a normal distribution. This type of distribution is typical of many pavement materials. In fact, many of the layers (bound and unbound) exhibit this type of distribution.

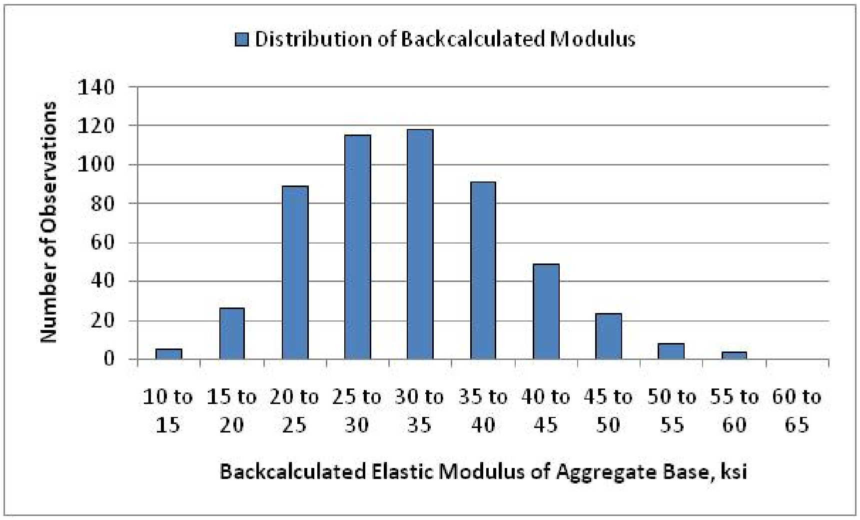


Figure 5. Graph. Normal distribution of calculated elastic modulus for a crushed stone base aggregate.

Conversely, figure 6 shows a bimodal distribution of results for the weathered soil layer at the Georgia 13-1005 site. A bimodal distribution can reflect a change in the results caused by changing material properties or thickness deviations along the section, compensating errors between two layers, and/or hitting a boundary condition or limit at multiple stations. Based on a review of previous backcalculated layer modulus values in the LTPP database, the results can also exhibit a uniform distribution.(4,46) However, none of the test sections included in the case studies exhibited this type of distribution.

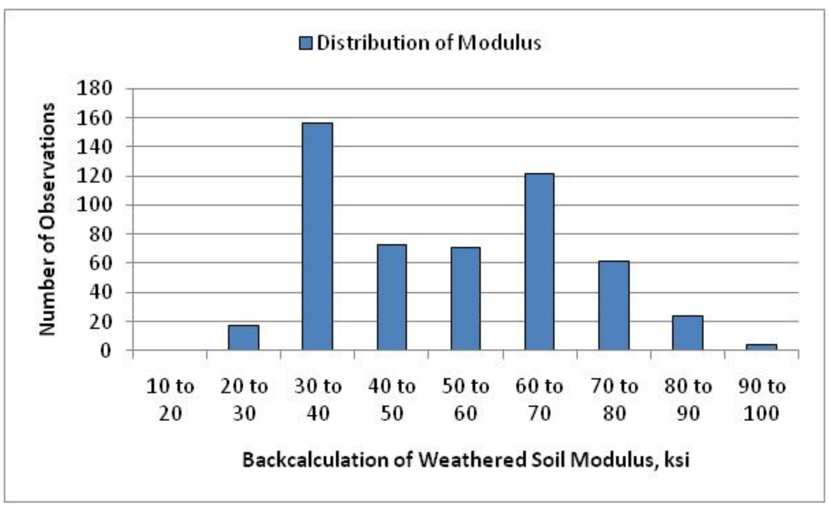


Figure 6. Graph. Bimodal distribution of calculated elastic modulus for the weathered soil layer.

Layer Stiffness Properties of Flexible Pavements

Figure 7 through figure 11 provide a comparison of the results from the candidate backcalculation methods in terms of elastic layer moduli for different layer or material types.

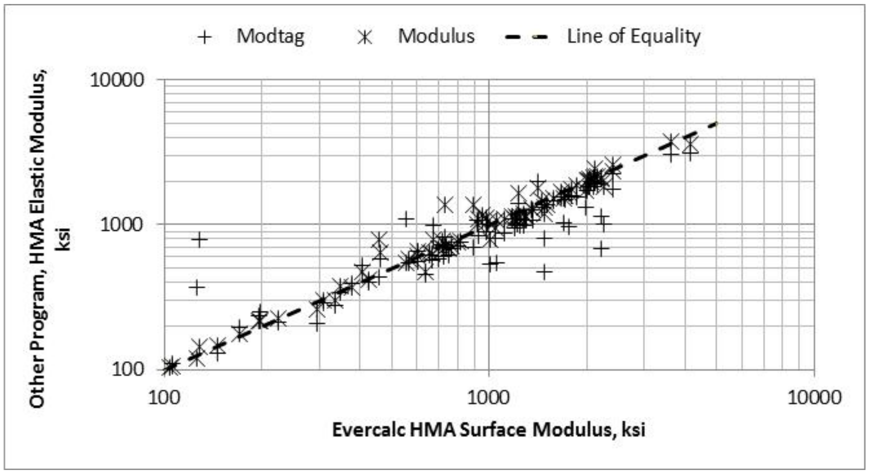


Figure 7. Graph. Comparison of backcalculated moduli from the candidate programs for the HMA layer.

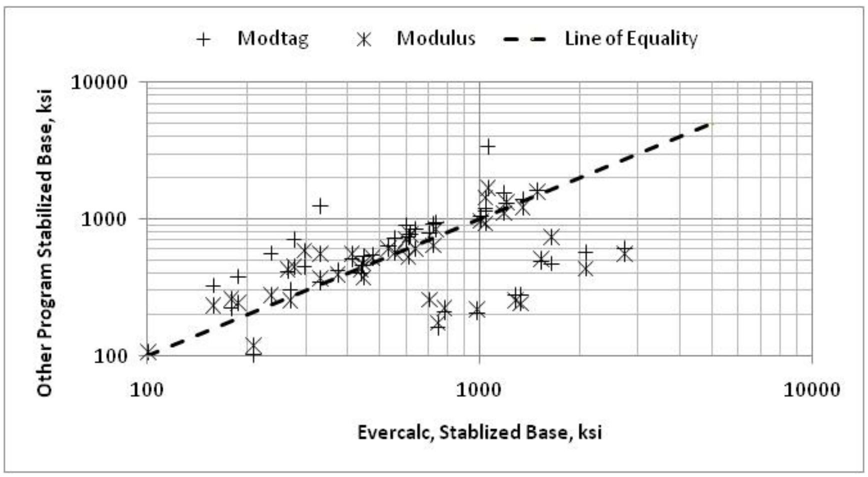


Figure 8. Graph. Comparison of backcalculated moduli from the candidate programs for the asphalt stabilized base layer.

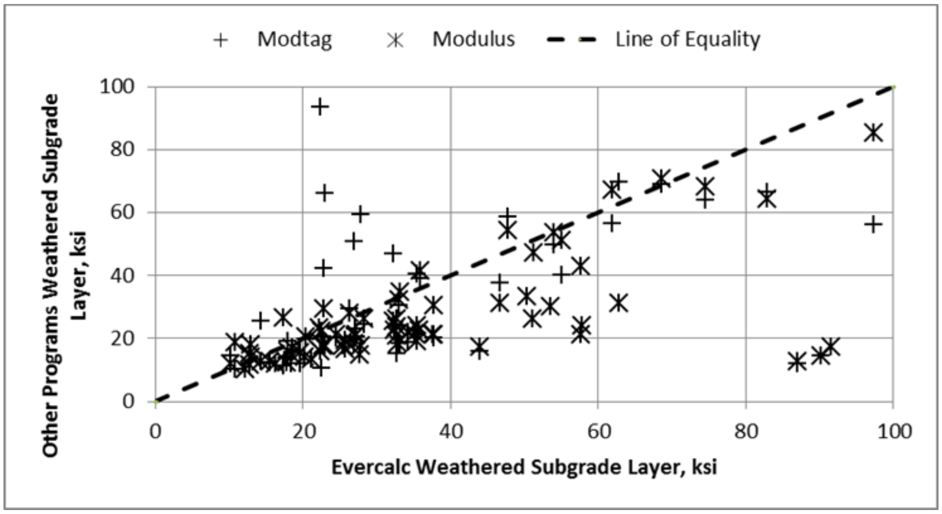


Figure 9. Graph. Comparison of backcalculated moduli from the candidate programs for the weathered soil layer modulus values.

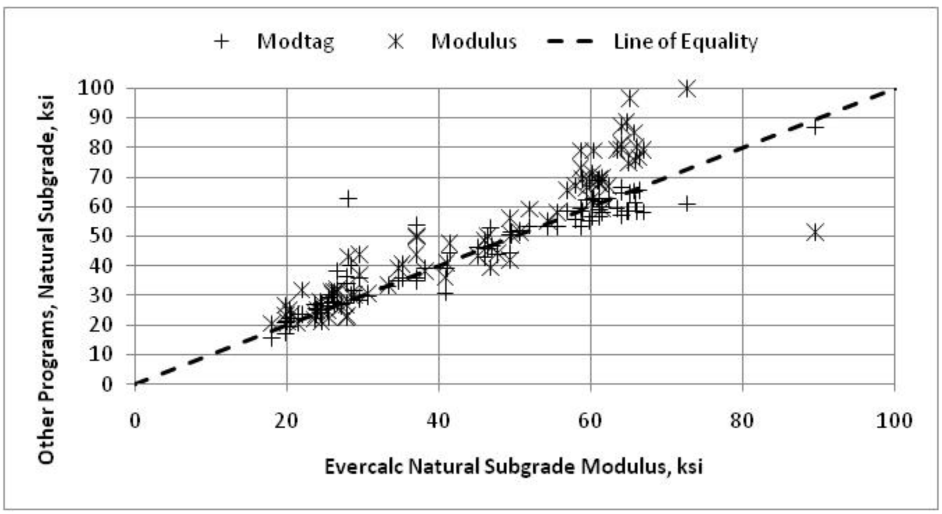


Figure 10. Graph. Comparison of backcalculated moduli from the candidate programs for the natural subgrade modulus values.

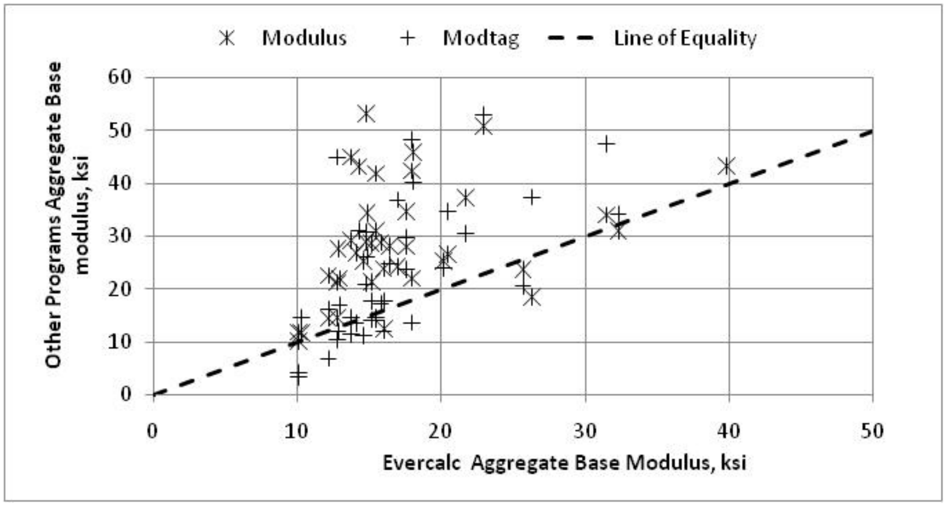


Figure 11. Graph. Comparison of backcalculated moduli from the candidate programs for aggregate base layers.

The following list summarizes the results related to selection of the backcalculation programs for flexible pavements:

- All three programs (EVERCALC©, MODCOMP©, and MODULUS) resulted in similar values with a lot less difference between the elastic layer moduli calculated by different procedures for the surface layer (figure 7) and subgrade (figure 10), regardless of the type of deflection basins.

- All three programs resulted in the same elastic layer moduli for the conditions when the deflection basins would be categorized as typical as defined by Von Quintus and Simpson and Von Quintus and Killingsworth.[4,46] For the type II deflection basins, as defined by Von Quintus et al., the three programs resulted in different elastic layer moduli for the intermediate layers (i.e., the weathered soil layer and thinner aggregate base layers) (see figure 9 through figure 11).[46]

- All three programs correctly identified some form of damage that was observed through forensic investigations or surface distress recorded in the LTPP database. Stripping, moisture damage, and debonding were identified as issues by all three programs.

- The MODULUS program consistently generated sets of layer moduli that exhibit much higher RMSE values than for EVERCALC© and MODCOMP©, while MODCOMP© consistently resulted in slightly lower RMSEs than EVERCALC© (see figure 3 and figure 4).

A *t*-test was used to determine if the average test day results from the two candidate programs with the lower RMSE values (EVERCALC© and MODCOMP©) were statistically indifferent. Table 3 provides a summary for a few of the test sections from three of the case studies. Both EVERCALC© and MODCOMP© resulted in indifferent elastic moduli for many of the test sections. About a fourth of the layers, however, resulted in statistically different datasets. The majority of the test sections with statistically different moduli were those for which the majority of the deflection basins are classified as type II.

Table 3. Comparison of datasets from selected LTPP flexible test sections.

Test Section	Number of Test Days	Layer Designation	EVERCALC© Results: Average Elastic Modulus	EVERCALC© Results: Standard Deviation of Elastic Modulus	MODCOMP© Results: Average Elastic Modulus	MODCOMP© Results: Standard Deviation of Elastic Modulus	Comments
Georgia 13-1005	29	Aggregate base	16.38	3.23	23.72	11.91	Statistically different datasets
		Subgrade	62.16	2.84	60.25	3.61	
Iowa 19-1001	7	Aggregate base	13.98	5.84	13.43	11.84	Statistically indifferent datasets
		Subgrade	20.37	1.67	20.41	3.70	
Mississippi 28-0501	7	Asphalt-treated base (ATB)	790.4	291.6	918.6	268.8	Statistically indifferent datasets
		Subgrade	54.43	15.65	55.35	14.18	

Layer Stiffness Properties of Rigid Pavements

The primary material properties needed for completing a rigid pavement rehabilitation design or evaluation in accordance with the MEPDG are the *k*-value of the lower pavement layers and subgrade, the static elastic modulus for the PCC, and the resilient modulus of aggregate base layers.[(1)] The area and best fit closed form solution methods were used to estimate the elastic modulus of the PCC and aggregate base layers and the *k*-value for the combined lower pavement layers and subgrade.

Figure 12 includes a comparison of the elastic modulus calculated with EVERCALC© and the moduli calculated using the area and best fit methods. As shown, the resulting elastic layer moduli from the EVERCALC© program and the area method are variable but have minimal bias between the two. In addition, the unbonded condition of the best fit method has less bias than its bonded condition to EVERCALC©. The bonded condition simply means the two layers are tied together, while the unbonded condition means the two layers are not tied together, and there is no shear transfer between the two layers. This brings up an issue of which method should be used in computing the elastic modulus of the PCC layer, the area or best fit method, as well as which condition should be simulated, bonded, or unbonded.

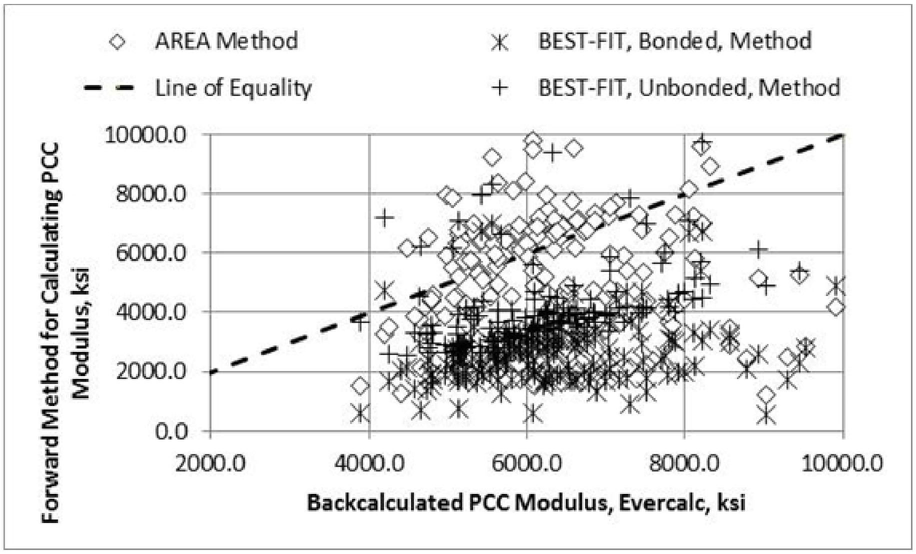


Figure 12. Graph. Backcalculated layer PCC modulus from EVERCALC© compared to the elastic modulus calculated with the area and best fit methods.

The best fit method (unbonded condition) was selected for rigid pavements because it was used for global calibration for the MEPDG under NCHRP Project 1-37A.[52]

Figure 13 and figure 14 show a comparison of results for the subgrade and aggregate base layers between EVERCALC© and the best fit unbonded condition, while figure 15 shows a comparison of results for PCC layers. The best fit method resulted in significantly different or lower elastic layer moduli than EVERCALC© for PCC (figure 12 and figure 15), while the bias was much less between the computed elastic layer moduli of the base layer between the best fit method and EVERCALC© (figure 14).

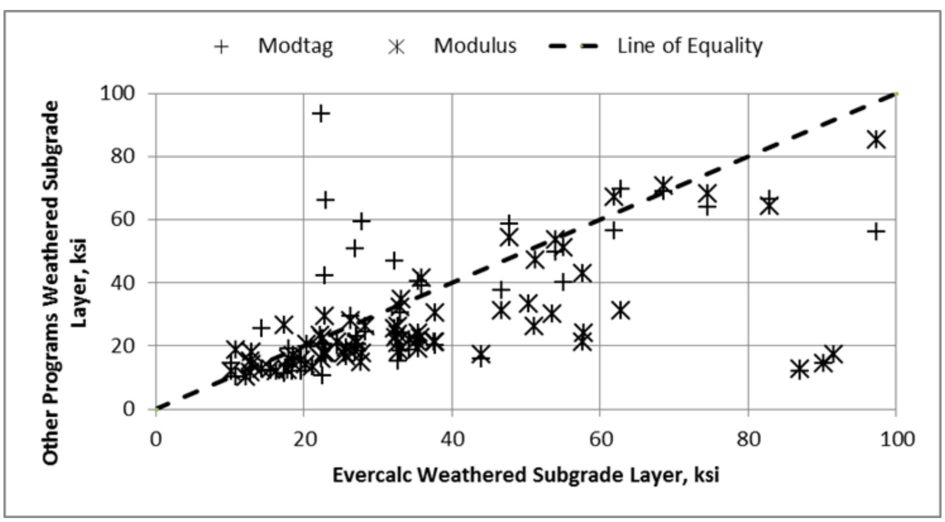


Figure 13. Graph. Comparison of forward and backcalculated moduli from the candidate programs for the subgrade layer.

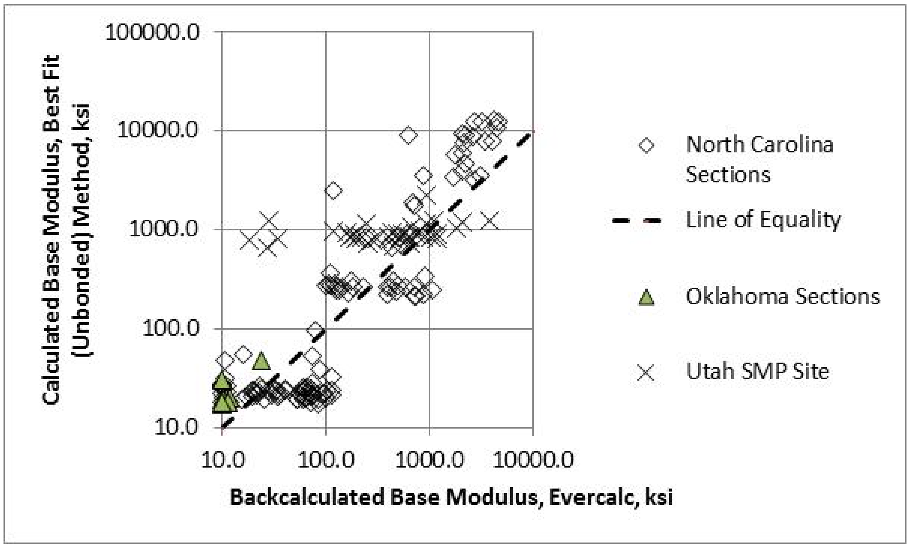


Figure 14. Graph. Comparison of forward and backcalculated moduli from the candidate programs for the aggregate base layer.

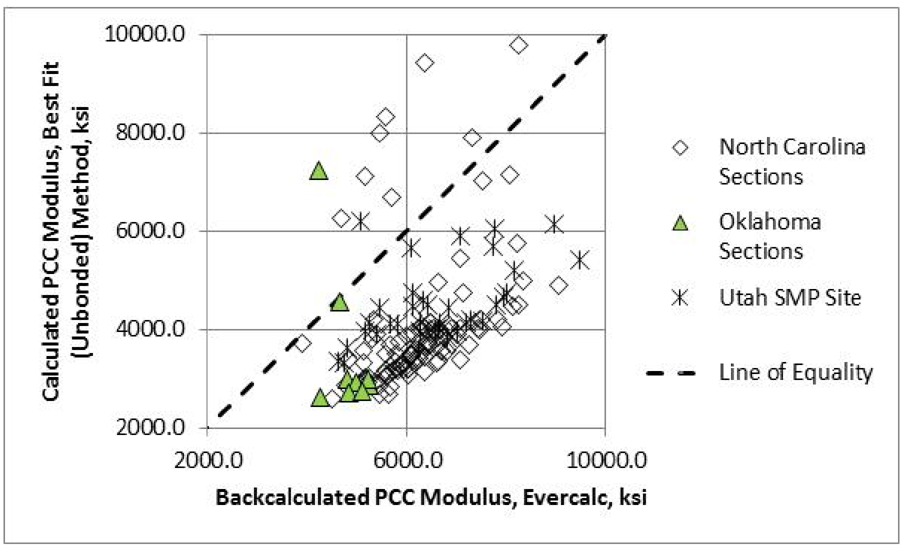


Figure 15. Graph. Comparison of forward and backcalculated moduli from the candidate programs for the PCC layer.

The *t*-test was used to determine if the average test day results from the forward and backcalculation programs were statistically indifferent. Table 4 provides a summary for a few of the test sections from three of the case studies for rigid pavements. As shown, the forward and backcalculation methods (best fit method and EVERCALC©) resulted in significantly different PCC elastic moduli for most of the test sections, while about half of the test sections resulted in significantly indifferent elastic moduli for the base layer. This large bias between EVERCALC© and the best fit method can have a critical impact in determining the PCC elastic modulus for input into the MEPDG.(1) This issue of bias is discussed further in the next section.

Table 4. Comparison of datasets from selected LTPP rigid test sections.

Test Section	Number of Test Days	Layer Designation	EVERCALC© Results		MODCOMP© Results		Comments
			Average Elastic Modulus	Standard Deviation of Elastic Modulus	Average Elastic Modulus	Standard Deviation of Elastic Modulus	
North Carolina 37-0201	48	PCC	5,795.5	601.3	3,125.5	1,601.8	Statistically different datasets
		Aggregate base	46.8	27.4	20.8	10.7	
Utah 49-3011	37	PCC	6,584.7	1,167.0	2021.2	570.6	Statistically different datasets
		Stabilized base	665.6	718.9	570.6	114.1	Statistically indifferent datasets
Oklahoma 40-0601	7	PCC	4,749.9	418.2	2,461.5	1,099.3	Statistically different datasets
		Aggregate base	12.5	4.9	16.4	7.3	Statistically indifferent datasets

Field-Derived and Laboratory-Measured Layer Stiffness Properties

PCC Materials

Static elastic moduli for the PCC layers were extracted from the LTPP database. Figure 16 compares the laboratory-measured elastic moduli and backcalculated values for the PCC layers. As shown, the results from EVERCALC© and the best fit method are highly variable in comparison to the measured PCC static modulus. The average elastic modulus ratio (i.e., *E*-ratio between the laboratory-measured and field-derived elastic moduli) for the PCC layer are as follows:

- **EVERCALC©**: Mean *E*-ratio = 0.77; standard deviation = 0.176.
- **Best fit method bonded**: Mean *E*-ratio = 1.92; standard deviation = 1.254.
- **Best fit method unbonded**: Mean *E*-ratio = 1.00; standard deviation = 0.436.

Results from the EVERCALC© program exhibited a coefficient of variation of 23 percent for the averages, which is much lower than the best fit method, which had a coefficient of variation of 65 percent for the bonded condition and 44 percent for the unbonded condition.

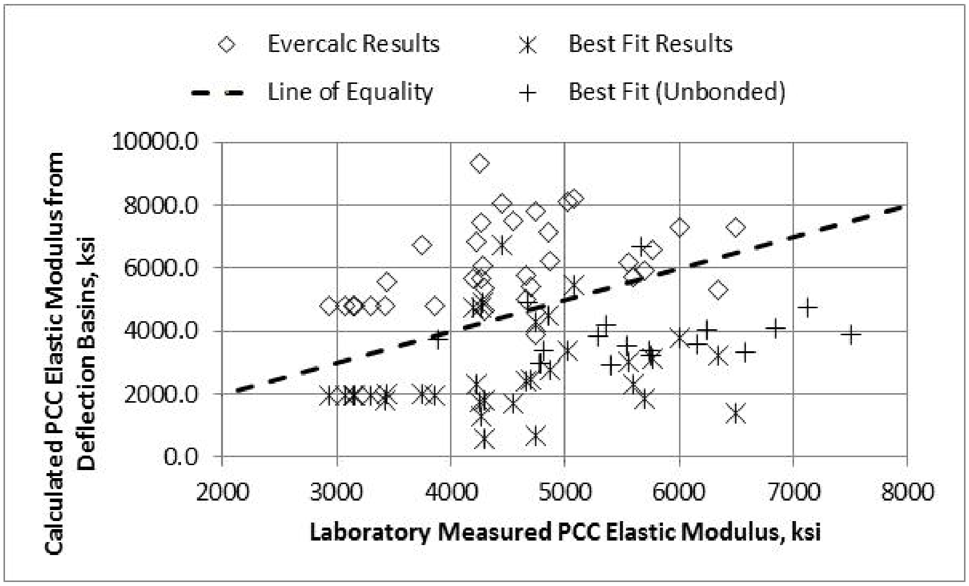


Figure 16. Graph. Comparison of backcalculated and laboratory-measured PCC moduli.[2]

The best fit bonded condition significantly underpredicted the measured values, while EVERCALC© overpredicted the measured values. On average, the best fit unbonded condition resulted in no bias.

In summary, there is a significant difference between the resulting PCC elastic moduli from EVERCALC© and the best fit method. The best fit unbonded condition resulted in an unbiased prediction of the laboratory-measured values. Assuming laboratory elastic moduli are used in the global or local calibration effort, an adjustment needs to be made to the EVERCALC© dataset for use with the MEPDG software, similar to using the *c*-factor for unbound layers.[45,46,1]

HMA and Bituminous Stabilized Materials

Backcalculated elastic layered moduli from deflection basins are used in the MEPDG for the rehabilitation and evaluation of flexible pavements.[1] Dynamic modulus values are estimated using the Witczak regression equation included in the MEPDG to represent the undamaged condition of HMA mixtures. These same values were calculated using the dynamic modulus regression equation from the MEPDG and included in the LTPP databases for the HMA and other bituminous layers.[1]

Dynamic moduli for the HMA layers were extracted from the LTPP database. Figure 17 through figure 26 compare the laboratory estimated dynamic moduli and backcalculated values for the HMA layers. As shown, most of the backcalculation programs underpredict the laboratory-measured values for the loading frequency typically used for the FWD (25 Hz). All three backcalculation programs resulted in similar average values on a day of testing basis for many of the test sections, but not all.

[2]Some of the PCC elastic modulus values from the best fit unbonded condition exceeded 10 million psi, and these are not shown in the figure. These high elastic moduli resulted in a much higher standard deviation than for the EVERCALC© method.

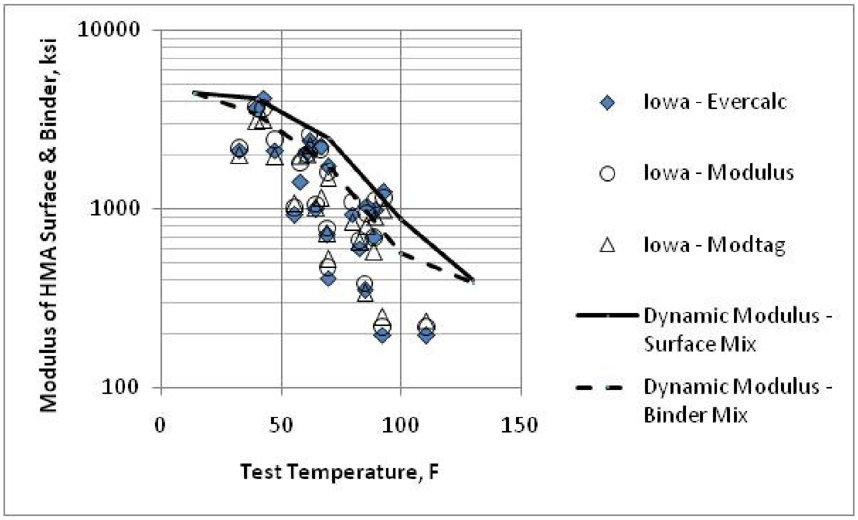


Figure 17. Graph. Comparison of backcalculated HMA surface and binder layer moduli and laboratory-measured moduli from the Iowa SPS-1 project.

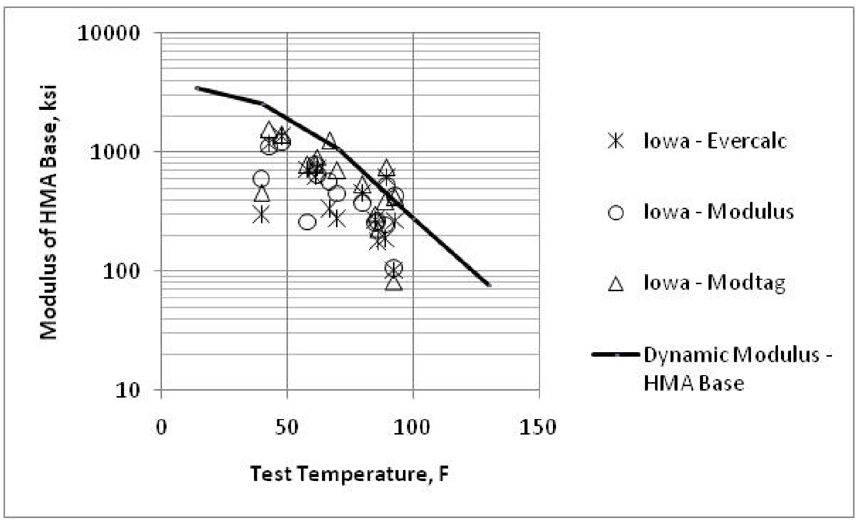


Figure 18. Graph. Comparison of backcalculated HMA base layer moduli and laboratory-measured moduli from the Iowa SPS-1 project.

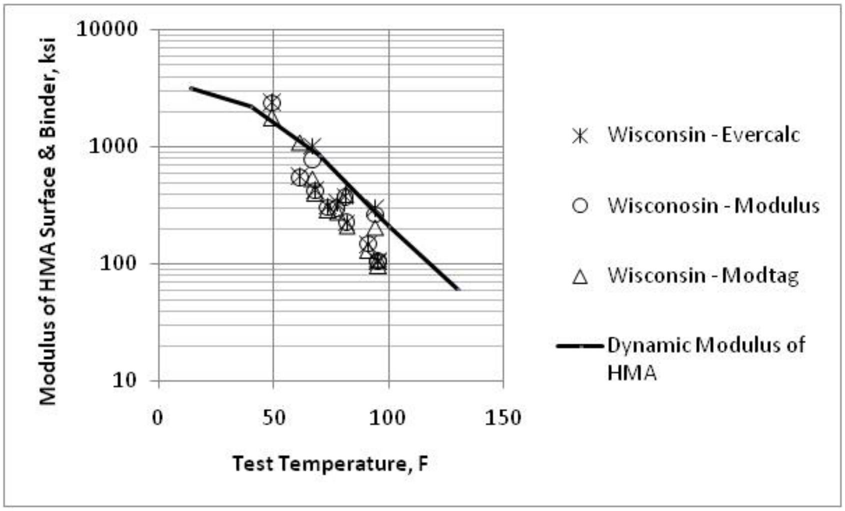


Figure 19. Graph. Comparison of backcalculated HMA surface and binder layer moduli and laboratory-measured moduli from the Wisconsin SPS-1 project.

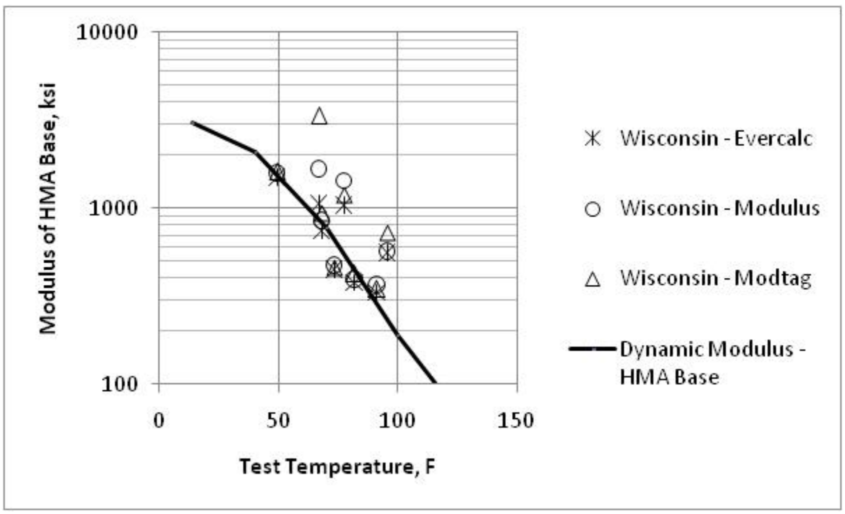


Figure 20. Graph. Comparison of backcalculated HMA base layer moduli and laboratory-measured moduli from the Wisconsin SPS-1 project.

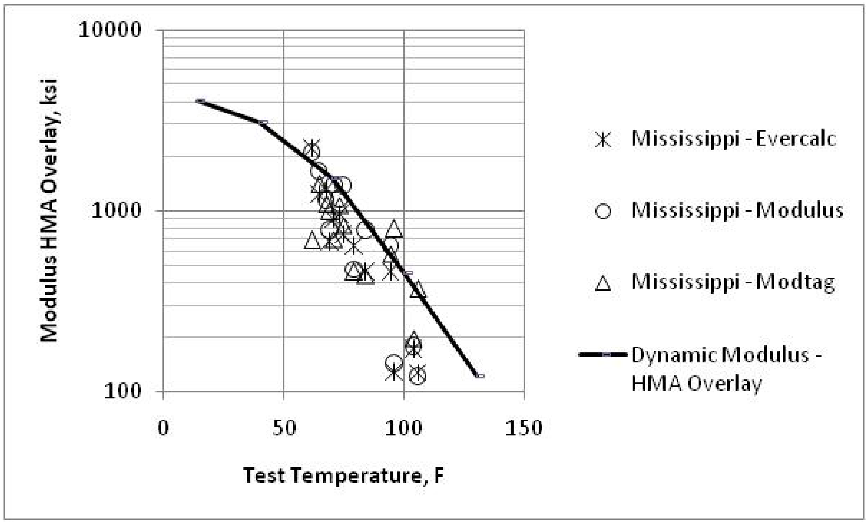


Figure 21. Graph. Comparison of backcalculated HMA overlay moduli and laboratory-measured moduli from the Mississippi SPS-5 project.

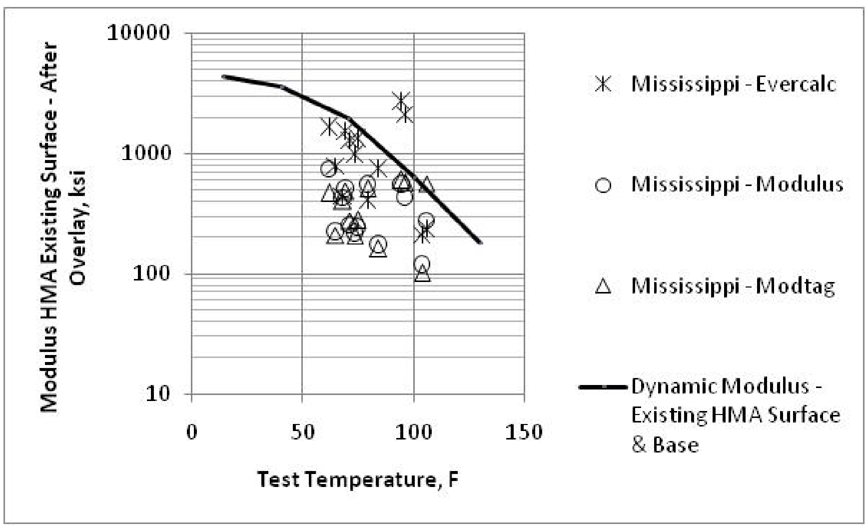


Figure 22. Graph. Comparison of backcalculated HMA surface layer moduli of the existing pavement after overlay placement and laboratory-measured moduli from the Mississippi SPS-5 project.

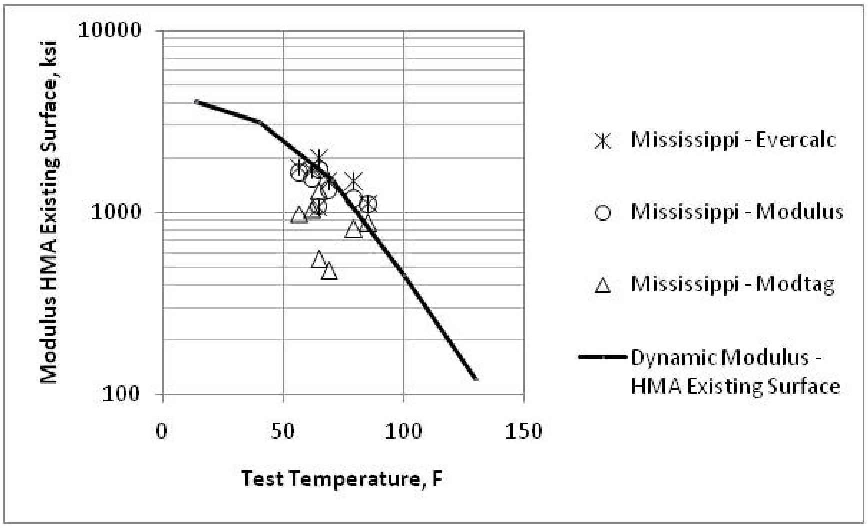


Figure 23. Graph. Comparison of backcalculated HMA surface layer moduli of the existing pavement prior to overlay placement and laboratory-measured moduli from the Mississippi SPS-5 project.

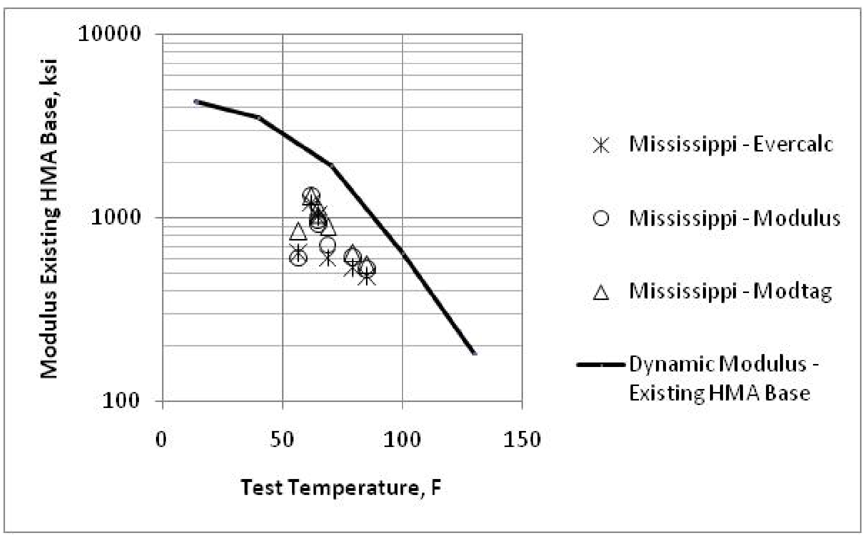


Figure 24. Graph. Comparison of backcalculated HMA base layer moduli of the existing pavement prior to overlay placement and laboratory-measured moduli from the Mississippi SPS-5 project.

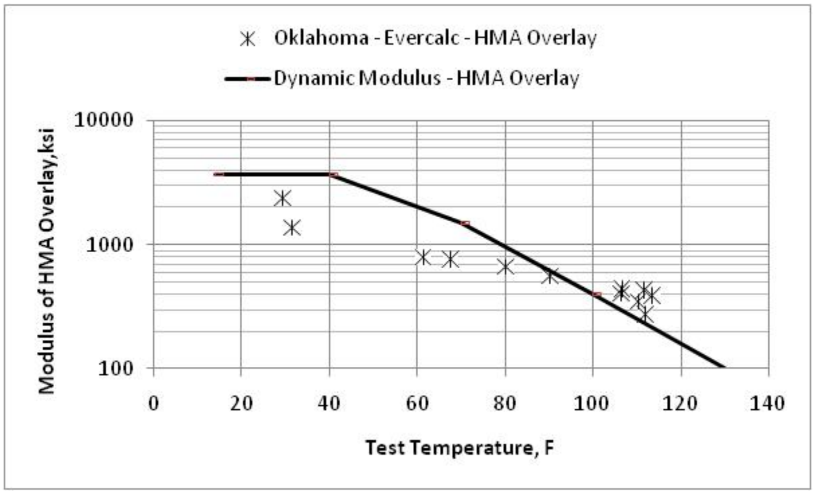


Figure 25. Graph. Comparison of backcalculated HMA moduli and laboratory-estimated dynamic modulus for the Oklahoma SPS-6 project.

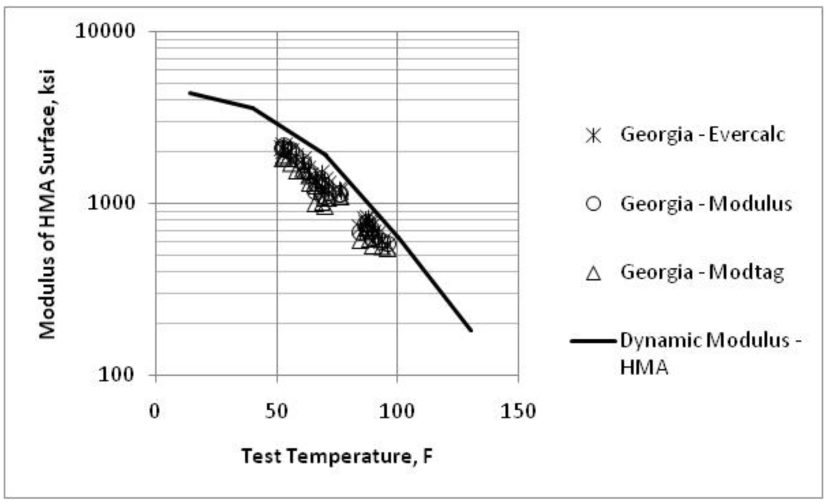


Figure 26. Graph. Comparison of backcalculated HMA moduli and laboratory-estimated dynamic modulus for the Georgia SMP project.

In summary, there is an insignificant difference between the resulting HMA elastic moduli from EVERCALC©, MODULUS, and MODCOMP©, but none of the programs resulted in unbiased predictions of the laboratory-measured values. This observation is important because it supports the MEPDG methodology for using FWD testing and backcalculated layer moduli of HMA layers for estimating the damage in those layers.(1) The sites that exhibited greater dispersion between the laboratory-estimated (undamaged dynamic moduli) and field-derived (damaged elastic moduli) moduli were found to have stripping or moisture damage and/or extensive cracking reported in the LTPP database.

Unbound Materials

Figure 27 through figure 29 compare the backcalculated elastic moduli from EVERCALC©, MODULUS, and MODCOMP©, respectively, and the laboratory-derived resilient moduli for each site for the weathered soil and subgrade layers. As shown, there is a lot of dispersion between the results, but the results are somewhat consistent with some of the earlier studies.(45,46) The average *c*-factors calculated for the subgrade layers using the three candidate programs are as follows:

- **EVERCALC©**: Average *c*-factor = 0.35; standard deviation = 0.136.
- **MODCOMP©**: Average *c*-factor = 0.36; standard deviation = 0.146.
- **MODULUS**: Average *c*-factor = 0.41; standard deviation = 0.266.

Results from EVERCALC© exhibited a coefficient of variation of 39 percent for the averages, which were about equal to the results from MODCOMP© with a coefficient of 40 percent but much lower than the results from MODULUS, which had a coefficient of variation of 65 percent.

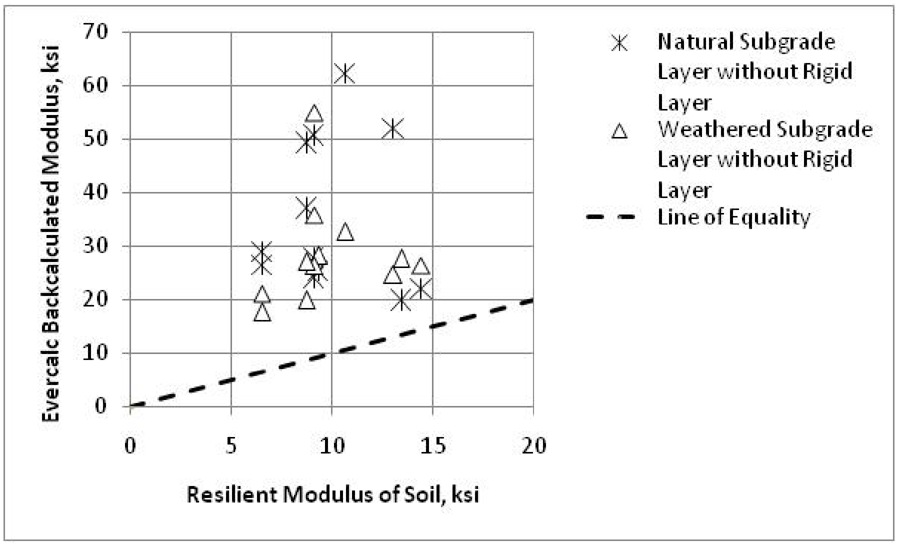


Figure 27. Graph. Comparison of backcalculated elastic moduli of unbound layers using EVERCALC© and laboratory-derived resilient modulus.

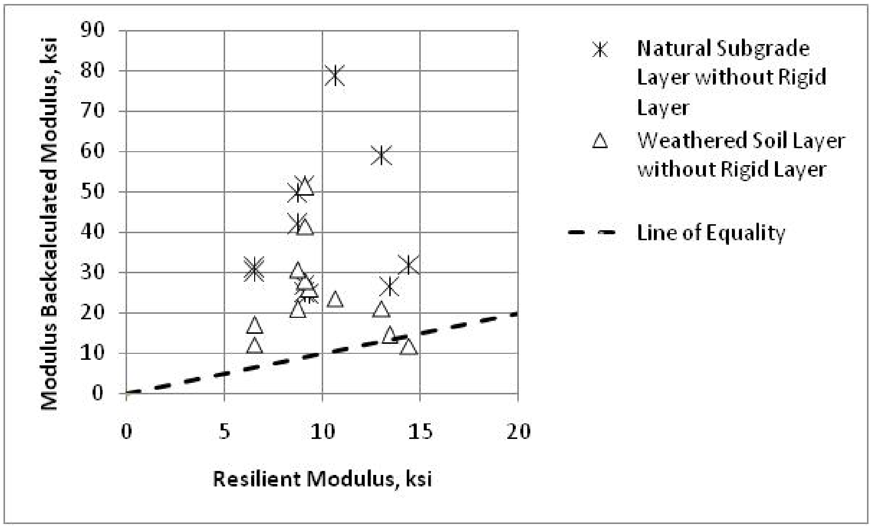


Figure 28. Graph. Comparison of backcalculated elastic moduli of unbound layers using MODULUS and laboratory-derived resilient modulus.

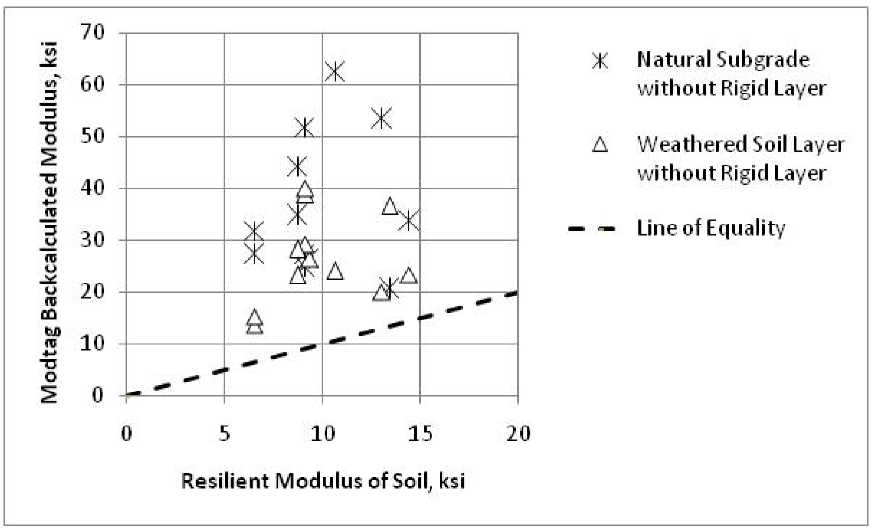


Figure 29. Graph. Comparison of backcalculated elastic moduli of unbound layers using MODTAG© and laboratory-derived resilient modulus.

CASE STUDY SUMMARY

Candidate programs were used to estimate elastic layer modulus values for the same deflection basins. Observations from the case studies were the same as those documented in the Smith study.[53] EVERCALC© consistently resulted in lower error terms and a higher number of successful modulus determination when considering all deflection basins. When only considering those deflection basins that ran successfully, the MODCOMP© program resulted in the lower RMSE values.

The results from the case studies suggest the use of multiple software packages for various pavement types. Thus, two software packages and one method were selected for use in the production runs for flexible and rigid pavements: EVERCALC© and MODCOMP© for flexible pavements and those two plus the best fit method for rigid pavements. EVERCALC© was selected as the primary package, while MODCOMP© was used to confirm discrepancies or anomalies identified by EVERCALC©. Another reason for selecting MODCOMP© is that EVERCALC© is restricted to five layers, including a rigid layer if present, while MODCOMP© can simulate up to seven layers.

CHAPTER 4. BACKCALCULATION PROCESS

One of the difficulties in backcalculation is that no unique solution or set of elastic layer moduli for a specific set of measured deflection basins is determined. More importantly, the quality of the results is heavily dependent on the knowledge and expertise of the user in setting up the problem. In other words, different users can obtain different results for the same set of deflection basins. This non-uniqueness of solutions has been a major deterrent for some agencies to take full advantage of backcalculation methods for routine rehabilitation design. Many agencies limit use of the deflection data to determine the subgrade elastic modulus. Thus, a key goal of this project was to automate the process and make it less dependent on the user so that others not directly involved in the development of the tools and procedures can recreate the results.

This chapter provides a general overview of the backcalculation process. In addition, it discusses the steps and decisions that were automated in setting up the problem and describes the tools written to simplify the backcalculation process while taking full advantage of the entire deflection basin data for rehabilitation design in accordance with the MEPDG.(1) The criteria used for determining whether the results are acceptable are also included in this chapter. The automated process is specific to LTPP and the data structure/tables included in the LTPP database. However, the steps and activities presented here can be used to improve the backcalculation of elastic layer moduli for individual rehabilitation projects.

Backcalculation Procedures and User Guide for Software Programs and Utility Tools includes a user's guide for the automated backcalculation process as well as executing the utility and software tools for organizing the results included in the CPTs in the LTPP database.(56) This chapter summarizes the decisions for the pre-processing part as well as the generation the inputs for the backcalculation programs and a review of the results for acceptability.

OVERVIEW OF PROCESS

Figure 30 shows a simplified flowchart of the major steps and decisions used in the backcalculation process.

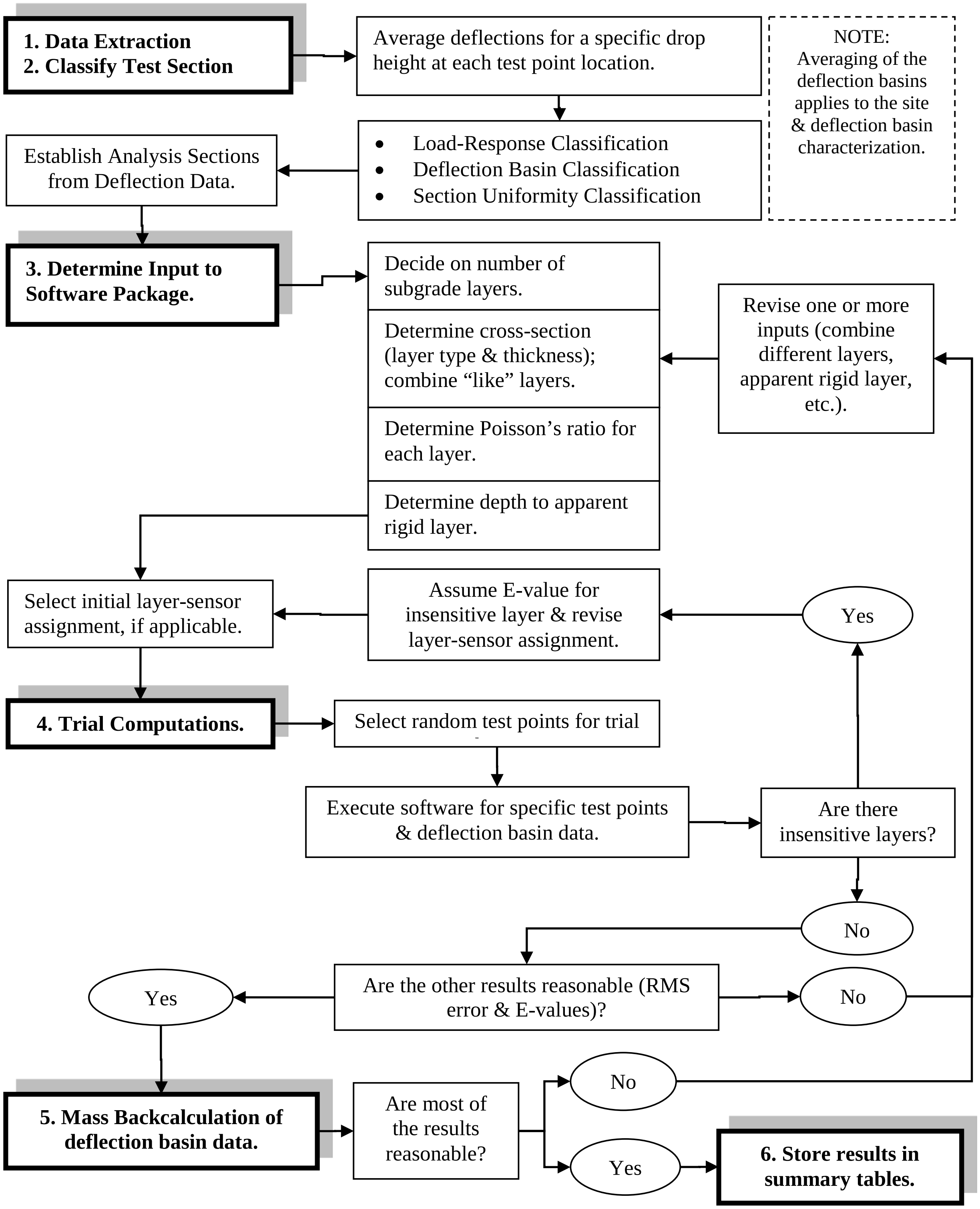


Figure 30. Flowchart. Major steps and decisions in linear elastic backcalculation process.[(4)]

The following list explains the major steps and activities for each step:

1. Extract the following data needed for the backcalculation and interpretation of results:

    - Deflection basin data and associated information (dates and times of testing, temperatures, etc.).
    - Sensor location or offset distance.
    - Pavement cross section (layer types and thicknesses).
    - Maintenance and rehabilitation activities. The maintenance and rehabilitation history of the selected sections were used for establishing the layering of each section with time.
    - Shoulder or boring information from the deeper samples. A macro was written to identify selected words on the boring logs to determine the depth to refusal or some hard layer as well as the depth to a saturated or wet layer.
    - Information on the types and magnitudes of distress along the test section.
    - Distress data measured over time, specifically, the distresses that affect the load-response behavior (cracking and distortion (rutting and faulting)).

2. Categorize test section and deflection basin data to identify anomalies and determine if there is an issue with the deflection basins. The important point of this step is to determine if the categories changed during different testing dates. If there appears to be a problem with the deflection basins within a specific date that is different from the others, these are marked and coded. Steps include the following:

    - Execute the deflection basin and load-deflection response classification. All deflection basins were characterized by the same four categories established by Von Quintus and Simpson: type 1, type 2, type 3, and typical.[4] The decision criteria for the categories are included in a flow chart in *Backcalculation Procedures and User Guide for Software Programs and Utility Tools*.[56]
    - Execute the Sensor Location Independent Check (SLIC) program within MODTAG© to confirm or check any anomaly identified.

3. Determine structure or layering assumptions to be used as follows:

    - Identify insensitive layers; assume the modulus of an insensitive layer or combine it with an adjacent layer.
    - Combine similar and adjacent layers but separate significantly different and thick soil strata as well as thick aggregate layers.
    - Identify layer anomalies and potential problem layers, such as sandwich sections, stiff soils above weaker or saturated soils, etc.

- Estimate depth to apparent rigid layer.
- Estimate depth to the water table.

4. Format deflection basin data into the requirements of the software package and set up preliminary trial runs. Most of the inputs are the same between the different programs, but the format for the deflection basin data is different. Steps are as follows:

   - Execute trial computations.
   - Compare the results with the allowable RMSE and acceptable modulus values for the layers and materials in question.
   - Review adjacent layer modulus ratios between unbound layers to identify unrealistic or improbable conditions.
   - Make any necessary adjustments to the layering assumptions.

5. Execute mass or batch backcalculation of deflection basin data for a specific site.
6. Extract and store results in summary tables from the backcalculation package (discussed further in chapter 5).

Backcalculation Programs

As discussed in chapter 3, two backcalculation programs and one method were used in step 5 and are described as follows:

- EVERCALC© was the primary program used for the analyses and was used for all data and all pavement types in LTPP. The pre- and post-processing utility tools for the EVERCALC© analyses were fully automated. The automation process included the generation of input files based on pavement simulation rules, the execution of EVERCALC©, and post-processing the results.
- MODCOMP6.0© was used as the auxiliary program to backcalculate results for those LTPP sections that did not yield acceptable results with EVERCALC©. The MODCOMP© analyses were semi-automated as an iterative approach, and the simulated backcalculation structure was selected on a case-by-case basis until the results converged within the selected criteria. A few test sections or portions of test sections did not converge to produce satisfactory results even after multiple efforts using EVERCALC© and MODCOMP©. Chapter 5 provides more information on the feedback reports and error flags to identify these sections as part of the post-processing process.
- The best fit method was used to analyze LTPP sections with a PCC surface to obtain the subgrade *k*-value and the elastic moduli of the PCC and base layers. The PCC and base modulus values were determined for two interface conditions—bonded and unbonded.

Prior to the execution of the backcalculation programs, the project team established the criteria for establishing a quantitative measure for categorizing the validity of the backcalculated modulus values. This was based on two parameters: the generated RMSE and the magnitude of the backcalculated modulus value for each layer depending on the layer type and layer category. The RMSE criterion was set at 3 percent (i.e., for the results to be valid, the RMSE needed to be at or below 3 percent). Also, the backcalculated modulus value for each layer had to fall within the acceptable or atypical range for each material type (see *Backcalculation Procedures and User Guide for Software Programs and Utility Tools*).(56) It was envisioned that all results would ultimately be categorized as follows and defined by the assigned ERROR_STATUS, which is a term used to identify the RMSE magnitude in a column within the LTPP backcalculated elastic layer moduli computed parameter table database:(57)

- **Accept:** This includes basins for which the RMSE values were less than or equal to 3 percent, and the backcalculated modulus results were within the specified acceptable range for each layer. The range specified for each layer depended on the layer type and layer category, which are discussed in *Backcalculation Procedures and User Guide for Software Programs and Utility Tools*.(56)

- **Atypical**: This includes basins for which the RMSE values were less than 3 percent and the backcalculated modulus values exceeded the acceptable range but were within the atypical range as defined in *Backcalculation Procedures and User Guide for Software Programs and Utility Tools*.(56)

- **Error:** This includes basins for which the RMSE values exceeded 3 percent and/or the backcalculated modulus values exceeded the atypical range defined in *Backcalculation Procedures and User Guide for Software Programs and Utility Tools*.(56)

The error status for the best fit results was based on the modulus values of the PCC and the base layers for the bonded condition. Additionally, the RMSE4 value, which is the RMSE value determined from the measured and computed deflections for the four sensors used in the best fit analysis, was the basis for assigning the error status for the best fit method.

All programs were executed in a batch mode process on a state-by-state basis to handle the large volume of deflection basins in the LTPP database. Most of this chapter focuses on the decisions made in automating the process to determine inputs to the EVERCALC© and MODCOMP© programs. The best fit method provides unique solutions for PCC-surfaced pavement using a three-layered structure. Appendix A provides more detailed information on the computations and equations used to calculate the unique solutions from selected sensors within the deflection basin. Some revisions were made to the method that was originally developed during the first round of backcalculation sponsored by FHWA.(3) Thus, appendix A focuses on describing the mathematics used to calculate the elastic modulus and *k*-value of the PCC-surfaced test sections.

The EVERCALC© and MODCOMP© analyses were performed in four main analysis phases. Each phase progressively identified and filtered out those cases with poor quality results and made appropriate adjustments to the analysis parameters to improve the convergence in the subsequent phase. The first phase included all LTPP data, while the second used a subset from the first phase. The third and fourth analysis phases, if required, used a subset from the second phase. The four phases include the following:

1. The first analysis phase included EVERCALC© analysis for all LTPP sections using material parameters selected to represent typical ranges of inputs values for each material/layer type. Results from the first phase analyses were examined to classify them into the accept, atypical, or error categories described previously.

2. The second analysis phase included an expanded modulus range for the analyses of the LTPP test sections or test days with more than 25 percent atypical (i.e., invalid) results in the first phase analysis (converged to one of the boundary limits with RMSE values less than 3 percent) and RMSE values for the other stations being less than 5 percent. If the majority of the results converged to one of the boundary modulus values and resulted in high RMSE values (greater than 5 percent) defined as errors, the results and pavement simulation structure were manually reviewed based on compensating error effects (two layers resulted in hitting upper and lower modulus boundary limits) and the potential for layer anomalies.

3. The third analysis phase included test days with erroneous results at the end of the second phase and was performed using MODCOMP©. Results from the second phase were evaluated between multiple test days for inconsistency in results. The focus of the third phase was performing a manual review of the results and making appropriate revisions of the simulated structure to obtain acceptable results. The pavement structure simulation was revised based on whether the second phase results showed an invalid layer modulus, whether there were compensating errors (defined in chapter 5), whether extensive distresses were present, and whether the potential for layer anomalies could exist.

4. In some cases, a fourth analysis phase analysis was performed using MODCOMP© and a revised pavement simulation structure based on the results from the second and third analysis phases. If unacceptable results were obtained after the fourth phase, no additional analyses were completed.

LTPP Data

The deflection data were extracted from LTPP Standard Data Release (SDR) 27.0 (released in 2013) and included specific data from all LTPP test sections for all days of deflection basin testing. The data needed for the backcalculation of layer modulus values were grouped into two categories: direct and indirect. Table 5 lists the LTPP data tables from which the direct and indirect data were extracted for the pre-processing tools to establish the inputs and the post-processing tools to evaluate the final results.

The direct data were from tables that needed to establish the inputs for the backcalculation and forward calculation of layer moduli, and the indirect data were from tables that needed to evaluate the results from the backcalculation process. The direct data elements were extracted from the LTPP database for all test sections on an experiment basis. The indirect data elements were extracted for those test sections that had an appreciable number of results that were considered unacceptable in order to identify potential reasons for the unacceptable or poor results.

Table 5. Tables from the LTPP database for evaluating data for the backcalculation process.

Data Category	Data Table Name	Purpose of Data Use
Direct use of data elements	EXPERIMENT_SECTION	Identifies the specific experiment and pavement type.
	MON_DEFL_LOC_INFO	FWD deflection basin data and location information measured along each section.
	MON_DEFL_MASTER	
	MON_DEFL_DROP_DATA	
	MON_DEFL_TEMP_DEPTHS	Pavement and air temperatures measured during FWD testing.
	MON_DEFL_TEMP_VALUES	
	MON_DEFL_DEV_SENSORS	Location of each sensor from loading plate.
	MON_DEFL_FLX_BACKCAL_BASIN	Backcalculated layer modulus values for flexible pavements from first round study; available in SDR 20.0. Structure listed in SDR 20.0 was used to set the initial cross section.[2]
	MON_DEFL_FLX_BACKCAL_LAYER	
	MON_DEFL_FLX_BACKCAL_POINT	
	MON_DEFL_FLX_BACKCAL_SECT	
	MON_DEFL_FLX_NMODEL_POINT	Backcalculated nonlinear values; these were not used in current study.
	MON_DEFL_FLX_NMODEL_SECT	
	MON_DEFL_RGD_BACKCAL_BASIN	Backcalculated layer modulus values for rigid pavements; available in SDR 20.0. Structure listed in SDR 20.0 was used to set the initial cross section.
	MON_DEFL_RGD_BACKCAL_LAYER	
	MON_DEFL_RGD_BACKCAL_POINT	
	MON_DEFL_RGD_BACKCAL_SECT	
	SECTION_LAYER_STRUCTURE	Layer type and thickness information for simulating pavement structure; both the layer thickness on each end of the project will be extracted as well as the representative thickness.
	TST_L05A	
	TST_ L05B	
	GPR_MASTER	Ground-penetrating radar (GPR) data for estimating thickness along the test section.
	GPR_THICK_POINT	
	GPR_THICK_SECT	
	GPR_LINK_LAYER	Layer identification for GPR data.
	TST_HOLE_LOG	Boring log information and data to determine or confirm depth to rigid layer and depth of water table of saturated materials.
	TST_SAMPLE_LOG	
Indirect Use of Data Elements	INV_GENERAL	Lane width, type of shoulder, and other information.
	TST_ESTAR_MASTER	Dynamic modulus for HMA mixtures. Other tables are included for the volumetric data.
	TST_ESTAR_MODULUS	
	TST_ACO2 and TST_ACO3	Data needed to determine the air voids of each HMA.
	TST_AG04 and INV_GRADATION	Data needed to determine the gradation of the HMA.
	TST_MR	Resilient modulus data for unbound materials.
	TST_ISD_MOIST	Moisture content data to confirm high or low values.
	MON_DIS_AC_REV	Flexible and rigid pavement distress data to confirm low elastic modulus values.
	MON_DIS_JPCC_REV	

Note: Other data elements were extracted and used indirectly from the LTPP database. The ones listed in this table are more commonly used.

Presence of Bedrock Layer

In the first and second phases of the analyses, all sections were analyzed using the following two assumptions:

- **Without a rigid layer:** All cases were analyzed using the EVERCALC© program interface. The execution of EVERCALC© using this assumption was automated, thereby eliminating the need for manual intervention to complete the analyses.

- **With a rigid layer:** All these cases were analyzed by running EVERCALC© using the backcalculation.exe application from the MS-DOS prompt. In many cases, the depth to a rigid layer was calculated, but the RMSE was high, exceeding its upper limit.

The automation process compared the RMSE and range of backcalculated elastic moduli resulting from the pavement simulation with and without a rigid layer. Whichever simulation resulted in the lower RMSE was used for further analyses. In many cases, the RMSEs were significantly different.

The presence of a rigid layer was also verified independently in the second and third analysis phases. The depth to a hard layer was included in the automation process by identifying selected words on the deeper borings or shoulder probes. Some of the words included in the search were refusal, hard layer, hard pan, rock, and limestone.

The best fit procedure did not require a different treatment of the data for sections with or without a stiff layer. The *k*-value was assumed to reflect, or at least account for, the presence of a bedrock layer in the backcalculation structure.

Presence of Ground Water or Wet Layer

It has been the authors' experience that separating dry and wet or saturated layers improves the accuracy of the solution. Thus, the same tool to determine the depth to a hard layer was used to search the shoulder probes for wet layers. The words used in the search were "water," "wet," "soft," and "saturated." This depth was used to initially separate the weathered subgrade layer from the natural subgrade.

Pre-Processing and Computational Tools

The analyses were performed in a systematic manner, as documented in *Backcalculation Procedures and User Guide for Software Programs and Utility Tools*.[56] In keeping with the requirements outlined by LTPP, the analyses were automated to minimize manual errors and to enable an independent user the ability to reproduce the results. In addition, the automation process was designed to enable users to generate results for additional data collected by LTPP in the future. The analyses utilized raw data in Microsoft Access® format from the LTPP database as the starting point to generate the backcalculation results. The results were merged back into Microsoft Access® tables with common reference fields with the original deflection tables, as explained in the description of the data schema provided in *Schema for the Computed Parameters Table*.[57] Therefore, Microsoft Access®-based macros, Microsoft Windows®-based utilities, and user interfaces were developed to do the following:

- Perform general data validity checks.

- Use the original LTPP tables to merge deflection, sensor spacing, and temperature data.

- Establish data flags to filter out problem basins (i.e., those with non-decreasing deflections, missing deflection data, or missing sensor spacing data). Missing temperature data were flagged but not discarded for backcalculation.

- Process pavement layer information from raw data in LTPP tables to develop backcalculation structure suitable for use in the EVERCALC© program. This involved combining pavement layers so as to reduce the pavement structure to an equivalent backcalculation layer structure meeting EVERCALC© requirements.

- Assign reasonable seed modulus values and range of modulus values for use in the backcalculation process.

- Generate the input files in the format necessary for use in the EVERCALC© program.

- Generate input files in the format necessary for use in the MODCOMP© analyses. Because the MODCOMP© analyses followed EVERCALC©, the input files for MODCOMP© were created by modifying the EVERCALC© input files.

- Generate the input files in the format necessary for the best fit analyses program. These files were created directly from the Microsoft Access® data tables and were independent of the EVERCALC© or MODCOMP© analyses.

- Execute the EVERCALC© analyses in a batch mode.

- Execute the MODCOMP© analyses in a batch mode.

- Execute the best fit analyses in a batch mode.

- Calculate the load transfer efficiency (LTE) across the transverse and longitudinal joints in JPCP sections and across transverse cracks in CRCP sections.

- Read output data files, merge results, and compute summary tables for inclusion in LTPP results database.

The macros were developed in Microsoft Access® primarily because the raw data resided in Microsoft Access® tables. The macros were used to perform the preliminary data checks and to create supplementary data tables. Supplementary data are all data other than the raw FWD deflection data that are necessary to perform the backcalculation analyses, including sensor spacing, temperature data, backcalculation layer structure and layer thicknesses, layer material information including specified ranges for EVERCALC© analysis, and beta factors for the best fit analysis methods.

A standalone software program, Back Calculator, was developed for this current study for bulk processing and filtering the deflection data, for executing the EVERCALC© program and the best fit method, and for processing the backcalculation results. Back Calculator is discussed in *Backcalculation Procedures and User Guide for Software Programs and Utility Tools*.(56) MODCOMP© analyses were not included in this program because only a limited number of sections were analyzed using MODCOMP©. MODCOMP© analyses were performed in a batch mode by executing the application file from an MS-DOS prompt.

Pre-Processing Deflection Data

The pre-processing tools for the deflection data were used to convert deflection basin data from the format in which they were collected to the format required for input to the backcalculation program as well as to identify deflection data anomalies that cause the program to generate unrealistic solutions and establish the pavement layering simulation.

Two parameters were checked in terms of pre-processing the deflection basin data: the type of deflection basins (typical and types I, II, or III) and type of structure (deflection softening, elastic, or deflection hardening). Von Quintus and Simpson and Von Quintus and Killingsworth defined and used these parameters during the first round of backcalculation of layer moduli as well as in other local calibration studies.(4,45) Deflection basins identified along a test section inconsistent with elastic layer theory were flagged.

The deflection basin and load-response behavior categories can also be used to guide the initial pavement layering simulation. For example, sites with a high percentage of type II deflection basins usually indicate some stiff layer close to the surface but not at the surface or some discontinuity at the surface varying from cracks to debonding. Different pre-processing activities related to the deflection data include the following:

- Pre-processing of deflection data was performed to determine the deflection basin and load-response categories, as well as identify sensor data issues using SLIC (part of the MODTAG© program for evaluating the deflection basin data). The decision criteria for categorizing each test section and deflection basin are documented in the Von Quintus and Simpson report.(4)

- An apparent rigid or stiff layer was estimated along each test section in accordance with the procedure identified by EVERCALC© and MODCOMP©. The depth to an apparent rigid layer can be highly variable along a test section as well as between test days.

- Deflection basin data were reviewed to identify changes in the categories over time, which could indicate a seasonal water table depth, increased damage, and/or occurrence of distress (cracking and distortion) or debonding between adjacent layers.

The representative thickness of the structural layers of an LTPP test section was determined to be the average thickness of that layer. For most of the LTPP test sections, layer thicknesses were only measured at the beginning and end of the section. In a few cases, the layer thickness and material types varied from one end of the section to the other. Thickness variations along a site can have a detrimental effect on trying to determine acceptable layer modulus values for that site.

The measured deflections were used to subdivide the sections into two parts when the layer thickness from the approach and leave ends of the section varied significantly. There were sites with an abrupt change in the measured deflections from one end to the other, and other sites where the measured deflections continually decreased or increased from one end to the other. LTPP sponsored a study using GPR data to estimate the variation of layer thickness throughout some of the test sections. These GPR data, when available, were used to make a decision on subdividing an individual section.

The process compared the layer thickness measured on the leave and approach ends of each test section. The initial criteria used for comparison was 0.5 inch for PCC and HMA layers and 1 inch for the unbound base and treated subgrade (TS) layers. If no significant difference in layer thickness was measured, LTPP materials data table TST_L05B within the LTPP materials database was used to determine the representative layer type and thickness at the site. For those sites with large deviations in layer thickness, the layer thicknesses determined from the GPR data were used to determine if the test section should be subdivided. If GPR data were unavailable, the deflection data were used to decide whether the test section should be subdivided into multiple test sections for backcalculating elastic modulus values.

PAVEMENT SIMULATION RULES

The number of layers and individual layer thickness are critical parameters for backcalculating the elastic modulus of structural layers (i.e., layers that have a significant impact on the deflection basin with reasonable changes or variation in modulus). Getting a reasonable starting pavement simulation for the measured deflection basin is probably the most important activity in the backcalculation process, and as such, was included as an automated feature in the pre-processing tools to remove subjectivity.

Most backcalculation software packages limit the number of layers that can be backcalculated to a maximum of three and five, but that number depends on the number of sensors and their spacing. The first and second phases of the backcalculation process were limited to five layers to accommodate the features of the selected backcalculation program. The third and fourth analysis phases explored the option of using up to seven layers, including any known layer modulus or insensitive layer. However, the results that were acceptable included no more than five layers. Therefore, under this project no more than five layers were backcalculated.

The rules of simulation reported in the MEPDG were used to set up the pavement structure for each LTPP test section.(1) Setting up the initial pavement layering simulation is straightforward, but there are factors that complicate the process. For example, layer thicknesses are not known at every deflection point, and some subsurface layer conditions can be overlooked or not adequately identified throughout the test section. The following lists provide some general rules of simulation for creating the pavement structure used in backcalculating elastic layered modulus for each of the structural layers. Many of these rules are discussed in other areas of the report, but they are repeated here for the convenience of the reader.

General notes include the following:

- It is optimal to start with the fewest number of layers possible and estimate the depth to an apparent rigid or stiff layer for each drop height along the test section prior to program execution.

- Thin non-structural layers should be combined with adjacent like layers. *Thin* is defined as less than 2 inches or less than half the thickness of the layer above the layer in question. As an example, an HMA open-graded friction course should be combined with the supporting HMA layer. In many cases, *thin layers* are defined as insensitive layers.

- The moduli for the insensitive layers were assumed using typical values included and reported in the MEPDG, or the layer was combined with an adjacent “like” layer.(1) As noted above, an *insensitive layer* is defined as one that has little to no impact on the measured deflection basin.

- GPR data were used to estimate the change in thickness and subsurface conditions along the test section. Where available, GPR data were reviewed to estimate significant changes along the test section from what is recorded in the L05B table (layer thickness, subsurface feature, etc.). If the GPR data suggested variable layer thickness between the ends of the section, a decision was made on whether to subdivide the section into two parts. If a substantial difference in surface layer thickness was found between the leave and approach ends and GPR data were unavailable, deflection data were used to determine the location of the transition. If an abrupt change was identified via the deflection basin, the section was subdivided into two subsections.

- Similar or like materials of adjacent layers should be combined into one layer. *Like* is defined as materials or layers with the same AASHTO classification exhibiting similar laboratory-measured modulus values and the same stress-sensitivity and physical properties. Like layers were combined in setting up the structure at a particular site. This is one of the reasons for extracting the layer material properties for use in this study.

- The lower layers should be combined first, and the upper pavement layers should be treated in more detail, if possible. The discussion and guidance that follows, however, starts with the foundation layers and proceeds up to the surface layers.

Subgrade layer notes include the following

- Boring logs and shoulder probes should be reviewed to determine the foundation soils and the vertical strata and their condition.

- At the beginning, the subgrade or foundation soils should be divided into two layers, especially when bedrock and other hard soils are not encountered. The lower layer represents the natural soil, while the upper layer represents the compacted soils just beneath the pavement materials. This layer is considered to be the weathered soil layer.

- Bedrock and other hard soils (such as hard pan, shale, sandstone, etc.) believed to be more than about 20 ft below the surface usually have an insignificant effect on the calculated pavement responses for predicting various distresses. In some cases, however, better results were obtained if that hard layer was simulated within 600 inches to the surface.

- Depth to a water table or wet layer is important for both structural evaluation and backcalculation of layer modulus. It is optimal to stratify the subgrade at the depth of the water table because of the different layer response to load. The water table can vary by season, so the layering at a site can be different within different seasons.

- Geo-synthetic fabrics and other materials are not simulated by themselves in the structural response program. However, these types of reinforcing fabrics can result in a higher modulus of the layer in which they are placed. Filter fabrics used for drainage purposes between a fine-grained soil and aggregate base material are not simulated in the pavement structure and usually have no impact on the structural response of the pavement.

Unbound aggregate material notes include the following:

- In most cases, the number of unbound granular base (GB) and subbase layers should not exceed two, especially when one of those layers is thick (more than 18 inches in thickness). Sand and other soil-aggregate materials should be simulated separately from crushed stone or crushed aggregate base materials.

- If thick, unbound aggregate or select materials (i.e., exceeding 18 inches) are used, this layer can be treated as the upper subgrade layer. Thick granular layers are typically used in northern climates as non-frost susceptible materials. When these layers are treated as the upper subgrade, then only one subgrade layer is needed.

- If a thin aggregate base layer is used between two thick unbound materials, the thin layer should be combined with the weaker or lower layer. For example, a 6-inch sand subbase layer placed between an A-1-b AASHTO classified subgrade soil (SS) and crushed stone base can be combined with the upper subgrade layer.

- When similar aggregate base and subbase materials are used, those materials can be combined into one layer.

Treated and stabilized material notes include the following:

- ATB layers, sometimes referred to as “blackbase,” should be treated as separate layers and not combined with dense-graded HMA base mixtures. Typically, these are crushed stone base materials that have a small amount of asphalt and/or emulsion that can be produced at a plant or mixed in place. However, ATB materials that are designed using the gyratory compactor or other compaction device and produced through a production facility can be treated as an HMA base material and combined with other dense-graded HMA layers.

- Cement-treated and other pozzolanic stabilized materials that are used as a base layer for structural support should be treated as a separate layer. In some cases, a small portion of cement, lime, or fly ash may be added to GB materials to improve the strength or lower the plasticity index of those materials for constructability issues. These materials should still be considered as a separate layer.

- Lime and lime-fly ash stabilized SSs should be treated as a separate layer, if possible. In some cases, a small amount of lime or lime-fly ash is added to soils in the upper subgrade to lower the plasticity index and from a constructability standpoint. For these cases, the lime or lime-fly ash stabilized soil should be combined with the upper subgrade layer.

Drainage layers/material notes indicate that permeable ATB drainage layers should be treated as separate layers and not combined with dense-graded HMA layers or ATB layers, if possible.

HMA mixture notes include the following:

- Similar HMA materials should be combined into one layer. For example, an HMA wearing surface or mix and an HMA binder layer can be combined into one layer without affecting the accuracy of the predictions.

- Thin HMA layers can be combined with an adjacent HMA layer. As noted earlier, thin is defined as less than 2 inches in thickness. Thin HMA leveling courses, or for the condition when the thickness of the leveling course is highly variable along the roadway, can be combined with the other HMA layers or ignored without affecting the overall accuracy of the results.

- The number of HMA layers should not exceed two, if at all possible. All layers that are dense-graded HMA mixtures should initially be combined.

DEFINING ACCEPTABLE ELASTIC LAYER MODULUS VALUES

Two parameters were used to judge the acceptability of the backcalculated values: (1) the error or RMSE between the measured and calculated deflection basins and (2) a comparison of the backcalculated values to the range of typical material specific values. A third factor was used (normality test for the results for a day's test) but only for evaluating the acceptability of the results.

Error Between Predicted and Measured Deflection Basins

All of the measurement points that have excessive error terms were flagged and not used in determining the statistics (means and standard deviation) for the test section and day of testing. *Excessive* is defined as an RMSE value greater than 3 percent. Deflection basins with RMSE values greater than 3 percent were included in the point-by-point CPTs (see *Schema for the Computed Parameters Table*) but excluded from the CPTs in determining the average of the in-place elastic moduli for each test section and test date.[57] Chapter 5 provides a summary of the CPTs for the backcalculation of elastic layer moduli.

Range of Calculated Modulus Values

The other criterion used in judging the acceptance of the results is the range of typical modulus values. The range of modulus values for typical materials and soils was determined to be consistent with values reported in the MEPDG.[1] Table 6 provides the range of typical modulus values included in the MEPDG.[1] The table also includes the range of values used for judging the reasonableness of the backcalculated layered elastic modulus values. Note that the table does not list all materials that are included in the LTPP program. It is a partial list to show examples of the typical range in material moduli.

Table 6. Typical range of modulus for different paving materials and soils.

Material Type		MEPDG Range (ksi)		Range for Backcalculation (ksi[a])	
		Lower Value	Upper Value	Lower Value	Upper Value
PCC, intact		1,000	7,000	1,000	10,000
Fractured PCC		200	5,000	30	2,000
HMA, uncracked		Temperature dependent		100	4,000
HMA, cracked		Temperature dependent		50	2,000
Cement-treated base		50	4,000	100	4,000
ATB		Same as HMA	Same as HMA	100	2,000
Stripped HMA		N/A	N/A	50	500
Cold in-place recycled		10	30	20	200
Crushed stone		20	45	10	80
Crushed gravel		20	30	10	60
Soil-cement		50	4,000	50	1,000
Lime-stabilized soil		50	4,000	20	100
AASHTO standard soil classes	A-1-a	16	42	10	60
	A-1-b	16	40		
	A-2-4	14	37.5	5	40
	A-3	14	35.5		
	A-4	13	29		
	A-5	6	25.5	5	40
	A-6	12	24		
	A-7-6	5	13.5		

N/A = Not applicable.
[a]The range of values for the backcalculation process are preliminary and depend on the physical properties and condition of the layers documented in the LTPP database or extracted from other reports and construction records.

During the first round of backcalculation values, some of the results were believed to be unacceptable because the backcalculated values fell outside the range of typical values. Although this factor was used to judge the results, the results are not necessarily unacceptable simply because the values fall outside a perceived range of values. Some of the results that were believed to be unacceptable from the first round have been found to be reasonable as a result of forensic and other investigations completed at specific LTPP test sections.

For example, some of the elastic modulus values for unbound aggregate base layers in Arizona were found to be greater than 100 ksi, which is extremely high. It was later found, however, that these unbound aggregate base layers had very low water content, and the fines were binding the base particles together so the aggregate layers were responding as bound layers. Some of the crushed limestone aggregates used in central Texas exhibited the same behavior when dry.

Normality Test Using Jarque-Bera Test Statistic

Another factor included in the automated process for evaluating the acceptability of the results was to determine if the calculated elastic layer moduli are characteristic of a normal distribution. Just about all volumetric and structural properties exhibit a normal distribution unless there is some type of bias that is created during construction or a boundary condition. Thus, results from a single test day were evaluated to determine if those results exhibited a normal distribution.

The verification for normal distribution was performed using the Jarque-Bera test statistic. For given data, x_1, x_2, …, x_n, the statistical terms shown in table 7 are calculated based on the normality test class.

Table 7. Statistical parameters calculated for normality check.

Statistic terms	Statistic Symbol	Functions from Code
Sample mean	$\bar{x}$	Mean
Second central moment (variance)	$\hat{\sigma}^2$	Variance
Third central moment (skewness)	S	Skewness
Fourth central moment (kurtosis)	K	Kurtosis
Jarque-Bera test statistic	JB	JarqueBeraTestStatistic

Figure 31 shows the formula for the skewness factor, figure 32 shows the equation for kurtosis factor, and figure 33 shows the equation for the Jarque-Bera statistic.

$$S = \frac{\frac{1}{n}\sum_{i=1}^{n}(x_i - \bar{x})^2}{\left(\frac{1}{n}\sum_{i=1}^{n}(x_i - \bar{x})^2\right)^{\frac{3}{2}}}$$

Figure 31. Equation. Skewness factor.

Where:

S = Skewness factor.
n = Number of data points in the sample.
i = Individual data point within the sample.
x_i = Data value within the sample.
$\bar{x}$ = Sample mean.

$$K = \frac{\frac{1}{n}\sum_{i=1}^{n}(x_i - \bar{x})^4}{\left(\frac{1}{n}\sum_{i=1}^{n}(x_i - \bar{x})^2\right)^2}$$

Figure 32. Equation. Kurtosis factor.

Where *K* = Kurtosis factor.

$$JB = \frac{n}{6}\left(S^2 + \frac{1}{4}(K-3)^2\right)$$

Figure 33. Equation. Jarque-Bera statistic used for verifying normality in data.

Where *JB* = Jarque-Bera statistic.

For a dataset that is normally distributed, it is expected that *S* and *K* both equal zero.

JB asymptotically has a chi-squared distribution with 2 degrees of freedom. The critical value is determined using table 8. Hence, at a significance level of 5 percent and 2 degrees of freedom, the critical value is 5.99 (shown in bold in the table). Therefore, if *JB* is greater than 5.99, *S* and excess *K* tend to deviate from zero, which does not imply a normal distribution. *JB* values less than 5.99 indicate a normal distribution.

Table 8. Critical chi-squared value for different degrees of freedom and levels of significance.

Degrees of Freedom	Chi-Squared Value										
1	0.004	0.02	0.06	0.15	0.46	1.07	1.64	2.71	3.84	6.64	10.83
2	0.1	0.21	0.45	0.71	1.39	2.41	3.22	4.60	**5.99**	9.21	13.82
3	0.35	0.58	1.01	1.42	2.37	3.66	4.64	6.25	7.82	11.34	16.27
4	0.71	1.06	1.65	2.20	3.36	4.88	5.99	7.78	9.49	13.28	18.47
5	1.14	1.61	2.34	3.00	4.35	6.06	7.29	9.24	11.07	15.09	20.52
6	1.63	2.20	3.07	3.83	5.35	7.23	8.56	10.64	12.59	16.81	22.46
7	2.17	2.83	3.82	4.67	6.35	8.38	9.80	12.02	14.07	18.48	24.32
8	2.73	3.49	4.59	5.53	7.34	9.52	11.03	13.36	15.51	20.09	26.12
9	3.32	4.17	5.38	6.39	8.34	10.66	12.24	14.68	16.92	21.67	27.88
10	3.94	4.86	6.18	7.27	9.34	11.78	13.44	15.99	18.31	23.21	29.59
p-value (probability)	0.95	0.90	0.80	0.70	0.50	0.30	0.20	0.10	0.05	0.01	0.001
	Typically Non-Significant Values							Significant Values			

Note: Bolding indicates the critical value.

CHAPTER 5. BACKCALCULATION RESULTS

This chapter provides a review of the procedures for post-processing the results and determining their accuracy as well as the CPTs used to store the backcalculated elastic layer moduli and other data.

LTPP DATA SOURCE

As stated in chapter 4, the deflection data were obtained from SDR 27.0 and included data from all LTPP test sections and all days of deflection testing. The dataset contained both GPS and SPS experimental sections and represented all pavement design alternatives included in the LTPP database.

BASIC FACTS ABOUT THE BACKCALCULATION PROCESS

There were a total of 7,771 test days, of which 4,534 sections had an HMA surface, and 2,237 sections had a PCC surface. All LTPP sections were grouped by State code, Strategic Highway Research Program (SHRP) ID, and construction number to facilitate the pre-processing described in chapter 4.

Number of GPS and SPS Test Sections

The number of sections by each LTPP experiment included 1,744 sections with an HMA surface and 1,008 sections with a PCC surface. The surface type changed in 381 of the test sections. For example, a JPCP with a PCC surface that was eventually overlaid with HMA was counted in two categories or experiments. Therefore, there were a total of 3,133 unique sections in all States combined, as listed in table 9. Table 10 lists the total number of deflection basins and those basins falling within each of the four categories. As shown, the LTPP quality control processes have resulted in nearly 97 percent of the basins falling within the typical and type 2 categories, which the authors consider excellent. As such, 5,847,770 deflection basins (typical and type 2) were used in the backcalculation process.

The number of deflection basins analyzed and included in the backcalculation process are listed in table 11. The table also lists the percentage of deflection basins that were found to be acceptable after the initial evaluation with EVERCALC© using an expanded range of the upper and lower modulus limits and for the final results. As shown, about 75 percent of all deflection basins were considered acceptable after the second phase analysis and defined as accept or atypical, while about 85 percent of the deflection basins resulted in acceptable values from EVERCALC© and MODCOMP©.

Table 12 lists the percentage of deflection basins defined as acceptable on a State-by-State basis. The percentage of acceptable deflection basins increased to about 85 percent after the fourth phase analysis using MODCOMP© for those basins considered unacceptable from the second and third phase analyses. Table 13 summarizes the percentage of deflection basins defined as acceptable on a State-by-State basis for the PCC-surfaced pavements from the best fit method.

Table 9. Summary of LTPP data used in the backcalculation analyses by experiment.

HMA Surface		PCC Surface	
LTPP Experiment	**Number of Sections**	**LTPP Experiment**	**Number of Sections**
GPS 1	233	GPS 3	133
GPS 2	145	GPS 4	69
GPS 6A	63	GPS 5	85
GPS 6B	131	GPS 9	26
GPS 6C	31	SPS 1	1
GPS 6D	24	SPS 2	205
GPS 6S	162	SPS 4	220
GPS 7A	35	SPS 6	170
GPS 7B	56	SPS 7	39
GPS 7C	18	SPS 8	16
GPS 7D	3	SPS 9C	7
GPS 7F	3	SPS 9J	37
GPS 7S	27		
SPS 1	245		
SPS 2	2		
SPS 3	445		
SPS 5	204		
SPS 6	123		
SPS 7	1		
SPS 8	37		
SPS 9C	7		
SPS 9J	38		
SPS 9N	50		
SPS 9O	42		
Total GPS sections	**931**	**Total GPS sections**	**313**
Total SPS sections	**1,194**	**Total SPS sections**	**695**
Grand Total	**2,125**	**Grand Total**	**1,008**

Note: Blank cells indicate no additional LTPP experiment within the pavement type.

Table 10. Summary of LTPP deflection basin data.

State/ Canadian Province/ Territory	Number of Drops					Percentage of Total Drops				Percentage of Typical and Type 2
	Type 1	Type 2	Type 3	Typical	Total	Type 1	Type 2	Type 3	Typical	
AL	593	56,826	3,326	150,435	211,180	0.28	26.91	1.57	71.24	98.14
AK	8	6703	20	17,856	24,587	0.03	27.26	0.08	72.62	99.89
AZ	982	117,565	5,720	253,549	377,816	0.26	31.12	1.51	67.11	98.23
AR	1,221	33,772	6,271	44,550	85,814	1.42	39.35	7.31	51.91	91.27
CA	2,566	72,207	5,384	129,688	209,845	1.22	34.41	2.57	61.80	96.21
CO	590	40,960	1,671	89,608	132,829	0.44	30.84	1.26	67.46	98.30
CT	87	13,727	1,350	43,544	58,708	0.15	23.38	2.30	74.17	97.55
DE	231	23,371	1,437	41,918	66,957	0.34	34.90	2.15	62.60	97.51
DC	0	311	2	711	1,024	0.00	30.37	0.20	69.43	99.80
FL	319	33,062	6,038	102,937	142,356	0.22	23.22	4.24	72.31	95.53
GA	813	53,464	7,195	99,894	161,366	0.50	33.13	4.46	61.91	95.04
HI	1	4,768	58	11,328	16,155	0.01	29.51	0.36	70.12	99.63
ID	2,104	35,038	1,321	45,974	84,437	2.49	41.50	1.56	54.45	95.94
IL	1,804	42,460	7,052	43,692	95,008	1.90	44.69	7.42	45.99	90.68
IN	1,384	56,244	13,013	54,283	124,924	1.11	45.02	10.42	43.45	88.48
IA	2,117	43,359	6,820	52,852	105,148	2.01	41.24	6.49	50.26	91.50
KS	2,122	47,191	3,343	80,159	132,815	1.60	35.53	2.52	60.35	95.89
KY	150	8,066	685	16,291	25,192	0.60	32.02	2.72	64.67	96.69
LA	242	7,165	1,241	10,932	19,580	1.24	36.59	6.34	55.83	92.43
ME	584	17,903	2,770	63,596	84,853	0.69	21.10	3.26	74.95	96.05
MD	300	44,640	2,009	61,514	108,463	0.28	41.16	1.85	56.71	97.87
MA	55	6,993	247	40,637	47,932	0.11	14.59	0.52	84.78	99.37
MI	775	27,481	3,224	66,084	97,564	0.79	28.17	3.30	67.73	95.90
MN	1,502	67,018	6,828	198,733	274,081	0.55	24.45	2.49	72.51	96.96
MS	615	42,521	1,112	101,452	145,700	0.42	29.18	0.76	69.63	98.81
MO	1,467	49,275	3,194	76,189	130,125	1.13	37.87	2.45	58.55	96.42
MT	455	38,957	2,782	139,478	181,672	0.25	21.44	1.53	76.77	98.22

NE	1,317	25,403	1,562	73,746	102,028	1.29	24.90	1.53	72.28	97.18
NV	1,403	27,078	894	75,115	104,490	1.34	25.91	0.86	71.89	97.80
NH	31	6,642	257	29,166	36,096	0.09	18.40	0.71	80.80	99.20
NJ	129	29,857	692	82,542	113,220	0.11	26.37	0.61	72.90	99.27
NM	39	17,194	551	90,288	108,072	0.04	15.91	0.51	83.54	99.45
NY	133	10,847	359	77,420	88,759	0.15	12.22	0.40	87.22	99.45
NC	1,067	40,461	2,584	91,811	135,923	0.79	29.77	1.90	67.55	97.31
ND	462	8,184	322	8,015	16,983	2.72	48.19	1.90	47.19	95.38
OH	2,072	40,984	4,895	62,117	110,068	1.88	37.24	4.45	56.44	93.67
OK	661	40,762	1,114	97,209	139,746	0.47	29.17	0.80	69.56	98.73
OR	1,257	10,349	2,505	9,067	23,178	5.42	44.65	10.81	39.12	83.77
PA	1,446	37,136	5,584	49,688	93,854	1.54	39.57	5.95	52.94	92.51
RI	1	4,035	295	1,701	6,032	0.02	66.89	4.89	28.20	95.09
SC	21	8,906	522	6,623	16,072	0.13	55.41	3.25	41.21	96.62
SD	704	33,400	2,553	100,325	136,982	0.51	24.38	1.86	73.24	97.62
TN	78	26,402	1,137	54,864	82,481	0.09	32.01	1.38	66.52	98.53
TX	1,381	113,126	8,176	425,696	548,379	0.25	20.63	1.49	77.63	98.26
UT	599	22,078	725	64,515	87,917	0.68	25.11	0.82	73.38	98.49
VT	310	13,392	1,314	53,877	68,893	0.45	19.44	1.91	78.20	97.64
VA	156	26,417	923	126,862	154,358	0.10	17.11	0.60	82.19	99.30
WA	635	22,207	1,348	60,124	84,314	0.75	26.34	1.60	71.31	97.65
WV	144	7,307	410	6,347	14,208	1.01	51.43	2.89	44.67	96.10
WI	1,237	37,348	6,628	46,604	91,817	1.35	40.68	7.22	50.76	91.43
WY	295	35,151	772	54,942	91,160	0.32	38.56	0.85	60.27	98.83
PR	31	2,384	10	4,942	7,367	0.42	32.36	0.14	67.08	99.44
AB	1	8,119	51	44,672	52,843	0.00	15.36	0.10	84.54	99.90
BC	0	1,228	2	16,096	17,326	0.00	7.09	0.01	92.90	99.99
MB	504	27,998	8,294	98,541	135,337	0.37	20.69	6.13	72.81	93.50
NB	0	2,771	154	10,640	13,565	0.00	20.43	1.14	78.44	98.86
NF	0	697	34	8,010	8,741	0.00	7.97	0.39	91.64	99.61
NS	0	109	1	3,761	3,871	0.00	2.82	0.03	97.16	99.97
ON	175	9,415	1,184	56,362	67,136	0.26	14.02	1.76	83.95	97.98

PE	0	1,235	0	9,597	10,832	0.00	11.40	0.00	88.60	100.00
QB	265	10,933	508	34,926	46,632	0.57	23.45	1.09	74.90	98.34
SA	125	17,359	5,470	55,714	78,668	0.16	22.07	6.95	70.82	92.89
Total	**39,766**	**1,717,961**	**155,943**	**4,129,809**	**6,043,479**	**0.66**	**28.43**	**2.58**	**68.33**	**96.76**

PR = Puerto Rico; AB = Alberta; BC = British Columbia; MB = Manitoba; NB = New Brunswick; NF = Newfoundland; NS = Nova Scotia; ON = Ontario; PE = Prince Edward Island; QB = Quebec; and SA = Saskatchewan.

Table 11. Number of deflection basins analyzed and percentage of those deflection basins considered acceptable.

EVERCALC© Analysis	Total Drops Analyzed[a]	Accept Results	Atypical Results	Atypical and Accept Results	Error Drops	Percentage Atypical and Accept Results
Run 1 using typical material-specific ranges for each layer	5,694,207	2,573,025	1,327,896[a]	3,900,921	1,793,286	68.5
Run 2 using wider range for cases where more than 25 percent of the run 1 results hit the limits	5,611,563	1,853,484	2,377,648[b]	4,390,049	1,380,431	75.4
Final Results (EVERCALC© and MODCOMP©)	5,662,494	1,817,186	2,494,628	4,311,814	1,350,680	76.1

Note: Different values are reported for the total number of basins analyzed because the total number accounts for basins that may have been dropped or added for the individual runs for basins that were borderline between typical and type 2 versus types 1 and 3.

[a]The atypical results in run 1 represent basins with backcalculated moduli that converge to the lower or upper limits of the specified typical range. These may include sections that may produce results outside the atypical range if the range is expanded. Therefore, these basins may include basins that can be categorized as errors if the range is expanded.

[b]The atypical results in run 2 represent basins with backcalculated moduli that converge within the lower or upper limits of the specified atypical range (i.e., these basins may not be categorized as errors).

Table 12. Deflection basins analyzed and percentage classified as acceptable drops using EVERCALC© and MODCOMP© for all pavements.

STATE_ CODE	TOTAL_ DROPS	ERROR_ DROPS	ATYPICAL_ DROPS	ACCEPT_ DROPS	Percent Acceptable
1	199,465	28,341	99,850	71,274	85.8
2	24,559	6,188	6,018	12,353	74.8
4	367,159	116,309	162,913	87,937	68.3
5	77,904	14,206	30,161	33,537	81.8
6	193,500	60,991	75,684	56,825	68.5
8	130,421	49,733	47,512	33,176	61.9
9	57,271	6,129	17,565	33,577	89.3
10	65,289	9,282	36,820	19,187	85.8
11	1,022	160	319	543	84.3
12	135,999	50,662	48,522	36,815	62.7
13	153,065	16,886	69,767	66,412	89.0
15	16,096	3,727	6,307	6,062	76.8
16	80,804	28,423	33,432	18,949	64.8
17	86,152	22,671	34,200	29,281	73.7
18	93,376	24,438	39,795	29,143	73.8
19	95,867	28,030	40,923	26,914	70.8
20	126,318	38,013	46,290	42,015	69.9
21	24,357	8,725	9,355	6,277	64.2
22	18,097	1,324	4,621	12,152	92.7
23	81,499	6,151	33,610	41,738	92.5
24	106,138	27,664	49,703	28,771	73.9
25	44,976	4,671	21,745	18,560	89.6
26	93,392	15,832	34,056	43,504	83.0
27	264,185	54,432	112,931	96,822	79.4
28	143,797	31,183	72,221	40,393	78.3
29	117,624	44,556	51,913	21,155	62.1
30	178,393	39,040	91,324	48,029	78.1
31	98,629	18,671	40,554	39,404	81.1
32	101,504	17,931	56,182	27,391	82.3
33	35,808	2,775	12,998	20,035	92.3
34	112,399	12,285	65,259	34,855	89.1
35	107,482	20,493	45,650	41,339	80.9
36	88,267	8,243	58,641	21,383	90.7
37	132,159	32,663	56,570	42,926	75.3
38	16,199	4,218	6,972	5,009	74.0
39	103,092	24,359	37,449	41,284	76.4
40	136,754	25,706	56,493	54,555	81.2
41	19,416	5,817	8,703	4,896	70.0
42	86,759	28,033	47,666	11,060	67.7
44	5,736	1,488	3,825	423	74.1
45	15,529	7,544	5,710	2,275	51.4

46	130,246	21,574	48,238	60,434	83.4
47	81,234	31,811	32,462	16,961	60.8
48	534,862	134,664	219,904	180,294	74.8
49	86,480	29,619	48,924	7,937	65.8
50	67,199	4,830	34,503	27,866	92.8
51	153,279	32,257	89,569	31,453	79.0
53	81,825	23,132	37,514	21,179	71.7
54	12,316	6,630	3,970	1,716	46.2
55	82,468	20,558	40,304	21,606	75.1
56	90,093	29,562	42,538	17,993	67.2
72	7,326	4,178	2,912	236	43.0
81	52,791	21,534	26,103	5,154	59.2
82	17,324	1,682	4,952	10,690	90.3
83	126,539	21,726	44,798	60,015	82.8
84	13,411	4,480	8,562	369	66.6
85	8,164	1,871	2,147	4,146	77.1
86	3,870	180	1,176	2,514	95.3
87	65,777	7,945	20,217	37,615	87.9
88	10,832	4,454	5,606	772	58.9
89	45,250	13,087	19,373	12,790	71.1
90	73,073	27,001	32,359	13,713	63.0

Note: Not all agencies are included within this table because of missing data that were needed for the backcalculation process for the LTPP sections, or there were no LTPP test sections within that agency.

Table 13. Deflection basins analyzed and percentage classified as acceptable drops using the best fit method for PCC-surfaced pavements.

STATE_ CODE	TOTAL_ DROPS	ERROR_ DROPS	ATYPICAL_ DROPS	ACCEPT_ DROPS	Percent Acceptable
1	7,246	1,076	580	5,590	85.2
4	23,495	1,950	1,913	19,632	91.7
5	20,167	2,242	1,976	15,949	88.9
6	22,712	3,455	5,539	13,718	84.8
8	15,798	733	4,040	11,025	95.4
9	960	4	44	912	99.6
10	11,698	449	1,248	10,001	96.2
12	6,793	1,707	777	4,309	74.9
13	14,018	1,985	6,400	5,633	85.8
16	6,103	256	1,357	4,490	95.8
17	8,646	438	211	7,997	94.9
18	11,663	406	6,296	4,961	96.5
19	16,935	482	4,399	12,054	97.2
20	24,563	1,942	3,348	19,273	92.1
21	1,788	229	89	1,470	87.2
22	655	12	174	469	98.2
23	1,603	8	822	773	99.5
26	15,148	955	2,388	11,805	93.7
27	19,250	1,110	4,494	13,646	94.2
28	4,922	892	2,210	1,820	81.9
29	20,662	2,192	1,818	16,652	89.4
31	11,970	576	6,561	4,833	95.2
32	8,772	2,101	2,946	3,725	76.0
34	337	0	0	337	100.0
35	953	131	89	733	86.3
36	5,265	330	426	4,509	93.7
37	17,420	1,202	4,440	11,778	93.1
38	13,673	241	1,200	12,232	98.2
39	21,524	991	4,701	15,832	95.4
40	8,077	565	4,508	3,004	93.0
42	16,876	4,409	1,865	10,602	73.9
45	1,161	12	0	1,149	99.0
46	12,766	771	3,272	8,723	94.0
47	4,146	59	579	3,508	98.6
48	18,083	2,384	11,062	4,637	86.8
49	12,253	1,173	5,004	6,076	90.4
50	433	24	0	409	94.5
51	156	47	8	101	69.9
53	21,151	1,937	5,909	13,305	90.8
54	1,489	312	61	1,116	79.0
55	22,021	2,701	5,139	14,181	87.7

56	1,110	1	331	778	99.9
72	1,892	1,126	154	612	40.5
83	4,096	485	34	3,577	88.2
84	564	1	21	542	99.8
89	8,103	361	681	7,061	95.5

Note: Not all agencies are included within this table because some of the agencies did not have any LTPP rigid pavement test sections.

Hardware Used in Backcalculation Processing

The following subsection provides a summary of the hardware used to backcalculate the results as well as an estimate of the length or amount of computational time to execute the first phase analysis using EVERCALC©.

The first and second phase analyses were performed in two modes using the interface for the cases with a bedrock layer and by running the executable from an MS-DOS prompt for the cases without a bedrock layer. The runs were executed in a batch mode for both cases.

For cases with the bedrock layer, three virtual machines were used, each with 2 GB of random access memory, and running the Windows XP® operating system. These machines had 2.4 Ghz dual core processors. The runs took about 2 weeks of computational time (336 h), with the programmer or user having to monitor the progress of the software's status. In some cases, the program had to be restarted twice each day.

For cases without the bedrock layer, three virtual machines were used, and they had the same specifications as those described. The analyses took about 1 week of computational time (168 h). These analyses were more stable, but the programmer still had to monitor the program's status when processing data for States with large data sets (e.g., Arizona, Colorado, and Texas).

EVALUATING THE SUCCESS OF BACKCALCULATION

The two parameters used to determine whether the results were acceptable were also used as a measure to judge the success of the backcalculation process: (1) the average error or difference between the measured and calculated deflection basin and (2) the percentage of points with acceptable modulus values for all layers. The criteria for determining acceptable and unacceptable backcalculated layer modulus values were discussed earlier. The following list provides a generic definition of success:

- **Definition for and measurement of success in terms of backcalculated modulus values:** The difference between the calculated and measured deflection basins or RMSE was determined for each test date or test point from the backcalculation process. The points with less than 3 percent RMSE were considered acceptable solutions, while the solutions with RMSE values greater than 5 percent were considered poor or unacceptable. Solutions with RMSE values between 3 and 5 percent were considered questionable. A similar definition was used in the first backcalculation project sponsored by FHWA.[(4)] Only the deflection basins with an RMSE less than 3 percent were used to determine the average and standard deviation elastic layer moduli on a test section and test day basis.

- **Definition for and measurement of success in terms of number of sites with acceptable values:** The percentage of test dates with backcalculated modulus values that meet the definition of a good or acceptable solution from the deflection basin for an appreciable number of points along the LTPP test section. *Appreciable* is defined as more than 75 percent of the points having RMSE values less than 3 percent with modulus values within the expected range of values.

For sites with anomalies or high RMSE, the resulting elastic layer moduli were identified as such. MODCOMP© was used to determine a probable reason for the results. These sites or days of testing were flagged for investigation, if still available. If forensics have not been completed and a site has been taken out of service, these were simply identified along with some potential causes for the differences encountered.

Table 14 lists the LTPP test sections and the areas within the test section for which the results were eliminated from the CPT because most of the results were found to be outside one or both of the acceptance criteria. Table 15 lists the error flags and their description used in the CPTs and included in the feedback reports.

Table 14. LTPP test sections identified as errors and eliminated from determining the test section statistics.

Test Section	Area Excluded Station	Type of Structure
01-4127	110+	Conventional flexible pavement structure
01-4129	-40	Conventional flexible pavement structure with a thin surface
04-1006	140+	Conventional flexible pavement structure
02-9035	80+	Conventional flexible pavement structure with a thin overlay
04-1022	-50	Conventional flexible pavement structure
04-1015	120+	Conventional flexible pavement structure with overlay
06-8534	130+	Conventional flexible pavement structure with a thin surface
30-7088	70+	Conventional flexible pavement structure with overlay
37-2824	-60	Semi-rigid pavement
38-2001	80+	Semi-rigid pavement
40-4088	50+	Semi-rigid pavement
42-1618	-35	Conventional flexible pavement structure with overlay
48-9005	-50	Conventional flexible pavement structure with overlay
53-1002	-40	Conventional flexible pavement structure

Table 15. Error flags used in the CPTs.

Report No.	Flag	Subject	Situation	Recommended Action
1	MISSING_DEFL	Missing deflection data	Deflection data is missing in the MON_DEFL_DROP_ DATA for this STATE_ CODE, SHRP_ID, TEST_ DATE, TEST_TIME, POINT_ LOC, and DROP_NO.	None. The basin was not used in backcalculation analysis.
2	LAYER_THK_ UNAVAILABLE	Missing thickness data	Layer thickness data is missing in the TST_L05B table for this STATE_CODE, SHRP_ID, TEST_DATE, and CONSTRUCTION_NO	None. The basin was not used in backcalculation analysis.
3	BLACKLISTED_ BASINTYPE	Non-decreasing deflection basin	Invalid deflection data for the basin in the MON_DEFL_ DROP_DATA table. The test location has a non-decreasing deflection basin and was characterized as either a type I or a type III basin.	None. The basin was not used in backcalculation analysis.
4	MISSING_TEMP	Missing temperature data and depth of temperature measurement	Temperature measurement and depth of measurement is missing in the MON_DEFL_TEMP_ DEPTHS and MON_DEFL_ TEMP_VALUES for this SHRP_ID, test_date, and Point_LOC.	None. The basin was used in backcalculation analysis.
5	MISSING_DEPTH_ THKCOR	Missing depth of temperature measurement	Missing layer depth Information in the MON_DEFL_TEMP_ DEPTHS table LAYER_TEMP_ DEPTH from the Supplementary Temperature Table).	None. The basin was used in backcalculation analysis.
6	TEMPERATURE_ DEPTH_MISMATCH	Temperature depth mismatch	The data for the layer thicknesses from TST_L05B and depth of temperature measurements do not align	None. The basin was used in backcalculation analysis.
7	MISSING TEMP_ DEPTH	Missing temperature within the surface layer	For the STATE_CODE, SHRP_ID, and TEST_DATE, the temperature within surface layer could not be determined using the temperature depth and temperature values reported in MON_DEFL_TEMP_DEPTHS and MON_DEFL_TEMP_ VALUES tables.	None. The basin was used in backcalculation analysis.

8	INVALID_LTE	Invalid LTE	Deflection measurement was considered invalid because of missing deflection or sensor spacing.	None. The LTE was not reported in the summary tables.
9	LTE_NON_DEC	LTE non decreasing	Invalid deflection data for the basin in the MON_DEFL_ DROP_DATA table. The test location has a non-decreasing deflection basin.	None. The LTE was not reported in the summary tables.
10	F_OUTPUT_IDD_ MISMATCH	Failure to obtain results for all basins for an identification descriptor designation	Results were generated for a subset of the drops for the IDD. The results are written to the drops starting from the first drop; however a mismatch might exist.	None. The results are reported for the IDD.
11	F_NO_IDD_MATCH	No results were obtained for this IDD	No output data are found for an IDD (i.e., POINT_LOC, TEST_DATE, TEST_TIME, SHRP_ID, and STATE (likely that the input data were not fully processed by EVERCALC©).	No results reported for IDD.
12	EXCLUDED_FROM_ SUMMARY	Subsection excluded from results summary	Subsection of the SHRP_ID showed high variability in calculated modulus values relative to the majority of the section. Subsection had higher error rate.	Results excluded from summary.

Note: “Report No.” refers to an integer that defines a specific error flag.

The individual test sections with error numbers 1 through 9 in table 15 were included in unpublished data feedback reports and were submitted to FHWA because these pertain to the data themselves. Error numbers 10–12 were excluded from the unpublished data feedback reports, which were prepared and submitted to LTPP to document and report errors or anomalies found in the database, because these errors only pertain to the results from the backcalculation programs. In addition, error numbers 1–3 were excluded in the datasets for the individual results because of missing critical data such that the backcalculation process could not be performed.

Manual Review of Results

The first level review of results was the post-processing of the backcalculated results. The post-processor groups and determines the number of deflection basins that are found to be acceptable and unacceptable based on the two parameters previously discussed. If the majority of the results were found to be acceptable, that test section and test date were accepted, and the averages, standard deviation, and other information were determined in the post-processing of the data. If a significant amount of the results are unacceptable, the test section and test date went through a second and possibly third level review.

The second level review was a more exhaustive review to identify possible causes for the unacceptable results. This included an indepth review of the post-evaluation factors and other LTPP data and layer properties to try to identify the reasons for the high error term or modulus values that fell outside the range of typical values. If the results were still considered unacceptable after the second level review, the test section and test date moved to a third level review.

The third level review included making additional runs with MODCOMP© based on all available information. If this third level did not result in acceptance, a feedback report was prepared for the test section and test dates. As part of this review level, a decision was made regarding the probable cause for the unaccepted results and the results flagged. The probable cause and recommended resolution were included in the feedback reports. Appendix B lists the test sections that exhibited a high percentage of moderate to high RMSE values and did not meet all of the acceptance criteria.

Post-Processing Evaluation Factors

Many factors can lead to erroneous results in the backcalculation process because they impact the measured deflection basin. Some evaluation factors include the following:

- Cracks in the pavement can cause the deflection data to depart drastically from the assumed conditions.
- Layer thicknesses are not uniform nor are materials in the layers completely homogeneous. For example, variations in layer thickness and material properties along the roadway affect the stiffness of the pavement layer, which in term affects the deflection basin.
- Some pavement layers are too thin to be backcalculated in the pavement model, and these are usually assumed or combined with an adjacent layer. The technique used to estimate the fixed modulus for these layers is important.
- Moisture content and the depth to a hard bottom layer can vary widely along the road, causing the results to be highly variable in the unbound layers.
- Temperature gradients in the pavement can lead to modulus variation in HMA layers and warping in PCC layers.
- Most unbound pavement materials are stress-dependent, and most backcalculation programs do not have the capability to handle this issue.

Another evaluation criterion was to compare the backcalculated elastic modulus values with those values measured in the laboratory for PCC, HMA, and unbound materials and soils. LTPP sponsored other projects to determine the dynamic and resilient modulus values that are consistent with the MEPDG methodology and inputs.[(1)] Dynamic moduli were calculated for the different HMA mixtures from volumetric and component properties and are included in the LTPP database, which represent an undamaged and unaged condition. The backcalculated modulus values, however, represented an in-place composite elastic modulus and were not discrete values, as measured in the laboratory. In addition, the backcalculated modulus values represented any in-place damage and aged conditions. As such, one-to-one correspondence was not expected between the backcalculated elastic modulus values and those calculated from volumetric properties (laboratory-derived dynamic modulus values).

The layer- or mixture-specific dynamic modulus values were combined to determine a composite modulus value using the equivalent modulus concept and compared to the backcalculated composite values. The equivalent modulus concept was used in the FHWA-sponsored study to compare backcalculated values to laboratory-derived values.(45) Use of the equivalent modulus concept to determine the composite laboratory-derived dynamic modulus was found to be of little value in explaining the difference between the laboratory-derived and field-derived values.

Compensating Layer Effects

Identifying compensating layer effects is an important step in the backcalculation process. Compensating layer effects occurs when one layer consistently increases in stiffness while an adjacent layer decreases in stiffness. Compensating layer effects can result in layer modulus values that are inappropriate for the pavement structure, even when the error between the measured and predicted deflection basins is considered acceptable. Characterizing the deflection basins can assist in identifying LTPP test sections that are prone to compensating layer effects. The deflection basins were categorized in the first backcalculation study to identify the sites where this characteristic is likely to occur.(4) The same process was used in this project to reduce the possibility for compensating layer effects on the calculated elastic modulus values. When compensating errors identified for a specific test section, MODOMP was used or the pavement structure was revised.

Discontinuities

Discontinuities in the pavement structure (i.e., cracks, joints, segregation, etc.) have an impact on selected deflection basins, especially if the discontinuity is supporting a sensor platform or located between two sensors near the loading plate. The sensor bar and loading plate are usually located in intact areas, but that is not always possible or the condition noted by the operator. The shape of the deflection basin can distinguish some of these conditions.

As part of the backcalculation process, the distress data were extracted for each site for review when selected areas along the LTPP site continually do not meet the acceptance criteria to explain the high RMSE or surface layer modulus values that deviate significantly from typical laboratory-derived values. These results were flagged as having extensive cracking or distress along the section as part of the post-processing of results.

HMA Stripping and Other Material Defects

Stripping can have a softening effect on HMA mixtures. Some of the forensic investigations that have been completed on the SPS-1 and SPS-2 supplemental sites have identified HMA mixtures that exhibit stripping in selected layers. This softening effect can result in low elastic modulus values backcalculated for that structure. The first LTPP backcalculation study recognized this behavior, and all layers that were found to exhibit stripping were simulated as a separate layer.

The error term using this approach was lower in comparison to combining all HMA layers into a composite layer.

Figure 34 illustrates this point for an LTPP site where deflection testing was done prior to any forensic investigation. The pavement structure was an HMA overlay of an existing HMA pavement. The backcalculated modulus reported for the in-place dense-graded base mixture beneath the HMA overlay was similar to that of a good quality aggregate base material. That modulus value was believed to be incorrect and rejected. After coring operations, the low modulus value was found to be representative of moisture-induced damage or stripping. Similar examples are applicable for the unbound layers (e.g., high water content resulting in very low modulus values to base layers with an excessive amount of fines or low water content (a dry condition) resulting in very high modulus values representative of a bound layer).

Figure 34. Photo. Cores recovered where moisture damage occurred, decreasing the in-place modulus of the layer/mixture (Texas SPS-5 project).

Loss of Bond between Layers

Most backcalculation studies and software packages assume adjacent layers are fully bonded. However, forensic investigations have shown that there were SPS-1 and -5 test sections where bond was lost with time. Some of these sections have been reconstructed or taken out of the LTPP monitoring cycle because the distress increased significantly.

The bond between adjacent bound layers can affect the deflection basin, but the effect is usually considered minor. Based purely on the deflection basins, it is difficult to determine if bonded or full slip between layers should be assumed. If adjacent layers become debonded, the distresses usually increase at a significant rate. Simulating this condition becomes difficult because of the limit on the number of layers that can be backcalculated, and most of the commonly used programs have the bond between layers fixed to full bond. If this condition is expected from the results of the backcalculation process through low modulus values, the results are flagged as such.

Variable or Perched Water Table Depth

The water content of unbound materials has a significant effect on the elastic properties of that layer. This was recognized during the first backcalculation study, so boring logs and water content were used to determine if this condition was exhibited at each LTPP site. Where this condition was found, two runs were made—one where the subgrade was combined as one layer and another where the subgrade was divided into two layers where the water table or nearly saturated conditions existed. The error between the measured and calculated deflection basins was almost always lower by simulating the depth of saturation. In most cases, the backcalculated elastic modulus values were also higher for the layer above the water table depth than the values below the water table depth. In some cases, these depths were seasonal.

Variable Depth of an Apparent Rigid Layer

The depth to bedrock can be determined from the shoulder borings that were drilled at all (or nearly all) of the LTPP test sections. However, a saturated or soft (weak) layer overlying a dry, overconsolidated clay layer can behave as a very stiff layer; all of the energy is being absorbed in the soft, weak layer. Similar to the comments relative to saturated layers, the boring logs and physical properties were used to identify these conditions. Where these conditions were found, two runs were made, one with and one without a rigid layer at the interface between the wet and dry layers. In most cases, the error between the measured and calculated deflection basins was less by simulating a rigid or stiff layer at that location or dividing the subgrade into two layers at that depth.

Warping and Curling of PCC Slabs

Curling of JPCP slabs can occur over a day’s test program and significantly impact the measured deflection basin. It this condition is not recognized, it will result in lower PCC elastic modulus values not representative of the in-place material.

CPTS

The CPTs were designed to store the results from the backcalculation process and assist in interpreting the results. One set of tables stores the EVERCALC© and MODCOMP© results, while a second set of tables stores the best fit results. The data in these sets of tables include the following:

- **Non-backcalculated values table:** This table includes general information on each test section analyzed through the backcalculation programs and compares the pavement structure included in the LTPP database to the structure simulated in the backcalculation process. It also includes the number of basins analyzed, number of basins and stations with acceptable moduli, whether the LTPP section has been subdivided into two sections, whether a rigid layer is present, etc.

- **Backcalculated values from individual deflection basins:** This table includes all results for individual deflection basins along a specific test section for all dates that deflection basins were measured. The calculated layer moduli, even those identified as errors, are included in this table. Test time and pavement temperatures are also included, as well as other factors that can be used to determine how the results are influenced from the different factors included in the backcalculation process. This information can be used to evaluate the stress sensitivity, temperature sensitivity, and seasonal sensitivity of the results.

- **Summary of results or processed data:** These are the representative values for each test section that are layer dependent, test lane dependent, drop height dependent, season dependent, temperature dependent, etc. This table includes the average and standard deviation of elastic layer moduli along the test section on a test day basis. The averages and standard deviations were determined using the individual deflection basins not identified as an error.

The data included in the CPTs are similar to those designed and prepared from the first round of backcalculation results in 2002 and include, as a minimum, the following:[(4)]

- Representative layer structure (material type and layer thickness) used in the backcalculation process. Some of the structure simulations varied from season to season because of fluctuations in water content and damage that occurred over time for some of the bound layers. In addition, the depth to bedrock was included in the structure and summary tables. In a few cases, including or excluding bedrock varied between test days.

- Deflection basin characterization and load-response category were included for the individual deflection basins.

- All deflection basins that do not meet the acceptance criteria were flagged and removed from the summary database. The individual deflection basins with error flags, however, were included in the tables for the individual deflection basins.

- Layer modulus and the error term from the results for each deflection basin as well as the average and standard deviation along the test lane on a test day basis of a test section were included in the tables.

- The spatial variability was included in the CPTs so that future users understand the mean and the amount of variation from those mean values.

A user's manual and source code, *Backcalculation Procedures and User Guide for Software Programs and Utility Tools*, was prepared for all software packages and tools that were modified, revised, or developed as a part of this study.[(56)] In addition, source codes were prepared for each of the pre- and post-processing utility tools used in this round of backcalculation. Source codes were not prepared for any program that was already available in the public domain and was not changed in any manner.

CHAPTER 6. APPLICATION AND USE OF BACKCALCULATION RESULTS

This chapter illustrates the use of the backcalculated elastic layer modulus values for a range of topics related to day-to-day design applications as well as for research purposes. These examples demonstrate the application of the backcalculated elastic moduli and not a detailed or complete analysis related to any one topic.

SETTING DEFAULTS FOR MATERIAL TYPES

Histograms can be prepared to determine the spread and mean for a particular material or pavement layer. Figure 5 and figure 6 in chapter 3 are examples of a test section basis for one of the case studies. These histograms can be used for judging the reasonableness of the results, identifying outliers, and comparing the mean value to the default value included in the MEPDG for that material.(1) Additionally, figure 35 and figure 36 show a histogram of the GB layers or aggregate bases classified as an AASHTO A-1-a material from all LTPP test sections in Georgia and Minnesota. The overall distribution has a positive skew for both sets of data with a mean of about 28 ksi for the Georgia sections and 23 ksi for the Minnesota sections.

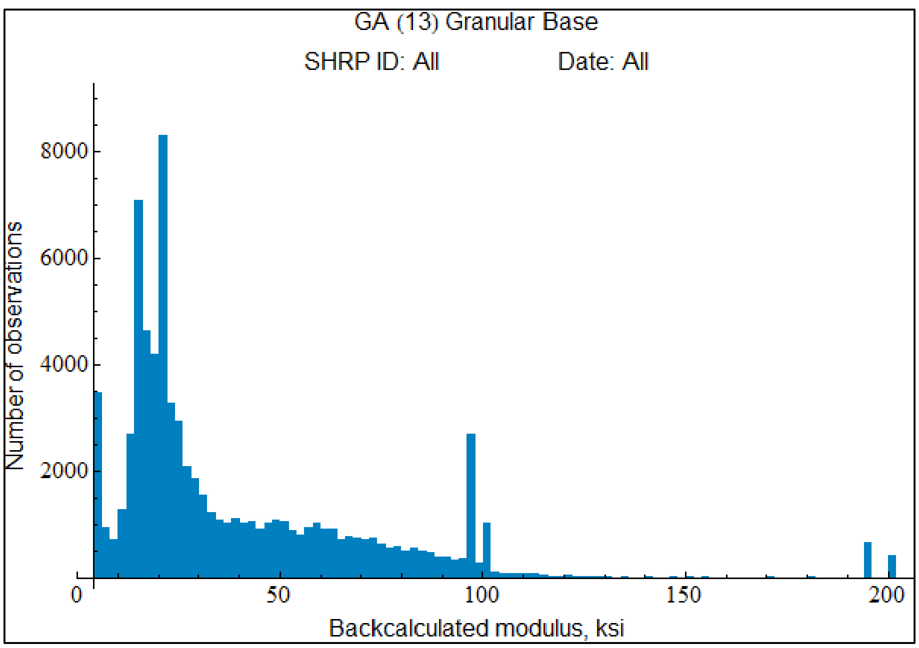


Figure 35. Graph. Backcalculated elastic moduli for all aggregate base layers for the Georgia (GA(13)) LTPP test sections classified as an AASHTO A-1-a material.

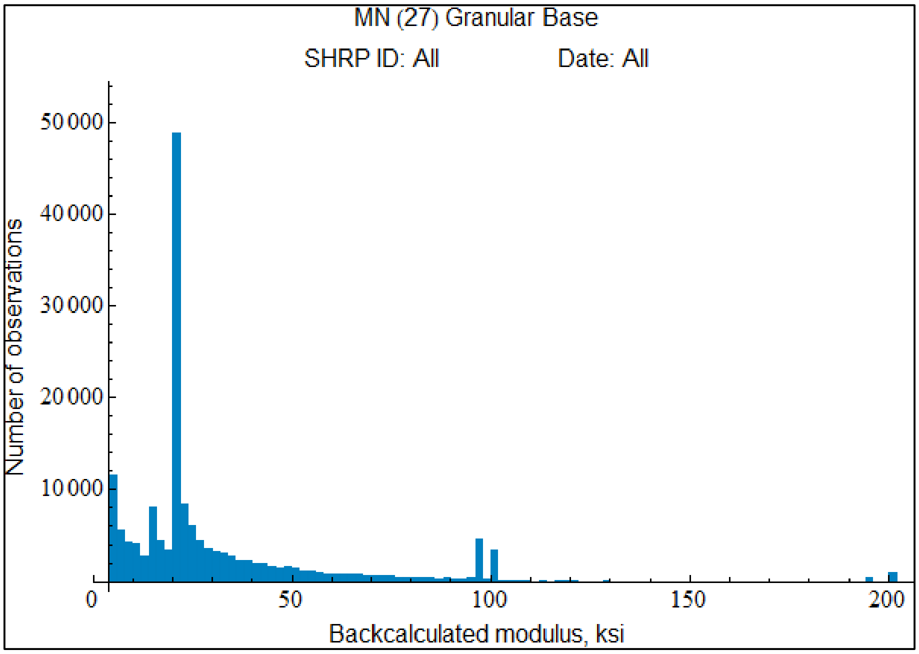


Figure 36. Graph. Backcalculated elastic moduli for all aggregate base layers for the Minnesota (MN(27)) LTPP test sections classified as an AASHTO A-1-a material.

The default resilient modulus included in the MEPDG is 40 ksi for an AASHTO A-1-a base, 30 ksi for crushed stone, and 25 psi for crushed gravel.[1] The values included in the MEPDG are for optimum conditions, and it is expected that optimum conditions do not exist in the field over time. The mean value from the distribution shown in figure 35 and figure 36 is probably more similar to the representative value that can be entered in the MEPDG—an average weighted value throughout the year.

There are outliers in the Georgia and Minnesota datasets of around 100 and 200 ksi; however, these values are believed to represent a frozen or partially frozen base layer. In addition, a fairly large number of elastic modulus values were computed around 5 ksi, which was the lower limit set during the backcalculation process. Although these values were previously eliminated during the first round of backcalculation from the LTPP database as being too low, they are believed to be representative of saturated or wet conditions, when the frozen layer thaws or water enters the aggregate base layer through lateral flow of water or cracks in the pavement surface. Similarly, the high values were also eliminated from the first round of backcalculation but may be accurate in the case where the base layer is very dry.

STRESS SENSITIVITY OF NONLINEAR MATERIALS AND SOILS

Most unbound aggregate base materials and soils are sensitive to changes in the applied stress, and the resilient modulus is dependent on the stress state or level. Coarse-grained aggregate base materials and coarse-grained soils generally exhibit a stress hardening pattern where the resilient modulus increases with increasing stress level, while most fine-grained soils exhibit a stress softening pattern where the resilient modulus decreases with increasing stress level. Some sands or soils at the transition between fine and coarse-grained soils exhibit no stress sensitivity in the practical range of applied stresses.

Deflection basins were measured over four drop heights on all LTPP test sections to determine the nonlinearity behavior of the unbound layers. Backcalculating the nonlinearity behavior or properties of the unbound layers was an objective during the first round of backcalculation. Determining the nonlinearity of the unbound layers was found to be problematic and resulted in a poor success rate. This round of backcalculation focused on using linear elastic methods to calculate the elastic moduli for each drop height. The layer moduli from each drop height could then be used to determine the nonlinearity coefficients of the selected constitutive equation.

Three SPS-8 projects (New York, Texas, and Utah) were used to demonstrate the variation in backcalculated elastic moduli for the four drop heights used in the LTPP deflection basin testing program. The SPS-8 projects were used in this demonstration because these sections generally have very low truck traffic and thin HMA layers—conditions that should exhibit a layer's nonlinearity response, if present. In other words, the differences in the in-place stresses from drop heights 1 to 4 should be the greatest because the HMA is thin for these sections.

Figure 37 through figure 45 show the change in elastic layer moduli between drop heights 1 to 4 for the aggregate base, weathered soil, and subgrade at the SPS-8 project sites. The average backcalculated elastic moduli were determined for 3 to 4 test days at each site. As shown, most of the layers did not exhibit a constant change in elastic moduli with increasing drop height or stress level, with the exception of the aggregate base at the Texas site and the coarse-grained SS at the New York site. Most of the unbound layers at these three sites exhibited no stress sensitivity or the moduli increased and then decreased, making the determination of the nonlinear coefficients of a constitutive equation difficult. In specific, the change in modulus between the drop heights was considered insignificant relative to the variation or standard deviation of moduli along the test section (not illustrated in the figures) as well as with time.

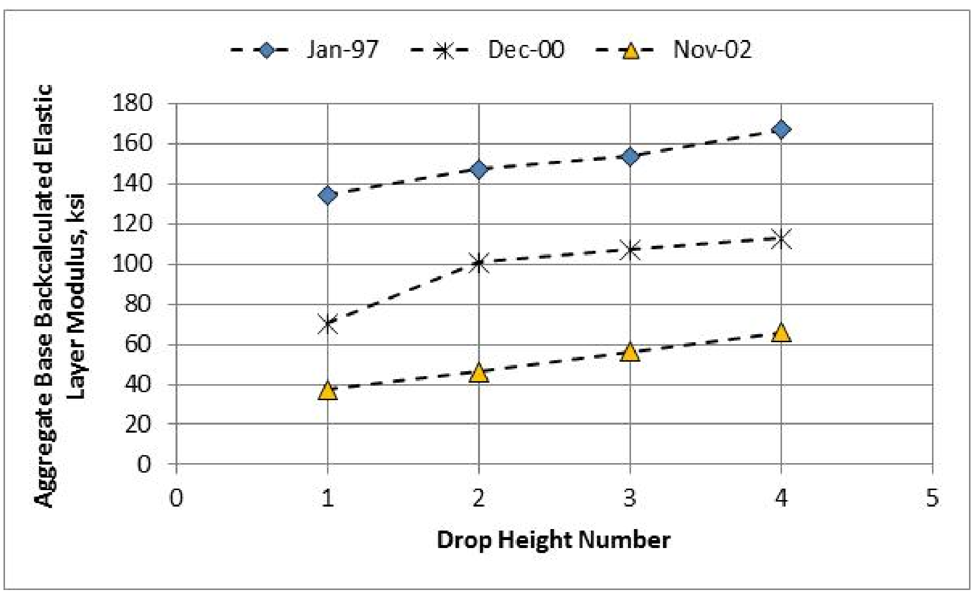


Figure 37. Graph. Comparison of backcalculated elastic moduli for the aggregate base layer from the Texas SPS-8 project 48-0801.

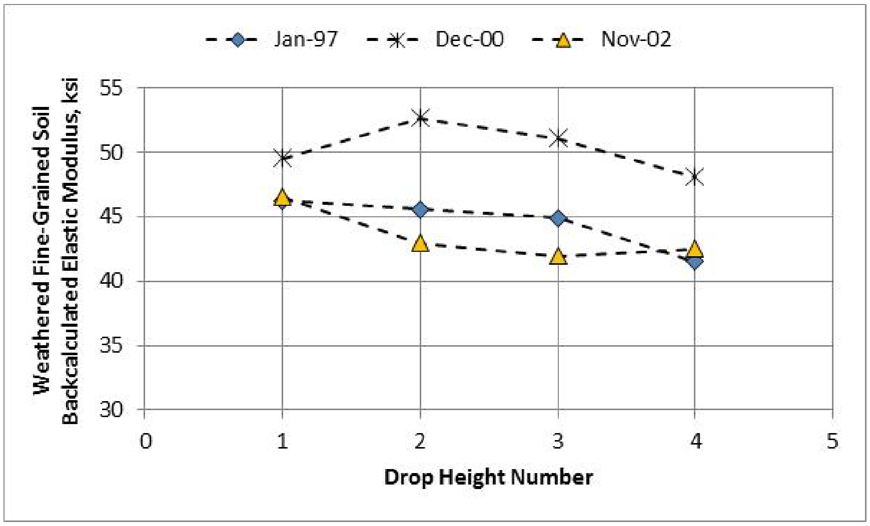


Figure 38. Graph. Comparison of backcalculated elastic moduli for the weathered fine-grained soil layer from the Texas SPS-8 project 48-0801.

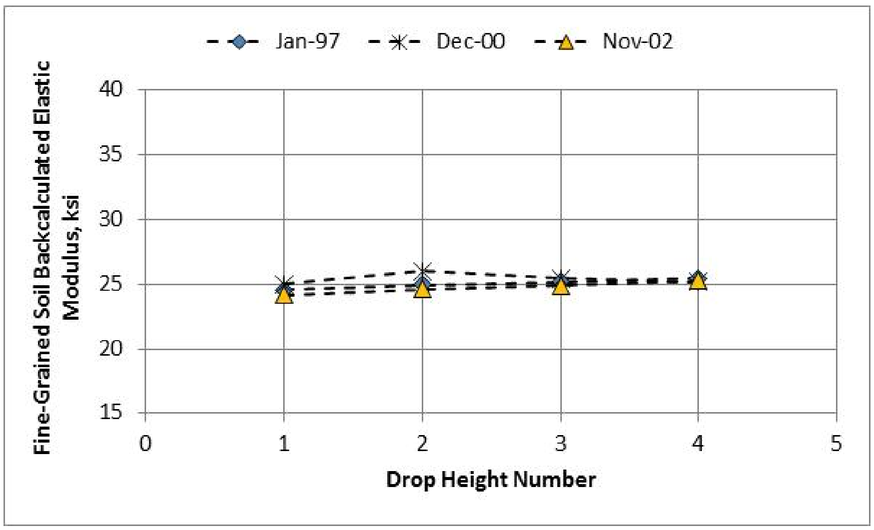


Figure 39. Graph. Comparison of backcalculated elastic moduli for the fine-grained subgrade from the Texas SPS-8 project 48-0801.

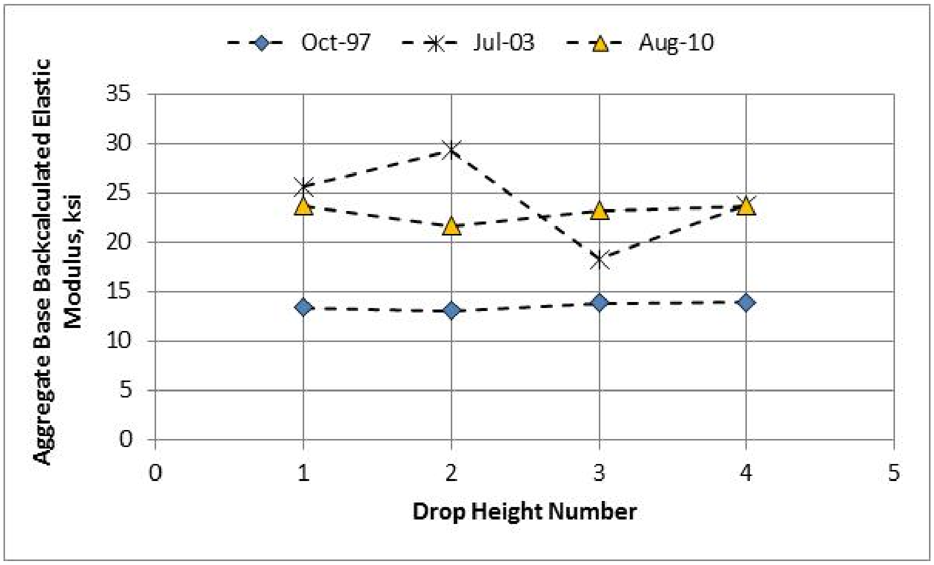


Figure 40. Graph. Comparison of backcalculated elastic moduli for the aggregate base layer from the Utah SPS-8 project 49-0803.

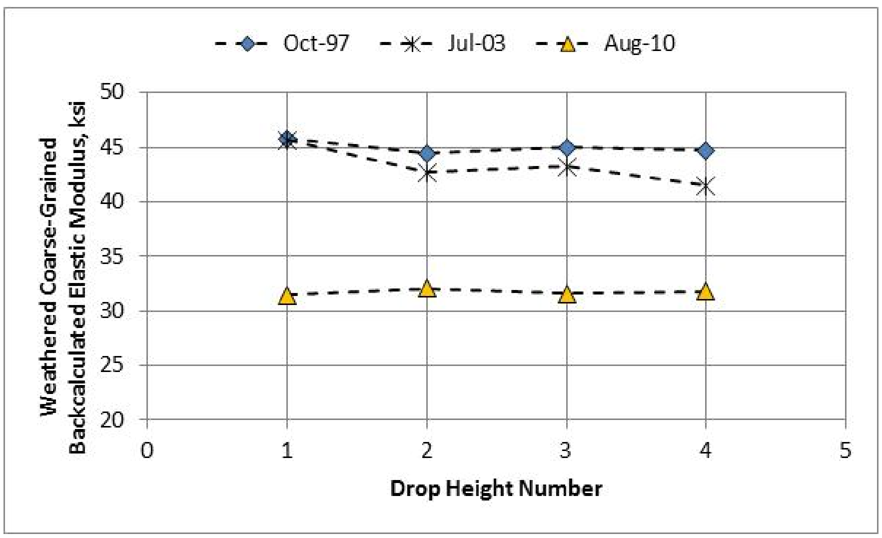


Figure 41. Graph. Comparison of backcalculated elastic moduli for the weathered coarse-grained layer from the Utah SPS-8 project 49-0803.

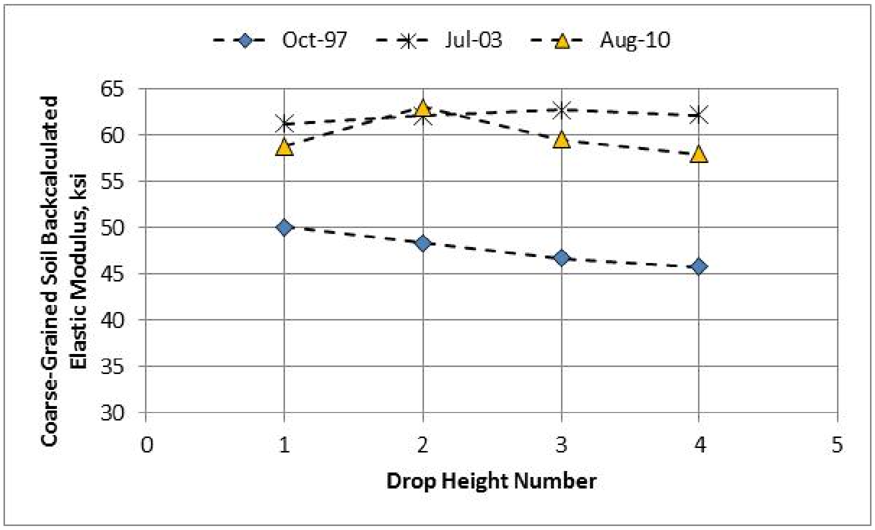


Figure 42. Graph. Comparison of backcalculated elastic moduli for the coarse-grained subgrade from the Utah SPS-8 project 49-0803.

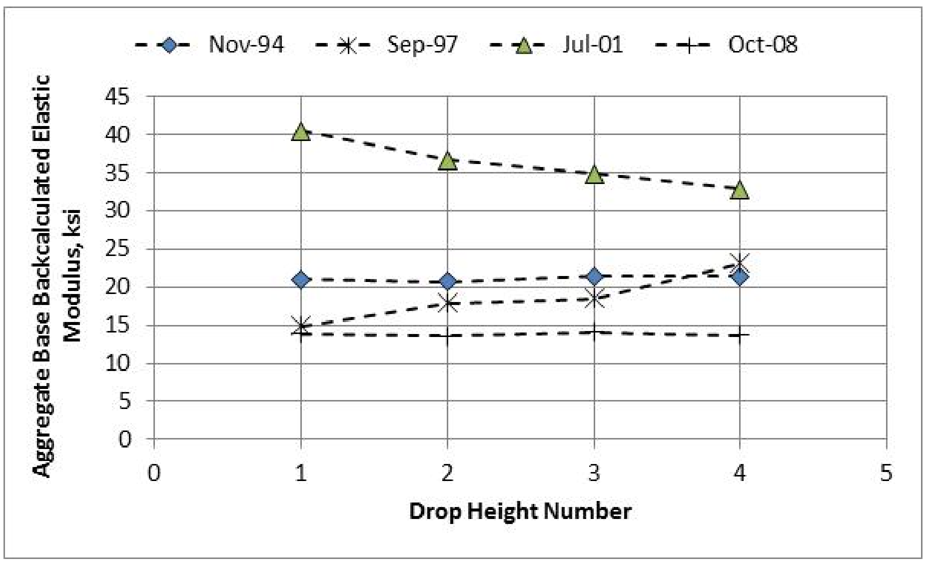


Figure 43. Graph. Comparison of backcalculated elastic moduli for the aggregate base layer from New York SPS-8 project 36-0802.

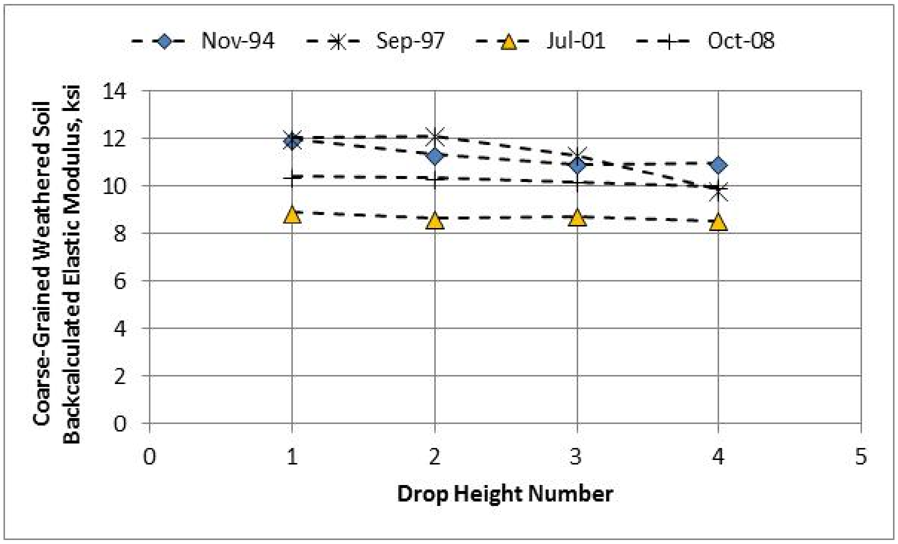


Figure 44. Graph. Comparison of backcalculated elastic moduli for the weathered coarse-grained layer from the New York SPS-8 project 36-0802.

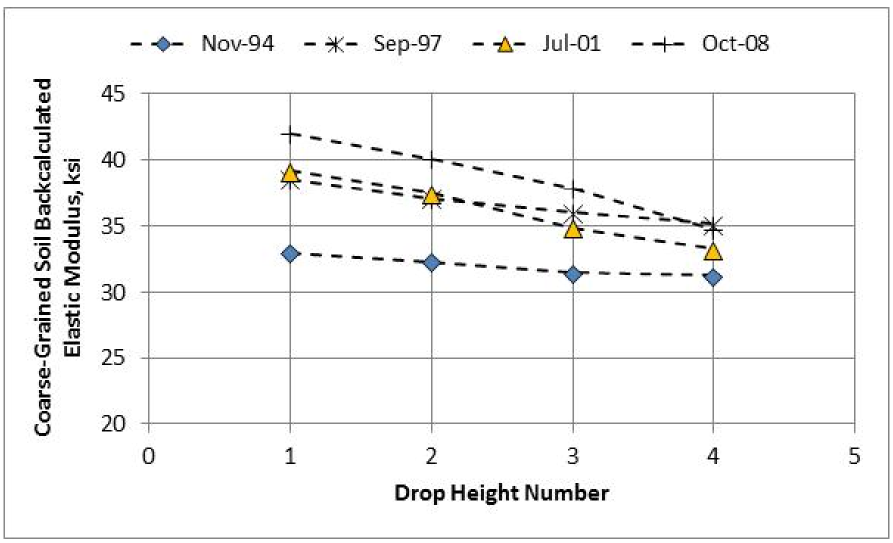


Figure 45. Graph. Comparison of backcalculated elastic moduli for the coarse-grained subgrade from the New York SPS-8 project 36-0802.

MEPDG HMA DAMAGE CONCEPT: FACT OR FICTION?

One of the unique components of the MEPDG methodology for rehabilitation design is the characterization of the in-place asphalt layers in terms of damage.(1) The MEPDG method uses backcalculated elastic layer moduli of the HMA or bituminous layer to determine the amount of damage in the existing asphalt layers by comparing the in-place backcalculated elastic layer modulus to that of an intact undamaged modulus measured in the laboratory. The damage is defined as the ratio of the backcalculated elastic layer modulus to the laboratory-measured dynamic modulus. The greater the damage or the lower the ratio, the greater the structural thickness required for an overlay. If this concept is correct, the backcalculated moduli should decrease over time as damage starts to accumulate.

Time-Dependent Damage Values

Figure 46 illustrates the change in modulus over time for LTPP GPS site 27-6251. As shown, the elastic layer moduli are about the same between 1990 and 1993, while there is a significant decrease in elastic moduli for 2003 when the pavement is about 10 years older. This decrease or softening in the moduli is defined as damage by the MEPDG.[1] Conversely, figure 47 illustrates no change in moduli and no damage or softening between 1990 and 1997 for LTPP GPS site 27-1018. In other words, this section did not exhibit any damage between 1990 and 1997. Thus, the LTPP backcalculated elastic layer moduli can be used to confirm or reject this damage concept determination and its use for pavement evaluation and rehabilitation design.

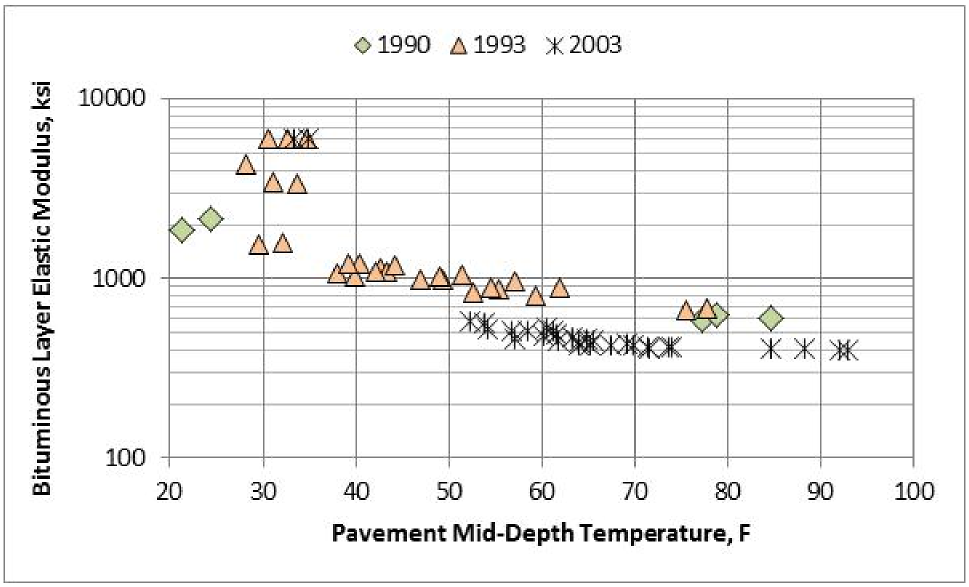


Figure 46. Graph. Decreasing elastic moduli of the asphalt layer over time for use in rehabilitation design for Minnesota GPS section 27-6251.

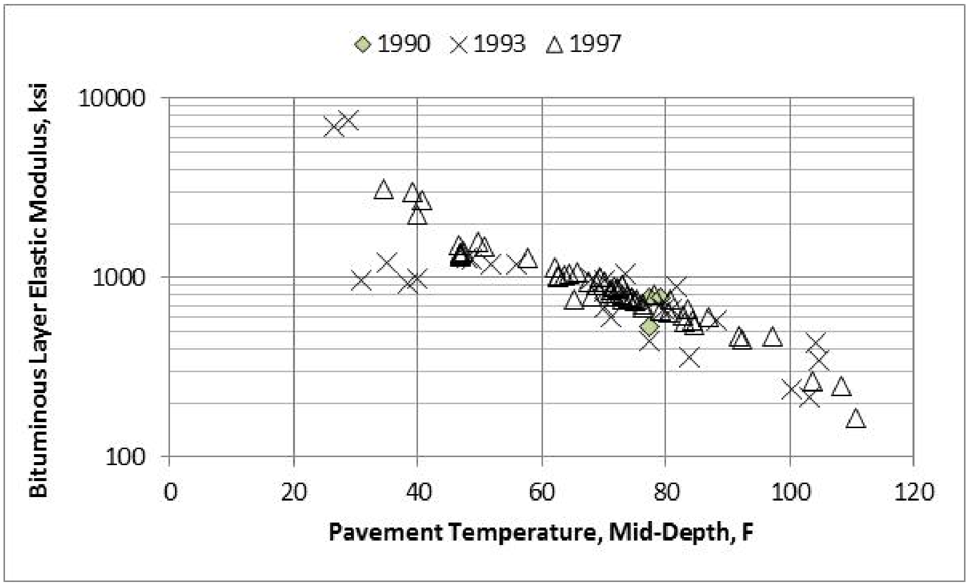


Figure 47. Graph. Decreasing elastic moduli of the asphalt layer over time for use in rehabilitation design for Minnesota GPS section 27-1018.

It can be seen that the backcalculated elastic layer modulus values were about the same at colder temperatures during the winter months and approached each other at the higher temperatures during the summer months. The difference in moduli over time is exhibited within the intermediate temperature range. Figure 48 and figure 49 illustrate the change in modulus within a narrow temperature range of 60 to 66 ºF for Minnesota section 27-1016 and section 27-6251, respectively. As shown, there is a continuous decrease in the elastic modulus from the deflection basin tests conducted between these temperatures. Thus, the time of year for measuring the amount of in place damage is probably important. If this observation holds true for many other LTPP test sections, the mathematical relationship used in the MEPDG for calculating damage may need to be revised to be temperature dependent.[1]

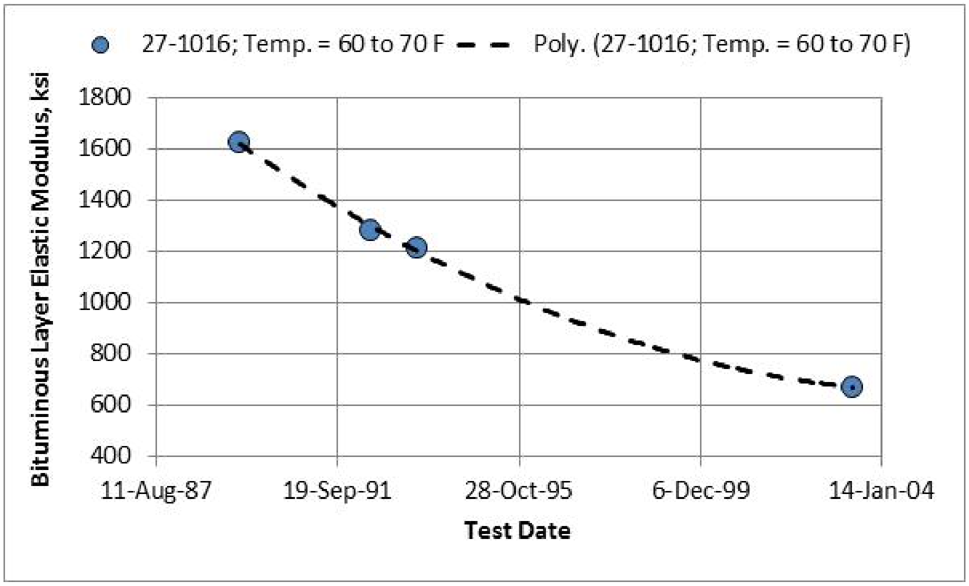


Figure 48. Graph. Decreasing elastic moduli of the asphalt layer between 60 and 66 ºF over time for use in rehabilitation design for Minnesota GPS section 27-1016.

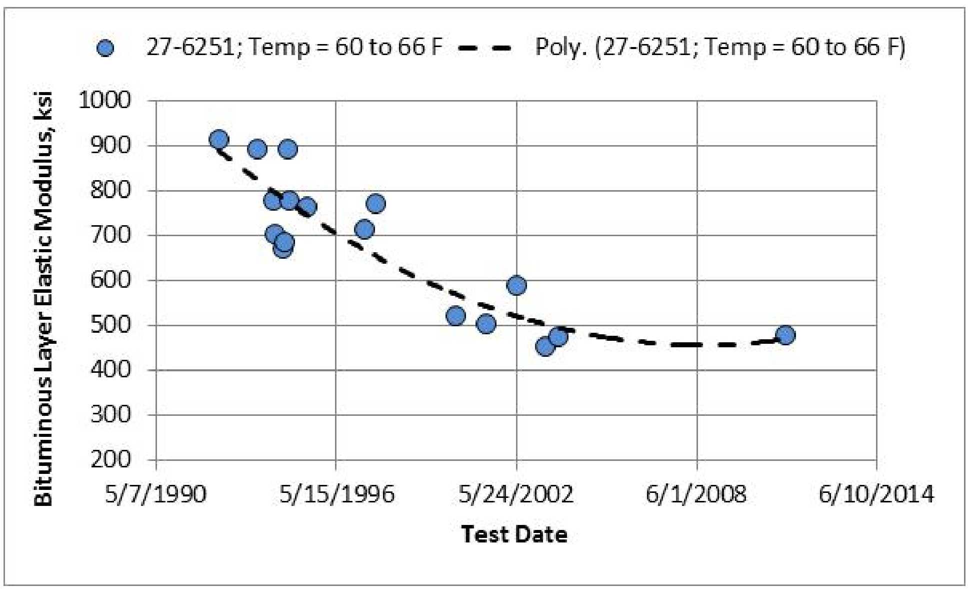


Figure 49. Graph. Decreasing elastic moduli of the asphalt layer between 60 and 66 ºF over time for use in rehabilitation design for Minnesota GPS section 27-6251.

Modulus Differences Between Wheel Paths and Non-Wheel Paths

Minnesota section 27-6251 exhibited significant damage as defined by the MEPDG, while Minnesota section 27-1018 did not exhibit any damage.(1) Deflection basins in LTPP were measured in the wheel paths (lane F3) as well as out of the wheel paths (lane F1) to determine if the load-response properties were different between the two areas. If the damage concept is correct, then the measurements within the wheel path should be statistically different than the non-wheel path measurements for the test section exhibiting damage, and there should be no difference between the two lines for the section not exhibiting damage.

Figure 50 and figure 51 include a comparison of the backcalculated elastic layer moduli for the wheel path and non-wheel path areas for these two LTPP sections in Minnesota. As shown, a significant difference was observed for GPS section 27-6251, and no difference was observed for GPS section 27-1018. This observation provides support for the damage concept incorporated within the MEPDG.(1) If this concept holds true for many more LTPP sections, this will make it easier for agencies to determine whether there is a difference in the loaded and non-loaded areas of the pavement by simply testing along two lanes, reducing the number of cores that are now required to determine the in-place damage for rehabilitation design and managing an agency's roadway network for planning future rehabilitation projects.

This observation by itself should be of significant value to agencies for improving their management prediction and planning capabilities. Simply measuring the deflection basins in the wheel path versus outside the wheel path provides a comparison of elastic moduli and whether damage is starting to occur. As extensive surface cracking starts to occur and spread beyond the wheel paths, however, any difference between measurements made in and outside the wheel paths is expected to decrease.

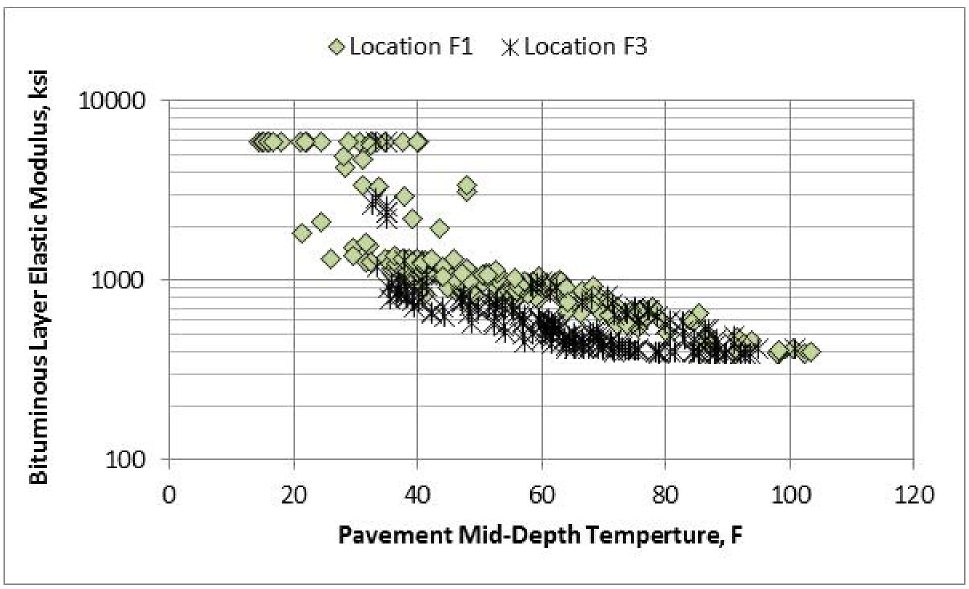


Figure 50. Graph. Elastic moduli of the asphalt layer between the wheel path and non-wheel path lanes for Minnesota GPS section 27-6251.

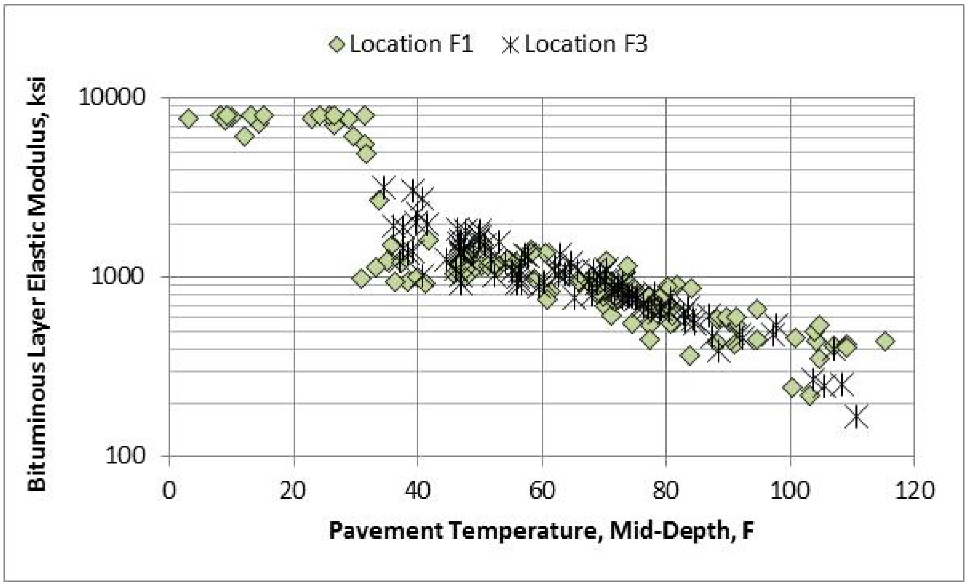


Figure 51. Graph. Elastic moduli of the asphalt layer between the wheel path and non-wheel path lanes for Minnesota GPS section 27-1018.

DIFFERENCES BETWEEN FIELD-DERIVED AND LABORATORY-MEASURED MODULI

The MEPDG software requires the entry of laboratory-measured moduli.(1) This section compares the backcalculated elastic layer moduli to laboratory-measured moduli.

HMA Layers

Elastic moduli were calculated and are in the CPTs in the LTPP database for all HMA-surfaced test sections. The projects included in the SPS-1 experiment were used to compare the laboratory-derived dynamic moduli and field-derived elastic moduli of the HMA layers for four test sections in Florida, Montana, New Mexico, and Wisconsin. The deflection basin test days used in this analysis were the first three recorded for each project because it is expected that no damage should have occurred shortly after the mixtures were placed. In addition, the backcalculated elastic moduli were derived from the deflection basins measured outside the wheel path to further reduce any possibility of damage skewing the comparison.

Figure 52 compares the laboratory-computed dynamic moduli using the Witczak regression equation to the backcalculated elastic moduli. A loading frequency of 20 Hz was used in the comparison. In addition, the mid-depth temperature for the layer in question was used to estimate the laboratory-derived value. As shown, there is a slight bias in the backcalculated moduli—slightly lower moduli were computed from the deflection basins in comparison to the laboratory-derived values computed with the dynamic modulus regression equation. This bias could be related to the assumed loading frequency and/or temperature used to estimate the laboratory-derived values. It could also be related to the thickness of the HMA layer used in the backcalculation process.

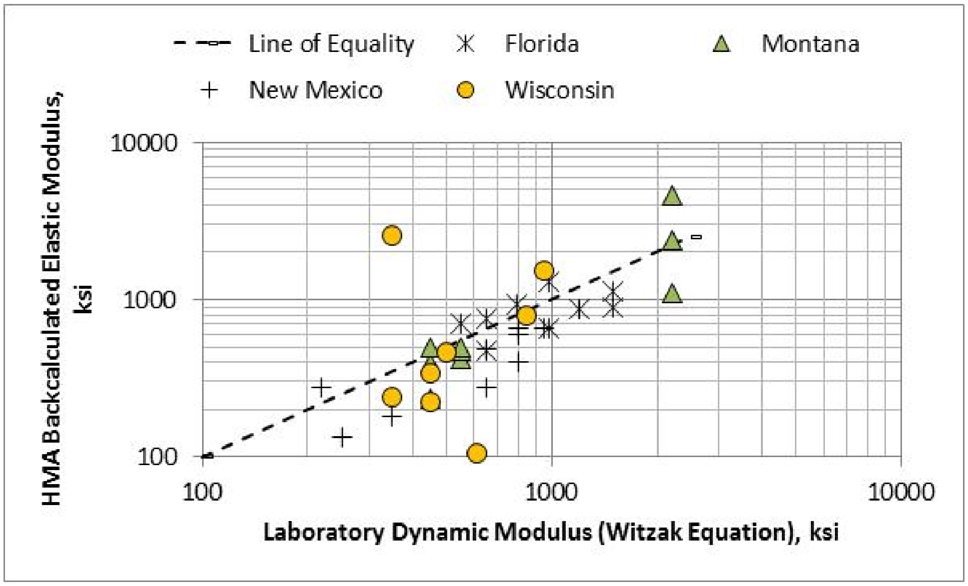


Figure 52. Graph. Comparison of the dynamic moduli computed from the Witczak regression equation and the backcalculated elastic moduli for four SPS-1 projects.

It is the authors' opinion that temperature is not the controlling factor causing the bias, but load frequency and thickness could be contributing factors. It is suggested that the LTPP backcalculated elastic moduli can be compared to the dynamic moduli calculated using Witczak's or another regression equation for making a recommendation on the loading frequency to be used and determine whether it is thickness dependent. By defining the equivalent load frequency and whether it is dependent on some other factor, no adjustments need to be made to the backcalculated elastic layer moduli for the HMA or bituminous layers.

PCC Layers

Static elastic moduli were measured in the laboratory for most of the PCC mixtures placed on the SPS-2 projects. The projects included in the SPS-2 experiment were investigated to compare the laboratory equivalent and field-derived elastic moduli of the PCC layers for four test sections. The deflection basin test days used in this analysis were the first ones recorded for each project after construction because it was expected that no damage occurred shortly after the mixtures were placed. The first deflection basin measurements for many of the SPS-2 projects, however, were taken more than 1 year after placement. As such, the elastic moduli measured on the GPS test sections were compared to the backcalculated moduli because both represent long-term properties. As was shown in figure 16, there was extensive variation in the backcalculated moduli, but the bias was minimal. One observation from the comparison is that the backcalculated elastic PCC moduli from EVERCALC© and MODCOMP© need to be adjusted to remove the bias for estimating laboratory-measured static elastic moduli and results from the best fit unbonded condition method. It is suggested that more sites be included in the comparison to confirm or reject the hypothesis.

Unbound Aggregate Base and Soils Layers

The case study sites were used to compare the laboratory-derived resilient modulus of the unbound layers at equivalent stress states under FWD testing to the average backcalculated elastic moduli. The resulting *c*-factors were found to be similar to the values reported in the literature as well as the default *c*-factors recommended for use in the MEPDG.(1) No further analyses comparing laboratory-derived resilient moduli to field-derived elastic moduli were completed under this study to determine if the *c*-factor was dependent on other factors.

TIME AND SEASONAL EFFECTS

The backcalculated elastic layer moduli for each pavement layer were reviewed from selected sites in the SMP experiment to evaluate the change in values over time or by month. Four SMP sites were used: two from a cold environment (Idaho (16-1010) and Minnesota (27-1018)) and two from a warm environment (New Mexico (35-1112) and Texas (48-1077)).

Seasonal Temperature Effects on HMA

Figure 53 through figure 56 show the backcalculated elastic layer moduli for the HMA layers from the four SMP sites. The backcalculated elastic moduli for the two SMP sites located in a warm climate had significantly lower elastic moduli during the winter months in comparison to the SMP sites located in a cold climate. The elastic moduli calculated for the winter months in the cold climates exceeded values that were considered too large in comparison to typical values measured in the laboratory. This represents a significant difference between the laboratory-derived and field-derived moduli during the winter months that should be investigated. It was expected that a partially frozen layer directly beneath the HMA had an effect on the HMA field-derived moduli.

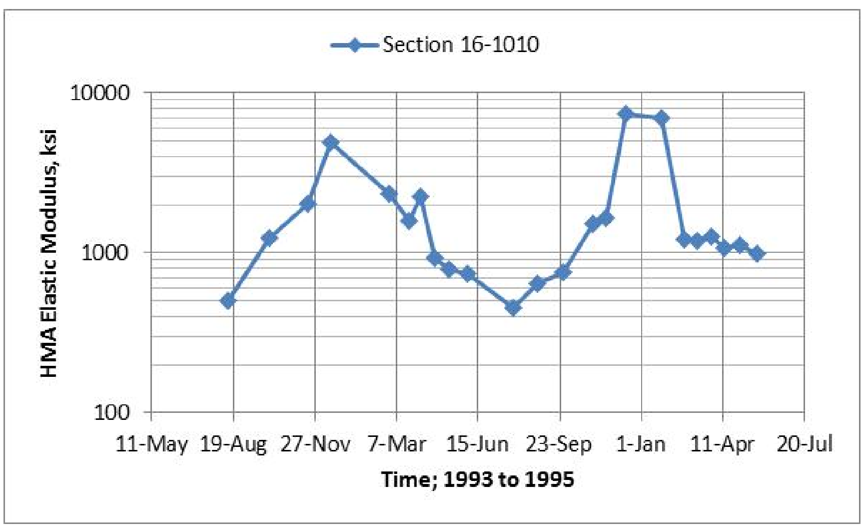


Figure 53. Graph. Comparison of HMA backcalculated elastic layer moduli for Idaho SMP section 16-1010.

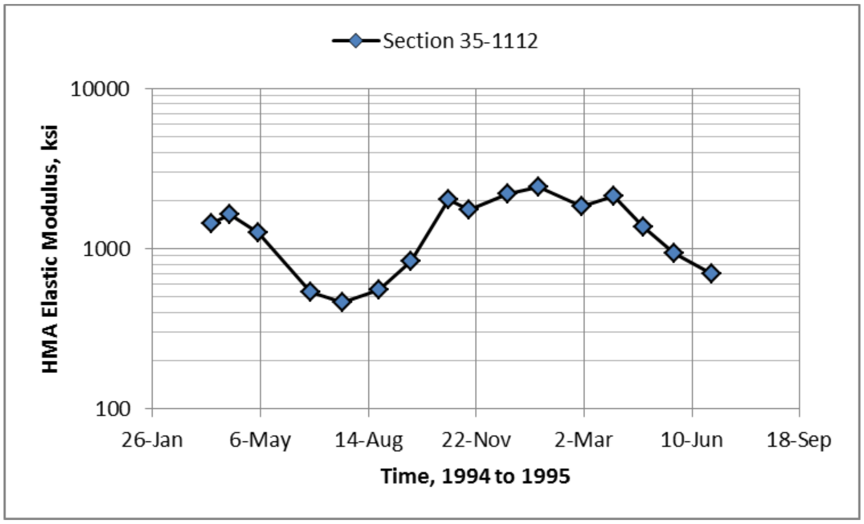


Figure 54. Graph. Comparison of HMA backcalculated elastic layer moduli for New Mexico SMP section 35-1112.

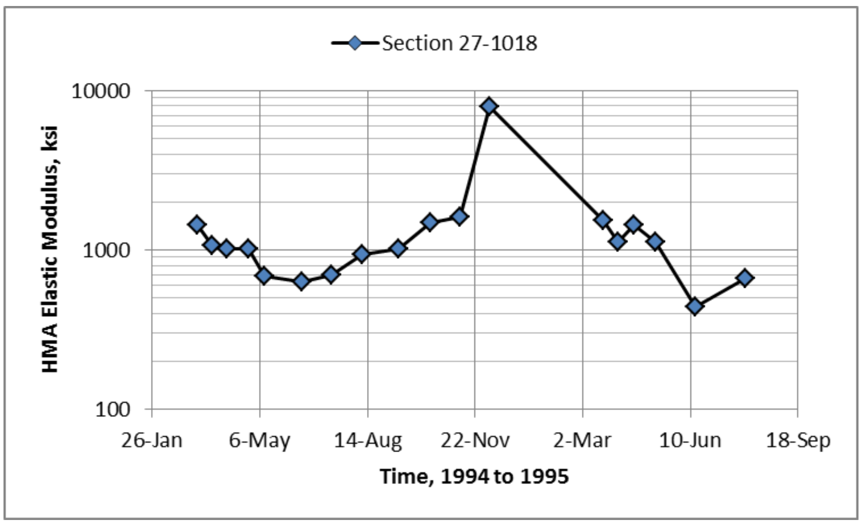


Figure 55. Graph. Comparison of HMA backcalculated elastic layer moduli for Minnesota SMP section 27-1018.

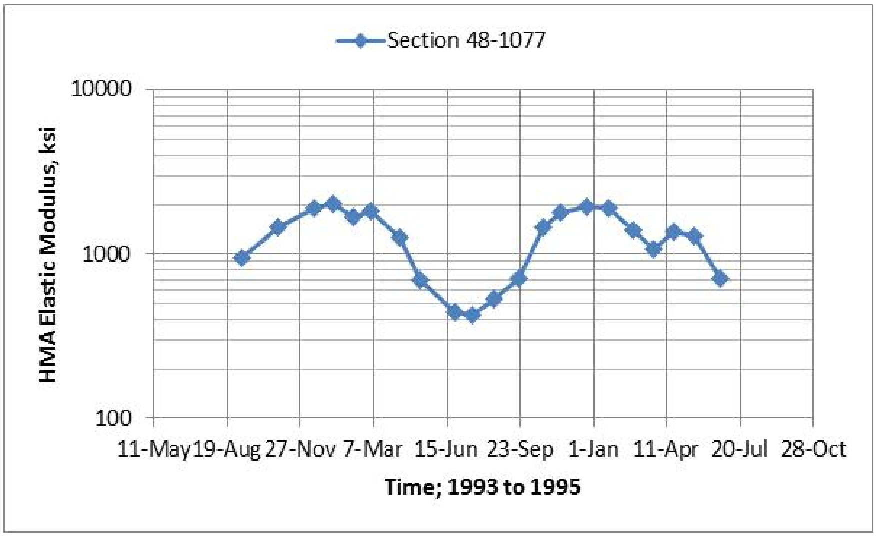


Figure 56. Graph. Comparison of HMA backcalculated elastic layer moduli for Texas SMP section 48-1077.

Seasonal Moisture Effects for Unbound Aggregate Base Layers

Figure 57 through figure 60 show the backcalculated elastic layer moduli for the unbound aggregate base from the four SMP sites. The two SMP sites located in a cold climate had very high elastic moduli during the winter months that were representative of a frozen or partially frozen layer (Idaho section 16-1010 and Minnesota section 27-1018). For the two SMP sites located in a hot climate, the elastic modulus was significantly higher during the summer months in comparison to the winter months (New Mexico section 35-1112 and Texas section 48-1077). The water content of the aggregate base layers in the summer months in a hot dry climate can be lower in comparison to the winter months and result in higher modulus values.

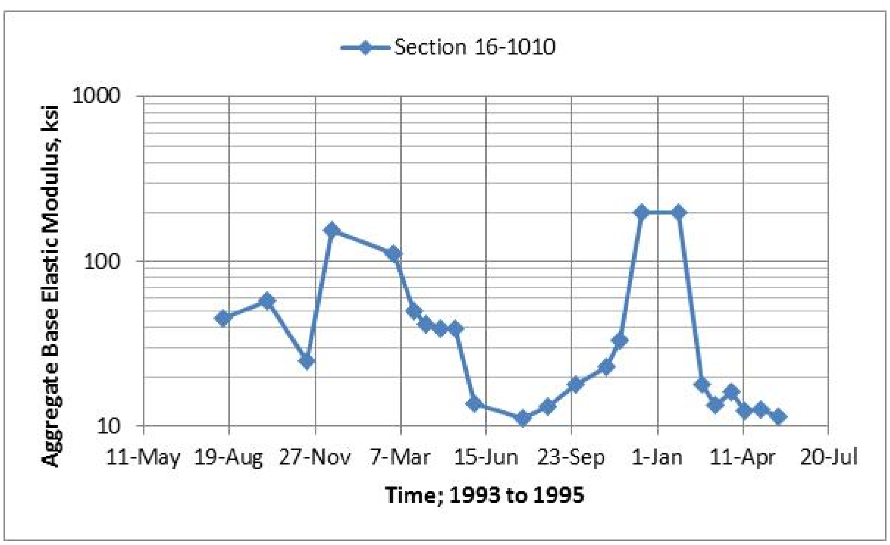


Figure 57. Graph. Comparison of aggregate base backcalculated elastic layer moduli for Idaho SMP section 16-1010.

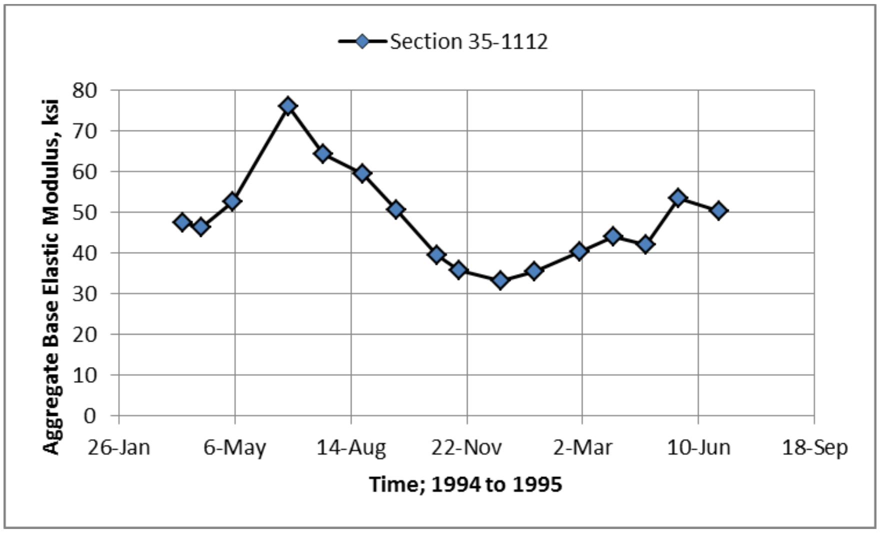


Figure 58. Graph. Comparison of aggregate base backcalculated elastic layer moduli for New Mexico SMP section 35-1112.

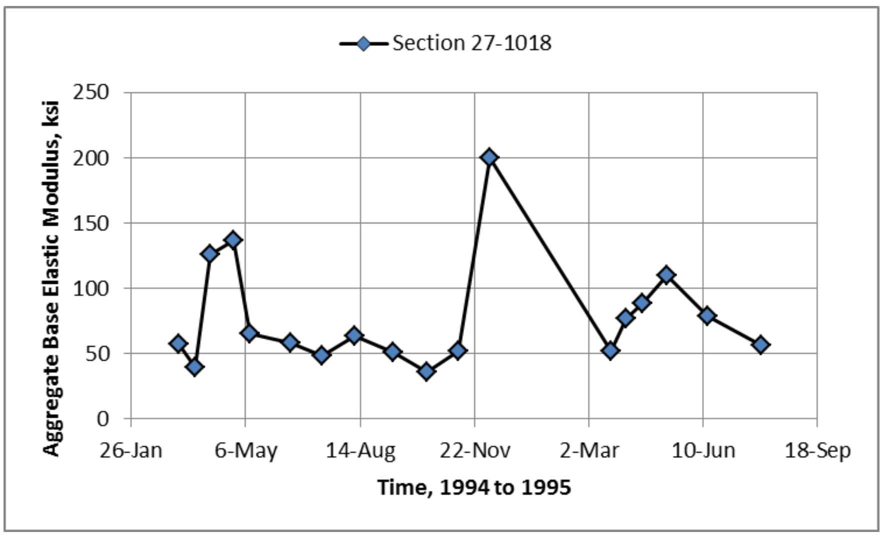


Figure 59. Graph. Comparison of aggregate base backcalculated elastic layer moduli for Minnesota SMP section 27-1018.

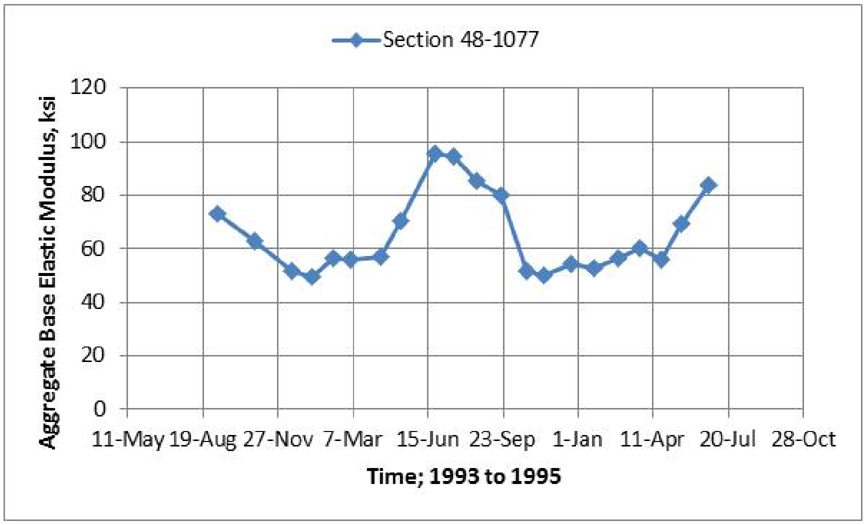


Figure 60. Graph. Comparison of aggregate base backcalculated elastic layer moduli for Texas SMP section 48-1077.

Seasonal Moisture Effects for the Weathered Soil Layers

Figure 61 through figure 63 show the backcalculated elastic layer moduli for the weathered soil layers at three of the SMP sites (Idaho, Minnesota, and Texas). A weathered layer was not included in the New Mexico SMP site because a bedrock or very stiff layer existed at this site. The two SMP sites located in a cold climate had very high elastic moduli during the winter months that were representative of a frozen or partially frozen layer (Idaho section 16-1010 and Minnesota section 27-1018). For the SMP site located in a hot climate with a weathered soil layer, the elastic modulus was significantly higher during the summer months in comparison to the winter months (Texas section 48-1077). The water content of the weathered soil in the summer months in a hot dry climate can be lower in comparison to the winter months and result in higher modulus values.

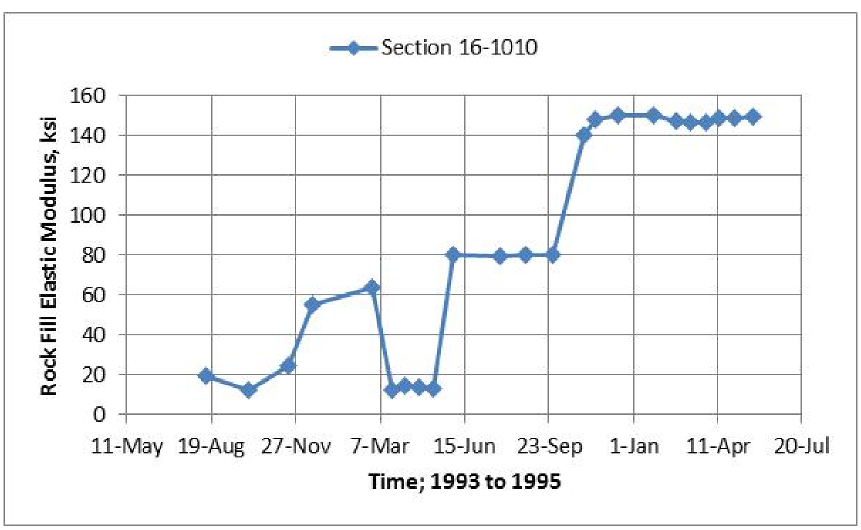


Figure 61. Graph. Comparison of weathered soil backcalculated elastic layer moduli for Idaho SMP section 16-1010.

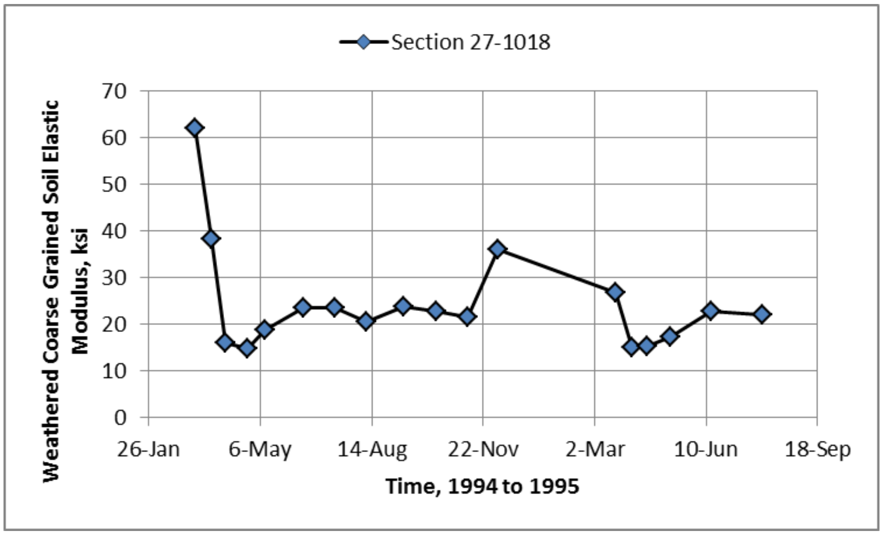


Figure 62. Graph. Comparison of weathered soil backcalculated elastic layer moduli for Minnesota SMP section 27-1018.

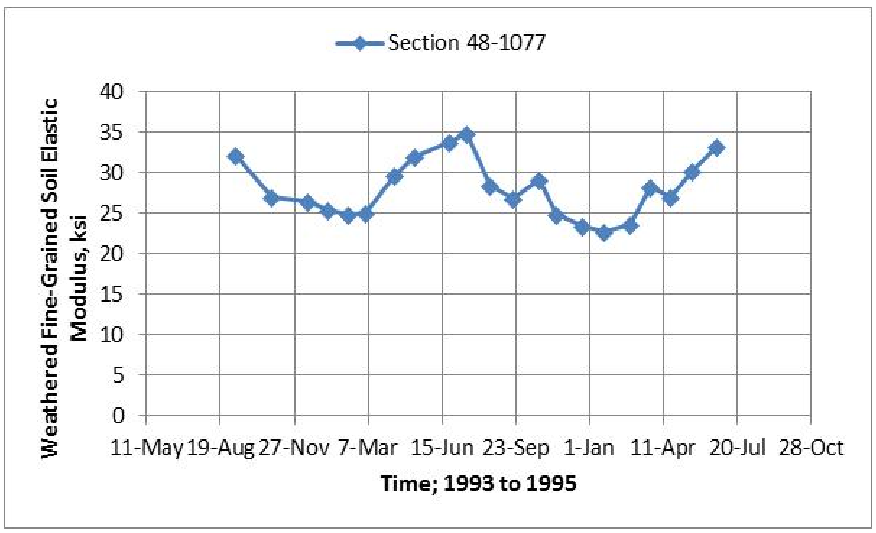


Figure 63. Graph. Comparison of weathered soil backcalculated elastic layer moduli for Texas SMP section 48-1077.

The Idaho SMP site included a thick rock fill. The elastic modulus of this layer steadily increased over time to a value of about 150 ksi. The authors completed deflection testing and backcalculation of elastic layer moduli using EVERCALC© on other commercial-type projects that included rock fills located in central Texas and Wyoming. Similar results were obtained from unpublished design reports, with the in-place elastic moduli varying from about 80 to over 150 ksi. However, time-dependent results from these other projects were unavailable. Rock fills have been placed at other LTPP test section locations and should be investigated to determine if they exhibit this same time-dependent characteristic and magnitude of in-place elastic moduli.

Seasonal Moisture Effects for the SS Layers

Figure 64 through figure 67 show the backcalculated elastic layer moduli for the SS at the four SMP sites. The two SMP sites located in a cold climate had higher elastic moduli during the winter months that would be representative of a partially frozen layer. For the two SMP sites located in a hot climate, the elastic modulus was about the same between the summer and winter months. Significant variations in water content of the deeper SSs do not usually occur unless there is an external factor causing the change in the water content, such as the lateral flow of water or seasonal perched water tables.

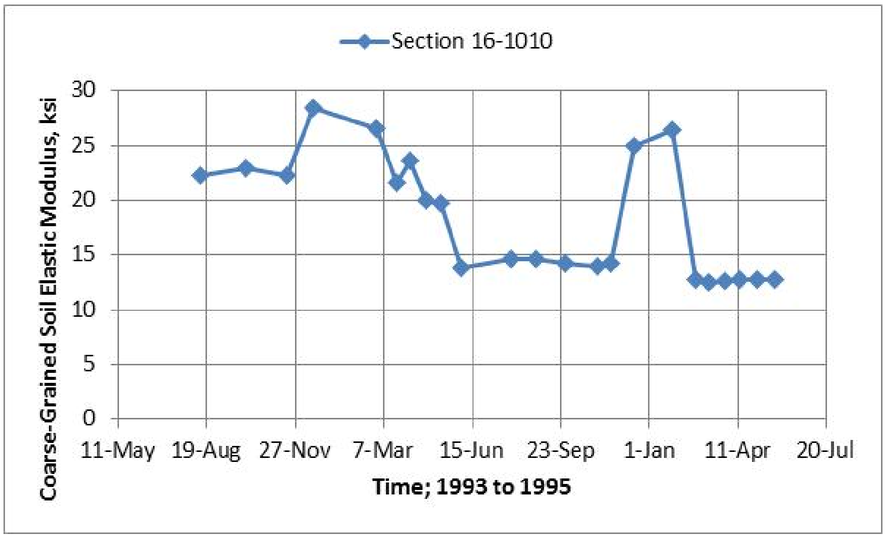


Figure 64. Graph. Comparison of SS backcalculated elastic layer moduli for Idaho SMP section 16-1010.

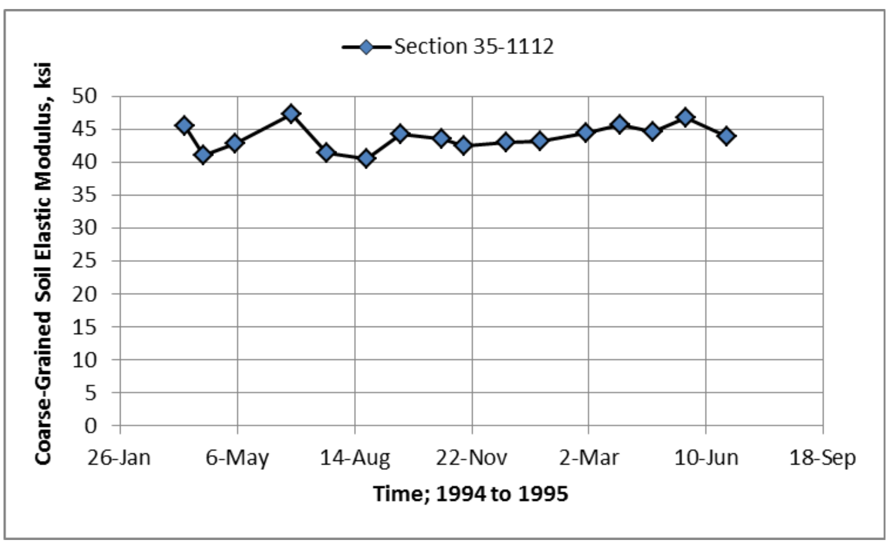


Figure 65. Graph. Comparison of SS backcalculated elastic layer moduli for New Mexico SMP section 35-1112.

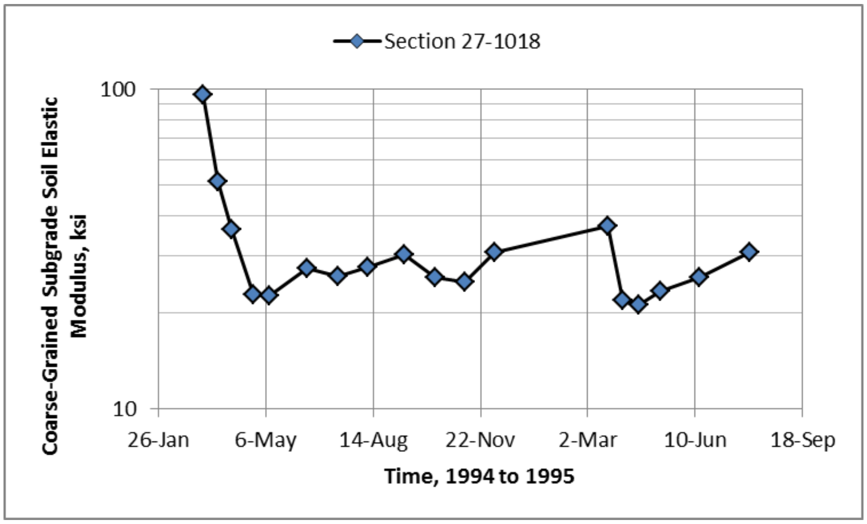


Figure 66. Graph. Comparison of SS backcalculated elastic layer moduli for Minnesota SMP section 27-1018.

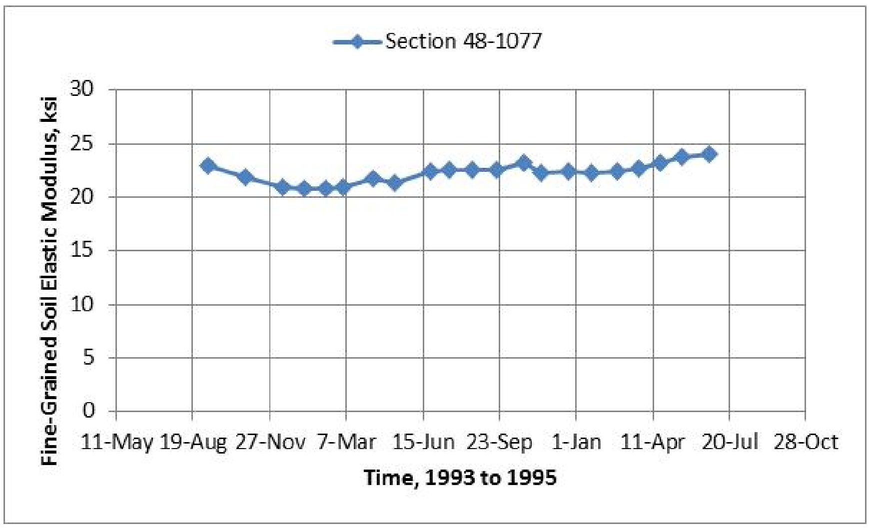


Figure 67. Graph. Comparison of SS backcalculated elastic layer moduli for Texas SMP section 48-1077.

MIXTURE TIME-DEPENDENT MODULI

HMA Aging

The SPS-1 and -5 test sections were investigated to determine the increase in elastic moduli over time and if the values could be used to estimate the hardening that occurs with time.
Figure 52 shows a comparison of the laboratory-derived dynamic moduli to the field-derived elastic moduli for the first 3 test days when the majority of the hardening occurred after HMA placement. The HMA layers were combined for most of the SPS-1 test sections and represent weighted or composite values for all of the HMA lifts or layers. Even for the SPS-5 test sections where the overlay was represented as a separate layer, there was no clear increase in the field-derived elastic moduli over time. More importantly, the HMA elastic layer moduli were heavily

influenced by temperature, so the increase in HMA elastic modulus through hardening could not be determined because of the variability in the computed results.

PCC Modulus-Gain Relationship

The PCC backcalculated elastic layer moduli from selected SPS-2 test sections were used to determine if these values could be used to confirm the modulus-time or strength gain relationship included in the MEPDG software.(1) Figure 68 and figure 69 show the backcalculated elastic layer moduli from the EVERCALC© program and best fit method, respectively, for multiple SPS-2 test sections. As shown, there was too much variation in the backcalculated moduli values over time to estimate the strength or stiffness versus time relationship. Figure 70 provides a comparison between the PCC elastic modulus from the best fit unbonded method to the elastic moduli backcalculated with EVERCALC©. The PCC elastic moduli from the unbonded best fit method are consistently higher than from the moduli backcalculated with EVERCALC©.

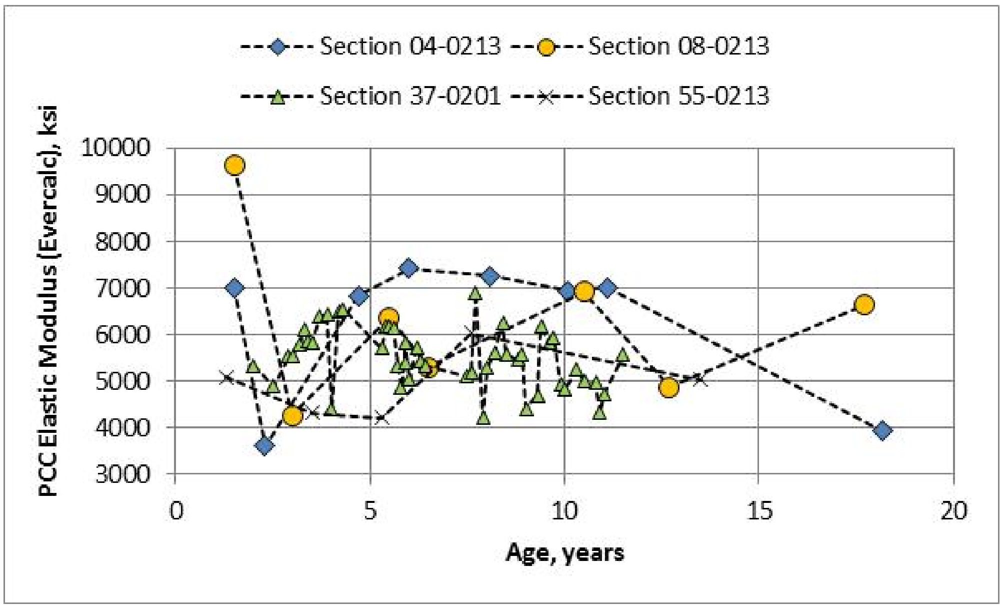


Figure 68. Graph. Backcalculated PCC elastic moduli over time from EVERCALC© for selected SPS-2 test sections.

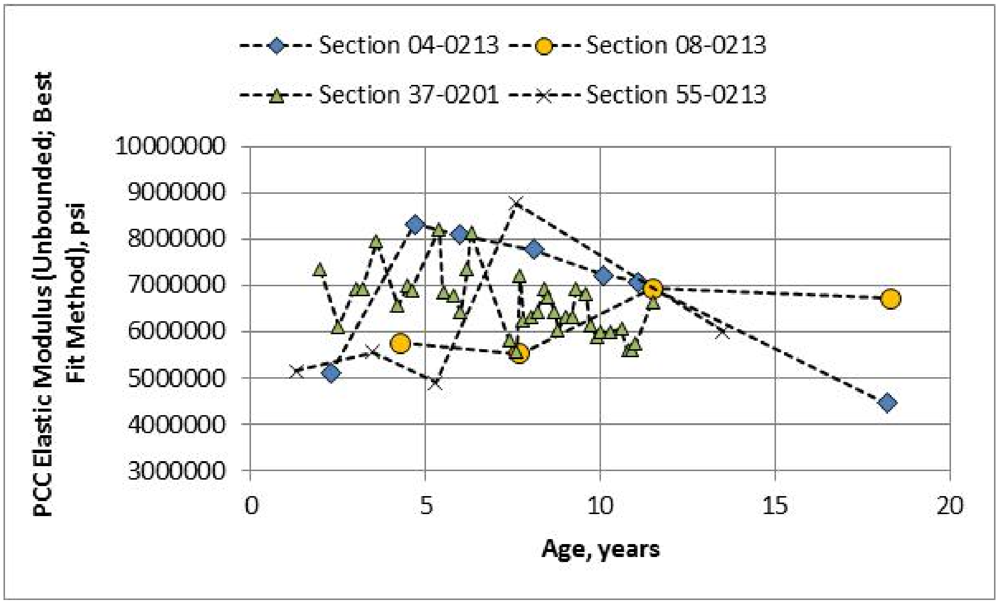


Figure 69. Graph. Backcalculated PCC elastic moduli over time from the best fit unbonded method for selected SPS-2 test sections.

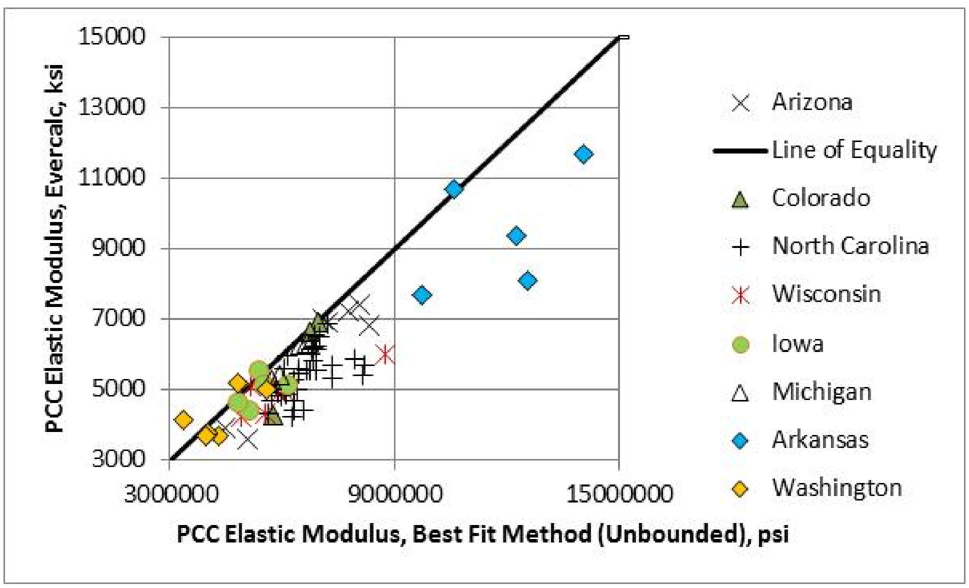


Figure 70. Graph. Comparison of backcalculated PCC elastic moduli from EVERCALC© and the best fit unbonded method for selected SPS-2 test sections.

MODULUS OF FRACTURED PCC LAYERS

The MEPDG provides recommended default elastic moduli for fractured PCC slabs, but two questions have been raised regarding the elastic moduli that are representative of the fractured PCC layer: (1) what is the representative elastic modulus after construction, and (2) does this value change over time? The LTPP backcalculated elastic layer moduli from SPS-6 test sections were used to determine if those two questions can be answered. Test sections from Arizona, Indiana, Michigan, Oklahoma, and Pennsylvania were used to compare the backcalculated elastic layer moduli between the fractured and intact PCC slabs. The Arizona, Michigan, and Pennsylvania projects included both crack and seat and rubblized test sections, but the Indiana and Oklahoma projects did not. The Indiana project only included the crack and seat method, while the Oklahoma project only included the rubblization method.

The Oklahoma SPS-6 project was used as one of the case studies because the existing pavement consisted of a JRCP that was rehabilitated using multiple techniques. The first layering simulation included the JRCP as one continuous layer for both the rubblization method as well as for the intact slabs. Table 16 lists the backcalculated layer moduli before and after rehabilitation for the last testing day at this project site. A second run was made for the rubblized section but with a different layering simulation: JRCP was divided into two layers above and below the reinforcement. The table also includes the values resulting from that condition for the last testing day included in the LTPP database.

Table 16. Backcalculation results for the Oklahoma SPS-6 project—intact and rubblized test sections.

	Section 0606 Major Restoration		Section 0608 Rubblization		
Item or Element	Intact Slabs[a]	Crack & Seat	Intact Slabs[a]	One Layer	Two Layers
PCC modulus	4,799	3,615	5,082	301	284 2,013
Aggregate base modulus	11.4	16.3	10.2	56.4	N/A
Weathered soil layer modulus	67.5	13.6	10.1	45.5	27.5
Subgrade natural modulus	33.6	32.5	37.8	34.5	35.0
HMA overlay modulus	N/A	617	N/A	848	880
Average RMSE	1.4	1.6	1.1	1.2	1.1

N/A = Layer not applicable or used in backcalculation process.
[a]Backcalculated elastic modulus values include those prior to major restoration and rubblization; there was no HMA overlay because deflection basins were measured prior to restoration or rubblization.

The simulation of two PCC layers resulted in about the same RMSE value as for the single layer simulation. The modulus of the upper PCC layer, however, was significantly lower than that of the lower PCC layer. More importantly, the elastic modulus of the upper layer was found to be only slightly lower than that of the single JRCP layer. Thus, it was decided the structure would initially be simulated as one PCC fractured layer. If high RMSE values resulted, then the PCC fractured layer was divided into two layers in an effort to reduce the RMSE.

Figure 71 shows the backcalculated elastic modulus of the rubblized PCC at the Oklahoma SPS-6 site. The elastic modulus of the rubblized PCC was less than 100 ksi after construction, but it steadily increased over time. The PCC moduli for intact slabs of the control section (without an HMA overlay) and the section with maximum restoration activities are also shown in figure 71. The elastic moduli varied from 3 to 6 million psi at this site.

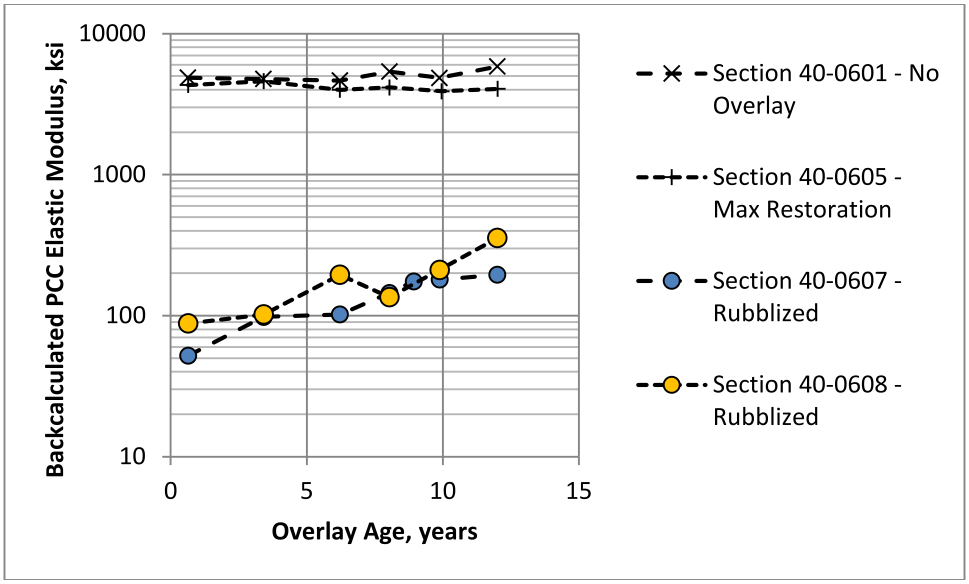


Figure 71. Graph. Backcalculated elastic moduli for the Oklahoma SPS-6 rubblized test sections.

Figure 72 shows the backcalculated elastic layer modulus for the PCC modulus for the Indiana crack and seat sections. As shown, the elastic modulus for the PCC crack and seat was about one-third the modulus of the intact slabs and then increased over time.

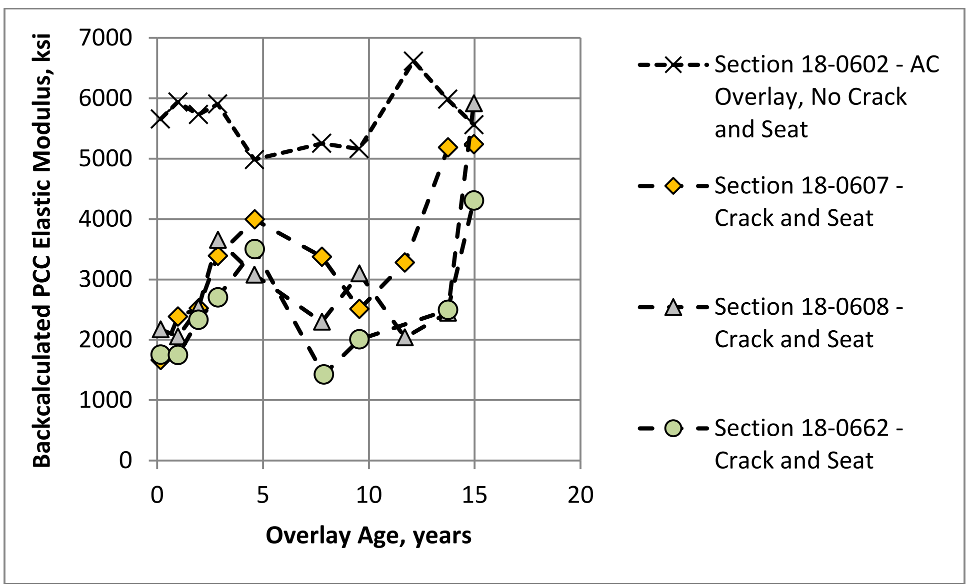


Figure 72. Graph. Backcalculated elastic moduli for the Indiana SPS-6 crack and seat test sections.

Figure 73 through figure 75 compare the backcalculated elastic moduli for the intact, crack and seat, and rubblized test sections from the Arizona, Michigan, and Pennsylvania SPS-6 projects. As shown, the Arizona crack and seat section was the only one where the elastic moduli decreased over time. All other SPS-6 sections stayed about the same or increased over time.

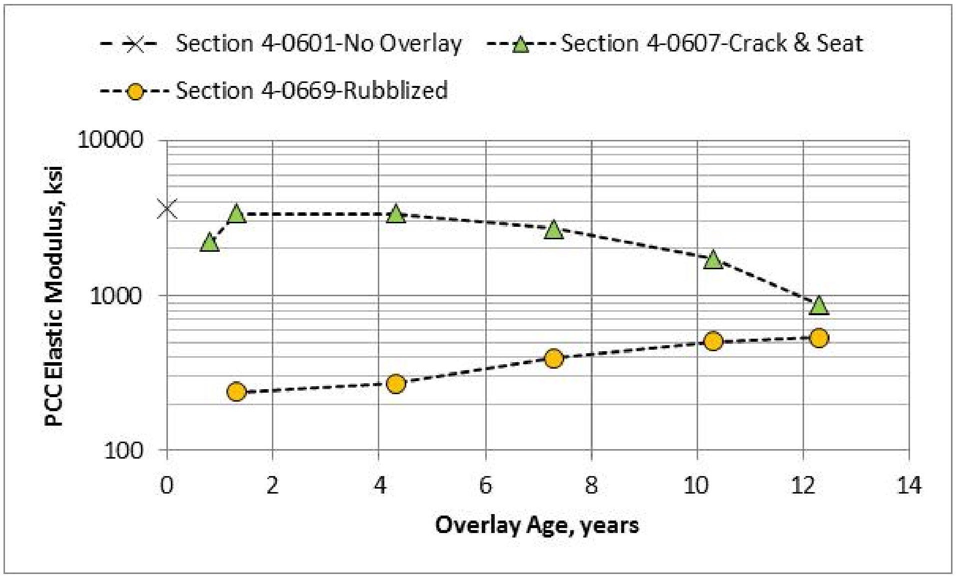


Figure 73. Graph. Backcalculated elastic moduli comparing the PCC intact, crack and seat, and rubblized test sections for the Arizona SPS-6 test sections.

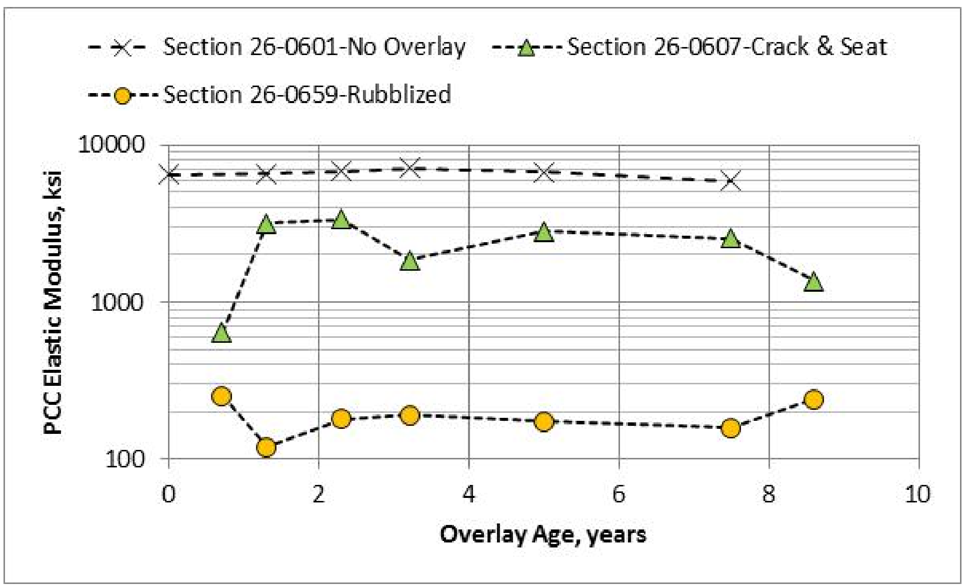


Figure 74. Graph. Backcalculated elastic moduli comparing the PCC intact, crack and seat, and rubblized test sections for the Michigan SPS-6 test sections.

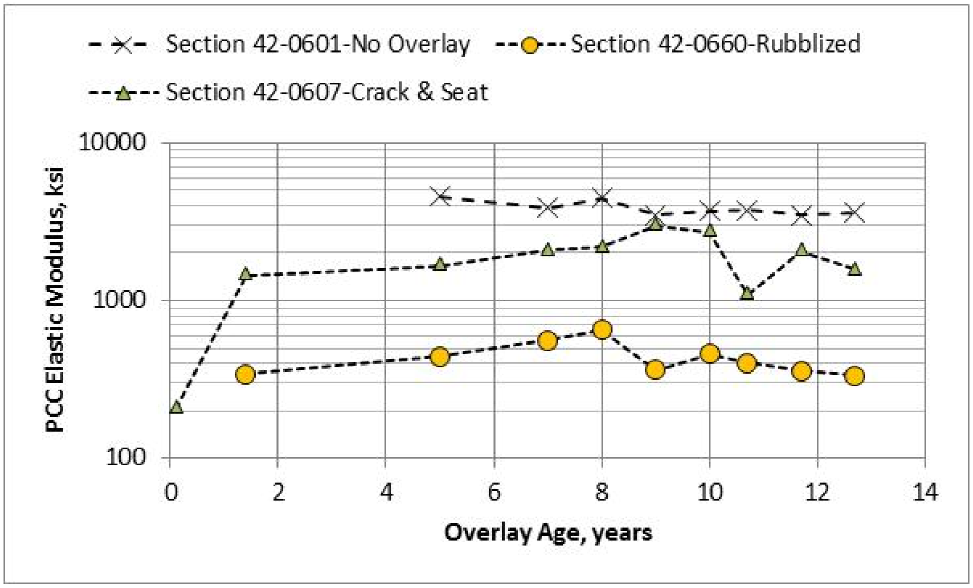


Figure 75. Graph. Backcalculated elastic moduli comparing the PCC intact, crack and seat, and rubblized test sections for the Pennsylvania SPS-6 test sections.

The default values included in the MEPDG for the crack and seat method are 150,000 to 2 million psi, and for the rubblization method the default values are 50,000 to 1 million psi.(1) Both represent a wide range of moduli. The following list summarizes some observations from these SPS-6 projects relative to the range of values included in the MEPDG:(1)

- With the exception of the Indiana project, the backcalculated elastic moduli for the crack and seat method increased over time to a value of about one-half to one-third of the elastic modulus of the intact slabs.
- For the rubblized sections, the backcalculated elastic moduli were greater than 50 ksi but less than 1,000 ksi for all test sections. The backcalculated elastic modulus stayed about the same after construction except at the Oklahoma project.
- The backcalculated elastic modulus values for the intact slabs without an HMA overlay were found to be greater than 5 million psi at the Michigan, Oklahoma, and Indiana projects but not the Arizona and Pennsylvania projects. The backcalculated elastic modulus of the intact slabs from the Arizona and Pennsylvania sections without an overlay were representative of cracked PCC for the test sections included in this preliminary evaluation.

Based on these observations, a detailed evaluation of the backcalculated elastic moduli for the fractured PCC slabs should be conducted for recommending a narrower range of default values included in the MEPDG.(1)

RECLAIMED ASPHALT PAVEMENT (RAP) AND VIRGIN MIXTURES

Many agencies have limits on the amount of RAP included in HMA base mixtures as well as for wearing surfaces. The asphalt industry has been pushing the use of higher percentages of RAP in asphalt mixtures in all layers of the pavement. The LTPP SPS-5 experiment was designed to provide data to evaluate the difference between mixtures with about 30 percent RAP and those without RAP. The backcalculated layer elastic modulus was used to evaluate whether there was a difference between the structural responses of the sections with and without RAP. Figure 76 provides a comparison of the RAP and virgin mixture backcalculated elastic layer moduli for the SPS-5 Minnesota project. As shown, there was no significant difference in the structural responses of the asphalt mixtures with and without RAP.

Another important observation from figure 76 is that the backcalculated elastic modulus for the existing asphalt mixture (the control section which was not overlaid) had a significantly higher in-place modulus value than the virgin and RAP mixtures of the overlay. This observation was expected because the existing HMA was much older than the two overlay mixtures, demonstrating the difference that can be caused by long-term aging.

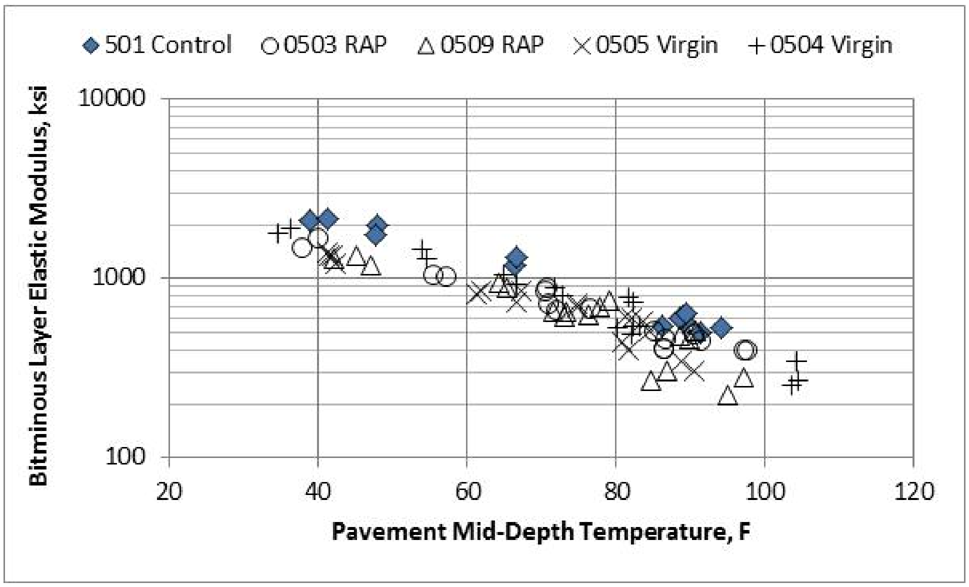


Figure 76. Graph. Comparison of RAP and virgin backcalculated elastic HMA moduli from the Minnesota SPS-5 project.

The backcalculated moduli from four additional SPS-5 projects were used to investigate the difference between the RAP and virgin mixtures in relation to the existing HMA layers. Figure 77 through figure 80 show a comparison of the backcalculated elastic moduli for the different mixtures at four of the SPS-5 projects.

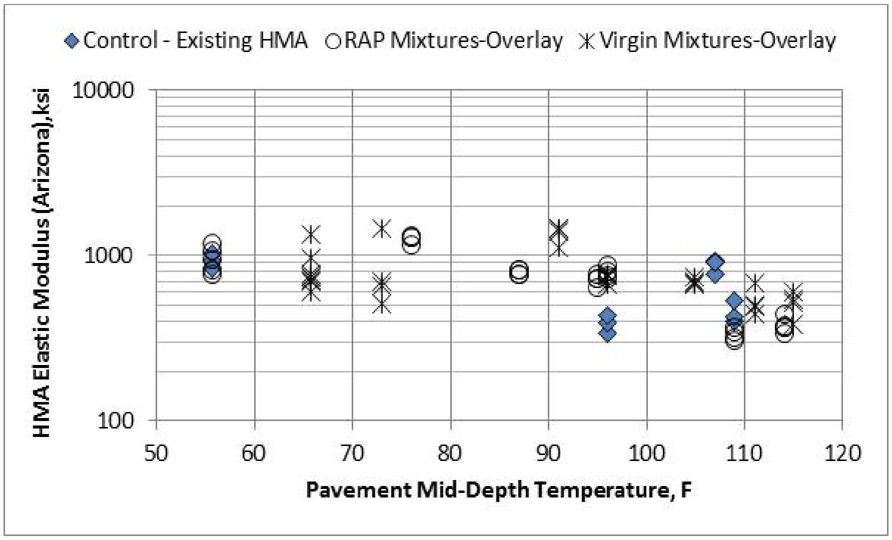


Figure 77. Graph. Comparison of RAP and virgin mix backcalculated elastic HMA moduli from the Arizona SPS-5 project.

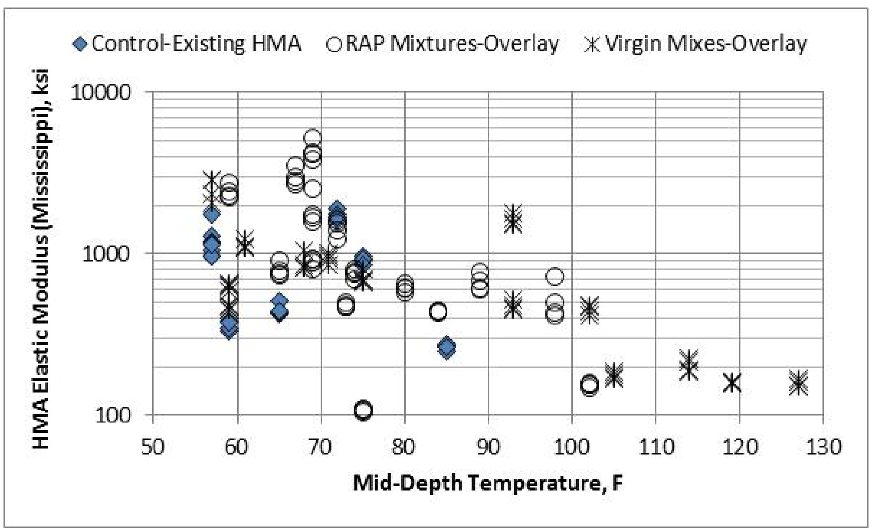


Figure 78. Graph. Comparison of RAP and virgin mix backcalculated elastic HMA moduli from the Mississippi SPS-5 project.

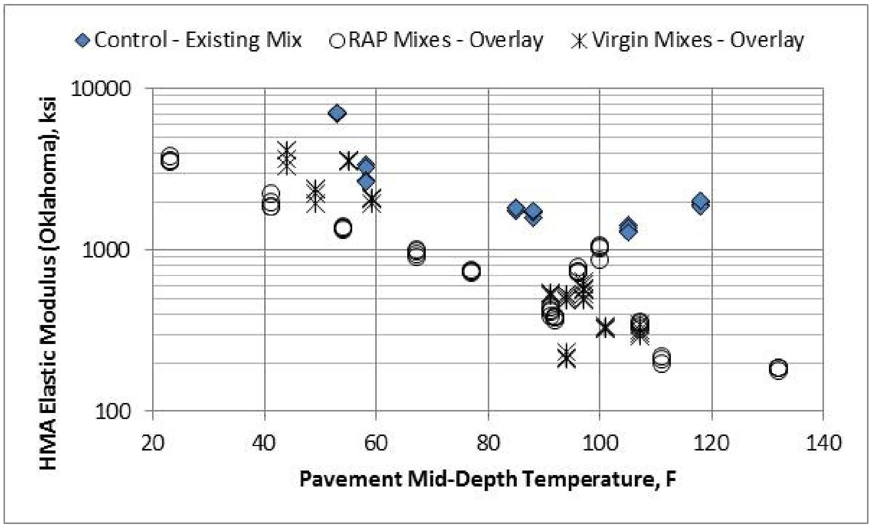


Figure 79. Graph. Comparison of RAP and virgin mix backcalculated elastic HMA moduli from the Oklahoma SPS-5 project.

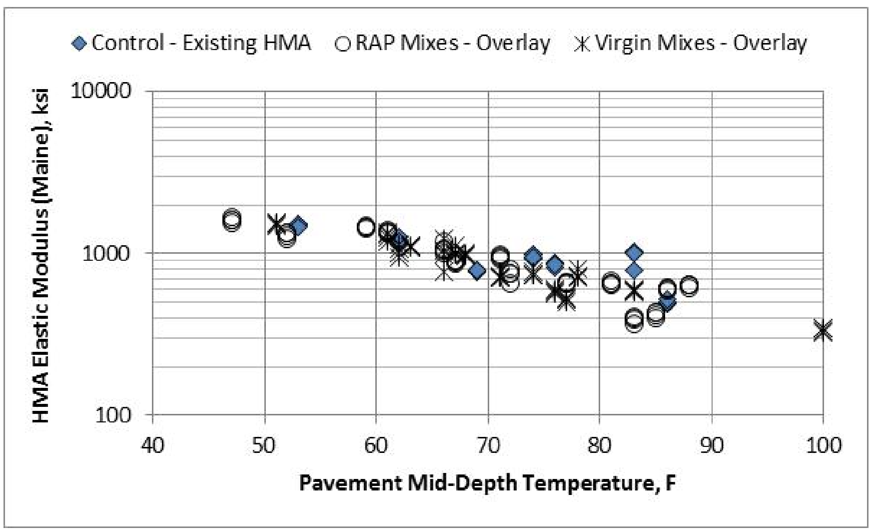


Figure 80. Graph. Comparison of RAP and virgin mix backcalculated elastic HMA moduli from the Maine SPS-5 project.

No significant and consistent difference was observed between the RAP and virgin mixtures used for the overlay. The Maine SPS-5 project exhibited the least difference between the mixtures, while the Arizona SPS-5 project exhibited the least difference across all pavement test temperatures.

The elastic moduli for the existing HMA layer for the Oklahoma project were very high across the entire temperature regime. These results are believed to be reasonable because the binder tests conducted on the extracted asphalt from the existing HMA layer suggest a severely aged material. Conversely, the elastic moduli of the existing HMA layer at the Maine project were only slightly greater than for the overlay mixtures during the summer months. The binder tests conducted on the extracted asphalt for the Maine project did not suggest a severely aged material.

The Mississippi project exhibited a lot of variation for all mixtures. This project experienced high rutting and was taken out of service because of stripping. As noted in chapter 3, it also exhibited high damage in the field-derived moduli.

CHAPTER 7. CONCLUSIONS

The automated backcalculation procedure and tools reported in this report were used to determine the elastic layer properties (or Young's modulus) from deflection basin measurements for all LTPP test sections. This report summarizes the reasons why EVERCALC© and MODCOMP© were selected for the computations and analyses of the deflection data, provides a summary of the results using the linear elastic modulus for selected test sections, and identifies those factors that can have a significant effect on the results. This chapter includes some of the highlights and findings from this study and recommendations for future activities in support of accomplishing the overall LTPP objectives.

FINDINGS

Backcalculation of elastic properties is not an exact science and requires user interaction in some cases. However, the process was automated through a series of utility functions and tools to reduce the impact of user interaction, bias, and/or inexperience. Results from this automated procedure provide elastic layer load response properties that are consistent with previous experience and laboratory material studies related to the effect of temperature, stress state, and seasonal effects on the material load-response behavior. The following list highlights some of the important findings from this study:

- In 1997, Von Quintus and Killingsworth recommended one software package to be used because of large differences between multiple programs.[46] Similarly, one package was used in the first backcalculation project, MODCOMP4.0©. The present study used three programs: EVERCALC© and MODCOMP© were used to calculate the elastic layer moduli of all pavement sections in the LTPP database, and the best fit method was used for all PCC-surfaced test sections. EVERCALC© and MODCOMP© are available in the public domain, and they provide non-unique solutions. The best fit method is a forward calculation procedure that provides unique solutions.

- EVERCALC© and MODCOMP© resulted in statistically indifferent results for deflection basins classified as typical or in conformance with elastic layer theory as defined by Von Quintus and Simpson and Von Quintus and Killingsworth.[4,46] For type 2 deflection basins, the EVERCALC© and MODCOMP© programs resulted in statistically different elastic moduli for the intermediate layers (the weathered soil layer and thinner aggregate base layers, which accounted for about 25 percent of the deflection basins analyzed). As reported in the first backcalculation study, the pavements exhibiting deflection-softening behavior with type 2 deflection basins were the most difficult to analyze and were generally found to have higher RMSEs.[4] Some of these deflection basin analyses resulted in no reasonable solution, or the solution provided unrealistic layer moduli for the type of material defined in the LTPP database.

- The PCC elastic moduli calculated with EVERCALC© resulted in significantly greater values in comparison to the moduli calculated with the best fit unbonded method. Thus, results from the two methods should not be combined, or a factor needs to be used to adjust the EVERCALC©-generated PCC moduli to the best fit unbonded condition method or laboratory-measured elastic moduli.

- Over 90 percent of the deflection basins analyzed with EVERCALC© and MODCOMP© resulted in layer moduli with an RMSE less than 3 percent and are considered acceptable.

- In the authors' opinion, there is still no consensus on the best backcalculation package that provides the most reliable and accurate results. However, the case study findings were very similar to the findings documented in the Smith study.(53) Specifically, EVERCALC© consistently resulted in lower error terms and a higher number of successful modulus determinations when considering all deflection basins. When only considering those deflection basins that ran successfully, however, the MODCOMP© program resulted in lower RMSE values.

- Historically, a constant modulus for the PCC rubblized slabs has been used for rehabilitation design projects. The elastic modulus of the rubblized PCC slabs, however, was found to steadily increase over time for some of the LTPP SPS-6 test sections.

- No difference was found in the load-response properties (stiffness) between the RAP and virgin mixtures of the SPS-5 experiment.

- Similar *c*-factor values were found in this project to the values included in the MEPDG.(1) More importantly, no significant difference or bias was found between the laboratory-derived dynamic modulus and the field-derived values for the HMA layers.

- The use of drop heights 1 to 4 in the LTPP deflection testing program did not result in significantly different elastic moduli for the unbound layers. As such, it was difficult to determine the coefficients of a constitutive equation to estimate the stress sensitivity of an unbound layer because of the variation in moduli over time and along a specific test section. The stress levels resulting from the four drop heights used in the LTPP deflection testing program are too narrow.

- Damage was determined in accordance with the MEPDG procedure for multiple LTPP test sections to demonstrate its use in rehabilitation design.(1) The results were found to be positive and used to support the MEDPG procedure. The damage concept as applied to interpreting the backcalculated moduli can be very useful in explaining low moduli. In addition, the Florida Department of Transportation was one of the first agencies to monitor changes in the deflection basin (similar to this damage concept) over time in planning rehabilitation projects from a pavement management standpoint. From the case study sites and examples of data use, the damage concept can be used to evaluate the condition of the existing pavement and plan future rehabilitation projects.

- The use of four layers generally resulted in lower RMSEs than the use of three layers. In many cases, breaking or separating the subgrade into at least two layers improved the match between the measured and calculated deflection basins.

RECOMMENDATIONS

The results from this study have shown that elastic layer moduli (or load-response properties) can be computed from deflection basins and provide pavement engineers with useful information about the pavement structure and subgrade condition. However, this study only touched on the different ways the backcalculated elastic layer modulus database can be used for improving pavement design and rehabilitation strategies. More detailed analysis can be completed to demonstrate the usefulness of the deflection data and resulting elastic moduli. The following list highlights some specific topics that can be investigated in the future:

- Compare the field-derived elastic moduli of HMA layers to the laboratory-derived dynamic moduli for determining the equivalent load frequency of the FWD for matching the two moduli.

- Compare the PCC laboratory-measured static elastic moduli to the field-derived values to determine the adjustment factor for the EVERCALC©/MODCOMP© backcalculated elastic modulus of PCC layer to be used in the MEPDG.(1)

- Use the LTPP database for preparing a set of guidelines for estimating damage through deflection basin testing and backcalculated elastic moduli between within and outside the wheel paths. Agencies can use this information for planning rehabilitation projects.

- Confirm or revise the default PCC elastic layer moduli of rubblized and crack and seat slabs, as well as define how those values change with time.

- Use the backcalculated results to confirm the default moduli included in the MEPDG or recommend revisions to those default values and determine whether these values depend on season or climate.(1)

APPENDIX A: BEST FIT METHOD—CALCULATING PCC ELASTIC LAYER MODULI

The best fit method proposed previously for the backcalculation of LTPP rigid pavement deflection data was adopted in this project.[3] All concrete-surfaced LTPP sections were analyzed using the best fit procedure, which involves the backcalculation of a two-layered (PCC and base) slab-on-grade.[28,58,59] The procedure was recommended after the completion of the case studies evaluation for the following reasons:

- The procedure is founded on sound mechanistic concepts. It is based on Westergaard's solution for an interior loading condition of a plate resting on a dense-liquid foundation. The plate is assumed to behave as a linear elastic, homogeneous, and isotropic material.

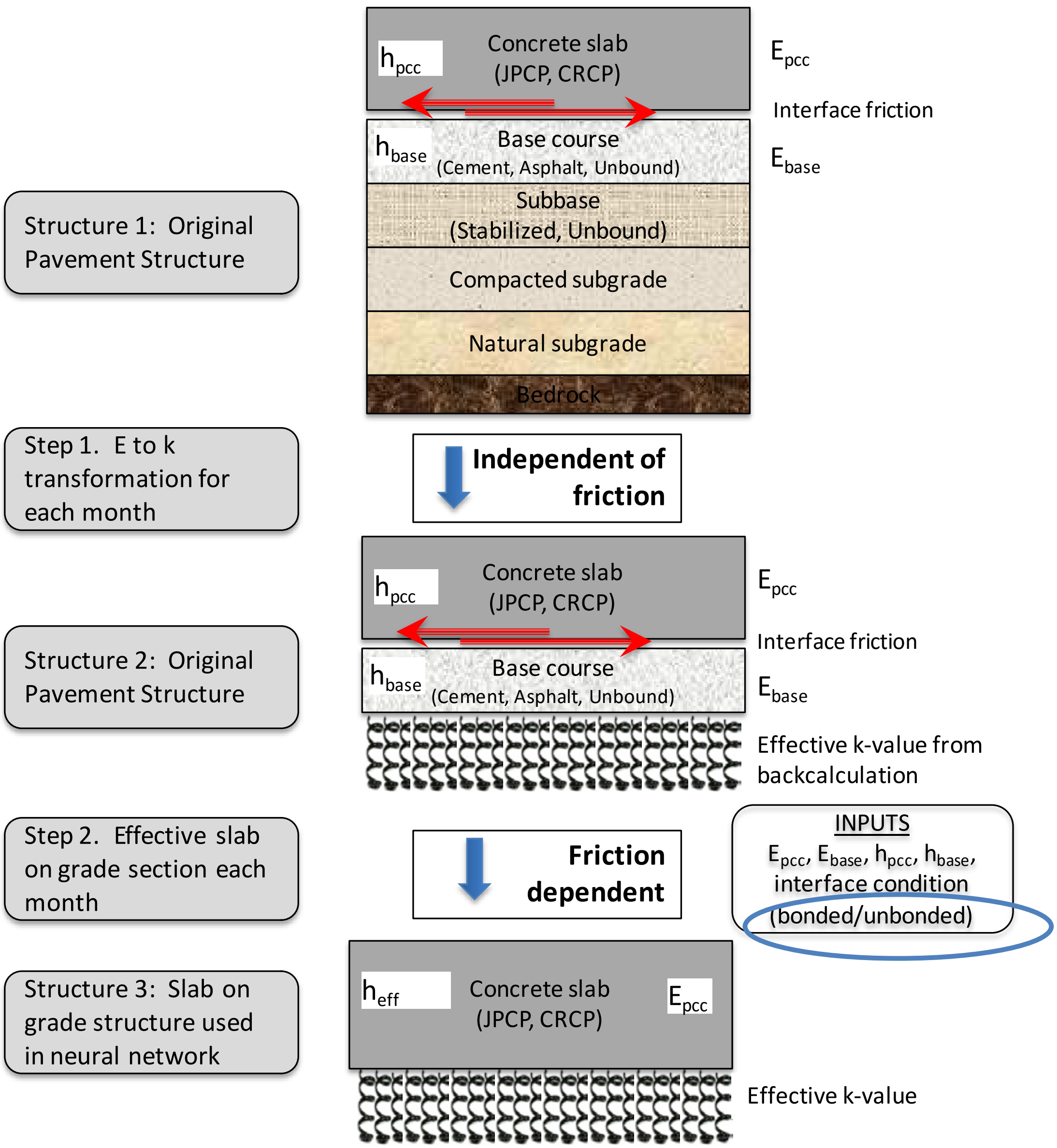
- The results were found to be reasonable and generally producing reasonable RMSE values for sections included in the case studies to demonstrate and compare the use of the candidate programs.

- The procedure can be used for any sensor configuration and provides the best fit between the measured deflection and the calculated deflections.

- The procedure is consistent with the MEPDG rigid pavement analysis in aspects relating to the reduction of the pavement layer structure to a two-layered PCC slab-base structure.[1] Within the framework of the MEPDG analysis, the two-layered structure is subsequently simulated as an effective slab-on-grade problem, with the slab assigned an effective structural capacity determined by the thicknesses of the slab and base and the contact friction between them (see figure 81). The best fit method analyzes the structure as a slab-on-grade problem to determine the composite modulus of the effective slab. Further, depending on the slab-base bond condition assumption, appropriate methods are used to apportion the stiffness of the effective slab between the individual slab and base.

- The results are generated rapidly, making it suitable for processing the large datasets used in this project. Each deflection basin is analyzed in a fraction of a second.

The best fit approach may be considered as one that determines the stiffness of a fictitious effective slab which deforms in a manner identical to the actual pavement under the applied FWD loads. Therefore, the procedure attempts to match the deflection of the simulated effective slab with the measured deflection from the FWD testing. The simulation uses the same level of load as the FWD test and positions the load in the slab interior comparable to the J1 point location in the LTPP database.



E_{PCC} = Elastic modulus of the PCC layer.
E_{base} = Elastic modulus of the base layer.
h_{PCC} = Thickness of the PCC layer.
H_{base} = Thickness of the base layer.
H_{eff} = Effective thickness of the pavement.

Figure 81. Illustration. Transformation of design structure to effective structure used by the neural networks to compute mechanistic responses.

In the figure, the effective thickness parameter derived from section transformation in step 2 changes with the interface bond condition (i.e., h_{eff}) is smaller for the unbond condition. Additionally, the JPCP faulting model uses an unbonded interface for the calculation of corner deflections, while CRCP is always modeled as an unbonded section.

The optimization procedure solves for the specific combination of the coefficient of subgrade reaction and the radius of relative stiffness, which result in slab deflections closest to the measured deflections at each sensor. The procedure allows for the use of weighting factors for the error at each sensor, and the convergence criterion is the minimization of the sum of the mean squared errors from each sensor, with the error weighted by a pre-defined factor for each sensor. Therefore, the solution is determined by the minimization of the error function expressed as follows:

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

Figure 82. Equation. Error function definition for best fit procedure.

Where:

F = Error function dependent on the elastic modulus and coefficient of subgrade reaction.
E = Elastic modulus.
k = Coefficient of subgrade reaction.
n = Number of increments.
α_i = Weighting factor.
$w(r_i)$ = Calculated deflection.
W_i = Measured deflection.

The deflection at any point at a radial distance measured from the center of a circular load plate distributing uniform pressure may be expressed as a function of r as follows:

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

Figure 83. Equation. Calculated deflection.

Where:

r = Radial distance.
p = Pressure.
f = Function.
l = Relative stiffness.

Where $f(r)$ is a function of two dimensionless parameters, the radius of the load plate normalized to the radius of relative stiffness, and the radial distance of the sensor normalized to the radius of relative stiffness. The pressure p is the uniform pressure under the applied load P, calculated as $P/\pi a^2$, where a is the loaded area under the loading plate.

The radius of relative stiffness and the subgrade k-value define the flexural rigidity of the effective slab. Most commonly, the radius of relative stiffness is expressed as a function of the effective plate thickness, h, elastic modulus of the effective plate, E, Poisson's ratio, μ, and the k-value as follows:

$$l = \left(\frac{D}{k} \right)^{1/4} = \left(\frac{Eh^3}{12(1-\mu^2)k} \right)^{1/4}$$

Figure 84. Equation. Radius of relative stiffness.

Where *D* = Stiffness of the PCC slab.

The error function in figure 82 can be rewritten using figure 83 as follows:

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

Figure 85. Equation. Error function in alternate form.

The best fit procedure satisfies the two conditions shown in figure 86 and figure 87 as follows:

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

Figure 86. Equation. Partial derivative of *F* with respect to *k*.

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

Figure 87. Equation. Partial derivative of *F* with respect to *l*.

The substitution of the error function in figure 85 in the conditions represented by figure 86 and figure 87 yields the equations to solve for *k* and *l*, as shown in figure 88 and figure 89.

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

Figure 88. Equation. *k*-value.

$$\frac{\sum_{i=0}^{n} \alpha_i f_i(l_k) f'_i(l_k)}{\sum_{i=0}^{n} \alpha_i \left[f_i(l_k) \right]^2} = \frac{\sum_{i=0}^{n} \alpha_i W_i f'_i(l_k)}{\sum_{i=0}^{n} \alpha_i W_i \left[f_i(l_k) \right]}$$

Figure 89. Equation. Radius of relative stiffness.

The computational effort involved in solving the equation in figure 89 forms the major component of the best fit procedure. The *k* and *l* values determined from the equations in figure 88 and figure 89 are substituted into the equation in figure 84 to determine the modulus of the plate or the effective slab.

ESTIMATION OF BASE LAYER MODULUS IN BEST FIT PROCEDURE

The modulus backcalculated for the effective slab using the best fit procedure is subdivided between the slab and the base, which are assumed to provide a composite section in the calculated deflections. The effective contribution of the base layer in the overall stiffness of the composite section depends on two factors: the relative stiffness of the materials itself and the bond condition at the slab base interface.

To estimate the relative stiffness of the slab and the base materials, an additional parameter is introduced to quantify the modular ratio of the slab and base. The modular ratio, β, is defined as follows (where the asterisk represents an adjustment to the modular ratio):

$$\beta^* = E_{Base} / E_{PCC}$$

Figure 90. Equation. Modular ratio.

Where:

E_{Base} = Base modulus.
E_{PCC} = PCC modulus.

The β^* values used in the analyses were based on the LTPP material codes for the base layer and were borrowed from Khazanovich et al. (see table 17).[(3)] Some material codes were assigned β^* values under the current study and have been identified in the table. The selected values are based on β^* values previously assigned for similar materials. In addition, for PCC layers overlaid using an unbonded PCC overlay, assuming the layer has undergone a fair level of damage, the stiffness was considered to be lower than a concrete slab in good condition (β^* = 1) but higher than an AC layer (β^* = 10). Therefore, a β^* value of 5 was assigned for PCC layers that have an unbonded overlay according to the TST_L05B layer structure. Also, a material code of 1000 was assigned within the best fit software code to identify PCC layers with unbonded overlay.

Table 17. Modular ratio to estimate the relative stiffness between PCC slab and base in the best fit procedure (for both bonded and unbonded conditions).

LTPP Code	$\beta^* = 1/\beta$	Base Type
1	10	HMA, dense graded
2	15	HMA, open graded
3	50	Sand asphalt
4	1	JPCP
5	1	JRCP
6	1	CRCP
7	1	PCC (prestressed)
8	1	PCC (fiber-reinforced)
9	20	Plant mix (emulsified asphalt) material, cold laid
10	20	Plant mix (cutback asphalt) material, cold laid
13	10	Recycled asphalt concrete (AC), hot laid, central plant mix
14	15	Recycled AC, cold-laid, central plant mix
15	15	Recycled AC, cold-laid, mixed-in-place
16	15	Recycled AC, heater scarification/recompaction
17	100	Recycled JPCP
18	100	Recycled JRCP
19	100	Recycled CRCP
78*	10	Dense-graded AC interlayer
80*	20	Open-graded AC interlayer
181	100	Fine-grained soils: lime-treated soil
182	50	Fine-grained soils: cement-treated soil
183	100	Bituminous-treated SS
292	150	Crushed rock
302	200	Gravel, uncrushed
303	150	Crushed stone
304	175	Crushed gravel
305	175	Crushed slag
306	250	Sand
307	400	Soil-aggregate mixture (predominantly fine-grained)
308	250	Soil-aggregate mixture (predominantly coarse-grained)
309*	250	Fine-grained soils
310*	250	Other (specify, if possible)
319	15	HMA
320	50	Sand asphalt
321	50	Asphalt-treated mixture
322	10	Dense-graded, hot-laid, central plant mix AC
323	15	Dense-graded, cold-laid, central plant mix AC
324	15	Dense-graded, cold-laid, mixed-in-place HMA
325	15	Open-graded, hot-laid, central plant mix HMA
326	15	Open-graded, cold-laid, central plant mix HMA
327	15	Open-graded, cold-laid, mixed-in-place HMA

328	10	Recycled HMA, plant mix, hot laid
329	15	Recycled HMA, plant mix, cold laid
330	15	Recycled HMA, mixed-in-place
331	5	Cement aggregate mixture
332	4	Econocrete
333	50	Cement-treated soil
334	2	Lean concrete
335	100	Recycled PCC
337*	150	Limerock, caliche
338	100	Lime-treated soil
339	10	Soil cement
340	100	Pozzolanic-aggregate mixture
341	25	Cracked and seated PCC layer
351	100	Treatment: lime, all classes of quick lime and hydrated lime
352	150	Treatment: lime-flyash
353	150	Treatment: lime and cement flyash
354	50	Treated: PCC
355	100	Treatment: bitumen (includes all classes of bitumen and asphalt treatments)
700	15	HMA
730	1	PCC
999	10000	No base (fictitious base)
1000*#	5	Existing PCC underneath unbonded overlay assumed damaged with lower modulus

*Represents material codes for which the modular ratios were established under this study.
#Represents a material code assigned in the software program for all PCC layers that have an unbonded overlay.

The best fit procedure considers two distinct cases for the bond condition at the interface between the upper (PCC) and lower (base) slabs: unbonded slab-base interface and fully bonded slab-base interface. Intermediate levels of interface bond are not analyzed.

In the case of unbonded PCC-base condition, flexural stiffness of the effective slab can be presented as follows:

$$D_e = D_{PCC} + D_{Base}$$

Figure 91. Equation. Flexural stiffness.

Where:

D_e = Flexural stiffness of the effective slab.
D_{PCC} = Flexural stiffness of the PCC.
D_{Base} = Flexural stiffness of the base.

For the unbonded conditions, PCC and base moduli are defined as follows:

$$E_{PCC} = \frac{h_{PCC}^3}{h_{PCC}^3 + \beta h_{Base}^3} E_e$$

Figure 92. Equation. Slab modulus from effective modulus for unbonded condition.

Where:

E_{PCC} =Elastic modulus of the PCC slab.
h_{PCC} = PCC thickness.
h_{Base} = Base thickness.
E_e = Effective modulus from best fit backcalculation.

$$E_{Base} = \frac{\beta h_{PCC}^3}{h_{PCC}^3 + \beta h_{Base}^3} E_e$$

Figure 93. Equation. Base modulus from effective modulus for unbonded condition.

For the case of the bonded base condition, the flexural stiffness of the effective slabs is derived using the parallel axis theorem. The PCC and base moduli are defined as follows, where *x* is the depth of the parallel axis from the surface as defined in figure 96 :

$$E_{PCC} = \frac{h_{PCC}^3}{h_{PCC}^3 + \beta h_{Base}^3 + 12 h_{PCC}(x - 0.5 h_{PCC})^2 + 12 \beta h_{Base}(h_{PCC} - x - 0.5 h_{Base})^2} E_e$$

Figure 94. Equation. Sab modulus from effective modulus for bonded condition.

$$E_{Base} = \beta E_{PCC}$$

Figure 95. Equation. Base modulus for bonded condition.

$$x = \frac{0.5 h_{PCC}^2 + \beta h_{Base}(h_{PCC} + 0.5 h_{Base})}{h_{PCC} + \beta h_{Base}}$$

Figure 96. Equation. Depth of the parallel axis from the surface.

DEFINING THE BASE LAYER IN THE PAVEMENT STRUCTURE

The project team developed procedures to identify layers in the pavement structure that could be treated as the base layer in the best fit analysis. Table 18 lists the layers below the PCC slab that were included in the base layer for different layer structures. The selection of the base layer was based on the following general rules:

- If the layer immediately beneath the PCC layer was an unbound GB layer with all layers below the GB layer of lower stiffness based on material type, the GB layer beneath the PCC layer was considered as the base layer.

- If the layer immediately beneath the PCC layer was a stabilized base layer with all layers below the stabilized base layer of lower stiffness based on material type, the stabilized base layer beneath the PCC layer was considered as the base layer.

- If the layer structure presented a stiffer layer below the layer immediately underneath the PCC slab, appropriate layers were combined to represent the base layer based on engineering judgment and as shown in table 18.

- If a TS layer was present, it was not combined into the base layer. Rather, the effect of the TS layer was apparent in the computed *k*-value of the subgrade.

- For unbonded overlay sections, the layers between the overlay up to and including the existing slab were included in the base layer.

- For bonded overlays, the existing slab and the overlay were combined into the surface layer. The layer immediately underneath the existing slab was used as the base layer.

Table 18. Effect of layer structure on base layer—number of layers underneath the PCC slab included in the effective base layer.

Number of Layers Between PCC Surface Layer and Subgrade	Layer Types in the Layer Structure Included in TST_L05B Table	Number of layers beneath the PCC layer included in the effective base layer
1	PCC, GB, SS	1
1	PCC, GS, SS	1
1	PCC, TB, SS	1
2	PCC, AC, PC, SS	2
2	PCC, AC, TB, SS	2
2	PCC, GB, GS, SS	1
2	PCC, GB, TS, SS	1
2	PCC, TB, GB, SS	1
2	PCC, TB, GS, SS	1
2	PCC, TB, TS, SS	1
3	PCC, AC, AC, GB, SS	2
3	PCC, AC, AC, PC, SS	3
3	PCC, AC, PC, GB, SS	2
3	PCC, AC, PC, TB, SS	3
3	PCC, AC, TB, GS, SS	2
3	PCC, AC, TB, TS, SS	2
3	PCC, GB, GB, GS, SS	2
3	PCC, GB, GS, GS, SS	1
3	PCC, GB, GS, TS, SS	1
3	PCC, TB, AC, GS, SS	2
3	PCC, TB, AC, TS, SS	2
3	PCC, TB, GB, GS, SS	1
3	PCC, TB, GB, TS, SS	1

3	PCC, TB, GS, GS, SS	1
3	PCC, TB, GS, TS, SS	1
3	PCC, TB, TS, GS, SS	2
3	PCC, TB, TS, TS, SS	1
4	PCC, AC, AC, PC, GB, SS	3
4	PCC, AC, PC, GB, GS, SS	2
4	PCC, AC, PC, GB, TS, SS	2
4	PCC, AC, PC, TB, GS, SS	3
4	PCC, GB, GS, GS, GS, SS	1
4	PCC, TB, GB, GB, GS, SS	1
4	PCC, TB, GB, GS, GS, SS	1
4	PCC, TB, GB, GS, TS, SS	1
4	PCC, TB, GS, GS, GS, SS	1
6	PCC, AC, AC, AC, PC, GB, GS, SS	4
6	PCC, AC, AC, AC, PC, GB, GS, SS	4
7	PCC, AC, AC, AC, AC, PC, TB, TS, SS	6

GS = granular subbase.
TB = Treated base.

In the case of more than one layer between the PCC and subgrade, all base layers were combined into one layer. Using parallel axis theorem and defining the equivalent base thickness, h_{eq}, as the sum of the base layers thicknesses, it was possible to calculate the equivalent base modular ratio, β_{eq}. β_{eq} calculations for a structure with up to five layers combined into the base layer is further described.

If h_i is the thickness of the i^{th} base layers and β_i is the modular ratio of the i^{th} layer (from table 17), then for the case of five base layers, the equivalent base modular ratio can be calculated as follows:

$$\beta_{eq} = \frac{Expr1 + 12Expr2}{h_{eq}^3}\beta_1$$

Figure 97. Equation. Equivalent beta when multiple layers are combined into the base.

Where:

Expri = A model parameter defined in figure 99 and figure 100.

The variables in figure 97 are defined as shown in figure 98 through figure 103.

$$h_{eq} = \sum_{i=1}^{5} h_i$$

Figure 98. Equation. Equivalent thickness.

$$Expr1 = h_1^3 + \beta_{21}h_2^3 + \beta_{31}h_3^3 + \beta_{41}h_4^3 + \beta_{51}h_5^3$$

Figure 99. Equation. *Expr*1.

$$Expr2 = h_1(0.5h_1 - x)^2 + h_2\beta_{21}(h_1 + 0.5h_2 - x)^2 + h_3\beta_{31}(h_1 + h_2 + 0.5h_3 - x)^2$$
$$+ h_4\beta_{41}(h_1 + h_2 + h_3 + 0.5h_4 - x)^2 + h_5\beta_{51}(h_1 + h_2 + h_3 + h_4 + 0.5h_5 - x)^2$$

Figure 100. Equation. *Expr*2.

$$x = \frac{Expr3}{Expr4}$$

Figure 101. Equation. Depth of parallel axis from the surface when multiple layers are combined into the base.

$$Expr3 = 0.5h_1^2 + \beta_{21}h_2(h_1 + 0.5h_2) + \beta_{31}h_3(h_1 + h_2 + 0.5h_3)$$
$$+ \beta_{41}h_4(h_1 + h_2 + h_3 + 0.5h_4) + \beta_{51}(h_1 + h_2 + h_3 + h_4 + 0.5h_5)$$

Figure 102. Equation. *Expr*3.

$$Expr4 = h_1 + \beta_{21}h_2 + \beta_{31}h_3 + \beta_{41}h_4 + \beta_{51}h_5$$

Figure 103. Equation. *Expr*4.

Note that in these equations, the β values are the inverse of the β* listed in table 17. The β_{eq} value calculated in figure 97 provides the combined effective multilayer β value used in figure 89 to calculate the modulus of the effective base layer.

APPENDIX B: LTPP TEST SECTIONS WITH A MODERATE AND HIGH PERCENTAGE OF ERRORS

This appendix lists the LTPP test sections with a moderate and high percentage of errors from the backcalculation process. Table 19 includes the sections with a moderate percentage of error terms of the total number of deflection basins, while table 20 includes the sections with a high percentage of error terms. The deflection basins classified as errors for the test sections included in these tables represent only 9.6 percent of the total number of deflection basins.

Table 19. LTPP test sections with a moderate percentage of errors.

State Code	SHRP ID	Total Drops	Error Drops	Atypical Drops	Accept Drops	Percent Error
1	663	1,714	649	0	1,065	37.9
1	607	1,832	610	0	1,222	33.3
1	B330	720	208	51	461	28.9
1	508	3,697	993	326	2,378	26.9
1	C320	1,043	268	32	743	25.7
2	1008	2,680	1,151	238	1,291	42.9
2	6010	2,344	705	157	1,482	30.1
2	1002	5,686	1,508	494	3,684	26.5
4	1036	4,103	1,910	8	2,185	46.6
4	163	1,965	852	98	1,015	43.4
4	A310	789	341	1	447	43.2
4	217	961	408	39	514	42.5
4	A320	837	345	4	488	41.2
4	1015	3,381	1,363	114	1,904	40.3
4	C340	792	318	1	473	40.2
4	B320	528	199	2	327	37.7
4	1001	2,018	739	133	1,146	36.6
4	1037	2,688	962	8	1,718	35.8
4	1034	4,028	1,391	1	2,636	34.5
4	1025	4,192	1,404	374	2,414	33.5
4	503	3,462	1,139	20	2,303	32.9
4	1018	4,928	1,519	5	3,404	30.8
4	C330	936	286	10	640	30.6
4	A903	2,103	601	88	1,414	28.6
4	666	1,718	466	1	1,251	27.1
4	1016	6,208	1,653	148	4,407	26.6
4	1017	7,388	1,957	69	5,362	26.5
4	903	2,112	554	96	1,462	26.2
5	A350	1,077	501	30	546	46.5
5	A320	1,109	500	43	566	45.1
5	218	555	143	0	412	25.8
6	3021	1,164	490	251	423	42.1
6	9048	974	392	0	582	40.2
6	A361	915	350	11	554	38.3
6	605	565	214	15	336	37.9
6	662	809	290	64	455	35.8
6	A363	845	300	43	502	35.5
6	A340	1,189	419	59	711	35.2
6	3005	636	220	0	416	34.6
6	663	723	245	0	478	33.9
6	661	2,348	780	277	1291	33.2
6	A351	1,027	315	103	609	30.7

6	A362	789	241	44	504	30.5
6	501	2,579	780	248	1,551	30.2
6	1253	4,777	1,444	220	3,113	30.2
6	603	2,148	640	47	1,461	29.8
6	A350	1,209	353	50	806	29.2
6	A320	1,196	338	68	790	28.3
6	A310	1,187	333	72	782	28.1
6	A352	829	232	73	524	28.0
6	502	2,956	817	220	1,919	27.6
6	A321	1,055	272	67	716	25.8
8	9020	802	396	0	406	49.4
8	9019	647	303	0	344	46.8
8	7781	4,719	2,165	0	2,554	45.9
8	6013	3,392	1,493	0	1,899	44.0
8	501	2,312	893	17	1,402	38.6
8	560	2,112	755	52	1,305	35.7
8	508	2,252	778	174	1,300	34.5
8	B310	648	216	0	432	33.3
8	507	2,295	754	101	1,440	32.9
8	3032	1,520	496	3	1,021	32.6
8	7036	982	320	186	476	32.6
8	1029	4,711	1,481	216	3,014	31.4
8	6002	4,672	1,407	337	2,928	30.1
8	214	819	240	111	468	29.3
12	C330	951	469	18	464	49.3
12	4107	2,047	883	19	1,145	43.1
12	4137	3,364	1,227	13	2,124	36.5
12	4136	3,344	1,165	16	2,163	34.8
12	C320	942	318	16	608	33.8
12	4109	1,082	325	9	748	30.0
12	C350	758	221	34	503	29.2
12	9054	2,176	588	27	1,561	27.0
12	C310	956	249	43	664	26.0
13	4093	3,356	1,047	423	1,886	31.2
16	B350	936	382	113	441	40.8
16	1021	3,723	1,430	560	1,733	38.4
16	B310	936	330	179	427	35.3
16	1009	2,364	673	511	1,180	28.5
16	C330	504	133	88	283	26.4
16	9034	3,387	849	607	1,931	25.1
17	5217	1,275	500	35	740	39.2
17	9327	2,182	554	232	1,396	25.4
18	6012	5,294	1,796	484	3,014	33.9
18	1028	5023	1,343	344	3,336	26.7
19	102	2461	1,080	610	771	43.9

19	105	2,475	694	278	1,503	28.0
19	709	216	60	76	80	27.8
20	A330	874	411	120	343	47.0
20	A320	926	423	130	373	45.7
20	105	3,140	1,141	195	1,804	36.3
20	102	720	250	32	438	34.7
20	B320	1,337	414	38	885	31.0
20	4063	888	255	0	633	28.7
20	108	2,956	847	360	1,749	28.7
20	109	3,330	920	171	2,239	27.6
20	3060	884	235	59	590	26.6
20	111	3,128	792	333	2,003	25.3
21	B320	1,059	471	3	585	44.5
21	B310	1,096	433	0	663	39.5
24	2805	5,360	2,168	1	3,191	40.4
24	961	1,230	412	0	818	33.5
24	960	1,350	448	0	902	33.2
24	901	1,261	406	0	855	32.2
24	903	1,363	387	0	976	28.4
26	6016	1,406	607	674	125	43.2
26	116	3,429	980	1,596	853	28.6
26	118	2,400	638	695	1,067	26.6
27	B330	960	417	214	329	43.4
27	1004	2,878	1,224	1	1,653	42.5
27	502	692	242	78	372	35.0
27	A330	1,088	363	230	495	33.4
27	D340	910	291	281	338	32.0
27	1020	2,653	755	783	1,115	28.5
27	508	3,515	914	707	1,894	26.0
27	C340	927	238	23	666	25.7
27	561	3,550	897	295	2,358	25.3
28	3083	3,998	1,745	453	1,800	43.6
28	503	2,800	722	317	1,761	25.8
28	504	2,326	583	341	1,402	25.1
29	507	1,038	509	169	360	49.0
29	501	687	290	146	251	42.2
29	502	1,056	411	169	476	38.9
29	503	1,040	393	143	504	37.8
29	5473	2,578	947	6	1,625	36.7
29	707	742	269	13	460	36.3
29	A351	1,310	435	282	593	33.2
29	607	429	140	0	289	32.6
29	7054	2,678	829	6	1,843	31.0
29	1002	3,638	1,021	368	2,249	28.1
29	A340	1,438	399	147	892	27.7

29	504	1,392	367	358	667	26.4
29	6067	1,351	350	98	903	25.9
30	6004	3,372	1,204	210	1,958	35.7
30	1001	3,520	1,175	70	2,275	33.4
30	7075	2,700	901	232	1,567	33.4
30	A320	864	224	44	596	25.9
30	A310	864	223	35	606	25.8
31	6701	654	293	0	361	44.8
31	7040	1,927	825	416	686	42.8
31	6702	1,961	788	9	1,164	40.2
31	A352	752	227	0	525	30.2
31	A310	877	223	3	651	25.4
31	A350	956	243	33	680	25.4
31	A320	972	244	49	679	25.1
32	A352	408	196	30	182	48.0
32	7000	2,047	892	0	1,155	43.6
32	1021	2,388	1,024	26	1,338	42.9
32	2027	2,064	714	273	1,077	34.6
32	3013	693	220	1	472	31.7
32	A320	1,032	312	5	715	30.2
32	A330	1,020	283	49	688	27.7
32	1030	2,704	730	567	1,407	27.0
32	B320	648	172	36	440	26.5
35	111	1,752	771	534	447	44.0
35	901	944	359	77	508	38.0
35	959	1,072	370	43	659	34.5
35	902	1,072	357	115	600	33.3
35	903	1,072	357	81	634	33.3
35	501	1,408	450	4	954	32.0
35	6033	4,048	1,154	111	2,783	28.5
35	1002	2,704	737	64	1,903	27.3
35	502	2,107	534	198	1,375	25.3
35	802	1,752	442	53	1,257	25.2
37	901	1,055	467	212	376	44.3
37	1817	6,013	2,512	0	3,501	41.8
37	960	1,056	371	166	519	35.1
37	962	1,056	367	38	651	34.8
37	964	1,048	344	281	423	32.8
37	961	1,067	344	2	721	32.2
37	902	1,050	314	70	666	29.9
37	963	1,056	274	138	644	25.9
39	105	1,517	584	255	678	38.5
40	118	2,117	1,039	103	975	49.1
40	503	2,143	1,038	60	1,045	48.4
40	560	2,112	998	2	1,112	47.3

40	506	2,112	977	89	1,046	46.3
40	502	2,112	961	46	1,105	45.5
40	117	2,112	955	172	985	45.2
40	B350	768	344	0	424	44.8
40	4088	1,952	809	1	1,142	41.4
40	114	2,030	775	155	1,100	38.2
40	C310	1,152	437	0	715	37.9
40	B310	752	265	0	487	35.2
40	121	2,108	725	0	1,383	34.4
40	4164	2,704	896	906	902	33.1
40	B330	768	239	0	529	31.1
40	C320	1,152	339	0	813	29.4
40	C330	1,147	329	0	818	28.7
40	120	2,112	586	442	1,084	27.7
40	7024	2,655	666	1,106	883	25.1
40	504	2,112	528	30	1,554	25.0
42	1599	4,608	2,108	164	2,336	45.7
42	B340	1,269	396	132	741	31.2
42	1627	1,186	313	85	788	26.4
45	1011	2,048	746	105	1,197	36.4
46	859	458	214	8	236	46.7
47	3104	2,143	882	105	1,156	41.2
47	3108	3,945	1,621	0	2,324	41.1
47	6015	2,720	999	0	1,721	36.7
48	A330	576	267	15	294	46.4
48	3579	1,744	779	1	964	44.7
48	1087	3,391	1,490	68	1,833	43.9
48	K310	960	419	59	482	43.6
48	1122	47,180	1,9345	427	27,408	41.0
48	1	1,325	542	174	609	40.9
48	F340	656	263	24	369	40.1
48	901	1,407	563	43	801	40.0
48	1069	3,768	1,478	766	1,524	39.2
48	A340	576	213	55	308	37.0
48	E340	768	282	0	486	36.7
48	F350	768	277	0	491	36.1
48	J351	764	262	49	453	34.3
48	160	2,430	827	463	1,140	34.0
48	A320	576	187	10	379	32.5
48	F320	768	241	46	481	31.4
48	5035	865	271	0	594	31.3
48	123	2,549	780	606	1,163	30.6
48	1061	704	215	127	362	30.5
48	162	2,463	748	369	1,346	30.4
48	124	1,969	565	161	1,243	28.7

48	L320	960	275	63	622	28.6
48	3865	3,555	1,006	92	2,457	28.3
48	161	2,419	679	131	1,609	28.1
48	121	2,451	683	778	990	27.9
48	A807	742	189	0	553	25.5
48	3679	1,344	340	252	752	25.3
49	B330	786	380	0	406	48.3
49	B390	648	300	0	348	46.3
49	1001	38,092	17,628	993	19,471	46.3
49	B320	360	141	88	131	39.2
49	B350	792	287	1	504	36.2
49	7082	1,206	413	0	793	34.2
49	1008	2,351	755	123	1,473	32.1
49	B331	432	135	1	296	31.3
49	7083	997	307	5	685	30.8
49	7085	1,195	350	4	841	29.3
49	C350	790	225	150	415	28.5
49	C361	648	180	2	466	27.8
49	804	2,094	577	299	1,218	27.6
49	3010	800	215	33	552	26.9
49	1004	4,131	1,067	167	2,897	25.8
51	121	3,830	1,353	246	2,231	35.3
51	A350	859	298	4	557	34.7
51	A320	845	261	171	413	30.9
51	A321	847	220	152	475	26.0
53	1002	2,597	1,019	97	1,481	39.2
53	1005	3,965	1,163	555	2,247	29.3
53	1801	3,501	937	393	2,171	26.8
54	4004	2,983	1,140	115	1,728	38.2
55	113	1,158	471	101	586	40.7
55	115	1,394	529	274	591	37.9
55	120	1,408	491	398	519	34.9
55	121	1,408	461	406	541	32.7
55	117	1,403	414	234	755	29.5
55	B903	1,951	571	146	1,234	29.3
55	B908	1,785	448	80	1,257	25.1
56	6031	2,842	1,242	0	1,600	43.7
56	6029	3,392	1,205	156	2,031	35.5
56	1007	41,739	10,568	1,724	29,447	25.3
72	4121	966	449	0	517	46.5
72	1003	2,717	1,102	99	1,516	40.6
81	508	2,830	1,367	10	1,453	48.3
81	502	2,656	1,060	19	1,577	39.9
81	1804	4,720	1,439	909	2,372	30.5
81	1803	4,047	1,064	56	2,927	26.3

82	9017	2,048	551	264	1,233	26.9
89	903	2,346	700	243	1,403	29.8
90	A340	1,079	468	1	610	43.4
90	A310	762	254	17	491	33.3
90	A320	1,031	310	6	715	30.1
90	A351	1,048	311	9	728	29.7
90	A330	853	216	7	630	25.3
Total number of drops		**638,739**	**221,144**	**42,268**	**375,327**	**30**

Table 20. LTPP test sections with a high percentage of errors.

State Code	SHRP ID	Total Drops	Error Drops	Atypical Drops	Accept Drops	Percent Error
4	504	3,355	3,318	0	37	98.9
4	507	3,087	2,918	0	169	94.5
4	502	3,857	2,912	46	899	75.5
4	501	1,553	1,035	8	510	66.6
4	508	3,353	2,102	96	1,155	62.7
4	6060	2,059	1,281	29	749	62.2
4	560	3,496	2,149	12	1,335	61.5
4	6054	1,869	1,134	0	735	60.7
4	506	3,878	2,347	27	1,504	60.5
4	A350	619	349	4	266	56.4
4	509	3,895	2,195	43	1,657	56.4
4	505	3,968	2,209	57	1,702	55.7
4	A330	792	428	3	361	54.0
4	1002	2,662	1,421	62	1,179	53.4
4	6055	2,720	1,446	4	1,270	53.2
4	6053	1,376	715	7	654	52.0
4	122	479	246	119	114	51.4
6	A353	719	603	4	112	83.9
6	8156	3,709	2,806	21	882	75.7
6	602	593	427	3	163	72.0
6	7454	3,309	1,991	63	1,255	60.2
6	569	1,882	1,044	9	829	55.5
8	2008	2,894	2,842	0	52	98.2
8	B330	295	222	0	73	75.3
8	B320	640	479	0	161	74.8
8	503	2,256	1,625	1	630	72.0
8	B350	360	254	40	66	70.6
8	509	2,252	1,496	1	755	66.4
8	506	2,281	1,451	2	828	63.6
8	502	2,292	1,418	0	874	61.9
8	505	2,256	1,214	34	1,008	53.8
8	1057	1,392	701	143	548	50.4
12	102	1,751	1,751	0	0	100.0
12	103	1,907	1,907	0	0	100.0
12	105	1,802	1,802	0	0	100.0
12	107	1,881	1,881	0	0	100.0
12	108	1,704	1,704	0	0	100.0
12	161	1,500	1,500	0	0	100.0
12	4103	1,864	1,860	0	4	99.8
12	109	1,792	1,785	0	7	99.6
12	106	1,893	1,881	0	12	99.4
12	110	1,800	1,748	1	51	97.1

12	111	2,016	1,940	2	74	96.2
12	104	1,749	1,640	7	102	93.8
12	101	1,796	1,636	157	3	91.1
12	112	1,873	1,426	2	445	76.1
12	1060	2,032	1,323	7	702	65.1
12	4135	3,316	1,977	67	1,272	59.6
12	4154	2,474	1,442	122	910	58.3
13	4118	1,126	649	0	477	57.6
16	1005	273	273	0	0	100.0
16	6027	1,375	776	41	558	56.4
16	1001	3,248	1,748	3	1,497	53.8
19	6049	1,560	1,481	66	13	94.9
19	1044	3,668	2,166	613	889	59.1
20	107	1,056	1,012	34	10	95.8
20	1006	2,073	1,647	0	426	79.5
20	103	3,123	2,297	355	471	73.6
20	6026	5,239	3,760	129	1,350	71.8
20	106	3,150	1,819	546	785	57.7
20	104	3,064	1,638	524	902	53.5
21	B350	1,045	892	2	151	85.4
21	A320	928	711	0	217	76.6
21	1034	4,940	2,511	0	2,429	50.8
24	962	1,201	782	0	419	65.1
24	902	1,353	743	0	610	54.9
26	1010	3,055	2,601	0	454	85.1
27	6064	3,376	3,316	59	1	98.2
27	2023	2,656	1,555	389	712	58.5
28	3085	3,363	1,895	38	1,430	56.3
29	802	1,401	1,399	0	2	99.9
29	B330	1,454	1,374	4	76	94.5
29	B351	1,470	1,308	3	159	89.0
29	506	1,392	1,046	101	245	75.1
29	508	1,052	642	1	409	61.0
29	1010	1,790	1,090	118	582	60.9
29	706	770	448	0	322	58.2
29	1005	3,687	1,916	265	1,506	52.0
30	7076	4,720	2,499	0	2,221	52.9
31	6700	2,516	1,574	4	938	62.6
32	206	136	68	0	68	50.0
35	105	1,748	1,533	0	215	87.7
35	801	1,758	1,179	35	544	67.1
37	1352	2,679	2,665	14	0	99.5
37	1024	4,182	3,159	6	1,017	75.5
39	159	605	605	0	0	100.0
39	A804	643	431	61	151	67.0

39	A803	455	252	2	201	55.4
39	103	2,032	1,042	406	584	51.3
40	509	2,128	1,684	6	438	79.1
40	1017	1,376	901	0	475	65.5
40	B360	192	121	0	71	63.0
40	6010	2,712	1,604	20	1,088	59.1
40	505	2,112	1,166	1	945	55.2
40	116	2,002	1,032	116	854	51.5
41	7019	1,903	1,137	156	610	59.7
42	A310	864	844	0	20	97.7
42	B350	1,296	1,260	0	36	97.2
42	1597	6,636	5,869	26	741	88.4
42	1618	2,701	2,190	0	511	81.1
42	A351	863	565	1	297	65.5
45	1024	3,684	3,132	13	539	85.0
45	1008	1,314	899	37	378	68.4
47	9025	3,954	3,954	0	0	100.0
47	9024	3,995	3,991	0	4	99.9
47	C350	764	722	0	42	94.5
47	C330	768	721	0	47	93.9
47	C311	576	520	0	56	90.3
47	C310	767	662	0	105	86.3
47	C320	766	658	0	108	85.9
47	1023	5,069	4,224	0	845	83.3
47	3109	3,979	3,294	62	623	82.8
47	1028	4,039	3,135	76	828	77.6
47	A320	806	508	6	292	63.0
47	3101	5,118	2,739	361	2,018	53.5
48	K340	944	944	0	0	100.0
48	1123	2,020	2,013	0	7	99.7
48	K330	835	826	0	9	98.9
48	1168	3,266	3,198	18	50	97.9
48	K351	748	715	0	33	95.6
48	K350	960	840	0	120	87.5
48	A310	576	500	1	75	86.8
48	902	1,301	1,111	1	189	85.4
48	9355	1,232	962	196	74	78.1
48	K320	960	727	3	230	75.7
48	5278	1,141	855	2	284	74.9
48	3855	3,299	2,446	93	760	74.1
48	9005	5,019	3,700	30	1,289	73.7
48	H351	384	238	0	146	62.0
48	1094	2,718	1,656	50	1,012	60.9
48	903	1,396	761	3	632	54.5
48	J310	1,136	584	0	552	51.4

48	3689	3,288	1,678	3	1,607	51.0
49	B352	134	122	5	7	91.0
49	1007	1,360	943	1	416	69.3
49	1005	1,376	722	9	645	52.5
51	1419	4,731	3,937	1	793	83.2
51	1417	5,904	3,375	37	2,492	57.2
53	7322	4,064	2,296	264	1,504	56.5
54	1640	4,640	2,787	517	1,336	60.1
55	114	1,759	1,379	108	272	78.4
55	116	1,405	1,010	156	239	71.9
56	6032	2,478	1,946	64	468	78.5
72	4122	2,717	1,978	1	738	72.8
81	504	2,844	2,070	3	771	72.8
81	503	2,862	1,770	2	1,090	61.8
81	509	2,735	1,643	54	1,038	60.1
85	1801	3,342	2,723	0	619	81.5
88	1646	3,376	1,813	18	1,545	53.7
89	902	1,626	1,494	3	129	91.9
89	901	351	317	18	16	90.3
89	A902	2,332	1,729	0	603	74.1
Total number of drops		**330,303**	**239,823**	**7,564**	**82,916**	**72.6**

APPENDIX C: DEVELOPMENT OF THE SIMULATED LAYER STRUCTURE FOR THE BACKCALCULATION PROCESS USING EVERCALC© AND MODCOMP©

This appendix includes the tables used for developing the simulated pavement structure for the first segment analysis using EVERCALC©. Chapter 4 provided the rules of simulation used to create or combine different layers in the pavement structure for the initial two phases of analysis, while this appendix presents the layering information. The appendix is divided into two parts: the first part shows results for the simulated structure with a bedrock or apparent rigid layer (table 21 to table 29), and the second part shows the results for the condition or simulation without a bedrock layer (table 30 to table 42). Each section includes a series of generic tables for specific layer combination.

BACKCALCULATION STRUCTURE FOR CASES USING BEDROCK IN THE BACKCALCULATION STRUCTURE

Table 21. AC surface with two layers between AC and subgrade.

LAYER_AFTER_AC_1	LAYER_AFTER_AC_2	SS_TYPE	BC_LAYER_2_DESIG	BC_LAYER_3_DESIG	BC_LAYER_SS_DESIG	BEDROCK_LAYER_NO
GB_COARSE	GS_COARSE	SS_COARSE	2	2	3	4
GB_COARSE	GS_FINE	SS_COARSE	2	2	3	4
GB_COARSE	GS_SAND	SS_COARSE	2	2	3	4
GB_COARSE	GS_TYP	SS_COARSE	2	2	3	4
GB_COARSE	TS_LIME	SS_COARSE	2	3	4	5
GB_COARSE	TS_STAB	SS_COARSE	2	3	4	5
GB_FINE	GS_SAND	SS_COARSE	2	2	3	4
GB_SAND	GS_SAND	SS_COARSE	2	2	3	4
GB_TYP	GS_COARSE	SS_COARSE	2	2	3	4
GB_TYP	GS_FINE	SS_COARSE	2	2	3	4
GB_TYP	GS_SAND	SS_COARSE	2	2	3	4
GB_TYP	GS_TYP	SS_COARSE	2	2	3	4
GB_TYP	TB_AC	SS_COARSE	2	3	4	5
GB_TYP	TS_AC	SS_COARSE	2	3	4	5
GB_TYP	TS_LIME	SS_COARSE	2	3	4	5
GB_TYP	TS_STAB	SS_COARSE	2	3	4	5
PC	GB_COARSE	SS_COARSE	2	3	4	5
PC	GB_SAND	SS_COARSE	2	3	4	5
PC	GB_TYP	SS_COARSE	2	3	4	5
PC	TB_AC	SS_COARSE	2	3	4	5
PC	TB_LCB	SS_COARSE	2	3	4	5
PC	TB_STAB	SS_COARSE	2	3	4	5
PC_RUBBLIZED	GB_TYP	SS_COARSE	2	3	4	5
PCC_CRACKED	GB_COARSE	SS_COARSE	2	3	4	5
PCC_CRACKED	GB_TYP	SS_COARSE	2	3	4	5
PCC_CRACKED	GS_COARSE	SS_COARSE	2	3	4	5
PCC_CRACKED	TB_STAB	SS_COARSE	2	3	4	5
TB_AC	GB_TYP	SS_COARSE	2	3	4	5
TB_AC	GS_COARSE	SS_COARSE	2	3	4	5
TB_AC	GS_FINE	SS_COARSE	2	3	4	5
TB_AC	GS_SAND	SS_COARSE	2	3	4	5
TB_AC	GS_TYP	SS_COARSE	2	3	4	5
TB_AC	TB_AC	SS_COARSE	2	2	3	4
TB_AC	TS_LIME	SS_COARSE	2	3	4	5

TB_AC	TS_STAB	SS_COARSE	2	3	4	5
TB_LCB	GS_COARSE	SS_COARSE	2	3	4	5
TB_LCB	GS_TYP	SS_COARSE	2	3	4	5
TB_STAB	GS_COARSE	SS_COARSE	2	3	4	5
TB_STAB	GS_FINE	SS_COARSE	2	3	4	5
TB_STAB	GS_TYP	SS_COARSE	2	3	4	5
TB_STAB	TS_LIME	SS_COARSE	2	3	4	5
GB_COARSE	GS_COARSE	SS_FINE	2	2	3	4
GB_COARSE	GS_FINE	SS_FINE	2	2	3	4
GB_COARSE	TS_LIME	SS_FINE	2	3	4	5
GB_COARSE	TS_STAB	SS_FINE	2	3	4	5
GB_FINE	TS_LIME	SS_FINE	2	3	4	5
GB_SAND	GS_SAND	SS_FINE	2	2	3	4
GB_TYP	GS_COARSE	SS_FINE	2	2	3	4
GB_TYP	GS_FINE	SS_FINE	2	2	3	4
GB_TYP	GS_LIME	SS_FINE	2	2	3	4
GB_TYP	GS_SAND	SS_FINE	2	2	3	4
GB_TYP	GS_TYP	SS_FINE	2	2	3	4
GB_TYP	TS_LIME	SS_FINE	2	3	4	5
GB_TYP	TS_STAB	SS_FINE	2	3	4	5
PC	GB_FINE	SS_FINE	2	3	4	5
PC	GB_SAND	SS_FINE	2	3	4	5
PC	GB_TYP	SS_FINE	2	3	4	5
PC	TB_AC	SS_FINE	2	3	4	5
PC	TB_CEMENT	SS_FINE	2	3	4	5
PC	TB_LCB	SS_FINE	2	3	4	5
PC	TB_LIME	SS_FINE	2	3	4	5
PC	TB_STAB	SS_FINE	2	3	4	5
PC_RUBBLIZED	GB_TYP	SS_FINE	2	3	4	5
PCC_CRACKED	GB_FINE	SS_FINE	2	3	4	5
PCC_CRACKED	GB_TYP	SS_FINE	2	3	4	5
PCC_CRACKED	TB_AC	SS_FINE	2	3	4	5
PCC_CRACKED	TB_CEMENT	SS_FINE	2	3	4	5
PCC_CRACKED	TB_STAB	SS_FINE	2	3	4	5
TB_AC	GB_TYP	SS_FINE	2	3	4	5
TB_AC	GS_COARSE	SS_FINE	2	3	4	5
TB_AC	GS_FINE	SS_FINE	2	3	4	5
TB_AC	GS_TYP	SS_FINE	2	3	4	5
TB_AC	TB_AC	SS_FINE	2	2	3	4

TB_AC	TS_LIME	SS_FINE	2	3	4	5
TB_AC	TS_STAB	SS_FINE	2	3	4	5
TB_CEMENT	TS_LIME	SS_FINE	2	3	4	5
TB_LCB	GS_COARSE	SS_FINE	2	3	4	5
TB_LCB	GS_FINE	SS_FINE	2	3	4	5
TB_LCB	GS_TYP	SS_FINE	2	3	4	5
TB_STAB	GS_COARSE	SS_FINE	2	3	4	5
TB_STAB	GS_FINE	SS_FINE	2	3	4	5
TB_STAB	GS_TYP	SS_FINE	2	3	4	5
TB_STAB	TS_LIME	SS_FINE	2	3	4	5

Note: Abbreviations found in the table are standard notations included in the LTPP data tables and are defined in the LTPP database.

Table 22. PCC surface with two layers between PCC and subgrade.

LAYER_ AFTER_PC_1	LAYER_ AFTER_PC_2	SS_TYPE	BC_LAYER_ 2_DESIG	BC_LAYER_ 3_DESIG	BC_LAYER_ SS_DESIG	BEDROCK_ LAYER_NO
AC	TB_CEMENT	SS_COARSE	2	3	4	5
AC	TB_STAB	SS_COARSE	2	3	4	5
GB_COARSE	GS_COARSE	SS_COARSE	2	2	3	4
GB_COARSE	GS_FINE	SS_COARSE	2	3	4	5
GB_COARSE	GS_SAND	SS_COARSE	2	3	4	5
GB_TYP	GS_COARSE	SS_COARSE	2	3	4	5
GB_TYP	GS_FINE	SS_COARSE	2	3	4	5
GB_TYP	GS_SAND	SS_COARSE	2	3	4	5
GB_TYP	GS_TYP	SS_COARSE	2	2	3	4
TB_AC	GB_COARSE	SS_COARSE	2	3	4	5
TB_AC	GB_TYP	SS_COARSE	2	3	4	5
TB_AC	GS_COARSE	SS_COARSE	2	3	4	5
TB_AC	GS_FINE	SS_COARSE	2	3	4	5
TB_AC	GS_SAND	SS_COARSE	2	3	4	5
TB_AC	GS_TYP	SS_COARSE	2	3	4	5
TB_AC	TS_AC	SS_COARSE	2	2	3	4
TB_AC	TS_LIME	SS_COARSE	2	3	4	5
TB_AC	TS_STAB	SS_COARSE	2	3	4	5
TB_CEMENT	GS_FINE	SS_COARSE	2	3	4	5
TB_LCB	GB_TYP	SS_COARSE	2	3	4	5
TB_LCB	GS_COARSE	SS_COARSE	2	3	4	5
TB_LCB	GS_TYP	SS_COARSE	2	3	4	5
TB_STAB	GS_COARSE	SS_COARSE	2	3	4	5
TB_STAB	GS_FINE	SS_COARSE	2	3	4	5
TB_STAB	GS_SAND	SS_COARSE	2	3	4	5
TB_STAB	GS_TYP	SS_COARSE	2	3	4	5
AC	PC	SS_FINE	2	3	4	5
AC	TB_STAB	SS_FINE	2	3	4	5
GB_COARSE	GS_COARSE	SS_FINE	2	2	3	4
GB_FINE	GS_COARSE	SS_FINE	2	2	3	4
GB_FINE	GS_SAND	SS_FINE	2	3	4	5
GB_TYP	GS_COARSE	SS_FINE	2	2	3	4
GB_TYP	GS_FINE	SS_FINE	2	3	4	5
GB_TYP	GS_SAND	SS_FINE	2	3	4	5
GB_TYP	GS_TYP	SS_FINE	2	2	3	4
GB_TYP	TS_LIME	SS_FINE	2	3	4	5

GB_TYP	TS_STAB	SS_FINE	2	3	4	5
TB_AC	GB_TYP	SS_FINE	2	3	4	5
TB_AC	GS_COARSE	SS_FINE	2	3	4	5
TB_AC	GS_FINE	SS_FINE	2	3	4	5
TB_AC	GS_TYP	SS_FINE	2	3	4	5
TB_AC	TS_LIME	SS_FINE	2	3	4	5
TB_CEMENT	GS_FINE	SS_FINE	2	3	4	5
TB_CEMENT	TS_LIME	SS_FINE	2	3	4	5
TB_LCB	GS_COARSE	SS_FINE	2	3	4	5
TB_LCB	GS_FINE	SS_FINE	2	3	4	5
TB_LCB	GS_SAND	SS_FINE	2	3	4	5
TB_LCB	TS_LIME	SS_FINE	2	3	4	5
TB_LCB	TS_STAB	SS_FINE	2	3	4	5
TB_STAB	GB_TYP	SS_FINE	2	3	4	5
TB_STAB	GS_COARSE	SS_FINE	2	3	4	5
TB_STAB	GS_FINE	SS_FINE	2	3	4	5
TB_STAB	TS_LIME	SS_FINE	2	3	4	5
TB_STAB	TS_STAB	SS_FINE	2	3	4	5

Note: Abbreviations found in the table are standard notations included in the LTPP data tables and are defined in the LTPP database.

Table 23. AC surface with three layers between AC and subgrade.

LAYER_ AFTER_AC_1	LAYER_ AFTER_AC_2	LAYER_ AFTER_AC_3	SS_TYPE	BC_LAYER_ 2_DESIG	BC_LAYER_ 3_DESIG	BC_LAYER_ 4_DESIG	BC_LAYER_ SS_DESIG	BEDROCK_ LAYER_NO
GB_COARSE	GS_COARSE	TS_AC	SS_COARSE	2	2	3	4	5
GB_COARSE	GS_SAND	TS_AC	SS_COARSE	2	2	3	4	5
GB_TYP	AC	GS_TYP	SS_COARSE	2	2	2	3	4
GB_TYP	GB_TYP	TS_LIME	SS_COARSE	2	2	3	4	5
GB_TYP	GS_COARSE	GS_COARSE	SS_COARSE	2	3	3	4	5
GB_TYP	GS_COARSE	TS_LIME	SS_COARSE	2	2	3	4	5
GB_TYP	GS_TYP	GS_COARSE	SS_COARSE	2	2	3	4	5
GB_TYP	GS_TYP	GS_SAND	SS_COARSE	2	2	3	4	5
GB_TYP	GS_TYP	GS_TYP	SS_COARSE	2	2	3	4	5
PC	GB_TYP	GS_COARSE	SS_COARSE	2	3	3	4	5
PC	GB_TYP	GS_FINE	SS_COARSE	2	3	3	4	5
PC	GB_TYP	GS_SAND	SS_COARSE	2	3	3	4	5
PC	GB_TYP	GS_TYP	SS_COARSE	2	3	3	4	5
PC	TB_AC	GS_COARSE	SS_COARSE	2	3	3	4	5
PC	TB_AC	GS_FINE	SS_COARSE	2	3	3	4	5
PC	TB_AC	GS_TYP	SS_COARSE	2	3	3	4	5
PC	TB_AC	TS_LIME	SS_COARSE	2	3	3	4	5
PC	TB_LCB	GS_TYP	SS_COARSE	2	2	3	4	5
PC	TB_STAB	GS_COARSE	SS_COARSE	2	3	3	4	5
PC	TB_STAB	GS_SAND	SS_COARSE	2	3	3	4	5
PC	TB_STAB	GS_TYP	SS_COARSE	2	3	3	4	5
PC_RUBBLIZED	TB_STAB	GS_TYP	SS_COARSE	2	2	3	4	5
PCC_CRACKED	TB_STAB	GS_COARSE	SS_COARSE	2	2	3	4	5
PCC_CRACKED	TB_STAB	GS_TYP	SS_COARSE	2	2	3	4	5
TB_AC	GB_TYP	GS_COARSE	SS_COARSE	2	3	3	4	5
TB_AC	GB_TYP	GS_FINE	SS_COARSE	2	3	3	4	5
TB_AC	GB_TYP	GS_TYP	SS_COARSE	2	3	3	4	5
TB_AC	GB_TYP	TS_LIME	SS_COARSE	2	3	3	4	5
TB_AC	GB_TYP	TS_STAB	SS_COARSE	2	3	3	4	5
TB_AC	GS_COARSE	GS_COARSE	SS_COARSE	2	3	3	4	5
TB_AC	GS_COARSE	GS_SAND	SS_COARSE	2	3	3	4	5
TB_AC	GS_COARSE	TS_LIME	SS_COARSE	2	3	3	4	5
TB_AC	GS_TYP	GS_COARSE	SS_COARSE	2	3	3	4	5
TB_AC	GS_TYP	GS_TYP	SS_COARSE	2	3	3	4	5
TB_AC	GS_TYP	TS_STAB	SS_COARSE	2	3	3	4	5
TB_AC	TB_AC	GS_COARSE	SS_COARSE	2	2	3	4	5

TB_AC	TB_AC	GS_TYP	SS_COARSE	2	2	3	4	5
TB_AC	TB_AC	TS_LIME	SS_COARSE	2	2	3	4	5
TB_AC	TB_AC	TS_STAB	SS_COARSE	2	2	3	4	5
TB_AC	TB_STAB	GS_COARSE	SS_COARSE	2	3	3	4	5
TB_AC	TS_AC	GS_COARSE	SS_COARSE	2	2	3	4	5
TB_STAB	GS_FINE	GS_COARSE	SS_COARSE	2	3	3	4	5
GB_SAND	GS_TYP	GS_TYP	SS_FINE	2	3	3	4	5
GB_TYP	GS_COARSE	GS_FINE	SS_FINE	2	2	3	4	5
GB_TYP	GS_COARSE	TS_STAB	SS_FINE	2	2	3	4	5
GB_TYP	GS_SAND	GS_FINE	SS_FINE	2	3	3	4	5
GB_TYP	GS_TYP	GS_TYP	SS_FINE	2	2	3	4	5

Note: Abbreviations found in the table are standard notations included in the LTPP data tables and are defined in the LTPP database.

Table 24. PCC surface with three layers between PCC and subgrade.

LAYER_AFTER_PC_1	LAYER_AFTER_PC_2	LAYER_AFTER_PC_3	SS_TYPE	BC_LAYER_2_DESIG	BC_LAYER_3_DESIG	BC_LAYER_4_DESIG	BC_LAYER_SS_DESIG	BEDRCK_LAYER_NO
AC	AC	GB_TYP	SS_COARSE	2	2	3	4	5
AC	AC	PC	SS_COARSE	2	2	3	4	5
AC	PC	GB_TYP	SS_COARSE	2	2	3	4	5
AC	TB_STAB	GS_COARSE	SS_COARSE	2	2	3	4	5
GB_TYP	GB_TYP	GS_COARSE	SS_COARSE	2	2	3	4	5
GB_TYP	GS_COARSE	GS_COARSE	SS_COARSE	2	3	3	4	5
GB_TYP	GS_COARSE	GS_FINE	SS_COARSE	2	2	3	4	5
GB_TYP	GS_COARSE	TS_LIME	SS_COARSE	2	2	3	4	5
GB_TYP	GS_FINE	GS_FINE	SS_COARSE	2	3	3	4	5
TB_AC	GB_TYP	GS_COARSE	SS_COARSE	2	3	3	4	5
TB_AC	GS_COARSE	GS_COARSE	SS_COARSE	2	3	3	4	5
TB_AC	GS_COARSE	TS_LIME	SS_COARSE	2	3	3	4	5
TB_AC	GS_TYP	GS_TYP	SS_COARSE	2	3	3	4	5
TB_AC	TS_STAB	GS_COARSE	SS_COARSE	2	3	3	4	5
TB_CEMENT	GS_FINE	TS_LIME	SS_COARSE	2	3	3	4	5
TB_LCB	GB_TYP	GS_COARSE	SS_COARSE	2	3	3	4	5
TB_LCB	GS_COARSE	TS_LIME	SS_COARSE	2	3	3	4	5
TB_LCB	GS_TYP	GS_COARSE	SS_COARSE	2	3	3	4	5
TB_STAB	GB_TYP	GS_COARSE	SS_COARSE	2	3	3	4	5
TB_STAB	GS_FINE	TS_LIME	SS_COARSE	2	3	3	4	5
TB_STAB	GS_TYP	GS_COARSE	SS_COARSE	2	3	3	4	5
TB_STAB	GS_TYP	GS_FINE	SS_COARSE	2	3	3	4	5
TB_STAB	GS_TYP	GS_TYP	SS_COARSE	2	3	3	4	5
TB_STAB	TS_STAB	GS_COARSE	SS_COARSE	2	2	3	4	5
AC	AC	PC	SS_FINE	2	2	3	4	5
AC	PC	GB_FINE	SS_FINE	2	2	3	4	5
AC	PC	GB_SAND	SS_FINE	2	2	3	4	5
AC	PC	GB_TYP	SS_FINE	2	2	3	4	5
AC	PC	TB_CEMENT	SS_FINE	2	2	3	4	5
AC	PC	TB_STAB	SS_FINE	2	2	3	4	5
AC	TB_STAB	TS_LIME	SS_FINE	2	3	3	4	5
GB_TYP	GS_COARSE	TS_LIME	SS_FINE	2	3	3	4	5
GB_TYP	GS_FINE	GS_TYP	SS_FINE	2	3	3	4	5
TB_AC	AC	GS_COARSE	SS_FINE	2	2	3	4	5
TB_AC	AC	GS_SAND	SS_FINE	2	2	3	4	5
TB_AC	AC	TS_LIME	SS_FINE	2	2	3	4	5

TB_AC	GB_TYP	GS_FINE	SS_FINE	2	3	3	4	5
TB_AC	GB_TYP	TS_LIME	SS_FINE	2	3	3	4	5
TB_AC	GB_TYP	TS_STAB	SS_FINE	2	3	3	4	5
TB_AC	TS_AC	TS_LIME	SS_FINE	2	2	3	4	5
TB_AC	TS_LIME	GS_FINE	SS_FINE	2	2	3	4	5
TB_CEMENT	GS_SAND	TS_LIME	SS_FINE	2	3	3	4	5
TB_LCB	GS_COARSE	TS_LIME	SS_FINE	2	3	3	4	5
TB_LCB	GS_FINE	GS_TYP	SS_FINE	2	3	3	4	5
TB_STAB	GS_COARSE	TS_LIME	SS_FINE	2	3	3	4	5
TB_STAB	GS_TYP	GS_COARSE	SS_FINE	2	3	3	4	5
TB_STAB	GS_TYP	GS_FINE	SS_FINE	2	3	3	4	5
TB_STAB	TS_STAB	GS_COARSE	SS_FINE	2	3	3	4	5

Note: Abbreviations found in the table are standard notations included in the LTPP data tables and are defined in the LTPP database.

Table 25. AC surface with four layers between AC and subgrade.

LAYER_AFTER_AC_1	LAYER_AFTER_AC_2	LAYER_AFTER_AC_3	LAYER_AFTER_AC_4	SS_TYPE	BC_LAYER_2_DESIG	BC_LAYER_3_DESIG	BC_LAYER_4_DESIG	BC_LAYER_5_DESIG	BC_LAYER_SS_DESIG	BEDROCK_LAYER_NO
PC	AC	PC	GB_TYP	SS_COARSE	2	2	2	3	4	5
PC	GB_TYP	GS_FINE	GS_FINE	SS_COARSE	2	3	3	3	4	5
PC	TB_AC	TS_STAB	GS_COARSE	SS_COARSE	2	3	3	3	4	5
PC	TB_CEMENT	GS_FINE	TS_LIME	SS_COARSE	2	3	3	3	4	5
PC	TB_STAB	GS_FINE	TS_LIME	SS_COARSE	2	3	3	3	4	5
PC	TB_STAB	TS_STAB	GS_COARSE	SS_COARSE	2	3	3	3	4	5
PCC_CRACKED	TB_STAB	GS_TYP	GS_FINE	SS_COARSE	2	3	3	3	4	5
TB_AC	GB_TYP	GB_TYP	GS_COARSE	SS_COARSE	2	3	3	3	4	5
TB_AC	GB_TYP	GS_COARSE	TS_LIME	SS_COARSE	2	3	3	3	4	5
TB_AC	GB_TYP	TS_STAB	GS_COARSE	SS_COARSE	2	3	3	3	4	5
TB_AC	GS_TYP	GS_COARSE	GS_COARSE	SS_COARSE	2	3	3	3	4	5
TB_AC	TB_AC	GB_TYP	GS_COARSE	SS_COARSE	2	2	3	3	4	5
TB_AC	TB_AC	GS_COARSE	TS_LIME	SS_COARSE	2	2	3	3	4	5
GB_TYP	TS_AC	GS_TYP	GS_TYP	SS_FINE	2	2	3	3	4	5
PC	TB_CEMENT	GS_COARSE	TS_LIME	SS_FINE	2	2	3	3	4	5
PC	TB_CEMENT	GS_SAND	TS_LIME	SS_FINE	2	3	3	3	4	5
PC	TB_STAB	GS_COARSE	TS_LIME	SS_FINE	2	3	3	3	4	5
PC	TB_STAB	GS_TYP	GS_COARSE	SS_FINE	2	3	3	3	4	5
PC	TB_STAB	TS_STAB	GS_COARSE	SS_FINE	2	3	3	3	4	5
PCC_CRACKED	TB_STAB	GS_TYP	GS_FINE	SS_FINE	2	3	3	3	4	5
TB_AC	GB_TYP	TS_STAB	GS_COARSE	SS_FINE	2	3	3	3	4	5
TB_AC	GB_TYP	TS_STAB	GS_FINE	SS_FINE	2	3	3	3	4	5
TB_AC	TB_AC	GB_TYP	TS_STAB	SS_FINE	2	2	3	3	4	5
TB_AC	TB_AC	TS_STAB	GS_FINE	SS_FINE	2	2	3	3	4	5
TB_AC	TS_AC	GS_TYP	GS_FINE	SS_FINE	2	2	3	3	4	5
TB_LCB	TB_STAB	TS_STAB	TS_STAB	SS_FINE	2	3	3	3	4	5

Note: Abbreviations found in the table are standard notations included in the LTPP data tables and are defined in the LTPP database.

Table 26. PCC surface with four layers between PCC and subgrade.

LAYER_ AFTER_ PC_1	LAYER_ AFTER_ PC_2	LAYER_ AFTER_ PC_3	LAYER_ AFTER_ PC_4	SS_TYPE	BC_ LAYER_ 2_DESIG	BC_ LAYER_ 3_DESIG	BC_ LAYER_ 4_DESIG	BC_ LAYER_ 5_DESIG	BC_ LAYER_ SS_DESIG	BEDROCK _LAYER_ NO
AC	AC	PC	GB_TYP	SS_COARSE	2	2	2	3	4	5
AC	PC	GB_TYP	GS_COARSE	SS_COARSE	2	2	3	3	4	5
AC	PC	GB_TYP	GS_SAND	SS_COARSE	2	2	3	3	4	5
AC	PC	TB_STAB	GS_COARSE	SS_COARSE	2	2	3	3	4	5
AC	PCC_ CRACKED	TB_STAB	GS_TYP	SS_COARSE	2	2	2	3	4	5
GB_ COARSE	GS_COARSE	GS_FINE	GS_FINE	SS_COARSE	2	2	3	3	4	5
TB_AC	GB_TYP	GB_TYP	GS_COARSE	SS_COARSE	2	3	3	3	4	5
TB_LCB	GS_COARSE	GS_COARSE	GS_TYP	SS_COARSE	2	3	3	3	4	5
AC	AC	PC	GB_TYP	SS_FINE	2	2	2	3	4	5
AC	PC	GB_COARSE	TS_LIME	SS_FINE	2	2	3	3	4	5
AC	PC	GB_TYP	GS_COARSE	SS_FINE	2	2	3	3	4	5
AC	PC	GB_TYP	GS_SAND	SS_FINE	2	2	3	3	4	5
TB_AC	GB_TYP	GS_COARSE	TS_LIME	SS_FINE	2	3	3	3	4	5
TB_AC	GB_TYP	GS_FINE	GS_TYP	SS_FINE	2	3	3	3	4	5

Note: Abbreviations found in the table are standard notations included in the LTPP data tables and are defined in the LTPP database.

Table 27. AC surface with five layers between AC and subgrade.

LAYER_AFTER_AC_1	LAYER_AFTER_AC_2	LAYER_AFTER_AC_3	LAYER_AFTER_AC_4	LAYER_AFTER_AC_5	SS_TYPE	BC_LAYER_2_DESIG	BC_LAYER_3_DESIG	BC_LAYER_4_DESIG	BC_LAYER_5_DESIG	BC_LAYER_6_DESIG	BC_LAYER_SS_DESIG	BEDROCK_LAYER_NO
PC	GB_COARSE	GS_COARSE	GS_FINE	GS_FINE	SS_COARSE	2	3	3	3	3	4	5
TB_AC	AC	AC	AC	TS_STAB	SS_COARSE	1	1	1	1	2	3	4
GB_TYP	TS_AC	GS_TYP	GS_TYP	GS_TYP	SS_FINE	2	2	3	3	3	4	5

Note: Abbreviations found in the table are standard notations included in the LTPP data tables and are defined in the LTPP database.

Table 28. PCC surface with six layers between PCC and subgrade.

LAYER_AFTER_PC_1	LAYER_AFTER_PC_2	LAYER_AFTER_PC_3	LAYER_AFTER_PC_4	LAYER_AFTER_PC_5	LAYER_AFTER_PC_6	SS_TYPE	BC_LAYER_2_DESIG	BC_LAYER_3_DESIG	BC_LAYER_4_DESIG	BC_LAYER_5_DESIG	BC_LAYER_6_DESIG	BC_LAYER_7_DESIG	BC_LAYER_SS_DESIG	BC_LAYER_NO
AC	AC	AC	PC	GB_COARSE	GS_TYP	SS_FINE	2	2	2	2	3	3	4	5

Note: Abbreviations found in the table are standard notations included in the LTPP data tables and are defined in the LTPP database.

Table 29. AC surface with seven layers between AC and subgrade.

LAYER_AFTER_AC_1	LAYER_AFTER_AC_2	LAYER_AFTER_AC_3	LAYER_AFTER_AC_4	LAYER_AFTER_AC_5	LAYER_AFTER_AC_6	LAYER_AFTER_AC_7	SS_TYPE	BC_LAYER_2_DESIG	BC_LAYER_3_DESIG	BC_LAYER_4_DESIG	BC_LAYER_5_DESIG	BC_LAYER_6_DESIG	BC_LAYER_7_DESIG	BC_LAYER_8_DESIG	BC_LAYER_SS_DESIG	BEDROCK_LAYER_NO
GB_TYP	GS_TYP	GS_TYP	TS_AC	GS_TYP	GS_TYP	GS_TYP	SS_FINE	2	3	3	3	3	3	3	4	5

Note: Abbreviations found in the table are standard notations included in the LTPP data tables and are defined in the LTPP database.

Table 30. PCC surface with seven layers between PCC and subgrade.

LAYER_AFTER_PC_1	LAYER_AFTER_PC_2	LAYER_AFTER_PC_3	LAYER_AFTER_PC_4	LAYER_AFTER_PC_5	LAYER_AFTER_PC_6	LAYER_AFTER_PC_7	SS_TYPE	BC_LAYER_2_DESIG	BC_LAYER_3_DESIG	BC_LAYER_4_DESIG	BC_LAYER_5_DESIG	BC_LAYER_6_DESIG	BC_LAYER_7_DESIG	BC_LAYER_8_DESIG	BC_LAYER_SS_DESIG	BEDROCK_LAYER_NO
AC	AC	AC	AC	PC	TB_CEMENT	TS_LIME	SS_FINE	2	2	2	2	2	3	3	4	5
AC	AC	AC	AC	PC	TB_STAB	TS_LIME	SS_FINE	2	2	2	2	2	3	3	4	5

Note: Abbreviations found in the table are standard notations included in the LTPP data tables and are defined in the LTPP database.

BACKCALCULATION STRUCTURE FOR CASES WITHOUT BEDROCK IN THE BACKCALCULATION STRUCTURE

Table 31. AC surface with one layer between AC and subgrade.

LAYER_AFTER_ AC_1	SS_TYPE	BC_LAYER_2_ DESIG	BC_LAYER_SS_ DESIG	BC_LAYER_ NO	SS_sub_ 24
GB_COARSE	SS_COARSE	2	2	3	1
GB_FINE	SS_COARSE	2	3	4	0
GB_SAND	SS_COARSE	2	3	4	0
GB_TYP	SS_COARSE	2	3	4	0
GS_COARSE	SS_COARSE	2	2	3	1
PC	SS_COARSE	2	3	4	0
TB_AC	SS_COARSE	2	3	4	0
TB_CEMENT	SS_COARSE	2	3	4	0
TB_STAB	SS_COARSE	2	3	4	0
GB_COARSE	SS_FINE	2	3	4	0
GB_FINE	SS_FINE	2	2	3	1
GB_SAND	SS_FINE	2	3	4	0
GB_TYP	SS_FINE	2	3	4	0
PC	SS_FINE	2	3	4	0
TB_AC	SS_FINE	2	3	4	0
TB_CEMENT	SS_FINE	2	3	4	0
TB_LCB	SS_FINE	2	3	4	0
TB_LIME	SS_FINE	2	3	4	0
TB_STAB	SS_FINE	2	3	4	0
TS_AC	SS_FINE	2	3	4	0
TS_LIME	SS_FINE	2	3	4	0
TS_STAB	SS_FINE	2	3	4	0

Note: Abbreviations found in the table are standard notations included in the LTPP data tables and are defined in the LTPP database.

Table 32. PCC surface with one layer between PCC and subgrade.

LAYER_AFTER_ PC_1	SS_TYPE	BC_LAYER_ 2_DESIG	BC_LAYER_ SS_DESIG	BC_LAYER_ NO	SS_sub_ 24
GB_COARSE	SS_COARSE	2	2	3	1
GB_FINE	SS_COARSE	2	3	4	0
GB_SAND	SS_COARSE	2	3	4	0
GB_TYP	SS_COARSE	2	3	4	0
GS_COARSE	SS_COARSE	2	2	3	1
TB_AC	SS_COARSE	2	3	4	0
TB_CEMENT	SS_COARSE	2	3	4	0
TB_LCB	SS_COARSE	2	3	4	0
TB_STAB	SS_COARSE	2	3	4	0
GB_COARSE	SS_FINE	2	3	4	0
GB_FINE	SS_FINE	2	2	3	1
GB_SAND	SS_FINE	2	3	4	0
GB_TYP	SS_FINE	2	3	4	0
TB_AC	SS_FINE	2	3	4	0
TB_CEMENT	SS_FINE	2	3	4	0
TB_LCB	SS_FINE	2	3	4	0
TB_STAB	SS_FINE	2	3	4	0
TB_STAB	SS_FINE	2	3	4	0

Note: Abbreviations found in the table are standard notations included in the LTPP data tables and are defined in the LTPP database.

Table 33. AC surface with two layers between AC and subgrade.

LAYER_AFTER_AC_1	LAYER_AFTER_AC_2	SS_TYPE	BC_LAYER_2_DESIG	BC_LAYER_3_DESIG	BC_LAYER_SS_DESIG	BC_LAYER_NO	SS_sub_24
PC	TB_AC	SS_COARSE	2	3	4	5	0
PC	TB_LCB	SS_COARSE	2	3	4	5	0
PC	TB_STAB	SS_COARSE	2	3	4	5	0
PC_RUBBLIZED	GB_TYP	SS_COARSE	2	3	4	5	0
PCC_CRACKED	GB_COARSE	SS_COARSE	2	3	3	4	1
PCC_CRACKED	GB_TYP	SS_COARSE	2	3	4	5	0
PCC_CRACKED	GS_COARSE	SS_COARSE	2	3	3	4	1
PCC_CRACKED	TB_STAB	SS_COARSE	2	3	4	5	0
TB_AC	GB_TYP	SS_COARSE	2	3	4	5	0
TB_AC	GS_COARSE	SS_COARSE	2	3	3	4	1
TB_AC	GS_FINE	SS_COARSE	2	3	4	5	0
TB_AC	GS_SAND	SS_COARSE	2	3	4	5	0
TB_AC	GS_TYP	SS_COARSE	2	3	4	5	0
TB_AC	TB_AC	SS_COARSE	2	2	3	4	0
TB_AC	TS_LIME	SS_COARSE	2	3	3	4	0
TB_AC	TS_STAB	SS_COARSE	2	3	4	5	0
TB_LCB	GS_COARSE	SS_COARSE	2	3	3	4	1
TB_LCB	GS_TYP	SS_COARSE	2	3	4	5	0
TB_STAB	GS_COARSE	SS_COARSE	2	3	3	4	1
TB_STAB	GS_FINE	SS_COARSE	2	3	4	5	0
TB_STAB	GS_TYP	SS_COARSE	2	3	4	5	0
TB_STAB	TS_LIME	SS_COARSE	2	3	3	4	0
GB_COARSE	GS_COARSE	SS_FINE	2	2	3	4	0
GB_COARSE	GS_FINE	SS_FINE	2	3	3	4	1
GB_COARSE	TS_LIME	SS_FINE	2	3	3	4	0
GB_COARSE	TS_STAB	SS_FINE	2	3	4	5	0
GB_FINE	TS_LIME	SS_FINE	2	3	3	4	0
GB_SAND	GS_SAND	SS_FINE	2	2	3	4	0
GB_TYP	GS_COARSE	SS_FINE	2	3	4	5	0
GB_TYP	GS_FINE	SS_FINE	2	3	3	4	1
GB_TYP	GS_LIME	SS_FINE	2	3	3	4	0
GB_TYP	GS_SAND	SS_FINE	2	3	4	5	0
GB_TYP	GS_TYP	SS_FINE	2	2	3	4	0
GB_TYP	TS_LIME	SS_FINE	2	3	3	4	0
GB_TYP	TS_STAB	SS_FINE	2	3	4	5	0
PC	GB_FINE	SS_FINE	2	3	3	4	1

PC	GB_SAND	SS_FINE	2	3	4	5	0
PC	GB_TYP	SS_FINE	2	3	4	5	0
PC	TB_AC	SS_FINE	2	3	4	5	0
PC	TB_CEMENT	SS_FINE	2	3	4	5	0
PC	TB_LCB	SS_FINE	2	3	4	5	0
PC	TB_LIME	SS_FINE	2	3	3	4	0
PC	TB_STAB	SS_FINE	2	3	4	5	0
PC_RUBBLIZED	GB_TYP	SS_FINE	2	3	4	5	0
PCC_CRACKED	GB_FINE	SS_FINE	2	3	3	4	1
PCC_CRACKED	GB_TYP	SS_FINE	2	3	4	5	0
PCC_CRACKED	TB_AC	SS_FINE	2	3	4	5	0
PCC_CRACKED	TB_CEMENT	SS_FINE	2	3	4	5	0
PCC_CRACKED	TB_STAB	SS_FINE	2	3	4	5	0
TB_AC	GB_TYP	SS_FINE	2	3	4	5	0
TB_AC	GS_COARSE	SS_FINE	2	3	4	5	0
TB_AC	GS_FINE	SS_FINE	2	3	3	4	1
TB_AC	GS_TYP	SS_FINE	2	3	4	5	0
TB_AC	TB_AC	SS_FINE	2	2	3	4	0
TB_AC	TS_LIME	SS_FINE	2	3	3	4	0
TB_AC	TS_STAB	SS_FINE	2	3	4	5	0
TB_CEMENT	TS_LIME	SS_FINE	2	3	3	4	0
TB_LCB	GS_COARSE	SS_FINE	2	3	4	5	0
TB_LCB	GS_FINE	SS_FINE	2	3	3	4	1
TB_LCB	GS_TYP	SS_FINE	2	3	4	5	0
TB_STAB	GS_COARSE	SS_FINE	2	3	4	5	0
TB_STAB	GS_FINE	SS_FINE	2	3	3	4	1
TB_STAB	GS_TYP	SS_FINE	2	3	4	5	0
TB_STAB	TS_LIME	SS_FINE	2	3	3	4	0
GB_COARSE	GS_COARSE	SS_COARSE	2	3	3	4	1
GB_COARSE	GS_FINE	SS_COARSE	2	3	4	5	0
GB_COARSE	GS_SAND	SS_COARSE	2	3	4	5	0
GB_COARSE	GS_TYP	SS_COARSE	2	3	4	5	0
GB_COARSE	TS_LIME	SS_COARSE	2	3	3	4	0
GB_COARSE	TS_STAB	SS_COARSE	2	3	4	5	0
GB_FINE	GS_SAND	SS_COARSE	2	3	4	5	0
GB_SAND	GS_SAND	SS_COARSE	2	2	3	4	0
GB_TYP	GS_COARSE	SS_COARSE	2	3	3	4	1
GB_TYP	GS_FINE	SS_COARSE	2	3	4	5	0
GB_TYP	GS_SAND	SS_COARSE	2	3	4	5	0

GB_TYP	GS_TYP	SS_COARSE	2	2	3	4	0
GB_TYP	TB_AC	SS_COARSE	2	3	4	5	0
GB_TYP	TS_AC	SS_COARSE	2	3	4	5	0
GB_TYP	TS_LIME	SS_COARSE	2	3	3	4	0
GB_TYP	TS_STAB	SS_COARSE	2	3	4	5	0
PC	GB_COARSE	SS_COARSE	2	3	3	4	1
PC	GB_SAND	SS_COARSE	2	3	4	5	0
PC	GB_TYP	SS_COARSE	2	3	4	5	0

Note: Abbreviations found in the table are standard notations included in the LTPP data tables and are defined in the LTPP database.

Table 34. PCC surface with two layers between PCC and subgrade.

LAYER_ AFTER_PC_1	LAYER_ AFTER_PC_2	SS_TYPE	BC_LAYER_ 2_DESIG	BC_LAYER_ 3_DESIG	BC_LAYER_ SS_DESIG	BC_LAYER_ NO	SS_sub_ 24
AC	TB_CEMENT	SS_COARSE	2	3	4	5	0
AC	TB_STAB	SS_COARSE	2	3	4	5	0
GB_COARSE	GS_COARSE	SS_COARSE	2	3	3	4	1
GB_COARSE	GS_FINE	SS_COARSE	2	3	4	5	0
GB_COARSE	GS_SAND	SS_COARSE	2	3	4	5	0
GB_TYP	GS_COARSE	SS_COARSE	2	3	3	4	1
GB_TYP	GS_FINE	SS_COARSE	2	3	4	5	0
GB_TYP	GS_SAND	SS_COARSE	2	3	4	5	0
GB_TYP	GS_TYP	SS_COARSE	2	2	3	4	0
TB_AC	GB_COARSE	SS_COARSE	2	3	3	4	1
TB_AC	GB_TYP	SS_COARSE	2	3	4	5	0
TB_AC	GS_COARSE	SS_COARSE	2	3	3	4	1
TB_AC	GS_FINE	SS_COARSE	2	3	4	5	0
TB_AC	GS_SAND	SS_COARSE	2	3	4	5	0
TB_AC	GS_TYP	SS_COARSE	2	3	4	5	0
TB_AC	TS_AC	SS_COARSE	2	2	3	4	0
TB_AC	TS_LIME	SS_COARSE	2	3	3	4	0
TB_AC	TS_STAB	SS_COARSE	2	3	4	5	0
TB_CEMENT	GS_FINE	SS_COARSE	2	3	4	5	0
TB_LCB	GB_TYP	SS_COARSE	2	3	4	5	0
TB_LCB	GS_COARSE	SS_COARSE	2	3	3	4	1
TB_LCB	GS_TYP	SS_COARSE	2	3	4	5	0
TB_STAB	GS_COARSE	SS_COARSE	2	3	3	4	1
TB_STAB	GS_FINE	SS_COARSE	2	3	4	5	0
TB_STAB	GS_SAND	SS_COARSE	2	3	4	5	0
TB_STAB	GS_TYP	SS_COARSE	2	3	4	5	0

AC	PC	SS_FINE	2	3	4	5	0
AC	TB_STAB	SS_FINE	2	3	4	5	0
GB_COARSE	GS_COARSE	SS_FINE	2	2	3	4	0
GB_FINE	GS_COARSE	SS_FINE	2	3	4	5	0
GB_FINE	GS_SAND	SS_FINE	2	3	4	5	0
GB_TYP	GS_COARSE	SS_FINE	2	3	4	5	0
GB_TYP	GS_FINE	SS_FINE	2	3	3	4	1
GB_TYP	GS_SAND	SS_FINE	2	3	4	5	0
GB_TYP	GS_TYP	SS_FINE	2	2	3	4	0
GB_TYP	TS_LIME	SS_FINE	2	3	3	4	0
GB_TYP	TS_STAB	SS_FINE	2	3	4	5	0
TB_AC	GB_TYP	SS_FINE	2	3	4	5	0
TB_AC	GS_COARSE	SS_FINE	2	3	4	5	0
TB_AC	GS_FINE	SS_FINE	2	3	3	4	1
TB_AC	GS_TYP	SS_FINE	2	3	4	5	0
TB_AC	TS_LIME	SS_FINE	2	3	3	4	0
TB_CEMENT	GS_FINE	SS_FINE	2	3	3	4	1
TB_CEMENT	TS_LIME	SS_FINE	2	3	3	4	0
TB_LCB	GS_COARSE	SS_FINE	2	3	4	5	0
TB_LCB	GS_FINE	SS_FINE	2	3	3	4	1
TB_LCB	GS_SAND	SS_FINE	2	3	4	5	0
TB_LCB	TS_LIME	SS_FINE	2	3	3	4	0
TB_LCB	TS_STAB	SS_FINE	2	3	4	5	0
TB_STAB	GB_TYP	SS_FINE	2	3	4	5	0
TB_STAB	GS_COARSE	SS_FINE	2	3	4	5	0
TB_STAB	GS_FINE	SS_FINE	2	3	3	4	1
TB_STAB	TS_LIME	SS_FINE	2	3	3	4	0
TB_STAB	TS_STAB	SS_FINE	2	3	4	5	0

Note: Abbreviations found in the table are standard notations included in the LTPP data tables and are defined in the LTPP database.

Table 35. AC surface with three layers between AC and subgrade.

LAYER_AFTER_AC_1	LAYER_AFTER_AC_2	LAYER_AFTER_AC_3	SS_TYPE	BC_LAYER_2_DESIG	BC_LAYER_3_DESIG	BC_LAYER_4_DESIG	BC_LAYER_SS_DESIG	BC_LAYER_NO	SS_sub_24
PC	TB_LCB	GS_TYP	SS_COARSE	2	3	4	4	5	0
PC	TB_STAB	GS_COARSE	SS_COARSE	2	3	4	4	5	1
PC	TB_STAB	GS_SAND	SS_COARSE	2	3	4	4	5	0
PC	TB_STAB	GS_TYP	SS_COARSE	2	3	4	4	5	0
PC_RUBBLIZED	TB_STAB	GS_TYP	SS_COARSE	2	3	4	4	5	0
PCC_CRACKED	TB_STAB	GS_COARSE	SS_COARSE	2	3	4	4	5	1
PCC_CRACKED	TB_STAB	GS_TYP	SS_COARSE	2	3	4	4	5	0
TB_AC	GB_TYP	GS_COARSE	SS_COARSE	2	3	4	4	5	1
TB_AC	GB_TYP	GS_FINE	SS_COARSE	2	3	4	4	5	0
TB_AC	GB_TYP	GS_TYP	SS_COARSE	2	3	3	4	5	0
TB_AC	GB_TYP	TS_LIME	SS_COARSE	2	3	4	4	5	0
TB_AC	GB_TYP	TS_STAB	SS_COARSE	2	3	4	4	5	0
TB_AC	GS_COARSE	GS_COARSE	SS_COARSE	2	3	3	4	4	1
TB_AC	GS_COARSE	GS_SAND	SS_COARSE	2	3	4	4	5	0
TB_AC	GS_COARSE	TS_LIME	SS_COARSE	2	3	4	4	5	0
TB_AC	GS_TYP	GS_COARSE	SS_COARSE	2	3	4	4	5	1
TB_AC	GS_TYP	GS_TYP	SS_COARSE	2	3	3	4	5	0
TB_AC	GS_TYP	TS_STAB	SS_COARSE	2	3	4	4	5	0
TB_AC	TB_AC	GS_COARSE	SS_COARSE	2	2	3	3	4	1
TB_AC	TB_AC	GS_TYP	SS_COARSE	2	2	3	4	5	0
TB_AC	TB_AC	TS_LIME	SS_COARSE	2	2	3	3	4	0
TB_AC	TB_AC	TS_STAB	SS_COARSE	2	2	3	4	5	0
TB_AC	TB_STAB	GS_COARSE	SS_COARSE	2	3	4	4	5	1
TB_AC	TS_AC	GS_COARSE	SS_COARSE	2	2	3	3	4	1
TB_STAB	GS_FINE	GS_COARSE	SS_COARSE	2	3	4	4	5	1
GB_SAND	GS_TYP	GS_TYP	SS_FINE	2	3	3	4	5	0
GB_TYP	GS_COARSE	GS_FINE	SS_FINE	2	3	4	4	5	1
GB_TYP	GS_COARSE	TS_STAB	SS_FINE	2	2	3	4	5	0
GB_TYP	GS_SAND	GS_FINE	SS_FINE	2	3	4	4	5	1
GB_TYP	GS_TYP	GS_TYP	SS_FINE	2	3	3	4	5	0
GB_TYP	TS_STAB	GS_COARSE	SS_FINE	2	3	4	4	5	0
GB_TYP	TS_STAB	GS_FINE	SS_FINE	2	3	4	4	5	1
GB_TYP	TS_STAB	TS_LIME	SS_FINE	2	3	4	4	5	0
PC	GB_COARSE	GS_COARSE	SS_FINE	2	3	3	4	5	0
PC	GB_COARSE	GS_TYP	SS_FINE	2	3	3	4	5	0

PC	GB_SAND	GS_SAND	SS_FINE	2	3	3	4	5	0
PC	GB_TYP	GS_COARSE	SS_FINE	2	3	3	4	5	0
PC	GB_TYP	GS_FINE	SS_FINE	2	3	4	4	5	1
PC	GB_TYP	GS_SAND	SS_FINE	2	3	4	4	5	0
PC	GB_TYP	TB_LIME	SS_FINE	2	3	4	4	5	0
PC	GB_TYP	TS_LIME	SS_FINE	2	3	4	4	5	0
PC	TB_AC	GS_COARSE	SS_FINE	2	3	4	4	5	0
PC	TB_AC	GS_TYP	SS_FINE	2	3	4	4	5	0
PC	TB_AC	TS_LIME	SS_FINE	2	3	4	4	5	0
PC	TB_CEMENT	GS_FINE	SS_FINE	2	3	4	4	5	1
PC	TB_LCB	TS_LIME	SS_FINE	2	3	4	4	5	0
PC	TB_STAB	GS_FINE	SS_FINE	2	3	4	4	5	1
PC	TB_STAB	TS_LIME	SS_FINE	2	3	4	4	5	0
PC_RUBBLIZED	GB_TYP	GS_SAND	SS_FINE	2	3	4	4	5	0
PCC_CRACKED	GB_TYP	GS_COARSE	SS_FINE	2	3	3	4	5	0
PCC_CRACKED	GB_TYP	GS_SAND	SS_FINE	2	3	4	4	5	0
PCC_CRACKED	TB_LCB	GS_COARSE	SS_FINE	2	3	4	4	5	0
TB_AC	GB_TYP	GS_COARSE	SS_FINE	2	3	4	4	5	0
TB_AC	GB_TYP	GS_FINE	SS_FINE	2	3	4	4	5	1
TB_AC	GB_TYP	GS_SAND	SS_FINE	2	3	4	4	5	0
TB_AC	GB_TYP	TS_LIME	SS_FINE	2	3	4	4	5	0
TB_AC	GB_TYP	TS_STAB	SS_FINE	2	3	4	4	5	0
TB_AC	GS_COARSE	GS_COARSE	SS_FINE	2	3	4	4	5	0
TB_AC	GS_TYP	GS_COARSE	SS_FINE	2	3	4	4	5	0
TB_AC	GS_TYP	GS_SAND	SS_FINE	2	3	4	4	5	0
TB_AC	TB_AC	GB_TYP	SS_FINE	2	2	3	4	5	0
TB_AC	TB_AC	GS_FINE	SS_FINE	2	2	3	3	4	1
TB_AC	TB_AC	GS_TYP	SS_FINE	2	2	3	4	5	0
TB_AC	TB_AC	TS_FINE	SS_FINE	2	2	3	4	5	0
TB_AC	TB_AC	TS_LIME	SS_FINE	2	2	3	3	4	0
TB_AC	TB_AC	TS_STAB	SS_FINE	2	2	3	4	5	0
TB_AC	TS_AC	GS_TYP	SS_FINE	2	2	3	4	5	0
TB_AC	TS_STAB	GS_FINE	SS_FINE	2	3	4	4	5	1
TB_CEMENT	GS_COARSE	GS_FINE	SS_FINE	2	3	4	4	5	1
TB_STAB	GS_COARSE	GS_FINE	SS_FINE	2	3	4	4	5	1
TB_STAB	GS_COARSE	TS_LIME	SS_FINE	2	3	4	4	5	0
TB_STAB	GS_TYP	TS_STAB	SS_FINE	2	3	4	4	5	0
TB_STAB	TS_LIME	GS_FINE	SS_FINE	2	3	4	4	5	1
GB_COARSE	GS_COARSE	TS_AC	SS_COARSE	2	2	3	4	5	0

GB_COARSE	GS_SAND	TS_AC	SS_COARSE	2	2	3	4	5	0
GB_TYP	AC	GS_TYP	SS_COARSE	2	3	4	4	5	0
GB_TYP	GB_TYP	TS_LIME	SS_COARSE	2	2	3	3	4	0
GB_TYP	GS_COARSE	GS_COARSE	SS_COARSE	2	3	3	4	4	0
GB_TYP	GS_COARSE	TS_LIME	SS_COARSE	2	3	4	4	5	0
GB_TYP	GS_TYP	GS_COARSE	SS_COARSE	2	2	3	3	4	1
GB_TYP	GS_TYP	GS_SAND	SS_COARSE	2	2	3	4	5	0
GB_TYP	GS_TYP	GS_TYP	SS_COARSE	2	3	3	4	5	0
PC	GB_TYP	GS_COARSE	SS_COARSE	2	3	4	4	5	1
PC	GB_TYP	GS_FINE	SS_COARSE	2	3	3	4	5	0
PC	GB_TYP	GS_SAND	SS_COARSE	2	3	4	4	5	0
PC	GB_TYP	GS_TYP	SS_COARSE	2	3	3	4	5	0
PC	TB_AC	GS_COARSE	SS_COARSE	2	3	4	4	5	1
PC	TB_AC	GS_FINE	SS_COARSE	2	3	4	4	5	0
PC	TB_AC	GS_TYP	SS_COARSE	2	3	4	4	5	0
PC	TB_AC	TS_LIME	SS_COARSE	2	3	4	4	5	0

Note: Abbreviations found in the table are standard notations included in the LTPP data tables and are defined in the LTPP database.

Table 36. PCC surface with three layers between PCC and subgrade.

LAYER_ AFTER_PC_1	LAYER_ AFTER_PC_2	LAYER_ AFTER_PC_3	SS_TYPE	BC_ LAYER_ 2_DESIG	BC_ LAYER_ 3_DESIG	BC_ LAYER_ 4_DESIG	BC_ LAYER_ SS_DESIG	BC_ LAYER_ NO	SS_sub_ 24
TB_AC	TS_STAB	GS_COARSE	SS_COARSE	2	3	4	4	5	1
TB_CEMENT	GS_FINE	TS_LIME	SS_COARSE	2	3	4	4	5	0
TB_LCB	GB_TYP	GS_COARSE	SS_COARSE	2	3	4	4	5	1
TB_LCB	GS_COARSE	TS_LIME	SS_COARSE	2	3	4	4	5	0
TB_LCB	GS_TYP	GS_COARSE	SS_COARSE	2	3	4	4	5	1
TB_STAB	GB_TYP	GS_COARSE	SS_COARSE	2	3	4	4	5	1
TB_STAB	GS_FINE	TS_LIME	SS_COARSE	2	3	4	4	5	0
TB_STAB	GS_TYP	GS_COARSE	SS_COARSE	2	3	4	4	5	1
TB_STAB	GS_TYP	GS_FINE	SS_COARSE	2	3	3	4	5	0
TB_STAB	GS_TYP	GS_TYP	SS_COARSE	2	3	3	4	5	0
TB_STAB	TS_STAB	GS_COARSE	SS_COARSE	2	2	3	3	4	1
AC	AC	PC	SS_FINE	2	2	3	4	5	0
AC	PC	GB_FINE	SS_FINE	2	2	3	3	4	1
AC	PC	GB_SAND	SS_FINE	2	2	3	4	5	0
AC	PC	GB_TYP	SS_FINE	2	2	3	4	5	0
AC	PC	TB_CEMENT	SS_FINE	2	2	3	4	5	0
AC	PC	TB_STAB	SS_FINE	2	2	3	4	5	0
AC	TB_STAB	TS_LIME	SS_FINE	2	3	4	4	5	0
GB_TYP	GS_COARSE	TS_LIME	SS_FINE	2	3	4	4	5	0
GB_TYP	GS_FINE	GS_TYP	SS_FINE	2	3	3	4	5	0
TB_AC	AC	GS_COARSE	SS_FINE	2	2	3	4	5	0
TB_AC	AC	GS_SAND	SS_FINE	2	2	3	4	5	0
TB_AC	AC	TS_LIME	SS_FINE	2	2	3	3	4	0
TB_AC	GB_TYP	GS_FINE	SS_FINE	2	3	4	4	5	1
TB_AC	GB_TYP	TS_LIME	SS_FINE	2	3	4	4	5	0
TB_AC	GB_TYP	TS_STAB	SS_FINE	2	3	3	4	5	0
TB_AC	TS_AC	TS_LIME	SS_FINE	2	2	3	3	4	0
TB_AC	TS_LIME	GS_FINE	SS_FINE	2	2	3	3	4	1
TB_CEMENT	GS_SAND	TS_LIME	SS_FINE	2	3	4	4	5	0
TB_LCB	GS_COARSE	TS_LIME	SS_FINE	2	3	4	4	5	0
TB_LCB	GS_FINE	GS_TYP	SS_FINE	2	3	3	4	5	0
TB_STAB	GS_COARSE	TS_LIME	SS_FINE	2	3	4	4	5	0
TB_STAB	GS_TYP	GS_COARSE	SS_FINE	2	3	3	4	5	0
TB_STAB	GS_TYP	GS_FINE	SS_FINE	2	3	4	4	5	1
TB_STAB	TS_STAB	GS_COARSE	SS_FINE	2	3	3	4	5	0

AC	AC	GB_TYP	SS_COARSE	2	2	3	4	5	0
AC	AC	PC	SS_COARSE	2	2	3	4	5	0
AC	PC	GB_TYP	SS_COARSE	2	2	3	4	5	0
AC	TB_STAB	GS_COARSE	SS_COARSE	2	2	3	3	4	1
GB_TYP	GB_TYP	GS_COARSE	SS_COARSE	2	2	3	3	4	1
GB_TYP	GS_COARSE	GS_COARSE	SS_COARSE	2	3	3	4	5	1
GB_TYP	GS_COARSE	GS_FINE	SS_COARSE	2	2	3	4	5	0
GB_TYP	GS_COARSE	TS_LIME	SS_COARSE	2	2	3	3	4	0
GB_TYP	GS_FINE	GS_FINE	SS_COARSE	2	3	3	4	5	0
TB_AC	GB_TYP	GS_COARSE	SS_COARSE	2	3	4	4	5	1
TB_AC	GS_COARSE	GS_COARSE	SS_COARSE	2	3	3	3	4	1
TB_AC	GS_COARSE	TS_LIME	SS_COARSE	2	3	4	4	5	0
TB_AC	GS_TYP	GS_TYP	SS_COARSE	2	3	3	4	5	0

Note: Abbreviations found in the table are standard notations included in the LTPP data tables and are defined in the LTPP database.

Table 37. AC surface with four layers between AC and subgrade.

LAYER_ AFTER_ AC_1	LAYER_ AFTER_ AC_2	LAYER_ AFTER_ AC_3	LAYER_ AFTER_ AC_4	SS_TYPE	BC_ LAYER _2_ DESIG	BC_ LAYER_ 3_ DESIG	BC_ LAYER _4_ DESIG	BC_ LAYER _5_ DESIG	BC_ LAYER _SS_ DESIG	BC_ LAYER _NO	SS_ sub_ 24
TB_AC	GB_TYP	TS_STAB	GS_COARSE	SS_COARSE	2	3	3	4	4	5	1
TB_AC	GS_TYP	GS_COARSE	GS_COARSE	SS_COARSE	2	3	4	4	4	5	1
TB_AC	TB_AC	GB_TYP	GS_COARSE	SS_COARSE	2	2	3	4	4	5	1
TB_AC	TB_AC	GS_COARSE	TS_LIME	SS_COARSE	2	2	3	4	4	5	0
GB_TYP	TS_AC	GS_TYP	GS_TYP	SS_FINE	2	2	3	3	4	5	0
PC	TB_CEMENT	GS_COARSE	TS_LIME	SS_FINE	2	2	3	4	4	5	0
PC	TB_CEMENT	GS_SAND	TS_LIME	SS_FINE	2	3	3	4	4	5	0
PC	TB_STAB	GS_COARSE	TS_LIME	SS_FINE	2	3	3	4	4	5	0
PC	TB_STAB	GS_TYP	GS_COARSE	SS_FINE	2	3	4	4	4	5	0
PC	TB_STAB	TS_STAB	GS_COARSE	SS_FINE	2	3	3	4	4	5	0
PCC_ CRACKED	TB_STAB	GS_TYP	GS_FINE	SS_FINE	2	3	4	4	4	5	1
TB_AC	GB_TYP	TS_STAB	GS_COARSE	SS_FINE	2	3	3	3	4	5	0
TB_AC	GB_TYP	TS_STAB	GS_FINE	SS_FINE	2	3	4	4	4	5	1
TB_AC	TB_AC	GB_TYP	TS_STAB	SS_FINE	2	2	3	3	4	5	0
TB_AC	TB_AC	TS_STAB	GS_FINE	SS_FINE	2	2	3	4	4	5	1
TB_AC	TS_AC	GS_TYP	GS_FINE	SS_FINE	2	2	3	4	4	5	1
TB_LCB	TB_STAB	TS_STAB	TS_STAB	SS_FINE	2	3	3	3	4	5	0
PC	AC	PC	GB_TYP	SS_COARSE	2	2	2	3	4	5	0
PC	GB_TYP	GS_FINE	GS_FINE	SS_COARSE	2	3	3	3	4	5	0
PC	TB_AC	TS_STAB	GS_COARSE	SS_COARSE	2	3	3	4	4	5	1
PC	TB_CEMENT	GS_FINE	TS_LIME	SS_COARSE	2	3	4	4	4	5	0
PC	TB_STAB	GS_FINE	TS_LIME	SS_COARSE	2	3	4	4	4	5	0
PC	TB_STAB	TS_STAB	GS_COARSE	SS_COARSE	2	3	3	4	4	5	1
PCC_ CRACKED	TB_STAB	GS_TYP	GS_FINE	SS_COARSE	2	3	4	4	4	5	0
TB_AC	GB_TYP	GB_TYP	GS_COARSE	SS_COARSE	2	3	3	4	4	5	1
TB_AC	GB_TYP	GS_COARSE	TS_LIME	SS_COARSE	2	3	4	4	4	5	0

Note: Abbreviations found in the table are standard notations included in the LTPP data tables and are defined in the LTPP database.

Table 38. PCC surface with four layers between PCC and subgrade.

LAYER_ AFTER_ PC_1	LAYER_ AFTER_ PC_2	LAYER_ AFTER_ PC_3	LAYER_ AFTER_ PC_4	SS_TYPE	BC_ LAYER _2_ DESIG	BC_ LAYER _3_ DESIG	BC_ LAYER _4_ DESIG	BC_ LAYER _5_ DESIG	BC_ LAYER _SS_ DESIG	BC_ LAYER_ NO	SS_ sub_ 24
AC	AC	PC	GB_TYP	SS_COARSE	2	2	2	3	4	5	0
AC	PC	GB_TYP	GS_COARSE	SS_COARSE	2	2	3	4	4	5	1
AC	PC	GB_TYP	GS_SAND	SS_COARSE	2	2	3	4	4	5	0
AC	PC	TB_STAB	GS_COARSE	SS_COARSE	2	2	3	4	4	5	1
AC	PCC_ CRACKED	TB_STAB	GS_TYP	SS_COARSE	2	2	3	4	4	5	0
GB_ COARSE	GS_ COARSE	GS_FINE	GS_FINE	SS_COARSE	2	2	3	3	4	5	0
TB_AC	GB_TYP	GB_TYP	GS_COARSE	SS_COARSE	2	3	3	4	4	5	1
TB_LCB	GS_ COARSE	GS_ COARSE	GS_TYP	SS_COARSE	2	3	3	4	4	5	0
AC	AC	PC	GB_TYP	SS_FINE	2	2	2	3	4	5	0
AC	PC	GB_ COARSE	TS_LIME	SS_FINE	2	2	3	4	4	5	0
AC	PC	GB_TYP	GS_COARSE	SS_FINE	2	2	3	4	4	5	0
AC	PC	GB_TYP	GS_SAND	SS_FINE	2	2	3	4	4	5	0
TB_AC	GB_TYP	GS_ COARSE	TS_LIME	SS_FINE	2	3	3	4	4	5	0
TB_AC	GB_TYP	GS_FINE	GS_TYP	SS_FINE	2	3	3	4	4	5	0

Note: Abbreviations found in the table are standard notations included in the LTPP data tables and are defined in the LTPP database.

Table 39. AC surface with five layers between AC and subgrade.

LAYER_AFTER_AC_1	LAYER_AFTER_AC_2	LAYER_AFTER_AC_3	LAYER_AFTER_AC_4	LAYER_AFTER_AC_5	SS_TYPE	BC_LAYER_2_DESIG	BC_LAYER_3_DESIG	BC_LAYER_4_DESIG	BC_LAYER_5_DESIG	BC_LAYER_6_DESIG	BC_LAYER_SS_DESIG	BC_LAYER_NO	SS_sub_24
PC	GB_COARSE	GS_COARSE	GS_FINE	GS_FINE	SS_COARSE	2	3	3	4	4	4	5	0
TB_AC	AC	AC	AC	TS_STAB	SS_COARSE	2	3	3	3	4	4	5	0
GB_TYP	TS_AC	GS_TYP	GS_TYP	GS_TYP	SS_FINE	2	3	4	4	4	4	5	0

Note: Abbreviations found in the table are standard notations included in the LTPP data tables and are defined in the LTPP database.

Table 40. PCC surface with six layers between PCC and subgrade.

LAYER_AFTER_PC_1	LAYER_AFTER_PC_2	LAYER_AFTER_PC_3	LAYER_AFTER_PC_4	LAYER_AFTER_PC_5	LAYER_AFTER_PC_6	SS_TYPE	BC_LAYER_2_DESIG	BC_LAYER_3_DESIG	BC_LAYER_4_DESIG	BC_LAYER_5_DESIG	BC_LAYER_6_DESIG	BC_LAYER_7_DESIG	BC_LAYER_SS_DESIG	BC_LAYER_NO	SS_sub_24
AC	AC	AC	PC	GB_COARSE	GS_TYP	SS_FINE	2	2	2	3	4	4	4	5	1

Note: Abbreviations found in the table are standard notations included in the LTPP data tables and are defined in the LTPP database.

Table 41. AC surface with seven layers between AC and subgrade.

LAYER_AFTER_AC_1	LAYER_AFTER_AC_2	LAYER_AFTER_AC_3	LAYER_AFTER_AC_4	LAYER_AFTER_AC_5	LAYER_AFTER_AC_6	LAYER_AFTER_AC_7	SS_TYPE	BC_LAYER_2_DESIG	BC_LAYER_3_DESIG	BC_LAYER_4_DESIG	BC_LAYER_5_DESIG	BC_LAYER_6_DESIG	BC_LAYER_7_DESIG	BC_LAYER_8_DESIG	BC_LAYER_SS_DESIG	BC_LAYER_NO	SS_sub_24
GB_TYP	GS_TYP	GS_TYP	TS_AC	GS_TYP	GS_TYP	GS_TYP	SS_FINE	2	2	2	3	3	3	3	3	4	0

Note: Abbreviations found in the table are standard notations included in the LTPP data tables and are defined in the LTPP database.

Table 42. PCC surface with seven layers between PCC and subgrade.

LAYER_AFTER_PC_1	LAYER_AFTER_PC_2	LAYER_AFTER_PC_3	LAYER_AFTER_PC_4	LAYER_AFTER_PC_5	LAYER_AFTER_PC_6	LAYER_AFTER_PC_7	SS_TYPE	BC_LAYER_2_DESIG	BC_LAYER_3_DESIG	BC_LAYER_4_DESIG	BC_LAYER_5_DESIG	BC_LAYER_6_DESIG	BC_LAYER_7_DESIG	BC_LAYER_8_DESIG	BC_LAYER_SS_DESIG	BC_LAYER_NO	SS_sub_24
AC	AC	AC	AC	PC	TB_CEMENT	TS_LIME	SS_FINE	2	2	2	2	3	4	4	4	5	1
AC	AC	AC	AC	PC	TB_STAB	TS_LIME	SS_FINE	2	2	2	2	3	4	4	4	5	1

Note: Abbreviations found in the table are standard notations included in the LTPP data tables and are defined in the LTPP database.

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