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FEASIBILITY OF USING LTPP DATA TO DEVELOP RELATIONSHIPS BETWEEN LABORATORY- AND FIELD-DERIVED PROPERTIES OF UNBOUND MATERIALS

Final Report

Prepared for
NCHRP
Transportation Research Board
of
The National Academies

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The research reported herein was performed under NCHRP Project 20-50(19) by Wood Environment & Infrastructure Solutions, Inc. (Wood E&IS) and Charles W. Schwartz and Associates, LLC (Schwartz LLC). Dr. Gonzalo R. Rada, P.E., Senior Principal at Wood E&IS, was the Project Director and Principal Investigator. In addition to Dr. Rada, Dr. Pedro Serigos of Wood E&IS was the primary report author. Other authors of this report were Dr. Charles W. Schwartz of Schwartz LLC and Mr. Gary Elkins of Wood E&IS.

ABSTRACT

This report presents the results of a study that evaluated the feasibility of using LTPP data for developing relationships between laboratory- and field-derived properties of unbound granular materials used in pavement. A total of 1,045 LTPP test sections were found to have relevant data to support development of the relationships, of which approximately 300 have data for two or more unbound layers. An exploratory analysis of those data provided information on the quantity, quality, and range of the data to understand their scope and limitations. Several important conclusions resulted, with the most important ones being that the LTPP data are adequate for development of the relationships and that improvements to the dataset to be used are possible and should be pursed. In light of these conclusions, a methodology for development of the relationships was formulated based on a non-point approach in which comparisons between nonlinear forward calculation and linear backcalculation analyses are used more holistically to define an equivalent homogeneous linear resilient layer modulus that gives similar pavement responses as obtained from the nonlinear analysis. A six-task work plan for development of the relationships based on the proposed methodology also was formulated.

ADDENDUM TO FINAL REPORT

Addendum by the research team dated August 2019.

Following the submittal of the final report, a concern has been expressed about validity of the report's conclusion concerning the availability of data in the LTPP database to support development of relationships between laboratory- and field-derived properties of unbound materials and requested further clarification. To address this concern, the research team re-evaluated the research findings and concluded that, contrary to the conclusion stated in the final report, the data presently contained in the LTPP database cannot be used to develop the sought-after relationships. Because of this contradiction, the research team prepared this addendum to inform the reader of the updated conclusion.

The research team proposed an approach for developing new data associated with laboratory- and field-derived properties of unbound materials (not currently in the LTPP database) that can be used to relate backcalculated resilient moduli to equivalent laboratory values. These data are:

- Laboratory-derived K1, K2 and K3 regression constants (derived from the LTPP laboratory resilient modulus results) in the universal resilient modulus constitutive equation or the 2002 Pavement Design Guide constitutive equation. These constants were computed during the project to aid in assessing the quality of the LTPP laboratory resilient modulus data, and they are included with the final report.
- Field-derived equivalent linear elastic layer moduli (derived from the LTPP field deflections and above referenced K constants). These moduli represent a weighted average of the stress states throughout a given layer. They were not computed as part of the project, but rather, data from two LTPP test sections were used to illustrate the proposed methodology.
- The research team believes that this approach, although it requires the development of data not currently available in the LTPP database, would provide a rational means for converting backcalculated resilient moduli to equivalent laboratory values, and would overcome some of the issues associated with the LTPP data, including the following:
- The LTPP backcalculated layer moduli currently included in the database assumes division of the subgrade into an upper two-foot "compacted" layer and semi-infinite lower layer, and the backcalculated layer moduli are sensitive to the arbitrary two-foot assumption for the upper subgrade. Moreover, there are no laboratory resilient modulus values for two subgrade layers in the LTPP database; i.e., a single value represents the entire subgrade layer.
- In many instances, multiple unbound granular layers were combined (e.g., base, subbase and subgrade) into a single layer because of backcalculation analysis limitations, which negates a one-to-one correlation between laboratory- and field-derived properties.
- In some cases, the "backcalculated" layer moduli stored in the LTPP database are not the actual backcalculated values but rather the arbitrarily selected upper or lower allowable values. These boundaries limit the outcomes to reasonable results, but are not necessarily the best solutions.

- Attempts to relate resilient modulus derived from the laboratory to those backcalculated from deflection measurements without establishing an equivalent stress state will not yield a logical solution.

In summary, the development of relationships between laboratory- and field-derived properties of unbound materials is not possible using those data presently available in the LTPP database; the research team should have stated this finding clearly in the final report.

CHAPTER 1. INTRODUCTION

BACKGROUND

The relationship between laboratory-derived mechanical properties of unbound materials and the field-derived properties of those materials has been the subject of previous research in transportation geotechnics and Pavement ME design. No single relationship has been shown to relate the two sets of properties, and as a result simplifications are implemented into the American Association of State Highway Transportation Officials (AASHTO) Mechanistic-Empirical Pavement Design Guide (MEPDG).

Understanding that unbound material properties affect pavement performance predictions, and thus affect pavement design, developing a relationship between laboratory-derived properties and those derived from field-collected data will lead to higher reliability in pavement design. This project represents the first step in developing such a relationship—assessing whether adequate data exists or can be readily collected to develop the relationships. The remainder of this chapter introduces concepts related to the comparison of laboratory- and field-derived unbound material properties. This background information directly affects the data requirements, which in turn directly affects the research approach.

The differences in laboratory- and field-derived properties are expected to be a function of many factors, some of which are detailed in the following section of this work plan. The laboratory-derived properties use specialized equipment to measure the responses of a sample of material obtained from the field, whereas field-derived properties are generally obtained using the falling weight deflectometer (FWD) or other deflection testing devices. For unbound materials, laboratory-derived values are the required inputs for the Pavement ME Design procedures, thus driving the need to convert field-derived values to equivalent laboratory values.

Important conceptual differences between laboratory and field tests are that laboratory tests measure material properties under controlled conditions and generally homogeneous stress states, whereas FWD test results are a measure of the material's response under in situ conditions under a complex spatially- and temporally-varying loading condition. In concept, the material property measurement should be such that the measured material response to load in the field can be predicted by the material properties measured in the laboratory after taking into account the stress-strain conditions known to affect the material's behavior. Among other complications, this relationship is confounded by material properties being measured on a small (often reconstituted) sample in the lab, whereas field measurements represent "average" material properties of the pavement structure based on a theory that approximates layered material behavior using homogenous properties for each layer. This "average" set of material properties is affected by variations in layer thicknesses and stress states, pavement conditions such as cracking and rutting, and slippage between the layers. This issue, along with issues pertaining to FWD testing and backcalculation of layer moduli, are well-documented in the three-volume series of ASTM International Special Technical Publications (STP) 1026 (Baladi and Bush, eds., 1989), 1198 (Bush, Von Quintos and Baladi, eds., 1994), and 1375 (Tayabji and Lukanen, eds., 1999).

The objective of this study was to evaluate the feasibility of using LTPP data for developing relationships between laboratory- and field-derived properties of unbound granular materials used in pavement. Moreover, the research was to be limited to those properties required

for pavement design analysis, in accordance with Pavement ME Design procedures. The current material inputs to characterize the properties of unbound materials used in the Pavement ME Design software include:

- Resilient modulus
- Poisson's ratio
- Classification and volumetric properties
- Moisture-density relationships
- Unit weight
- Soil-water characteristic curve
- Saturated hydraulic conductivity
- Other thermal properties

The resilient modulus of unbound layers in a pavement structure is an engineering property that relates applied stresses to recoverable strains, and can be derived from in-situ deflection measurements taken in the field or derived from laboratory-measured properties. The relationship between the resilient modulus derived from the field and laboratory measurements is currently accounted for through the use of a scaling factor (AASHTO, 2015). The current scaling factors, which were derived using LTPP data, represent a simple approach to relate field-derived to laboratory-derived resilient modulus values. Furthermore, the recent increase in the available data in the LTPP database improved the possibility of developing more robust relationships to address the differences in laboratory- and field-derived properties of unbound materials.

Review of Previous Studies Correlating Lab- and Field-Derived Properties

Equation 1 shows the relationship from the 1993 AASHTO Pavement Design Guide that is used to relate field-derived moduli to those derived from laboratory tests (AASHTO, 1993):

$$M_R = C \times E_{FWD} \quad (1)$$

Where:

M_R = Resilient modulus derived from laboratory measurements.

E_{FWD} = Resilient modulus derived from FWD measurements taken in the field.

C = Correction factor.

The correction factor (C) in Equation 1 generally ranges from 0.35 to 0.75 for subgrade soils depending upon the pavement structure (Von Quintus & Killingsworth, 1997). However, Dawson et al. (2009) demonstrated that, by controlling for many factors, laboratory- and field-derived moduli are nearly equivalent.

George (2003) found no consensus among researchers in relating FWD-derived moduli to laboratory-derived moduli. George (2003) also compared laboratory-derived resilient modulus values for several subgrades to those derived from FWD measurements directly on the subgrade. The results showed considerable variability in field-derived moduli based on the location of the FWD and equal field- and laboratory-derived moduli values in some cases.

Other studies have investigated the use of different relationships for estimating resilient moduli. For example, Flintsch et al. (2003) evaluated the models shown in Equations 2 through 4 for unbound materials:

$$M_r = k_1 \cdot \theta^{k_2} \tag{2}$$

Where:

θ = Bulk stress (kPa),

M_r = Resilient modulus (kPa), and

k_1 and k_2 = Regression parameters.

$$M_r = k_3 \cdot \theta^{k_4} \cdot \sigma_d^{\ k_5} \tag{3}$$

Where:

σ_d = Deviator stress (kPa), and

k_3, k_4, and k_5 = Regression parameters.

$$Log_{10} M_r = C_0 + C_1 \cdot S_r + C_2 \cdot PC + C_3 \cdot Log_{10}\theta \tag{4}$$

Where:

S_r = degree of saturation (%),

PC = modified relative Proctor compaction (%), and

C_0, C_1, C_2, and C_3 are regression parameters.

Equations 2 through 4 represent additional complexity in estimating resilient modulus values by considering factors such as stress dependencies and moisture. Flintsch et al. (2003) reported strong correlation between lab- and field-derived moduli when accounting for stress dependencies. Von Quintus and Simpson (2002) evaluated the use of the nonlinear models in backcalculating LTPP data; the study used the MODCOMP software for developing the backcalculated data contained in the LTPP database (Von Quintus and Simpson 2002). MODCOMP was used because it provides several nonlinear model options for evaluating the subgrade. The study showed that different models were more representative of different materials; the general model characterizing the materials in terms of the modulus (E) is given by Equation 5.

$$E = k_1 \exp(S \times k_2) \tag{5}$$

For coarse-grained soils, S was defined by the bulk stress as follows:

$$S = \theta = \sigma_z + \sigma_t + \sigma_r$$

σ_z = Vertical stress.

σ_t = Tangential stress.

σ_r = Radial stress.

For fine-grained soils, S was defined by the deviator stress as follows:

$$S = \theta = \sigma_1 - \sigma_2$$

σ_1 = Major principal stress at the mid-depth of the layer.

σ_2 = Minor principal stress at the mid-depth of the layer.

When neither of these models successfully characterized the nonlinear material behavior, the minor principal stress model was used indicating that the parameters of Equation 5 were identified by:

$$S = \theta = \sigma_3$$

σ_3 = Minor principal stress.

However, the Von Quintus and Simpson (2002) report identifies that the model recommended for use in characterizing the materials, the Universal model (Equation 6), was not available in the MODCOMP software.

$$E = K_1 p_a \left[\frac{\theta}{p_a}\right]^{k_2} \left[\frac{\sigma_d}{p_a}\right]^{k_3} \quad (6)$$

Where:

θ = Bulk stress.

σ_d = Deviator stress.

p_a = Atmospheric pressure.

Other investigations of laboratory- and field-derived properties of unbound materials include Tayyeb et al. (1994), Mikhail et al. (1999), and Richter (2006). The level of complexity in modeling found in the literature ranges from simple (e.g., estimating a correction factor) to complex (e.g., accounting for stress dependencies). Many studies that investigate the relationship between laboratory- and field-derived properties found the following:

- The accuracy of the relationship between laboratory- and field-derived properties depends on the level of complexity of the underlying models that are assumed, and
- The level of complexity of the models is dependent upon data availability for the factors under consideration (e.g., moisture, etc.).

Studies that evaluated the relationship between laboratory- and field-derived properties highlight the dependency of the models on data availability. Therefore, evaluating data availability in the LTPP database must be done with the potential outcomes as the main factor. For example, developing a new set of correction factors requires less data than developing more complex models. Therefore, it will be important to specify the possible model types or correction factors that can be developed, and assess which of them the available data will support.

Factors Affecting Laboratory- and Field-Derived Properties

The review of available literature also revealed several key factors that affect laboratory- and field-derived modulus values. Many of the required laboratory testing procedures for unbound materials have been standardized and adopted by AASHTO. Modulus values calculated from FWD test are influenced by the following factors:

- Analysis method:
  - The constitutive model (e.g., static linear, dynamic nonlinear, etc.).
  - The procedure for estimating the modulus (e.g., backcalculation, forward calculation, etc.).
- Input parameters for the calculation procedure:
  - Deflection basin parameters, layer thicknesses, load distribution, number of pavement layers, depth to stiff layer, and seed moduli.
- FWD testing parameters, specifically:
  - Drop height, drop weight, number of sensors, sensor location/spacing, loading plate size.
- Pavement condition (e.g., cracking for asphalt pavements and joint condition for concrete pavements, etc.).
- Seasonal variations:
  - Moisture content, depth to water table, temperature profile, frost depth.
- Pavement/material characteristics:
  - Layer types (including the presence of layer treatments), layer thicknesses, the presence of special materials (e.g., geosynthetic membranes), and compaction.

The information from FWD testing is used to backcalculate a modulus value and other pertinent material properties. Backcalculation of layer moduli is an inverse problem, which requires calculating model parameters (moduli) from observed data (deflection basins). For pavement layer moduli determination, the complexity of the backcalculation procedure and number of assumptions made further contribute to the non-uniqueness of the solution; e.g., different backcalculation seed moduli will produce different solutions. Similarly, several factors are expected to affect the laboratory-measured moduli, including:

- The characterization method, specifically in terms of the constitutive model.
- Environmental conditions, specifically the moisture content of the sample.
- Material characteristics:
  - Compaction (whether field or lab compacted) and the geometry of the sample.
- Testing parameters.
- Input parameters and assumptions in the analysis, including:
  - Stress distributions, deformation, dimensions of the sample, and Poisson's ratio.

Unlike the backcalculation of the layer moduli using the FWD, the calculation of the material moduli from laboratory results is generally standardized and performed using closed-form solutions, such that the analysis method should not significantly affect the results. However, material damping and inertial effects may introduce some variability in the results. Also, because the precision of the laboratory equipment means that some inputs (e.g., deformation and stresses) can be carefully controlled and measured, lending a high level of reliability to laboratory results, some earlier studies have sought simple relationships (Von Quintus & Killingsworth, 1997), and others sought to develop more complex relationships accounting for many factors (Flintsch et al., 2003). It appears that the data do exist to derive the most basic relationships (the current AASHTO relationships are derived from LTPP data), but it is unclear if the data exist to derive more detailed relationships.

PROJECT OBJECTIVES AND SCOPE

The objective of this research is to evaluate the feasibility of using LTPP data for developing relationships between laboratory- and field-derived properties of unbound materials used in pavements. The research is limited to those properties required for pavement design and analysis in accordance with the Pavement ME Design procedures.

To accomplish the stated objective, the following five tasks were conducted:

1. Identified properties of unbound materials in accordance with the MEPDG and Pavement ME Design software.
2. Reviewed the LTPP database to estimate the availability of the properties identified in Task 1.
3. Evaluated the available LTPP data with consideration to quality, quantity, ranges, and other relevant factors.
4. As warranted, formulated an actionable research plan to develop relationships between laboratory- and field-derived properties.
5. Documented the entire research effort.

REPORT ORGANIZATION

The objective of this report is to document the entire research effort. This report presents the major findings, outcomes, conclusions, and recommendations from the research effort. The information presented in this report has been organized into six chapters. This chapter provides background information and project objectives, and summarizes the approach used for conducting the research. The next one, Chapter 2, addresses the key unbound material inputs from Pavement ME, including a summary of the sensitivity of distress predictions to unbound material inputs. Chapter 3 details the evaluation of available LTPP data, which have been grouped into primary and supplementary data. Chapter 4 presents the results from the assessment of LTPP data in terms of the feasibility of using LTPP data for developing relationships between laboratory- and field-derived properties of unbound granular materials. The recommended methodology and proposed work plan for actual development of the relationships between laboratory- and field-derived properties is presented in Chapter 5, while the major findings, conclusions, and recommendations from the project are presented in Chapter 6. The references cited throughout the report are listed at the end of the report.

CHAPTER 2. KEY INPUTS FROM PAVEMENT ME

The objective of the effort documented in this chapter was to identify the properties of unbound pavement layers required for pavement design and analysis in accordance with Pavement ME Design procedures and the data elements required for their estimation. From section 10.5 of the MEPDG Manual of Practice related to unbound materials and foundations, their physical properties include dry density, moisture content, and classification properties, while their engineering properties include the resilient modulus. (AASHTO, 2015) In addition, the required data and approaches for unbound material properties are discussed in multiple locations throughout the MEPDG Manual of Practice.

UNBOUND MATERIAL INPUTS FOR PAVEMENT ME DESIGN

Unbound pavement materials include unbound aggregate base materials and engineered embankments (subgrades). The unbound material properties required by Version 2.5 of the Pavement ME Design software are organized into three major categories in the Pavement ME Design input screens:

1. General
2. Modulus
3. Gradation and Other Properties

These unbound material property inputs are the same for flexible, rigid, and composite pavements and for new and rehabilitation designs. Details of the unbound input properties in each category are summarized in Table 1. This table also specifies whether each input property can be developed in the laboratory and/or the field and includes some explanatory comments.

There are a few related inputs and/or input variations in addition to those in the three major categories:

- The layer material type, which is specified when the layer is created for the pavement structure. For unbound materials, this is the AASHTO soil class. Other options are “sandwiched granular” or “chemically stabilized” (with specification of chemical type).
- Sandwiched granular and chemically stabilized material types are also included in Table 1. Sandwiched granular layers consist of unbound granular base materials but used in a nonconventional structural configuration. Chemically stabilized materials are intermediate between bound (AC, PCC) and unbound materials; since they share many characteristics of unbound materials, they are included in Table 1 for completeness.
- For chemically stabilized layers, flexural strength is required in addition to resilient modulus.
- Chemically stabilized and sandwiched granular layer types also provide for input of thermal properties (heat capacity, thermal conductivity). Although these thermal properties are also required for the modeling of unbound layers, default values are built into the software and the user has no option to override.

Table 1. Inputs required by Pavement ME Design for aggregate base materials and engineered embankments (subgrades).

Category	Property	Symbol	Determination		Comments
			Lab	Field	
Layer Material Type	Soil class (unbound materials)				Specified when layer is created
General	Coefficient of lateral earth pressure	K_o			Assumed/estimated
	Layer thickness	D		X	Not required for infinite subgrade
	Poisson's ratio	ν	X		Usually assumed/estimated
Modulus/Strength	Resilient modulus (Level 1)	M_r			Level 1 input of M_r is not incorporated in current version of Pavement ME
	Resilient modulus (Level 2)	M_r	X	X	• Specify at optimum moisture and density or representative annual value • Lab determination requires estimation of appropriate stress state (Table 10-9 in AASHTO 2015) • Field determination requires field-to-lab correction factor (Table 10-8 in AASHTO 2015)
		CBR	X		California Bearing Ratio correlation with M_r
		R	X		R-value correlation with M_r
		a			Structural layer coefficient correlation with M_r
		DCP		X	Dynamic Cone Penetration index correlation with M_r
		PI & gradation	X		Plasticity Index and gradation correlation with M_r

	Resilient Modulus (Level 3)	M_r			Default value based on soil classification (Table 10-7/chemically stabilized layers or Table 10-10/unbound layers in AASHTO 2015)
	Flexural strength (modulus of rupture)	MOR			Required only for chemically stabilized layers in flexible pavements
Thermal (Input only for chemically stabilized or sandwiched granular layer types)	Heat capacity	C	X		
	Thermal conductivity	k	X		
Gradation and Other Engineering Properties (Not input for chemically stabilized or sandwiched granular layer types)	Gradation	%passing	X		Defaults for soil class populated for #200, #80, #40, #10, #4, 3/8", ½", ¾", 1", 1 ½", 2", and 3 ½" sieves
	Liquid Limit	LL	X		
	Plasticity Index	PI	X		
	Maximum dry unit weight	$\gamma_{d.max}$	X		
	Saturated hydraulic conductivity	k_s	X	X	
	Specific gravity of solids	G_s	X		
	Water content	W	X	X	
	Soil Water Characteristic Curve	a_f, b_f, c_f, h_r	X		Default values for soil class typically used
Other	Depth to groundwater	z_w		X	

- Depth to groundwater is arguably an embankment/subgrade property and has been included in Table 1 for completeness.

All of the unbound material properties in the Pavement ME Design input screens conform to the documentation in the Mechanistic-Empirical Pavement Design Guide Manual of Practice (AASHTO, 2015).

As previously mentioned, Table 1 identifies whether each property can be determined in the laboratory and/or the field. The relationships between laboratory- and field-derived properties are the principal focus of this project. The only properties that can be determined in both the laboratory and the field are the resilient modulus (with appropriate caveats), saturated hydraulic conductivity, and water content. As will be shown later, the Pavement ME Design distress predictions are insensitive to saturated hydraulic conductivity, so any discrepancies between laboratory- and field-derived properties will be relatively unimportant. There are no issues with laboratory- vs. field-determination of water content. However, Pavement ME Design distress predictions are sensitive to resilient modulus and there are large discrepancies between laboratory- and field-determined values, as summarized Table 10-8 in AASHTO (2015). Resilient modulus is consequently the main focus of this study, as expected.

SENSITIVITY OF DISTRESS PREDICTIONS TO UNBOUND MATERIAL INPUTS

Table 1 lists over a dozen input properties for unbound materials. Not all of these are equally important with regard to their impact on predicted pavement performance. The sensitivity of predicted pavement performance to unbound material inputs will also be different for flexible versus rigid pavements.

NCHRP Project 1-47 (Schwartz et al., 2011) provided a global sensitivity analysis for the impacts of MEPDG inputs on predicted pavement performance. In the NCHRP 1-47 study, comprehensive global sensitivity analyses (GSA) of flexible and rigid (JPCP, CRCP) pavement performance predictions to MEPDG design inputs were performed for five climatic conditions and three traffic levels. Design inputs evaluated in the analyses included traffic volume, layer thicknesses, material properties, groundwater depth, and others. Correlations among design inputs were also considered where appropriate.

The sensitivity metric developed in NCHRP 1-47, a "design limit" normalized sensitivity index defined as:

$$S_{ijk}^{DL} = NSI = \left(\frac{\Delta Y_{ji}}{\Delta X_{ki}}\right)\left(\frac{X_{ki}}{DL_j}\right) \tag{7}$$

In which X_{ki} is the value i of design input k, ΔX_{ki} is the change in design input k about X_{ki}, ΔY_{ji} is the change in predicted distress j corresponding to ΔX_{ki}, and DL_j is the design limit for distress j. For simplicity, the design limit normalized sensitivity index S_{ijk}^{DL} is termed the "normalized sensitivity index" or NSI, as shown in Equation 7.

As an example, consider total rutting as distress j and granular base resilient modulus as input k (i.e., X_{ki}). The design limit for total rutting (DL_j) is 0.75 inches. For some combination of inputs (location i in the problem domain), the design limit normalized sensitivity of total rutting to granular base layer resilient modulus (or NSI) equals -0.25. The negative sign implies that a

decrease in base resilient modulus (ΔX_{ki}) will cause an increase in total rutting (ΔY_{ji}). The increase in total rutting caused by a 10% decrease in granular base resilient modulus can then be calculated as (see Equation 8):

$$\Delta Y_{ji} = NSI * \Delta X_{ki} * \frac{DL_j}{X_{ki}} = NSI * \left(\frac{\Delta X_{ki}}{X_{ki}} \right) * DL_j = -0.25 * 0.10 * 0.75 \text{ in.} = 0.01875 \text{ inches} \quad (8)$$

In the NCHRP 1-47 study, the sensitivity analysis results are categorized as: Hypersensitive (NSI ≥ 5), Very Sensitive (1≤NSI<5), Sensitive (0.1≤NSI<1), and Insensitive (NSI<0.1). Table 2 summarizes the sensitivity categories for the various unbound material inputs for the different distress types in flexible pavements; Table 3 summarizes similar results for JPCP rigid pavements. Empty cells in Table 2 and Table 3 imply that the corresponding distress (column) was insensitive to the corresponding input (row). Unbound material inputs that do not appear at all in Table 2 and Table 3 did not achieve a Sensitive or above value for NSI for any of the distresses. None of the unbound material inputs reached the Hypersensitive category (NSI>5); only some of the HMA properties for flexible pavements and slab width for JPCP pavements reached the Hypersensitive category.

Table 2. Sensitivity of flexible pavement distresses to unbound material properties.

	Longitudinal Cracking	**Alligator Cracking**	**AC Rut Depth**	**Total Rut Depth**	**IRI**
Base thickness	VS	VS	S		
Base resilient modulus	VS	VS	S	S	S
Base Poisson's ratio	S	S	S		
Subgrade resilient modulus	VS	VS	S	S	S
Subgrade Poisson's ratio	VS	S			
Subgrade % passing #200	VS	S		S	S
Subgrade Liquid Limit	S	S	S		
Subgrade Plasticity Index	S	S			
Groundwater depth	S	S			

Note: VS = very sensitive to input, S = sensitive to input, and blank cell = insensitive to input.

Table 3. Sensitivity of rigid (JPCP) pavement distresses to unbound material properties.

	Faulting	Transverse Cracking	IRI
Base thickness	S	S	
Base resilient modulus	S	S	S
Base Poisson's ratio			
Subgrade resilient modulus	S	S	S
Subgrade Poisson's ratio			
Subgrade % passing #200			
Subgrade Liquid Limit			
Subgrade Plasticity Index			
Groundwater depth			

Note: VS = very sensitive to input, S = sensitive to input, and blank cell = insensitive to input.

Some observations from Table 2 and Table 3 include:

- For flexible pavements (Table 2), most of the distresses are sensitive or very sensitive to multiple unbound material property inputs. All flexible pavement distresses are sensitive or very sensitive to both base and subgrade resilient modulus values.
- For rigid pavements (Table 3), the sensitivity of predicted distresses to the unbound material property inputs is significantly less than for flexible pavements. This conforms to conventional wisdom. Nonetheless, all rigid pavement distresses are moderately sensitive to base and subgrade resilient modulus values.
- The NCHRP 1-47 study did not include the unbound material hydraulic properties (saturated hydraulic conductivity, soil-water characteristic curve parameters) in the global sensitivity analyses. It is therefore impossible to quantify the sensitivity of predicted distresses to these inputs. However, engineering judgment suggests that these sensitivities should be low.

Although the NCHRP 1-47 analyses were performed using the research-grade Version 1.1 of the MEPDG software, the overall findings regarding the sensitivity of predicted pavement performance to the various input properties should be broadly applicable to the current Version 2.5 of Pavement ME Design. One exception to this might be the influence of fines on rigid pavement performance. Version 1.1 of the MEPDG software quantified this via a subjective Erodibility Index, which has been dropped from the current version of the Pavement ME Design software.

HIGHLIGHTS

Of the many unbound material property inputs required for the Pavement ME Design software, the only significant properties that can be determined in both the laboratory and the field are the resilient modulus values of aggregate base and subgrade layers. Predicted pavement

performance is sensitive to very sensitive to resilient modulus values for the aggregate base and subgrade layers, although less so for rigid pavements. Improved harmonization between laboratory- and field-derived resilient modulus values is much needed. The very approximate correction factors summarized in Table 10-8 of AASHTO (2015), which are duplicated in Table 4 of this document, are incompatible with the more refined algorithms embedded elsewhere in the MEPDG.

Table 4. C-Values Recommended to convert backcalculated resilient moduli to equivalent laboratory values. (AASHTO, 2015)

Layer Type	Location	C-Value or M_R/E_{FWD} Ratio[a]
Aggregate Base/Subbase	Between a stabilized and HMA layer	1.43
	Below a portland cement concrete (PCC) layer	1.32
	Below a hot mixed asphalt (HMA) layer	0.62
Subgrade/Embankment	Below a stabilized subgrade/embankment	0.75
	Below an HMA or PCC layer	0.52
	Below an unbound aggregate base	0.35

a. M_R refers to the laboratory equivalent resilient modulus adjusted for stress state, whereas E_{FWD} refers to the elastic modulus backcalculated from FWD testing.

CHAPTER 3. EVALUATION OF AVAILABLE LTPP DATA

In this chapter, the results of the review of the LTPP database to estimate the availability of the properties identified in the previous chapter are documented. More specifically, this chapter describes the evaluation of available LTPP data to support efforts to enhance the Pavement ME inputs related to the laboratory-measured resilient modulus and elastic modulus of unbound pavement layers based on interpretation of FWD measurements. The ultimate goal of the effort was to determine whether or not adequate data from the LTPP database are available to support logical pursuit of a follow-up Phase II analysis.

Table 5 shows LTPP data availability for laboratory resilient modulus data of unbound materials and backcalculation data from the July 2017 standard data release. For subgrade, laboratory-measured resilient moduli on remolded samples and undisturbed Shelby Tube samples of cohesive soils are included in Table 5—the data quantities listed in this table are those test sections which have available data from backcalculation and laboratory tests. In this data count, a subset of FWD tests were performed at a time close to when the material samples were obtained to eliminate the effect of change in moisture content and frost conditions on data relationships. While initial state conditions and measurements are important, change over time is also an important aspect of pavement design based on mechanistic principles.

Table 5. Number of test sections with laboratory-measured resilient moduli and matching backcalculation results from the July 2017 LTPP data release.

Layer Type	Number of test sections			
	Lab Resilient Modulus Tests			Matching Backcalculation Data
	Remolded	Shelby tube	Total	
Aggregate base/subbase below PCC layer	240		240	158
Aggregate base/subbase in between a stabilized and HMA layer	39		39	29
Aggregate base/subbase below HMA layer	243		243	176
Subgrade-embankment below stabilized subgrade/ embankment layer	157	102	215	158
Subgrade-embankment below an HMA or PCC layer	199	111	278	191
Subgrade-embankment below an unbound aggregate base layer	772	274	919	632

The total number of unique LTPP test sections that have data available for this analysis is 1,045, of which approximately 300 have laboratory-measured resilient modulus data for both granular base and subgrade on the same test section. The number of potentially useful test sections to use on this study may be reduced if the time lag between laboratory and field tests and other factors are considered.

The remainder of the discussion in this chapter on available data is classified by primary and supplementary data. Primary data are those data elements directly associated with determination of the relationships between elastic moduli estimated from field deflection measurements and laboratory resilient modulus measurements performed on material samples obtained in the field. Supplementary data are other data that can potentially be used to classify, explain, or expand on the primary relationships discovered from the primary dataset.

PRIMARY DATA

The two classifications of primary data investigated under this project include backcalculation interpretations of FWD measurements and laboratory resilient modulus on unbound pavement layers.

Backcalculation Interpretations from FWD Measurements

The most recent LTPP backcalculation research contract was performed on data contained in the January 2013 public data release. The results of this project represent the most current and up-to-date interpretations of LTPP FWD measurements, which will be used in this analysis effort (Von Quintus, 2015). The backcalculation results from the project stored in the LTPP database included those based on elastic layer theory and the best fit algorithm for PCC-surfaced pavements. For this study, estimates based on elastic layer theory will be used, since the best fit algorithm only produces a composite modulus for the combined PCC and base layers.

The backcalculation data currently available used the following considerations to judge the adequacy of the backcalculation results:

- FWD deflection basins were pre-screened prior to backcalculation to include only those which are consistent with elastic layer theory. This helped to remove measurements at cracks or highly distressed locations, basins with increasing deflections for sensors further from the applied load, and other anomalies known to result in poor backcalculation results.
- For the results of the backcalculation to be used in computation of test section summary statistics, the root-mean squared error (RMSE) of the measured-computed deflections must be less than 3 percent.
- On a test section, during a measurement pass conducted on the same day, at least 75% of the backcalculated point deflection measurements must have had a RMSE of less than 3%.
- When these data were added to the LTPP database, other quality control checks were added based on past experience with these data to check changes to pavement layer data from those used in the backcalculation analysis, and other referential data quality concerns that could potentially compromise the backcalculated layer moduli from this computed parameter exercise.

In the LTPP data extraction request, LTPP data at RECORD_STAUS equal to level “E” was requested, so that the data analysis team did not have to replicate all the functions the previous LTPP data analysis contractor performed. Members of the current research team participated in the quality control review of the backcalculation data from this research project; it should be expected that because of the large volume of data being reviewed, there was also a

large amount of data corrections and re-computations performed. The current LTPP backcalculation dataset is judged to be one of the most thorough-examined mass FWD ever released for public use.

One of the data issues to be addressed in this analysis is matching up the laboratory-measured properties of unbound layers with the layer structure used in analysis of field data. Combination of pavement layers is a common practice in backcalculation of layer moduli from FWD measurements. The practice of combining pavement layers in backcalculation analysis is typically related to thin AC bound pavement surface layers, since interpretation of the influence of a thin surface layer on the total deflection of a pavement structure is not possible using current technology. For this investigation, interpretation of how base and subgrade layers were combined is a primary concern. As noted in the analysis report from the last backcalculation project, various methods were used to adjust to shallow-depth ridged layers and within-pavement-structure ground water tables. While these types of pavement structures appear to be the exception to the general nature of typical pavement structures, they still deserve attention in this type of analysis that attempts to relate field measurements to laboratory measurements of material properties.

The backcalculation data requested for the project in question includes the following:

- BACKCAL_MODULUS_SECTION_LAYER – This table contains section-level statistics from elastic layer backcalculation that passed all the data quality control checks designed to report creditable backcalculation statistics over the entire test section.
- BAKCAL_STRUCTURE_LAYERS – Layer thickness used in the backcalculation process.
- BAKCAL_LAYER_LINK – Mapping of backcalculation pavement layers against actual pavement layers.
- BAKCAL_MODULUS_SECTION_MASTER – This provides potentially useful diagnostic information on the section statics contained in the BAKCAL_*_SECTION_LAYER tables.
- BALCAL_PASS – This table links results in the BAKCAL tables to the raw FWD measurement tables. A critical field in this table is LANE_NO, which indicates the nature of where the FWD measurements were performed. For this investigation, wheelpath basin tests are desired, thus LANE_NO should be in (C0, C1, F0, F3, J0, J1, J6, J9).
- Within these tables, backcalculation results at RECORD_STATUS = “E” indicates that they have passed all of the quality control checks imposed by the data analysis contractor to eliminate backcalculation results from highly distressed areas, unnormal deflection basins, and extreme outliers from the pool of location specific FWD measurements.

Laboratory-Measured Resilient Modulus

Laboratory-measured resilient modulus of unbound base measurements and subgrade material samples were performed using the LTPP P-46 protocol. These are the primary

laboratory measurements of interest used in development of the models used for development of the current Pavement ME design/analysis software.

In an attempt to match laboratory test results with field-interpreted backcalculation results, the following are critical issues that must be addressed:

1. Interpolation of stress states between field-measured backcalculation results and laboratory measurements. It is well known that the elastic properties of unbound materials used in pavements are sensitive to applied load, confining pressures, compaction, and moisture content.
2. Fitting the resilient modulus model shown in Equation 6, which establishes stress sensitivity of modulus values from lab measurements, needs to be performed using available data.
3. Laboratory resilient modulus measurements are performed at one state of compaction and one moisture level from material samples obtained outside of the ends of the monitoring portion of LTPP test sections. Proper interpretation of point-specific field measurements matched up with material sampling locations may provide greater insights into the lab-field relationship than generalized test section averaged statistics.

Data from the TST_UG07_SS07_* tables will be used in this analysis.

SUPPLEMENTARY DATA

General Information

These tables include information on the pavement type, layer thickness, layer types, general material types, location, and geometric details.

- Pavement structure (Pavement_Layer_Structure, TST_L05A, TST_L05).
- Project identification information (PROJECT_ID_EXP).
- General pavement information (Section_General_Exp).
- History of construction events on each test section (SECTION_STRUCTURE_HISTORY_EXP).
- Test section location (SECTION_COORDINATES).
- Experimental history of each test section (EXPERIMENT_SECTION).

AC Pavement Layers

While the investigation of field-to-laboratory properties is not focused on bound pavement layers, some of the following properties can be used to estimate overburden stresses in the underlying unbound material layers, and others are basic material properties that are prudent to obtain in case they become important during the investigation:

- Bulk specific gravity (TST_AC02).
- Maximum specific gravity (TST_AC03).
- Air voids (TST_AIR_VOIDS_SECT).

- Asphalt content (TST_AC04).
- Aggregate properties (TST_AG01, TST_AG02, TST_AG04).
- Resilient modulus, creep compliance, indirect tensile strength (TST_AC07,* tables).
- Dynamic modulus estimates (TST ESTAR.* tables).

PCC Pavement Layers

The following properties were obtained for PCC pavement layers.

- Static modulus of PCC, which includes unit weight and Poisson's ratio (TST_PC04).
- Density of PCC, which includes air voids (TST_PC05).

Unbound Pavement Layers

These are the primary layers of interest in this investigation. While laboratory measurements of resilient modulus are the primary property of interest, it is also important to obtain supporting data to enable potential insights into other empirical properties that might be useful in implementation of these findings in the MEPDG and Pavement ME software.

- Classification of unbound base and subgrade (TST_SS04_UG08).
- Gradation of coarse, fine, and combined aggregate (TST_SS01_UG01_UG02).
- Specific gravity of unbound materials (TST_UNBOUND_SPEC_GRAV).
- Maximum lab dry density and optimum moisture content (TST_UG05_SS05).
- Density of subgrade soil (TST_SS08).
- In situ moisture and density from nuclear gage in test pits (TST_ISD_MOIST).
- Natural moisture content of unbound materials from jar samples (TST_UG07_SS09).
- Permeability of subgrade soil including saturated hydraulic conductivity (TST_SS11). Limited dataset, primarily on SPS project sites.
- Permeability of unbound base and subbase layers including saturated hydraulic conductivity (TST_UG09).
- Dynamic Cone Penetrometer (DCP) tests. (TST_SS14_UG14_* tables). While dynamic cone penetrometer tests are empirical, they do offer an assessment of AASHTO standards based on these field measurements.

Climate

Annual and monthly climate statistics will be used for the initial download of climate data for this study. Annual climate statistics are limited to years when more than 300 days of data in a year are available. Monthly climate statistics are limited to months where 24 or more days of data are available for each month. If daily or hourly data are needed during the assessment of the available data, then this data can be obtained for test sections and time of interest.

Virtual weather stations – Virtual weather stations are based on nearby ground-based weather stations. Data for the selected test sections of interest from the following table was obtained from the expanded tables in InfoPave:

- CLM_VWS_PRECIP_ANNUAL_EXP – Annual precipitation statistics from expanded InfoPave tables.
- CLM_VWS_PRCIP_MONTH_EXP – Monthly precipitation statistics from expanded InfoPave tables.
- CLM_VWS_TEMP_ANNUAL_EXP – Annual air temperature statistics including mean, maximum, and minimum air temperatures; days above 32-degree C; freeze index; and freeze thaw air temperature cycles.
- CLM_VWS_TEMP_MONTH _EXP – Monthly air temperature statistics.

MERRA climate data – Modern-Era Retrospective Analysis for Research and Applications (MERRA) is a reanalysis dataset developed by the National Aeronautics and Space Administration (NASA). This dataset provides a continuous set of data starting in 1980. This dataset is also chosen since it provides a much more comprehensive set of data than that available from ground-based weather stations. MERRA-2 data for LTPP test sections is available from InfoPave.

The following data was downloaded from InfoPave in expanded format:

- MERRA_PRECIP_YEAR_EXP – Includes total annual precipitation, total annual evaporation, and number of days with precipitation events.
- MERRA_PRECIP_MONTH_EXP – Includes monthly data for the same data elements as in the precipitation year table.
- MERRA_TEMP_YEAR_EXP – Incudes yearly average, maximum, and minimum annual air temperature; days above 32-degree C; days below 0-degree C; freeze index; average soil temperatures at 6 depths; and average temperature in saturated and unsaturated zone.
- MERRA_TEMP_MONTH_EXP – Includes monthly data for the same data elements as in the temperature year table.

Traffic Data

While the primary thrust of this investigation is pavement layer material properties, basic-level traffic data were specified to serve as classification variables, since within the LTPP database, with pavement test sections which started in the GPS experiments, there is an expected correlation between truck loading and thickness or “strength” of the combined pavement layer structure.

ESALS and traffic volume characteristics are the primary variables to be included in the LTPP database form the following tables:

- TRF_MON_EST_ESAL – This table can be used to establish reasonable levels of ESAL applications.

- TRF_TEND – This is a new table introduced in July 2018 that includes a complete set of annual measured or estimated traffic truck statistics for every LTPP test section during its active time in-service within the LTPP experiments.

Seasonal Monitoring Program

The Seasonal Monitoring Program (SMP) dataset is an LTPP sub-study designed to investigate the causes of seasonal variations in FWD measurements. For this study, measurements and interpretations of data from the subsurface pavement layer temperature, moisture content, ground water table, and subsurface frost zones can be coupled with the results of FWD backcalculation data. This dataset enables a unique investigation of the available LTPP SMP data on causative factors in seasonal variations in FWD measurements and resulting impacts on field versus lab measurements of unbound materials.

Data from the following tables are recommended for this analysis:

- SMP_FREEZE_STATE, SMP_FROST_PENETRATION, SMP_FROST_PRESENCE – These tables contain interpreted data from previous LTPP analysis studies of the SMP subsurface temperature, electrical resistivity, and TDR measurements to provide states of freezing in the test sections included in the SMP.
- SMP_TDR_MANUAL_MOISTURE, SMP_TDR_MOISTURE_SUPPORT, SMP_TDR_AUTO_CALIBRATION_TLE, SMP_TDR_AUTO_MOISTURE, SMP_AUTO_MOISTURE_TLE – These tables provide a suite of previously interpreted raw data based on SMP Time Domain Reflectivity measurements that provide potential uninvestigated data resources that can potentially be used to help explain how field moisture contents in unbound pavement layers affect field measurements and their relationship to laboratory measurements.
- SMP_GRAV_MOIST – This table contains the baseline field/laboratory-measured volumetric moisture contents of the material immediately surrounding the TDR probes at the time of placement.
- SMP_WATERTAB_DEPTH_MAN – This table contains water tables depths measured at LTPP SMP test sections, which is a significant input into the MEPDG mechanistic models.
- SMP_LAYOUT_INFO – This table provides details on the locations and depths of placement of the SMP subsurface probes.

Dynamic Load Response

The LTPP Dynamic Load Response dataset is another specialty research-based dataset that has the potential to aid in the investigation of laboratory-to-field measurements from FWD backcalculation and laboratory resilient modulus measurements. LTPP DLR measurements consist of stress, strain, multi-depth LVDT based deflection measurements, and pressure cells imbedded in a pavement structure at known locations. The point of these measurements is to correlate field measurements taken when moving load from a test truck whose axle loads have been measured, moving at a known speed, or in some cases an FWD, with the baseline mechanistic structural response theory that the Pavement ME models are based upon. Because

the measurements were only performed on the Ohio Road project and the North Carolina SPS-2 project sites, acquisition of this data into the initial project database was not performed at this time. This data can always be accessed in the future as required by the initial data analysis.

HIGHLIGHTS

This chapter looked at the availability of LTPP data to support development of relationships between laboratory- and field-derived properties of unbound materials used in pavements. It was determined that a total of 1,045 LTPP test sections have data available to support the project objective, of which approximately 300 have laboratory-measured resilient modulus data for both granular base and subgrade on the same test section. However, the number of potentially useful test sections to use to develop the referenced relationships may be reduced if the time lag between laboratory and field tests and other factors are considered.

In addition to the available primary LTPP data—i.e., those data elements directly associated with determination of the relationships between elastic moduli estimated from field deflection measurements and laboratory resilient modulus measurements performed on material samples obtained in the field—supplementary LTPP data are also available to support the project objective. These supplementary data refer to those data that can potentially be used to classify, explain, or expand on the relationships discovered from the primary LTPP dataset.

CHAPTER 4. LTPP DATA ASSESSMENT

This chapter presents the findings from an exploratory data analysis of relevant data elements extracted from the LTPP database to evaluate the feasibility of using these data for developing valid relationships between laboratory- and field-derived properties of unbound materials. More specifically, the analyses focus on the assessment of the LTPP database to develop relationships between laboratory and backcalculated resilient modulus (M_r). The data characteristics explored included their completeness, quality, spatial and temporal coverage, ranges, correlations between experimental factors, and other relevant features.

The findings and conclusions from the exploratory data analyses are presented in the following four sections:

- Project LTPP test sections – Describes the main characteristics of the pavement section layers selected for analysis.
- Laboratory resilient modulus data – Provides the main features of the available laboratory M_r data in the LTPP database.
- Backcalculated layer moduli data – Describes main features of the available layer moduli data backcalculated from FWD testing results.
- Summary and conclusions – Summarizes the main findings and conclusions from the assessment of LTPP data for use in the project.

LTPP TEST SECTIONS

This section provides a general description of the LTPP test sections identified in the previous chapter for the comparison between the laboratory M_r and FWD-derived layer moduli data of unbound materials. The observational units for the analyses are defined in the section, and descriptive statistics of the selected LTPP test sections are then presented. The last part discusses the main aspects to consider in order to achieve similar conditions for the comparison between laboratory M_r and FWD-derived layer moduli data.

Observational Units

Each resilient modulus or layer modulus value in the LTPP database corresponds to an unbound layer within a specific pavement structure and over a specific time period. The following bullets items address data considerations related to the definition of observational units for the laboratory-to-field data comparison:

- Unbound layer – The pavement structure of each of the 1,045 LTPP test sections identified in the previous chapter is comprised of a number of unbound layers—subgrade (SS), granular subbase (GS), and/or granular base (GB) layers. The number of unbound layers per pavement structure ranged from one (i.e., the subgrade) to five, with two being the most frequent number of unbound layers.
- Test sample location and date – The number of resilient modulus or layer modulus values per unbound layer for each LTPP test section varied depending on the number of sample locations (i.e., locations at which the material was sampled for laboratory testing, or locations where the FWD tests were conducted), as well as on the number of measurements over time (i.e., FWD testing conducted at different points in time).

For instance, the number of sample locations for laboratory M_r testing ranged between 1 and 5, with two per section being the most frequent number.

- In-situ stress state – Since the M_r of unbound materials is stress-dependent, each time the pavement changes, the in-situ stress states within the unbound layer change. Therefore, each unbound layer was defined as a different observational unit each time the pavement structure changed.

Based on these considerations and for the sake of simplicity, the term "unbound layer" in this chapter refers to a specific unbound layer at a specific location within a given pavement structure over a specific time period. Based on this definition, the total number of unbound layers for the 1,045 LTPP test sections available for the comparison between laboratory M_r and field layer moduli is 3,572, or 2,051 layers if structural changes at each test section over time are not considered. However, not all of these unbound layers contain the required information.

Laboratory triaxial testing on the unbound layer material was generally performed at a single point in time, and not all of these unbound layers have laboratory test results. FWD testing, on the other hand, was conducted at different points in time, and layer moduli were backcalculated for each of the different unbound layers. This is reflected in Table 6, which shows the breakdown of LTPP test section observational units for both laboratory and field data.

Table 6. Break-down of test section observational units.

Number of	Laboratory M_r	Backcalculated Layer Modulus
Test Sections	1,045	1,045
Unbound Layers	1,591	2,047
Unbound Layers-Structure	1,602	3,164
Unbound Layers-Structure-Test Locations	2,645	6,234
Unbound Layers-Structure-Test Locations-Test Date	2,651	25,605

Most (97.3%) of the 1,602 project unbound layers with laboratory M_r data also have backcalculated data. However, the test locations and test dates for laboratory and field data do not necessarily coincide. A description of the 1,559 (of 1,602) test section unbound layers that present both laboratory and field data is provided next.

Description of Unbound Layers

Table 7 shows the number of unbound layers for each combination of layer type (i.e., SS, GS, and GB) and material type, which was divided into three groups: "Fine Soils" (layers with LTPP material code less than or equal to 200), "Coarse Soils" (material codes between 201 and 267), and "Sand/Crushed Stone" (material codes greater than 267). As shown in the table, most (91.3%) LTPP test sections contain SS layer information, while a smaller number have GS or GB layers with the required data. The proportions of fine and coarse soils in SS layers is balanced (close to 50-50), while the material types of the GS and GB layers are predominantly sand or crashed stone.

Table 7. Number of unbound layers by layer type and material type.

Layer Type	Fine Soil	Coarse Soil	Sand/Crushed Stone	Total
SS	454	500	0	954
GS	22	14	187	223
GB	0	0	382	382
Total	476	514	569	1,559

Most (64.2%) of unbound layers in question correspond to the LTPP General Pavement Studies (GPS) test sections, while the remaining ones (35.8%) correspond to LTPP Specific Pavement Studies (SPS). Table 8 shows the distribution of test section unbound layers by experiment type and layer type. The experiments with the greatest number of unbound layers (sorted by predominance) are GPS-1, GPS-3, GPS-2, SPS-2, and SPS-1.

Table 8. Number of inbound layers by layer type and experiment type.

Experiment Type	SS	GS	GB	Total	Total [%]
GPS-1 (AC on Granular Base)	163	34	96	293	18.78%
GPS-2 (AC on Bound Base)	103	39	2	144	9.23%
GPS-3 (Jointed Plain PCC)	108	20	38	166	10.64%
GPS-4 (Jointed Reinforced PCC)	54	8	27	89	5.71%
GPS-5 (Continuously Reinforced PCC)	73	14	9	96	6.15%
GPS-6A (AC Overlay of AC)	48	14	19	81	5.19%
GPS-6B (AC Overlay of AC)	12	4	4	20	1.28%
GPS-6S (AC Overlay of AC)	7	4	2	13	0.83%
GPS-7A (AC Overlay of PCC)	32	5	17	54	3.46%
GPS-7B (AC Overlay of PCC)	6	1	4	11	0.71%
GPS-7C (AC Overlay of PCC)	0	0	1	1	0.06%
GPS-9 (Unbonded PCC overlay of PCC)	21	2	10	33	2.12%
SPS-1 (New AC)	97	11	29	137	8.78%
SPS-2 (New PCC)	76	24	39	139	8.91%
SPS-5 (Rehabilitation of AC)	54	29	22	105	6.73%
SPS-6 (Rehabilitation of PCC)	52	2	18	72	4.62%
SPS-7 (Bonded PCCC Overlay of PCC)	7	3	2	12	0.77%
SPS-8 (AC and PCC)	37	8	42	87	5.58%
SPS-9N (AC – SuperPave)	4	1	1	6	0.38%
Total	954	223	382	1,559	100%

Table 9 shows the number of unbound layers by layer type and pavement group. These two factors affect the in-situ stress states during FWD testing. The pavement types were grouped into: Asphalt Concrete (AC), Portland Cement Concrete (PCC), and composite pavements (either AC over PCC or PCC over AC). Most of the available unbound layers are within the AC and PCC groups—the numbers are significantly lower for the composite group.

Table 9. Number of unbound layers by layer type and pavement type.

Layer Type	AC	PCC	AC over PCC	PC over AC	Total
SS	515	355	58	26	954
GS	140	75	6	2	223
GB	207	129	36	10	382
Total	862	559	100	38	1,559

Table 10 shows the number of unbound layers in the pavement structure by pavement group. As shown, the majority of the LTPP test sections under consideration have between 1 and 3 unbound layers. Similarly, Table 11 shows the total number of layers (i.e., bound and unbound) in the pavement structure as a function of the pavement group. As shown, most AC pavements have a total of 3 to 7 layers, while most PC pavements have between 3 and 5 layers.

Figure 1 shows the spatial coverage of SS unbound layers, based on the combined laboratory and field data. The locations on the map are color-coded according to material type. As shown, coarse subgrade soils are more widely distributed than fine subgrade soils, which have a greater presence in the mid- and eastern-region of US and Canada. While not shown, GS and GB unbound layers are also widely distributed throughout North America, with GB layers more densely present in the mid- and eastern-regions of the US.

Table 10. Number of unbound layers by pavement type.

Unbound Layers	AC	PC	AC over PC	PC over AC	Total
1	119	118	18	12	267
2	309	196	42	14	561
3	126	61	5	2	194
4	11	3	0	0	14
5	0	1	0	0	1
Total	565	379	65	28	1,037

Table 11. Number of unbound layers by total number of layers and pavement type.

Pavement Layers	AC	PC	AC over PC	PC over AC	Total
2	1	4	0	0	5
3	52	202	1	0	255
4	134	136	10	5	285
5	189	33	30	15	267
6	107	4	16	7	134
7	46	0	8	0	54
8	25	0	0	0	25
9	9	0	0	1	10
10	2	0	0	0	2
Total	565	379	65	28	1,037

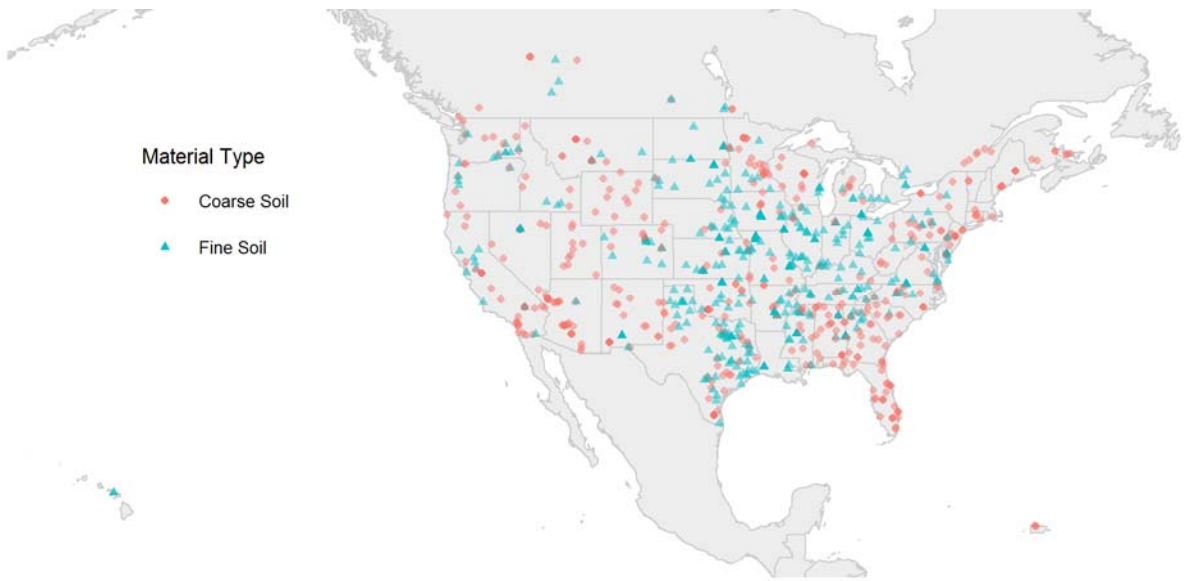

Figure 1. Location of unbound subgrade layers according to material type.

Data Considerations for Comparison between Laboratory and Backcalculated M_r

Laboratory M_r is derived from triaxial test results, while field layer modulus is backcalculated from the FWD test results. Differences between these two procedures may help explain, at least in part, the difference between the resulting laboratory- and field-derived values. Therefore, accounting for the conditions under which the unbound layer materials were tested is important to understanding what factors may affect the relationships between the two and to quantify their effect.

A direct comparison between laboratory- and field-derived data should be carried out under comparable conditions (e.g., similar date, location, and stress state), but that is not the case for the LTPP unbound material M_r and layer moduli data. Accordingly, the differences between the laboratory and field conditions are described next. In addition, possible experimental factor

considerations are addressed in order to better understand the scope and potential limitations of the LTPP dataset for performing the comparative analysis required by the project.

Major testing conditions to consider when setting up the comparative analysis between laboratory- and field-derived data include:

- Location – The locations at which material for laboratory testing was extracted and at which FWD testing was performed for a specific test section is expected to have an effect on the resulting data (e.g., measurements taken at the outer wheelpath may produce different value than those taken at the mid-lane for distressed pavement sections).
- Date – M_r and layer modulus values change over time as a result of the separate and combined effects of diurnal, seasonal, and annual moisture and temperature changes and traffic loadings. As such, the testing dates for the laboratory- and field-derived values should be as close to each other as possible to reduce the effect of changes in the material structural response over time.
- Stress state – The in-situ stress state of each pavement layer during FWD testing depends on a number of factors, such as the total number of layers and the material type and thickness for each layer, as well as climatic conditions. Once the field stress state is estimated for a specific backcalculated layer modulus value, the corresponding laboratory M_r can be either selected as the one measured under a comparable triaxial stress state (combination of confining stress and deviatory stress) or estimated through a constitutive model (e.g., K1-K3 model) calibrated to the triaxial test results for the material sample.
- Other testing conditions, such as the moisture content of the laboratory sample and the in-situ moisture content of the unbound layer during the FWD testing.

LABORATORY RESILIENT MODULUS DATA

The laboratory M_r of unbound materials in the LTPP database were determined in accordance with LTPP Testing Protocol P46: "Resilient Modulus of Unbound Granular Base/Subbase Materials and Subgrade Soils" (LTPP Protocol, 1996). Figure 2 (Elkins et al., 2003) illustrates the relationship between some of the LTPP tables containing data related to the laboratory M_r measurements. The unbound material samples tested consisted of either remolded or thin-walled field specimens, and the M_r was measured at different stress states corresponding to various combinations of confining pressure (CON_PRESSURE field) and axial load (NOM_MAX_AXIAL_STRESS field) levels. The summary statistics to characterize the laboratory-derived M_r data for the unbound layers in the LTPP program are detailed next.

Description of Unbound Layers with Laboratory M_r Data

Table 12 shows the number of unbound pavement layers that have laboratory M_r values in the LTPP database as a function of layer type and material type—the total number of unbound layers with laboratory M_r values is 2,645. As shown, the distribution is similar to the one observed in Table 7 (the number of unbound layers in Table 7 is smaller because it does not account for multiple locations from which the laboratory specimens were sampled). In addition, Table 13 shows the distribution of unbound layers by layer type and sample type. Based on the

information presented in this table, 67.3% of the SS layers were tested using remolded specimens, and all GS and GB layers were tested using remolded specimens.

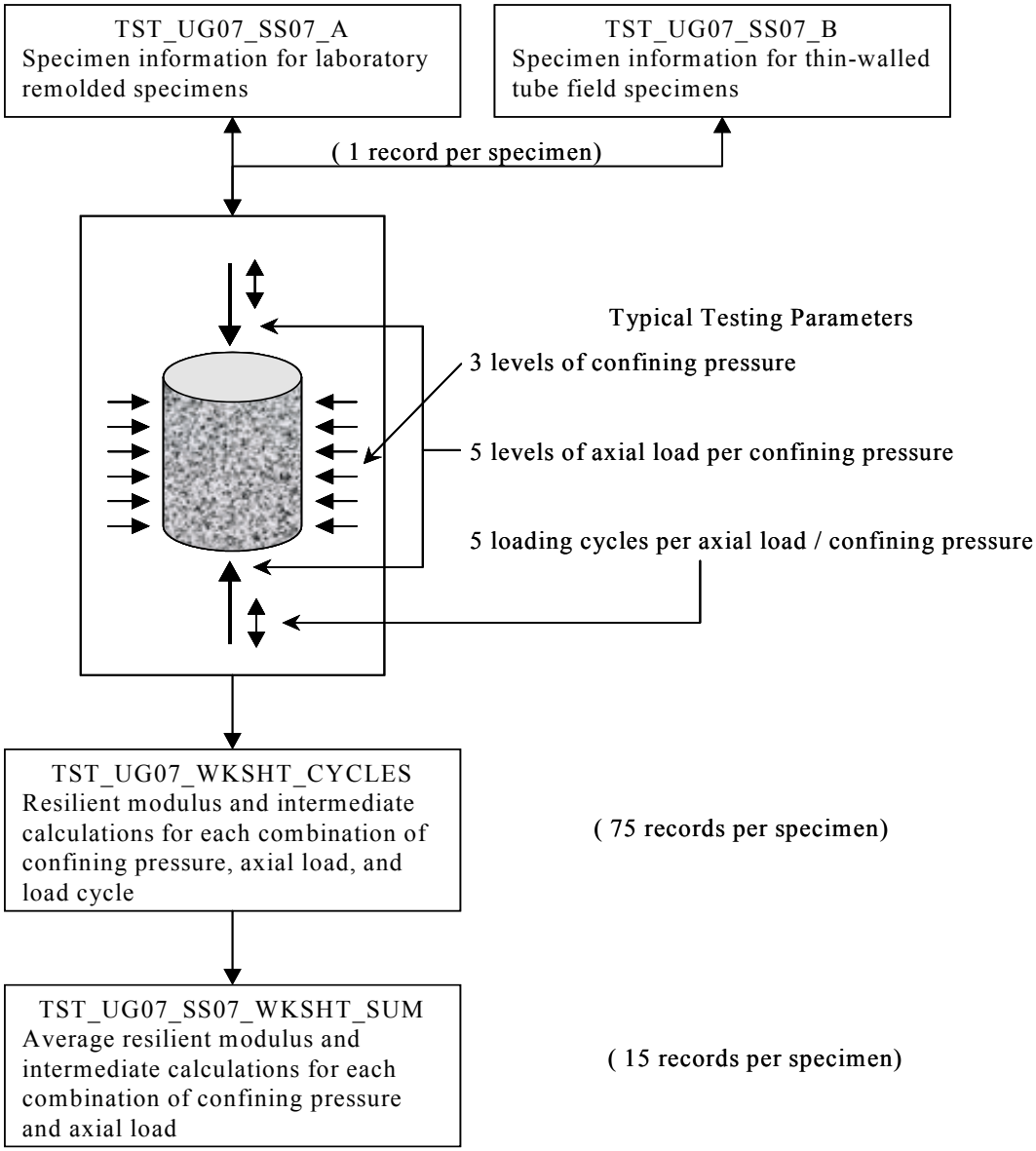

Figure 2. Relationship between LTPP Laboratory M_r data tables (Elkins et al., 2003)

Table 12. Number of unbound layers with M_r values by layer type and material type.

Layer Type	Fine Soil	Coarse Soil	Sand/Crushed Stone	Total
SS	797	881	0	1,678
GS	28	22	297	347
GB	0	0	620	620
Total	825	903	917	2,645

Table 13. Number of unbound layers with M_r values by layer type and specimen type.

Layer Type	remolded	thin-wall	split-spoon	Total
SS	1,130	547	1	1,678
GS	347	0	0	347
GB	620	0	0	620
Total	2,097	547	1	2,645

Table 14 shows the distribution of unbound layers containing laboratory M_r values per layer type and test sample location, which indicates whether the material sample was extracted from the "approach end" area (i.e., just before the beginning of the test section), within the test section limits, or the "leave end" area (i.e., just after the end of the test section). As shown, the large majority of samples (97%) were extracted outside of the section limits. As reported in Elkins et al. (2003), the number of samples within test section limits was minimized to avoid alteration of the performance characteristics of the pavement section.

Table 14. Number of unbound layers with M_r values by layer type and sample location.

Layer Type	Approach End	Within Section	Leave End	Total
SS	752	64	862	1,678
GS	155	4	188	347
GB	285	11	324	620
Total	1,192	79	1,374	2,645

Figure 3 shows comparison plots between the in-situ moisture content, representing the moisture content of the unbound layer at the time the material sample was extracted, and the after testing moisture content, representing the moisture of the material sample just after the triaxial testing was completed, by sample type. Moisture content affects the M_r of the unbound material, and therefore differences in moisture content between laboratory and field conditions contribute to the differences in the measured values. The overall set of differences between in-situ and after testing moisture contents have a median of 0.63% and a standard deviation of 3.26%, and 90% of the observed differences ranged between -4.60% and 5.58%. The median difference between in-situ and after testing moisture content for the remolded specimens was slightly larger than for the thin-wall specimens (0.75% and 0.12%, respectively).

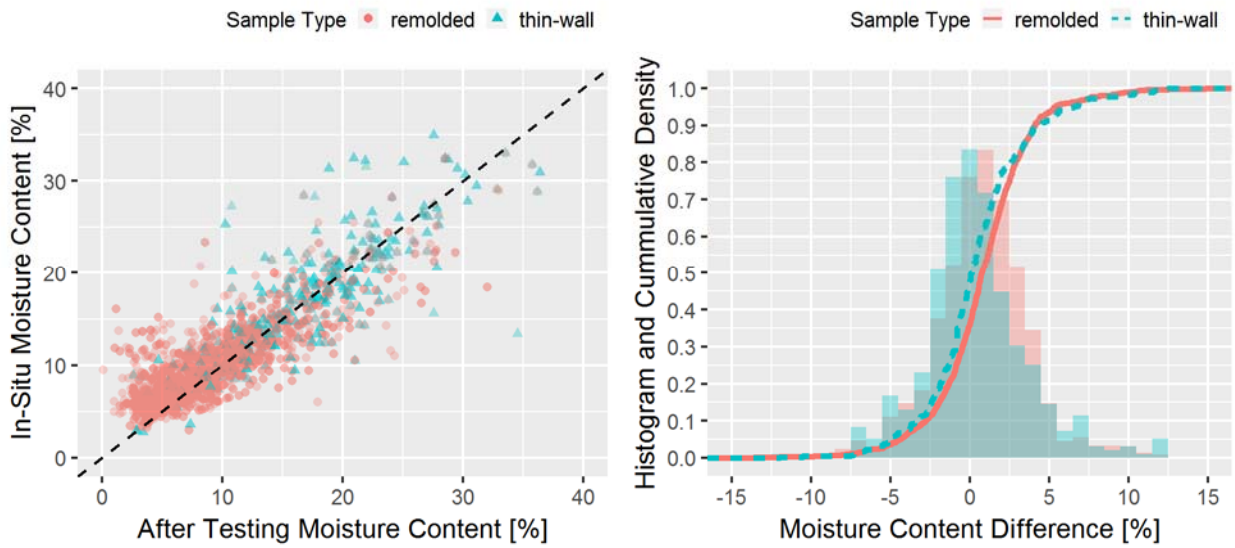

Figure 3. Comparison between in-situ and after laboratory testing moisture by sample type.

Description of Laboratory-Derived M_r Data

Table 15 shows summary statistics for the unbound layer laboratory-measured M_r data. These statistics were computed using the available M_r values (i.e. including results from all 15 combinations of confining pressure and axial stress levels for each triaxial test). The coefficients of variation (COV) for the three layers types ranged between 43% and 51%, which indicates that the available dataset covers a wide range of M_r values. Since these data were measured at different stress states, the statistics in Table 15 should not be used for direct comparison between layer types, but are intended to provide information regarding the number of observations, expected values, and range of the available data.

Table 15. Summary statistics for the measured M_r values.

Layer Type	Nr Obs	Mean [psi]	Std Dev. [psi]	Median [psi]	Minimum [psi]	Maximum [psi]
SS	25,008	10,778.4	4,630.1	10,152.7	870.2	52,793.8
GS	5,185	20,728.5	10,565.5	18,419.8	2,030.5	65,702.2
GB	9,269	24,038.0	11,396.1	22,480.9	1,305.3	74,549.5

The box plot in Figure 4 shows the measured M_r values for the different combinations of confining pressure and axial stress levels. As expected, the M_r of SS materials tended to increase with the confining pressure level and to slightly decrease with the axial stress level. Similarly, the M_r of the GS and GB materials tended to increase with both the confining pressure and axial stress levels, and these effects were larger than for the SS materials. The effects of the triaxial test stress states on the M_r constitutive model coefficients are addressed next.

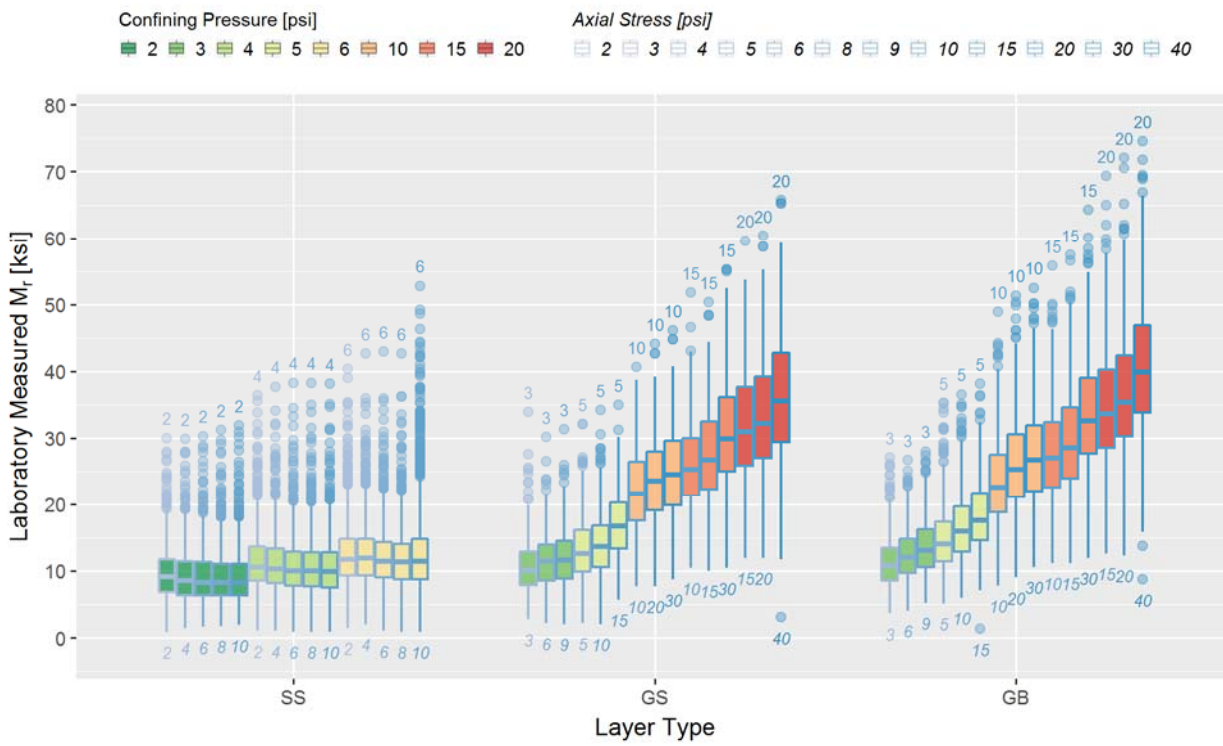

Figure 4. Laboratory-measured M_r data by confining pressure and axial stress level.

Description of Estimated M_r Constitutive Models

The constitutive model regressions parameters for each of the 2,645 unbound layers were estimated using the triaxial testing results. Two constitutive models were considered for analysis: the universal constitutive equation (Equation 9) and the 2002 Pavement Design Guide constitutive equation (Equation 10).

$$Mr = k_1 P_a \left(\frac{\theta}{P_a}\right)^{k_2} \left(\frac{\sigma_d}{P_a}\right)^{k_3} \tag{9}$$

$$Mr = k_1 P_a \left(\frac{\theta}{P_a}\right)^{k_2} \left(\frac{\zeta_{\text{oct}}}{P_a} + 1\right)^{k_3} \tag{10}$$

Where:

M_r = laboratory resilient modulus
σ_1 = major principal stress = NOM_MAX_AXIAL_STRESS + CON_PRESSURE
σ_2 = intermediate principal stress = CON_PRESSURE
σ_3 = minor principal stress = σ_2
θ = bulk stress = $\sigma_1 + \sigma_2 + \sigma_3$
σ_d = deviatory stress = $\sigma_1 - \sigma_3$
ζ_{oct} = octahedral shear stress = $\frac{\sqrt{2}}{3}\sigma_d$
P_a = atmospheric pressure = 101 kPa (14.7 psi)
k_1, k_2, k_3 = regression parameters

Figure 5 shows the distribution (on the left) and cumulative distribution (on the right) of the coefficient of determination (R^2) values of the models estimated for each unbound layer. At least 95% of the estimated universal (in red) and 2002 Pavement Design Guide (in green) constitutive models presented an R^2 coefficient greater than 0.7, which indicates satisfactory performance of the model specifications. Low R^2 coefficient may be indicative of testing anomalies, such as sensor measurement errors. Therefore, it is recommended that testing results with a model R^2 coefficient lower than 0.50 are flagged for further investigation and potentially removed from the analysis dataset.

Both models have overlapping R^2 distributions showing a high similarity in the results, which is due to the fact that the triaxial test ζ_{oct} is proportional to σ_d and therefore, the term involving k_3 in Equation 10 can be expressed as a linear transformation of the term involving k_3 in Equation 9. Given the similarity between the two model specifications, the 2002 Pavement Design Guide constitutive model was selected for use in the analysis presented next.

The box plot in Figure 6 shows descriptive statistics for the estimated 2002 Pavement Design Guide constitutive model regression parameters for those unbound layers with laboratory M_r data (for illustration purposes the k_1 values were scaled by a factor of 1/1000). As shown, the estimated k_1 values were similar for the three layer types, while k_2 and k_3 differed according to layer types—e.g., the k_2 and k_3 values were larger for GB layers. The effect of bulk stress was mostly positive for all GS and GB layer types, while the effect of deviator stress was mostly negative for all layer types. In addition, SS soils showed lower stress-stiffening k_2 values and larger stress-softening k_3 values than GS and GB materials, as would be expected.

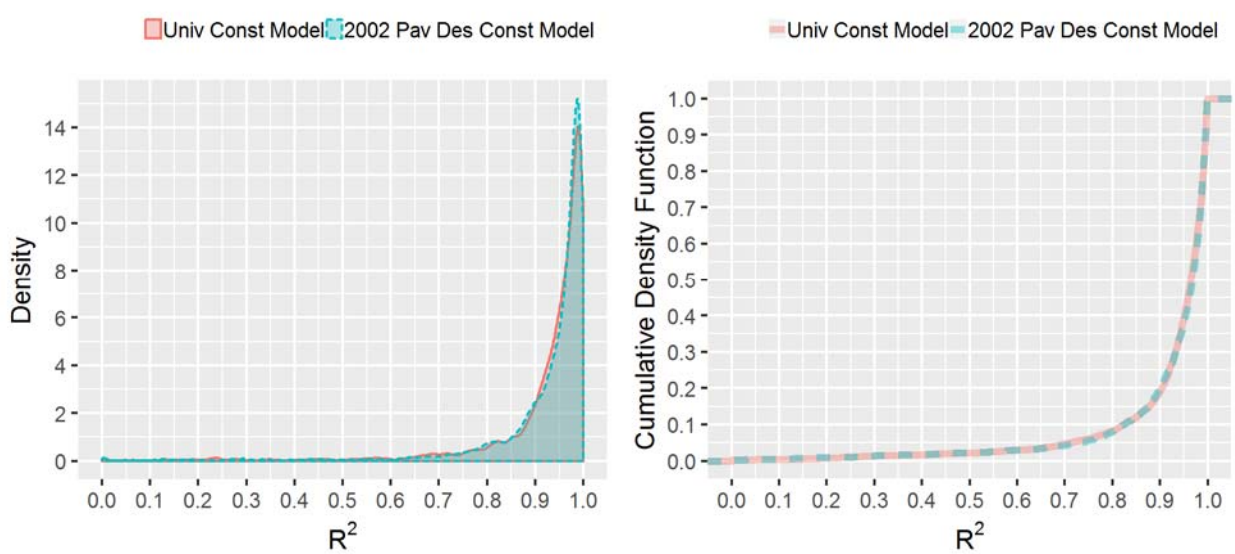

Figure 5. Distribution (left) and cumulative distribution (right) of R^2 for estimated Universal and 2002 Pavement Design Guide models.

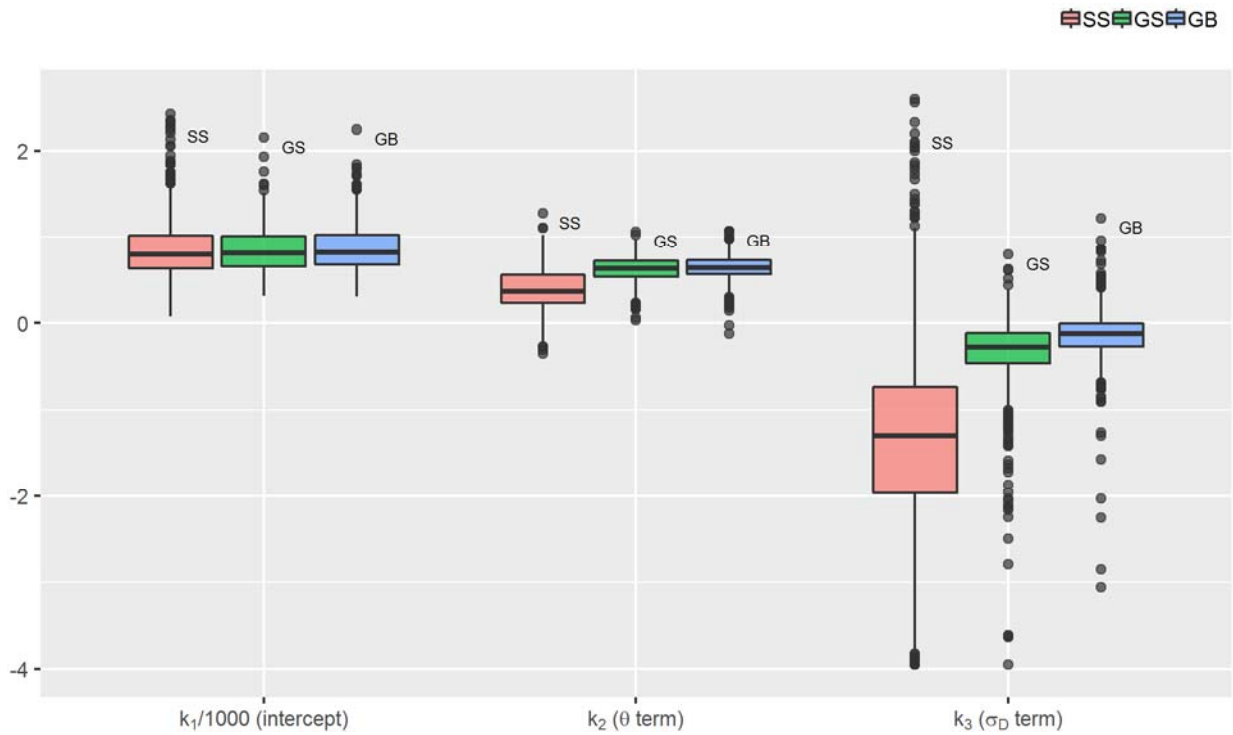

Figure 6. Estimated regression parameters of 2002 Pavement Design Guide constitutive model.

Table 16 shows summary statistics by layer type for the M_r values estimated using the 2002 Pavement Design Guide constitutive model[1]. In order to use a normalized reference for the comparison, these values were computed using a unique stress state across laboratory tests for the SS layers and a different unique stress state for the GS and GB layers. The stress state used to compute the M_r values were the ones corresponding to testing sequence number 8, as determined in LTPP Protocol P46 (1996)—i.e. confining stress of 4 psi and axial stress of 6 psi for SS layers, and confining stress of 10 psi and axial stress of 20 psi for GS and GB layers.

As shown in Table 16 and as expected, the closer the unbound layer is to the pavement surface, the higher the M_r value. This relationship may not necessarily hold for the field stress conditions that occur during FWD testing. In addition, it is observed that some of the summary statistics, such as the M_r standard deviation, were affected by outliers. The effect of these outliers can be reduced by filtering out sections with low model R^2.

Table 16. Summary statistics of estimated M_r values from 2002 Pavement Design Guide constitutive model.

Layer Type	Nr Obs	Mean [psi]	Std Dev. [psi]	Median [psi]	Minimum [psi]	Maximum [psi]
SS	1,682	10,753.6	4,173.5	10,101.5	960.6	37,342.3
GS	348	22,087.2	7,585.2	21,945.8	842.7	45,555.2
GB	621	25,577.0	6,945.5	25,135.6	6,477.4	49,946.2

[1] M_r value computed for SS layer of section 48-5301 was excessively large (1,469,624.8 psi) relative to other values; therefore, it was excluded from the computation of the summary statistics in Table 16.

The map in Figure 7 shows the spatial coverage of GB unbound layers with laboratory data, color-coded according to the M_r values (in the log scale) estimated using the 2002 Pavement Design Guide constitutive model. Estimates with R^2 lower than 0.8 were not included in these maps. As shown, the map suggests that there is no strong spatial clustering of M_r values—i.e., low and high M_r values were observed throughout the different geographical regions included in the data. Similarly, there was no strong spatial clustering of the distribution of SS and GS layers.

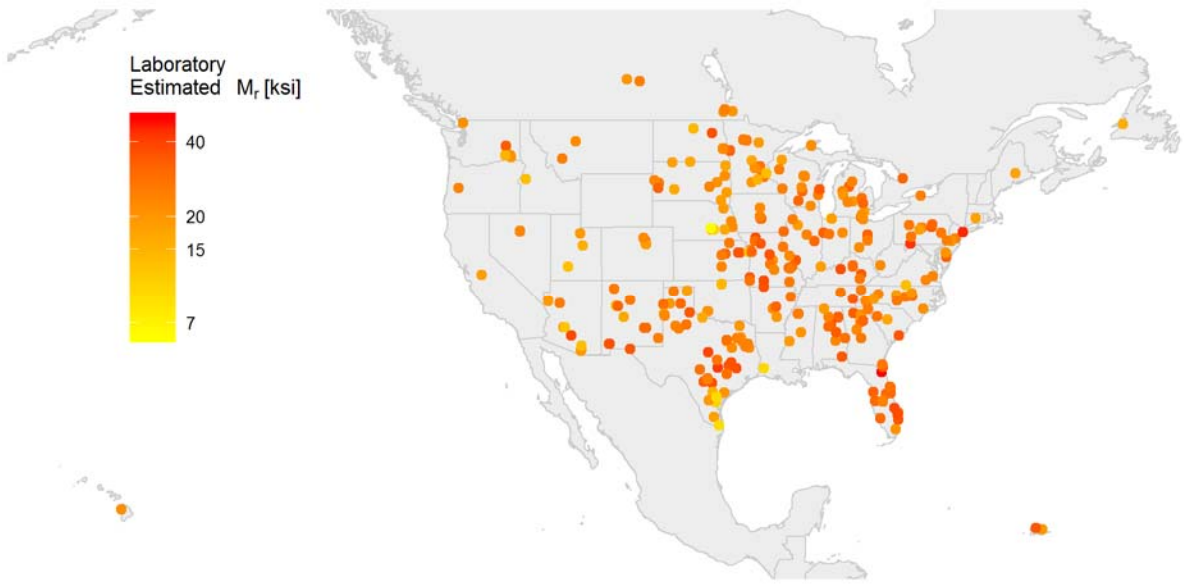

Figure 7. Spatial distribution of estimated laboratory M_r values for unbound base layers.

BACKCALCULATED LAYER MODULI DATA

The backcalculated layer moduli data in the LTPP database were derived from the results of FWD testing conducted at different points in time in accordance with the "LTPP Manual for Falling Weight Deflectometer Measurements" (Schmalzer, 2006). The layer moduli were computed using the EverCalc and Modcomp 6.0 programs. EverCalc was used as the primary program for all LTPP data, whereas Modcomp 6.0 was used for sections that did not yield acceptable results with EverCalc (Elkins et al., 2003). Detailed information regarding backcalculated layer moduli data available in the LTPP database can be found in Elkins et al. (2003).

FWD testing at each project site was conducted at different locations within a test section. As an example, Figure 8 to Figure 10 present the test plans (Schmalzer, 2006) for GPS 1 (test plan 1), GPS 3 (test plan 2), and GPS 5 (test plan 3) test sections respectively, which show the specific locations where FWD testing was performed. The test location codes included in the 1,045 test sections under consideration in this study were F1, F3, F0, J1, and C1. Accordingly, these data include measurements taken at test pit (TP) areas (located outside of the test section limits) and within test section limits at either the mid-lane (ML) or outer wheel-path (OWP) on AC pavements while only within test section limits at the ML on concrete pavements.

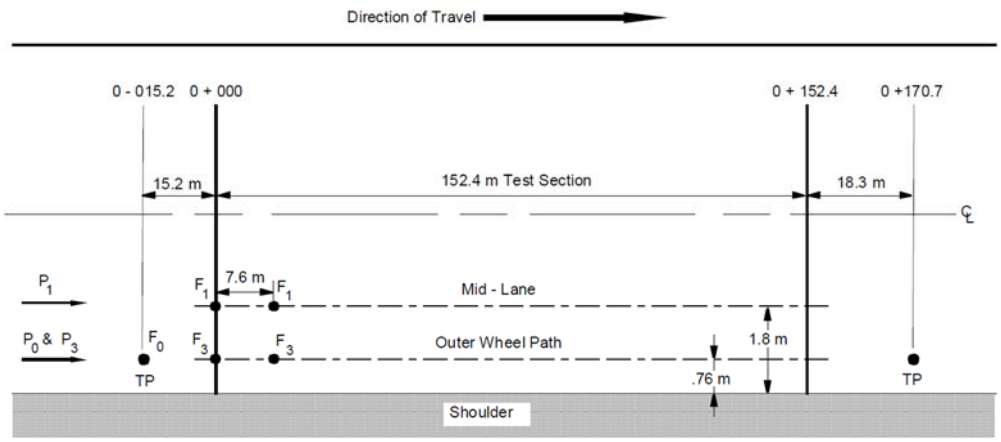

Figure 8. Diagram of FWD Test Plan 1.

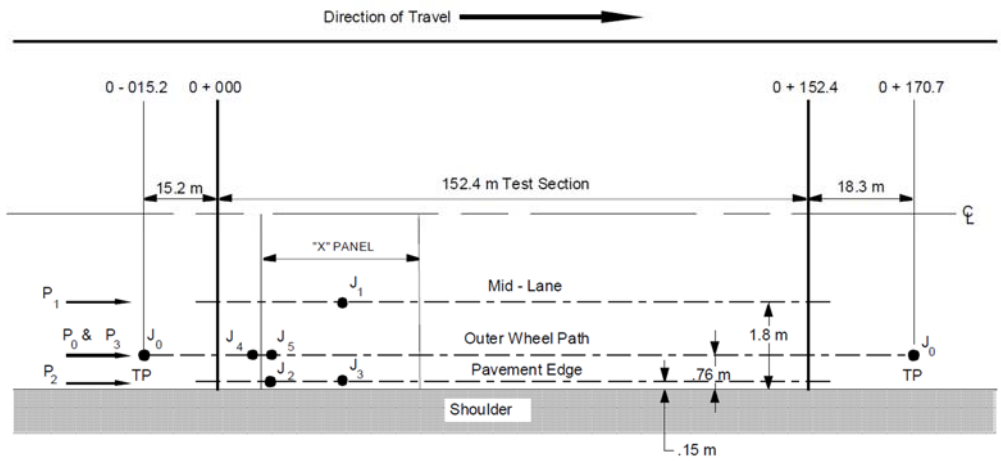

Figure 9. Diagram of FWD Test Plan 2.

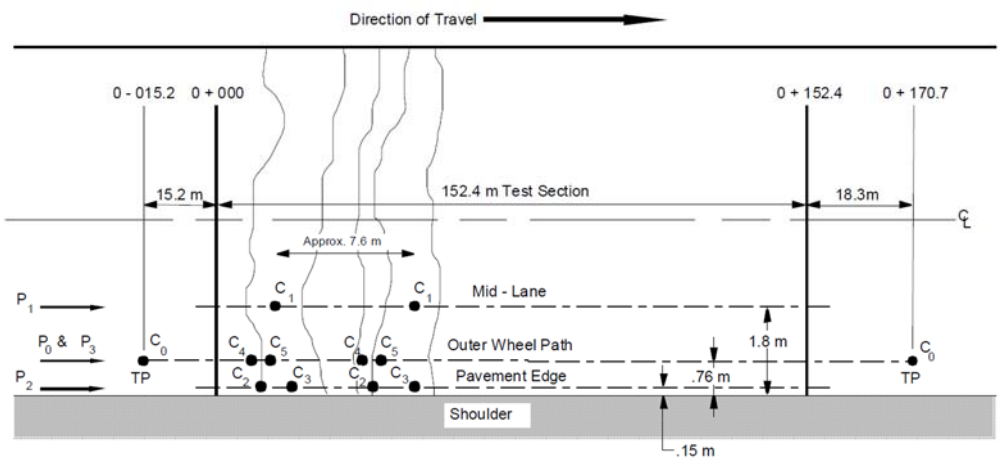

Figure 10. Diagram of FWD Test Plan 3.

Description of Backcalculated Layer Moduli Data

Descriptive statistics of the backcalculated layer moduli data are presented in this section. These statistics were computed using the 1,559 unbound layers, for which both laboratory M_r and backcalculated layer moduli data were available. Furthermore, the results presented in this section are the ones obtained from the initial FWD tests performed on the test section in question.

Table 17 shows the distribution of FWD tests according to location and layer type. As opposed to the test location distribution for the laboratory M_r data, most (82.5%) FWD tests were performed within the test section limits, and most (62.2%) of those tests were conducted at the ML.

Table 17. Distribution of FWD tests according to location and layer type.

Layer Type	Within Section		Test Pit	Total
	ML	OWP	OWP	
SS	961	571	316	1,848
GS	225	145	100	470
GB	387	241	122	750
Total	1,573	957	538	3,068

Table 18 shows the number of backcalculation (BC) layers used to model the different unbound pavement layers in the test section. As shown, almost all GS and GB layers were treated as one layer, whereas most SS layers (74.8%) were divided into 2 BC layers. Consequently, the backcalculated layer moduli for the SS pavement layers are referenced as corresponding to the top ("SS_top") or bottom ("SS_bottom") BC layer.

Table 18. Number of BC layers used to model the different unbound pavement layers.

Layer Type	1 BC Layers	2 BC Layers	Total
SS	466	1,382	1,848
GS	470	0	470
GB	748	2	750
Total	1,684	1,384	3,068

Table 19 shows summary statistics of the backcalculated layer moduli for the unbound layers available for the comparative analysis. The individual backcalculated layer moduli used to produce this summary table were taken as the median value for the four FWD drop heights results. A shown in this table, the mean layer moduli for the GS and GB layers are greater than those for the SS layers, but the median values show lower differences across layer types.

The median values tended to be lower than the corresponding means, reflecting the skewness of backcalculated layer moduli distributions as well as the effects of the data outliers in the data. In addition, the same minimum backcalculated layer moduli values were observed for

three layer types. These minimum values may have been set in the backcalculation software during the calculation process to prevent unreasonable values.

Table 19. Summary statistics for the backcalculated layer moduli data.

Layer Type	Nr Obs	Mean [psi]	Std Dev. [psi]	Median [psi]	Minimum [psi]	Maximum [psi]
SS_bottom	1,848	34,154.5	18,014.4	30,025.0	5,300.0	145,900.0
SS_top	1,382	33,133.8	25,829.8	25,600.0	5,100.0	146,600.0
GS	470	44,020.2	43,552.1	29,525.0	5,100.0	332,300.0
GB	750	41,001.3	55,505.8	28,100.0	5,100.0	1,080,500.0

The box plot in Figure 11 summarizes the backcalculated layer moduli summary statistics according to BC layer type and FWD test location, along with the data flagged as outlier (black dots). 4.2% of the backcalculated layer moduli data were flagged as mild outliers (i.e., data lying between 1.5 and 3 times the interquartile range (IQR) above the 75th percentile or below the 25th percentile), while 1.2% were flagged as extreme outliers (i.e., data lying more than 3 times the IQR above the 75th percentile or below the 25th percentile). As opposed to the relationship observed for the laboratory data, the SS layers tended to have similar (or slightly higher) median layer moduli than for the GS and GB layers. This is explained by the effect of depth in the stress state during the FWD test. GS materials would be expected to be less stiff than GB, yet their backcalculated modulus is higher because they are at a lower depth. The same occurs for SS materials as compared to GS and GB. The difference observed between the GS and GB layer moduli were not significant in practical terms. In addition, the median backcalculated layer modulus at the ML tended to be greater than those at the OWP for GS and GB layers, while these differences tended to be smaller for SS layers. The difference in median backcalculated layer modulus also tended to be smaller when comparing results from FWD testing conducted on the OWP within test section limits and outside test section limits (test pit).

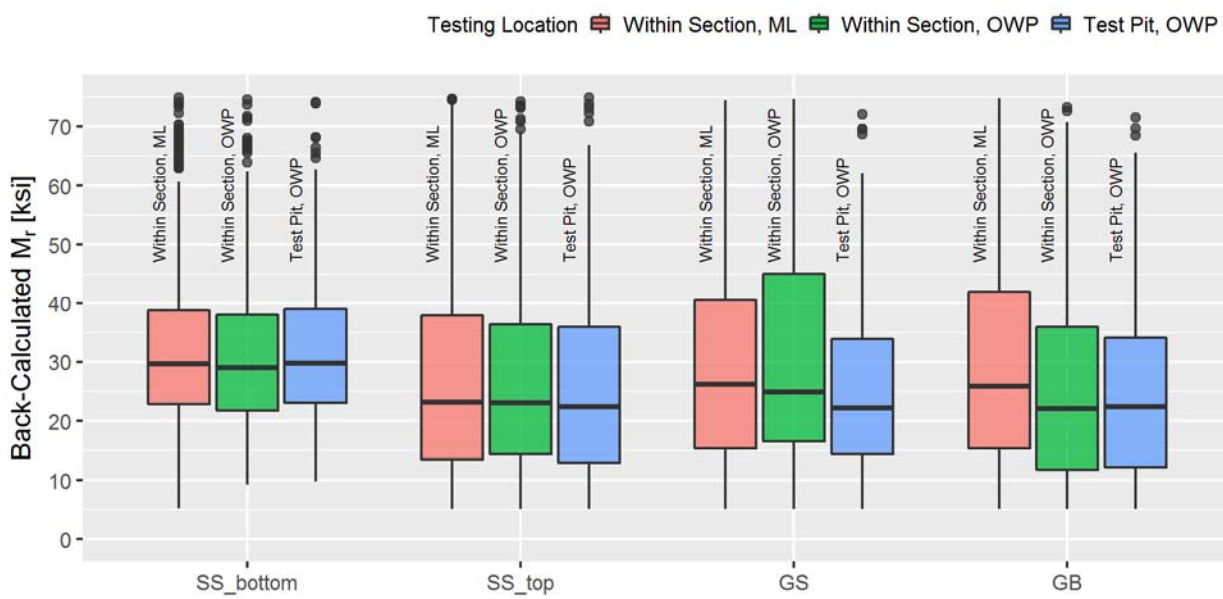

Figure 11. Boxplot of backcalculated layer moduli according to layer type and test location.

A paired t-test for each layer type was conducted to assess the difference in backcalculated layer modulus between FWD testing conducted within and outside test section limits. The p-values from these tests are reported in the last column of Table 20, along with summary statistics of this comparison. (This comparative analysis included only test sections that presented both backcalculated layer moduli on the OWP within test section limits and outside test section limits.) In addition, the scatterplots in Figure 12 allow visualization of the relationship between these two modulus values. Based on the resulting p-values, there is not enough evidence to conclude that the backcalculated layer modulus from within section limits is different than the modulus from outside section limits. From an engineering perspective, although some of the paired differences were large, the median of the absolute differences for all layers ranged between 2.5 ksi and 6.8 ksi, which is not significant considering the different uncontrolled factors that may affect the repeatability of the test.

Table 20. Summary statistics of paired comparison between backcalculated layer modulus from within and outside section limits by layer type.

Layer Type	Nr Obs	Median Abs Diff [ksi]	Mean Diff [ksi]	Min Diff [ksi]	Max Diff [ksi]	Paired t-test p-value
SS_bottom	288	2.475	0.170	-24.150	25.500	0.654
SS_top	254	4.850	-1.616	-79.800	41.850	0.075
GS	84	6.750	-1.032	-120.550	82.100	0.719
GB	112	5.975	0.560	-47.100	87.050	0.754

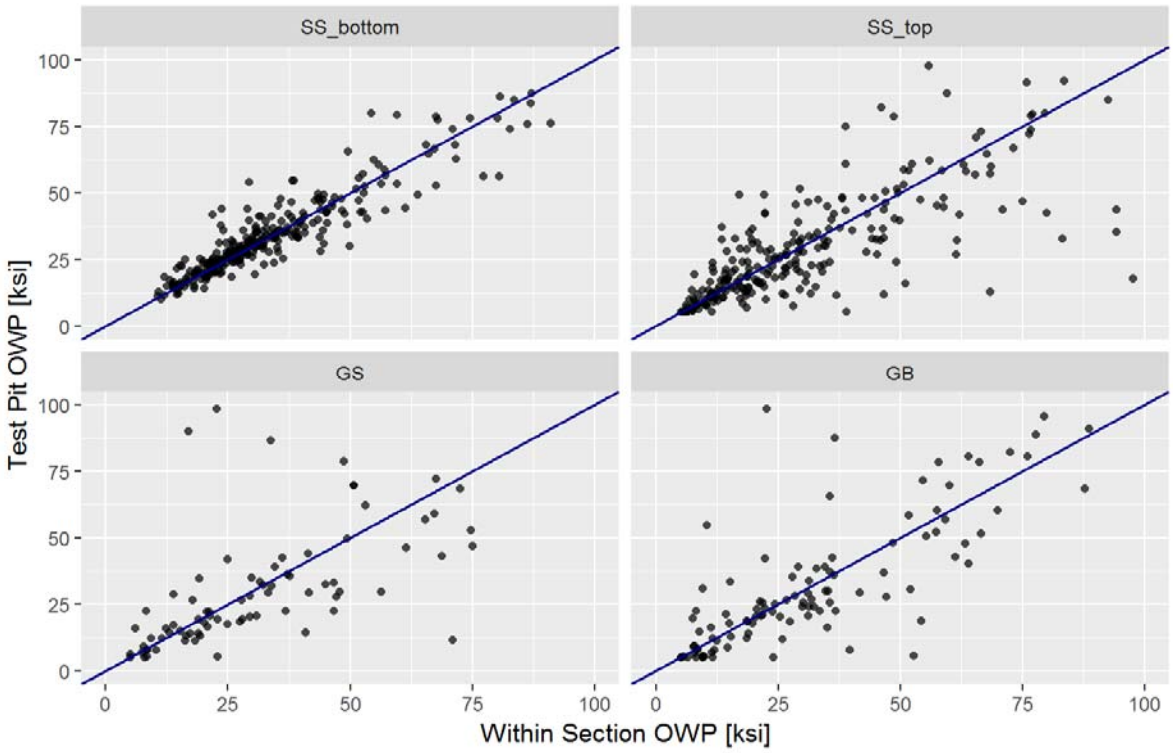

Figure 12. Paired comparison between backcalculated layer modulus from within and outside section limits by layer type.

The maps in Figure 13 and Figure 14 show the spatial coverage of unbound layers with backcalculated data, color-coded according to the backcalculated layer modulus (in the log scale) for the bottom and top BC layer types. As shown in the maps, the largest differences in backcalculated layer moduli between bottom and top SS layers occurred in the central region.

HIGHLIGHTS

An exploratory analysis of LTPP data was conducted to evaluate the feasibility of using these data for developing valid relationships between laboratory M_r and backcalculated layer moduli. This analysis provided information on the quantity, quality, and range of the data to understand the scope and limitations of using these data for the purposes of the study. The variables included in this analysis were variables expected to influence either the laboratory M_r or backcalculated layer moduli data and included variables such as laboratory testing stress state, moisture content of the material sample, and test location.

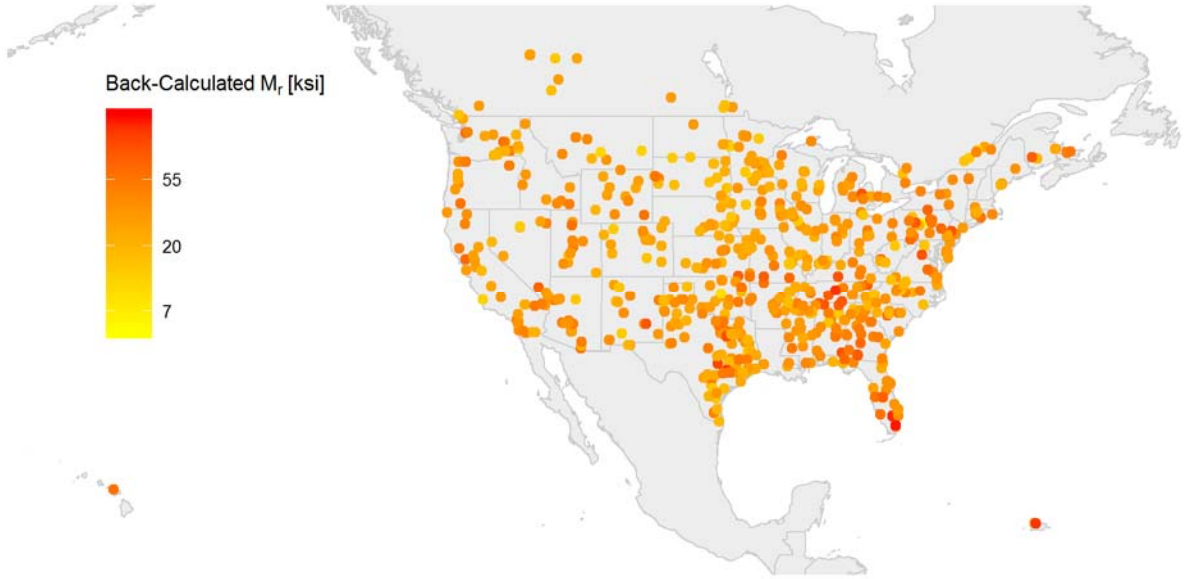

Figure 13. Spatial distribution of backcalculated layer moduli for bottom subgrade layers.

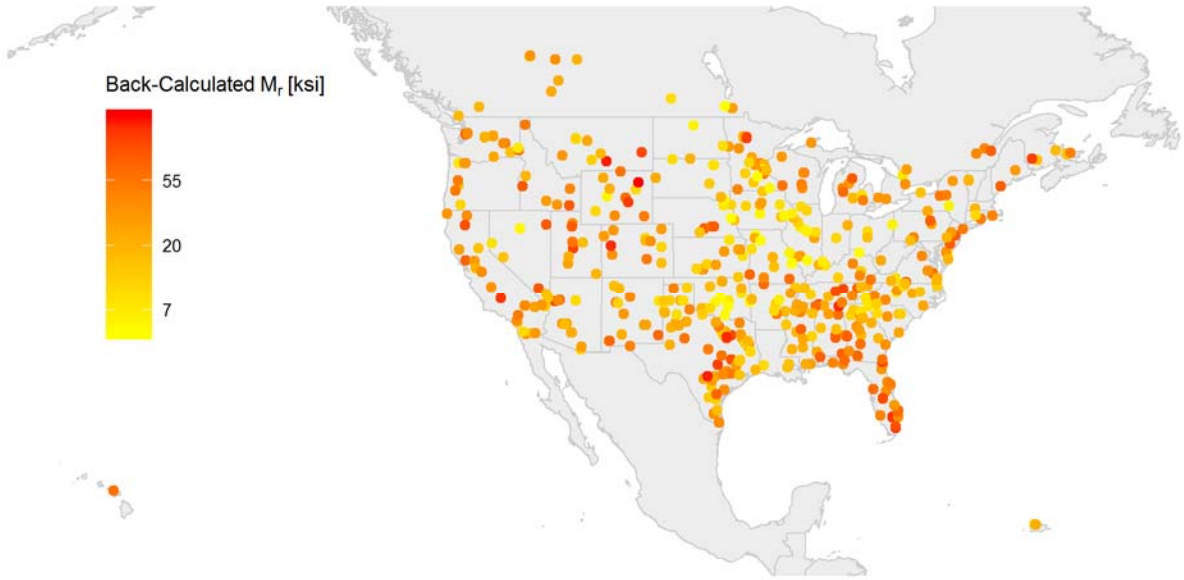

Figure 14. Spatial distribution of backcalculated layer moduli for top subgrade layers.

The main findings and conclusions from this exploratory data analysis are the following:

- A total of 1,559 test section unbound layers with both laboratory and field data were identified in the LTPP database to be potentially used for the development of relationships between laboratory- and field-derived M_r values. The M_r and layer moduli data cover a wide range of values. They are spread out geographically,

covering a wide range of pavement structures and environmental conditions. The number of observations required for developing a relationship between laboratory- and field-derived M_r as well as the explanatory variables considered depend on the researcher's proposed analysis. However, based on the general rule of thumb of 10 to 20 observations per covariate to expect significant size effects with reasonable statistical power on a multivariate regression analysis (Harrel 2001), the total number of test section unbound layers available in the LTPP database is adequate for the development of relationships between laboratory- and field-derived M_r values.

- The locations at and dates when samples were extracted for laboratory testing or FWD testing was conducted do not necessarily match. For example, most laboratory samples were extracted from the test pits outside the LTPP test sections, whereas most FWD testing data was conducted within the test section limits. Sub-sampling data to minimize such differences would significantly reduce the number of observations for analysis. However, a statistical comparison between the backcalculated layer moduli within and outside test section limits showed that the differences were generally not significant for the purpose of obtaining a unique representative value for the section.
- The relationship between laboratory M_r values across layer types was as expected (i.e. M_r values tended to decrease with the layer depth). Also, a large proportion of the estimated constitutive models from the triaxial test results showed strong fits as measured by their coefficient of determination. Low coefficient of determination values may reflect anomalies in the triaxial testing—such as sensor measurement errors or samples breaking apart during testing—and therefore should be used as a criterion to exclude data (e.g. testing results with model R^2 lower than 0.70) for the comparative analyses.
- 90% of the observed differences between in-situ and after testing moisture content for the laboratory M_r data ranged between -4.60% and 5.58%, with a median difference of 0.63% (differences are expressed as percentage points). Differences between in-situ and after testing moisture content are possible to occur; therefore, this variable should be accounted for when developing the relationship between laboratory- and field-derived M_r values in order to assess its effect. If, instead, the laboratory- and field-derived M_r values were analyzed through a direct comparison (i.e., not incorporating the effect of the difference in moisture content between in-situ and after testing), samples with a large difference in moisture content should be excluded from the analysis. The determination of a filtering threshold difference in moisture content should be based on its effect on the M_r value, which should be quantified as part of the development of relationships between laboratory- and field-derived properties.
- The relationship between backcalculated layer moduli values across pavement layer types was different than the one observed for laboratory M_r values (i.e. the difference in backcalculated layer moduli values between GB and GS layers and SS layers did not tend to be as large as the ones observed for the laboratory M_r values) due to, in part, the field stress state occurring during FWD testing. Other contributing reasons may include miscalculations caused by inaccuracies of backcalculation software.

- 4.2% of the backcalculated layer moduli data were flagged as mild outliers while 1.2% were flagged as extreme outliers. Extreme outliers in backcalculated data may be indicative of anomalies in FWD testing or data processing and therefore should be further investigated and potentially excluded from the analysis dataset.
- It is recommended that values flagged by the different checks and criteria indicated earlier in the chapter (e.g. backcalculated layer moduli significantly higher than others) be subject to further investigation, as opposed to directly discarding them. If all the mild outliers identified for the backcalculated layer moduli, laboratory M_r values, and flagged data from the triaxial testing results with model R^2 lower than 0.70 are removed from the dataset of 1,559 test section unbound layers, the total number of test section unbound layers would be reduced to 1,494, which is large enough for the development of relationships between laboratory- and field-derived M_r values.

Based on the quantity, quality, and range analysis results as well as on the experimental factors covered, the research team has concluded that the LTPP data are adequate for developing relationships between laboratory- and field-derived properties of unbound materials used in pavements. However, improvements can be made by performing additional filtering to identify the best possible dataset for use in the development of the relationships. This additional filtering will allow for a reduction in the impact of factors that are expected to explain the differences in laboratory M_r and field-derived layer moduli (e.g., large differences in moisture level) and to filter out anomalies in the measured data. The recommended criteria for identifying the best possible dataset have been included in a different part of this chapter. A conservative estimate of the resulting number of test section unbound layers after applying all suggested filtering of flagged data would result in a reduction of approximately 4.2% (from 1,559 to 1,494 test section unbound layers for potential use in the development of relationships between laboratory- and field-derived M_r values).

CHAPTER 5. RESEARCH PLAN

METHODOLOGY

Problem Statement

There is one simple reason why layer resilient moduli backcalculated from FWD tests do not agree with laboratory measured values: the homogeneous linearly elastic theory underlying FWD backcalculation assumes that there is a single linear elastic modulus value for the layer when in fact there is a near infinite variety of stress-dependent resilient modulus values for the material, a fact that is explicitly acknowledged in the laboratory resilient modulus (M_r) testing protocols. The resilient modulus value for an unbound material will be a function of: (1) stress state, (2) moisture content, and (3) density. Of these factors, stress state varies the most through the depth and across the horizontal extent of the pavement layer, moisture content varies much less so, and density varies the least. The influences of moisture content and density are most significant under extreme conditions, such as moisture during spring thaw or density when construction fails to meet compaction specifications. The influence of stress state is significant under all conditions.

Past research into the stress dependency issue attempted to identify locations within the granular base layer and subgrade where the stress states were "representative" of the entire layer. These "representative" stress states were then used to evaluate the stress-dependent laboratory M_r results for comparison against FWD backcalculated layer modulus values and for design. These attempts have largely been unsuccessful because the "representative" locations vary as functions of the pavement structure, loading configuration, and the stress-dependent properties of the unbound material.

Instead of "representative" values of stress states, what is needed is a weighted average of the stress states throughout the layer. The weight factors would be largest in regions close to the load where the modulus influence on the response under load is most significant and smaller in regions far from the load. Unfortunately, there is not any direct way to estimate these spatially varying weight factors.

The alternative methodology proposed here is a non-point approach in which comparisons between nonlinear forward calculation and linear backcalculation analyses are used more holistically to define an "equivalent" homogeneous linear elastic layer modulus that gives similar pavement responses as obtained from the nonlinear analysis. This approach eliminates the need for a single "representative" point estimate of stress state. The equivalent linear elastic layer modulus determined from this approach implicitly reflects a weighted average of stress state that directly incorporates the influences of pavement structure, loading magnitude, and material properties.

The equivalent linear elastic modulus from the approach proposed here will represent the best input value to use for the layered elastic pavement response models incorporated in Pavement ME Design. Ideally, these equivalent layer elastic moduli derived from laboratory testing data and used for design would also agree closely with the layer elastic moduli backcalculated from FWD testing in the field. Confirming this agreement is the objective of the research proposed herein.

The following sections describe the computation tools used to evaluate this methodology and its evaluation against a representative LTPP dataset.

Computational Tools

A forward nonlinear calculation is used to compute the surface deflection basin for a flexible pavement structure in which the unbound materials follow the stress-dependent relationship incorporated into the AASHTOware Pavement ME Design software:

$$M_r = k_1 p_a \left(\frac{\theta}{p_a} \right)^{k_2} \left(\frac{\tau_{oct}}{p_a} + 1 \right)^{k_3} \tag{11}$$

Where:

M_r = Resilient modulus.

θ = Bulk stress.

τ_{oct} = Octahedral shear stress.

p_a = Atmospheric pressure.

k_1, k_2, k_3 = Material constants.

In the forward nonlinear calculation, the bound asphalt concrete layers are treated as homogeneous and linearly elastic.

The FEAP finite element program provided by Jacob Uzan incorporates the stress-dependent modulus model in Equation 11. This program was used for the forward nonlinear calculations. Some minor modifications to finite element mesh limits, output quantities, and other miscellaneous input and calculation details in the FEAP program were required for this purpose.

The EverCalc software was used for the homogeneous linear backcalculation analyses. This is the same software that was employed to derive the bulk of the backcalculation analysis results stored in the LTPP database. The analysis settings used in EverCalc were equivalent to those used for the LTPP calculations.

Evaluation of Proposed Methodology

The proposed analysis methodology was evaluated using material property and FWD test results from the LTPP database. The analysis methodology consists of the following steps:

1. Determine the pavement structure and FWD loading from the LTPP database.
2. Determine the laboratory-derived material property inputs from the LTPP database.
3. Perform the nonlinear forward calculation using FEAP to determine the surface deflection basin under the FWD loading.
4. Use the surface deflections from Step 3 as input to the EverCalc backcalculation software to compute the equivalent linear elastic layer moduli.

5. Compare the backcalculated layer moduli from Step 4 against the layer moduli backcalculated from the field FWD tests in the LTPP database.

LTPP Section 39_0101 in Ohio was selected for initial evaluation. All of the data required for the evaluation were downloaded from InfoPave. The analyses were conducted for one load level corresponding to an FWD plate pressure of 0.58 MPa.

The material property inputs required for the forward nonlinear analysis were determined from laboratory test data. The linearly elastic modulus for the asphalt concrete layer was determined from the laboratory dynamic modulus test results at the FWD field test temperature and an assumed loading rate of 0.1 Hz. The stress-dependent elastic moduli inputs for the granular base and subgrade were the K1, K2, and K3 parameters determined from the laboratory triaxial resilient modulus tests. The values of the inputs for the forward nonlinear analysis are summarized in Table 21.

Table 21. Material property inputs for nonlinear forward analysis (Section 39_0101).

Layer	Thickness (in)	M_r (linear)	M_r (nonlinear)		
			K1	K2	K3
AC	7	1226 ksi			
Base	12		1448	0.662	-0.017
Subgrade	354		1080	0.167	-0.044

The surface deflections from the nonlinear forward analysis were then used as inputs to a linear backcalculation analysis. Consistent with what is done in the LTPP database, the subgrade is divided into an upper 24 inches of so-called “compacted” subgrade and a lower natural subgrade. The equivalent linear elastic modulus values backcalculated from the forward nonlinear analysis deflections are summarized in Table 22. Also included in Table 22 for comparison are the linear elastic moduli values for each layer backcalculated from the FWD field test.

Table 22. Comparison of equivalent linear elastic modulus values backcalculated from forward nonlinear analysis deflections against linear elastic modulus values backcalculated from FWD field test (Section 39_0101).

Layer	Thickness (in)	Computed Equivalent Linear Modulus (ksi)	FWD Backcalculated Modulus (ksi)	Error (FWD-Computed)
AC	7	1244	965	-22%
Base	12	15.3	13.5	-12%
Upper Subgrade	24	13.6	13.9	+2%
Lower Subgrade	330	21.8	25.4	+16%

The agreement between the computed and measured equivalent linear elastic moduli is quite good. The largest discrepancy is for the AC layer, but this may be a result of using an assumed 0.1 Hz loading rate for interpreting the laboratory dynamic modulus data. The effects of damage of the AC layer in the field are also not considered.

It is well known that there is considerable inherent variability and uncertainty in field properties for unbound materials. A second set of comparisons was performed to examine this using data for LTPP Section 36_0802 in New York. Analyses were performed for 44 FWD drops conducted on November 9, 1994. All drops were for the mid-lane location (location F1) for one load level corresponding to an FWD plate pressure of 0.78 MPa. The variability of the equivalent linear elastic layer moduli backcalculated from the FWD tests was evaluated as well as the comparisons between the field- and laboratory-estimated layer moduli.

The material property inputs required for the forward nonlinear analysis were determined from the laboratory test data in the LTPP database. The linear elastic modulus for the asphalt concrete layer was determined from the laboratory dynamic modulus test results at the FWD field test temperature and an assumed loading rate of 0.1 Hz. The stress-dependent elastic moduli inputs for the granular base and subgrade were the K1, K2, and K3 parameters determined from the laboratory triaxial resilient modulus tests. The values of the inputs for the forward nonlinear analysis are summarized in Table 23. It was assumed that these values were representative for all 44 FWD test locations examined in this section.

Table 23. Material property inputs for nonlinear forward analysis (Section 36_0802).

Layer	Thickness (in)	M_r (linear)	M_r (nonlinear)		
			K1	K2	K3
AC	7.6	1871			
Base	10.0		1046	0.525	0.078
Subgrade	156		428	0.754	-0.317

The surface deflections from the nonlinear forward analysis were then used as inputs to a linear backcalculation analysis. The FWD backcalculation analyses used to populate the LTPP database arbitrarily divide the subgrade into an upper 24 inches of so-called “compacted” subgrade and a lower natural subgrade. Since there is no objective basis for this subdivision of the subgrade, the FWD deflections were used with EverCalc to backcalculate the equivalent linear elastic layer moduli for the actual three-layer pavement structure. This was done for all 44 FWD drops examined.

The equivalent linear elastic modulus values backcalculated from the FWD measured deflections and from the forward nonlinear analysis deflections are summarized in Table 24. Also included in Table 24 are the COV for the linear elastic modulus values backcalculated from the 44 FWD drops examined.

Table 24. Comparison of equivalent linear elastic modulus values backcalculated from forward nonlinear analysis deflections against linear elastic modulus values backcalculated from FWD field test.

Layer	Computed Equivalent Linear Modulus (ksi)	FWD Backcalculated Modulus		Error (Mean FWD-Computed)
		Mean (ksi)	COV	
AC	1416	1482	21%	+4%
Base	5.3	6.0	37%	+13%
Subgrade	30.6	36.8	23%	+17%

As before, the equivalent linear elastic layer moduli computed using the forward nonlinear analysis and the laboratory-measured material property data agree well with the mean values of the equivalent linear elastic layer moduli backcalculated from the measured FWD deflections in the field. The maximum discrepancy was 17% for the layer moduli of the subgrade. However, this discrepancy is smaller than the location-to-location variability for the equivalent moduli backcalculated from the measured field FWD deflections; the COV for these were 37% for the granular base and 23% for the subgrade.

These limited investigations demonstrate real potential for this proposed approach. The equivalent linear elastic layer moduli backcalculated from the forward nonlinear finite element analysis deflections using laboratory-measured material property data agree reasonably well with the equivalent linear elastic layer moduli backcalculated from the measured field FWD deflections. Software tools can be easily developed to enable application of the approach case by case. Alternatively, a large set of parametric analyses for a range of pavement structures, material properties, laboratory-measured stress-dependent stiffness characteristics, and load levels could be executed to generate corresponding sets of "equivalent" linear modulus values for the nonlinear granular base and subgrade layers. Machine learning techniques (e.g., artificial neural networks) could then be employed to generate a predictive model relating equivalent linear modulus to the other pavement characteristics, including—most importantly—the laboratory-measured stress dependent stiffness constants.

WORK PLAN

The pervious section detailed an alternative for more holistically relating laboratory-derived resilient moduli to field-derived layer moduli such that the outcome is a correction factor ("C" factor) approaching 1—i.e., one-to-one correlation between laboratory- and field-derived values as should rationally be the case. Moreover, the approach has been demonstrated via examples using data from the LTPP program. In addition, two options for implementation of recommended approach were suggested:

- Development of a software tool to enable application of approach on a case-by-case basis.

- Development of predictive model relating equivalent linear modulus to the other pavement characteristics, including the laboratory-measured stress dependent stiffness constants.

Given the objective of the project at hand and taking into consideration the level of effort required to implement each, the first option is recommended. The work plan for accomplishing this option consists of the six tasks detailed next.

Task 1. Identify LTPP test sections to apply methodology

As indicated in earlier chapters, there are 1,045 test sections in the LTPP database containing both laboratory resilient moduli and FWD backcalculated layer moduli for the unbound layers. Because more than 300 of those test sections contain two or more unbound layers, the actual number of datasets available for use in the development of the proposed relationships consists of 1,559 unique test section-unbound layer combinations.

Unfortunately, the proposed non-point methodology does not lend itself to automation and, consequently, applying it to the available dataset of 1,559 test section-unbound layer combinations is not realistic or needed. Instead, the first task in the work plan focuses on the selection of a reasonable and statistically sound subset of test section-unbound layer combinations. The selection criteria should include the following factors:

- Layer types – Base versus subbase versus subgrade.
- Material type – Crushed stone, gravel, sand, etc.
- Climatic conditions – Moisture and temperature regimes.
- Pavement types – Flexible and rigid pavements should be considered, but with an emphasis on the former (i.e., conventional asphalt concrete pavements) because of the sensitivity of the Pavement ME software to the resilient modulus of unbound layers and also because of the challenges associated in getting reasonable backcalculated moduli in more complex pavement structures.
- Pavement structures – Various combinations of material types and layer thicknesses.
- Subgrade types – Granular and cohesive soils.

It is anticipated that approximately 100 test sections will be required to adequately test the proposed methodology, but this number will need to be confirmed as part of the work effort.

Because the list of LTPP test sections selected is critical to success of the tasks that follow, it is important that the list be submitted to the NCHRP for review and approval before the effort can proceed to Task 2.

Task 2. Apply methodology to set of LTPP test sections

Once the list of LTPP test sections has been finalized, the proposed methodology will be tested using the data associated with those test sections in conjunction with the five-step process detailed earlier in the chapter:

1. Determine pavement structure and FWD loading for each test section from the LTPP database.

2. Determine the laboratory-based material property inputs from the LTPP database.
3. Perform non-linear forward calculation to predict surface deflection basin under FWD loading.
4. Use surface deflections from Step 3 as input to EverCalc backcalculation software to compute equivalent linear elastic layer moduli.
5. Compare backcalculated layer moduli from Step 4 against layer moduli backcalculated from field FWD data as stored in LTPP database.

Given the large quantity of data associated with validation of the proposed methodology, it is important that those data be organized in such a manner as to facilitate the analyses to be carried out under Task 3.

Task 3. Perform statistical analyses of Task 2 results

Under this task, the agreement between laboratory- and field-derived modulus values from task 2 will be compared to confirm that the proposed methodology is or is not valid on the basis of testing using a larger dataset of LTPP test sections than used in this feasibility study. Although the exact procedures for executing this comparison will be defined during the Task 3 work, it is envisioned that most will be standard statistical analyses (e.g., regression analysis, t-tests, etc.).

Where significant differences occur in the moduli values, further analyses should be carried out to determine those factors that are or are not relevant to the laboratory-to-field relationship. For example, can the differences be explained as the result of differences in the asphalt concrete surface properties (loading frequency, temperature, aging, etc.), differences in moisture content in the unbound layers, etc.

If the methodology is confirmed to be feasible, then this task will also include preparation of a white paper detailing recommendations for development of a standalone software tool to enable application of the proposed methodology approach on a case-by-case basis as well as a detailed plan for testing and verification of the tool.

Task 4. Prepare interim report and participate in panel meeting

After the completion of Task 3, an interim report documenting the Tasks 1 through 3 effort and findings will be prepared and submitted to the NCHRP. Approximately one month after submittal of the report, the NCHRP will schedule a project panel meeting to review and to discuss the referenced findings. The research team will work with the NCHRP to decide on a meeting date and time.

The research team will also prepare for and participate in the meeting, but will not proceed with the remaining tasks until receiving approval from the NCHRP based on the project panel meeting outcomes.

Task 5. Develop software tool

Once approval has been received from the NCHRP, development of the software tool consistent with the recommendations from Task 3, as modified based on NCHRP input received under Task 4, will commence. The purpose of the software tool will be to implement the analysis

approach outlined in this report (i.e., steps 1 through 4 outlined under Task 2 above) and further refined in the proposed work plan for the envisioned follow-on study. The main inputs to the software will be: (1) pavement structure (i.e., layer types, thicknesses) and (2) laboratory-measured stiffness properties (e.g., dynamic modulus for asphalt layers, stress-dependent resilient modulus values for the unbound layers). The main outputs will be the equivalent linear layer moduli determined from backcalculation of the deflection basins obtained from the nonlinear forward response. The beta version of the software tool will be thoroughly tested and verified in accordance with the plan developed under Task 3, as modified based on NCHRP input received under Task 4.

This task also includes the development of detailed and specific recommendations for implementation of the software tool within the Pavement ME Design and MEPDG methodology.

Task 6. Prepare and submit final deliverables

At the conclusion of the project, a ready-to-use standalone software tool and a draft of the user's guide will be prepared and submitted to the NCHRP. A draft report documenting the entire research effort will also be prepared and submitted to the NCHRP. It is anticipated that a two-month period will be required for review of the referenced deliverables, and by the end of that period, feedback will be provided by the NCHRP for revising and finalizing the deliverables. The final deliverables will be submitted to the NCHRP as a single package that includes not only the deliverables but also point-by-point responses to the review comments provided by the NCHRP.

Schedule and Budget

It is estimated that a 24-month period and funds totaling $400,000 will be required to complete the proposed work plan.

CHAPTER 6. SUMMARY AND CONCLUSIONS

The objective of this study was to evaluate the feasibility of using LTPP data for developing relationships between laboratory- and field-derived properties of unbound granular materials used in pavement. This study was limited to those properties required for pavement design analysis using the Pavement ME Design procedures. These properties include resilient modulus, Poisson's ratio, classification and volumetric properties, moisture-density relationships, unit weight, soil-water characteristic curve, saturated hydraulic conductivity, and other thermal properties. Of these properties, the only significant ones that can be determined in both the laboratory and the field are the elastic modulus values of aggregate base and subgrade layers. Moreover, predicted pavement performance is most sensitive to these resilient modulus values for the aggregate base and subgrade layers, although less so for rigid as compared to flexible pavements.

The relationship between laboratory-derived resilient moduli and field-derived layer moduli has been the subject of previous research, but no single relationship has been shown to work well, and as a result a diverse set of correction factors are implemented into the AASHTO MEPDG methodology. Clearly, improved harmonization between laboratory- and field-derived modulus values is much needed. The very approximate correction factors currently used by the AASHTO MEPDG methodology are incompatible with the more refined algorithms embedded elsewhere in the MEPDG.

Based on the stated objective, the research team first looked at the availability of LTPP data to support development of the laboratory-to-field relationships. It was determined that a total of 1,045 LTPP test sections have data available to support the project objective, of which approximately 300 have laboratory-measured resilient modulus data for two or more granular base, subbase, or subgrade layers on the same test section. In addition, a considerable amount of supplementary data exists in the LTPP database to support the development of relationships. These supplementary data refer to those data that can potentially be used to classify, explain, or expand on the relationships discovered from the primary LTPP dataset.

The research team then conducted an exploratory analysis of the available LTPP data to evaluate the feasibility of using these data for developing valid relationships between laboratory resilient modulus and backcalculated layer modulus. This analysis, which was the focus of this study, provided information on the quantity, quality, and range of the data available to support the study. The variables included in this analysis were variables expected to influence either the laboratory resilient moduli or backcalculated layer moduli data and included variables such as laboratory testing stress state, moisture content, and test location. Key findings and conclusions from this exploratory data analysis included:

- A total of 1,559 test section unbound layers with both laboratory and field data were identified in the LTPP database for possible development of relationships between laboratory- and field-derived modulus values. These data cover a wide range of values, pavement structures, and environmental conditions. Based on the general rule of thumb that 10 to 20 observations per covariate are required to provide reasonable statistical power in a multivariate regression analysis, the number of LTPP test sections with unbound layers appear adequate for the development of laboratory- and field-derived resilient modulus relationships.

- The locations where laboratory samples were extracted or where FWD tests were performed do not necessarily match nor do the corresponding dates. However, sub-sampling data to minimize such differences would significantly reduce the number of observations for analysis. Moreover, a statistical comparison between the backcalculated layer moduli within and outside test section limits showed that the differences were generally not significant for the purpose of obtaining a unique representative value for the section.
- The relationship between laboratory resilient modulus values varied rationally with stress state increased with confinement and increased (granular) or decreased (fine grained) with deviatoric. Also, a large proportion of the estimated constitutive models from the triaxial test results showed strong fits as measured by their coefficient of determination.
- 90% of the observed differences between in-situ and after testing moisture content for the laboratory M_r data ranged between -4.60% and 5.58%, with a median difference of 0.63%. Because these differences in moisture do occur, this variable should be accounted for when developing the proposed relationships. On the other hand, if the laboratory- and field-derived layer modulus values are simply compared directly (i.e., without incorporating the effect of moisture differences), samples with large differences in moisture content should be excluded from the analysis. The determination of a filtering moisture content threshold should be based on its effect on the resilient modulus value, which should be quantified as part of the relationship's development effort.
- The relationship between backcalculated layer moduli values across pavement layer types (i.e., base versus subbase versus subgrade) was different than that observed for laboratory resilient modulus due, in part, to the difficulty of defining the appropriate stress state in the field under FWD testing. Other contributing reasons may include miscalculations caused by inaccuracies of backcalculation software.
- 4.2% of the backcalculated layer moduli data were flagged as mild outliers, while 1.2% were flagged as extreme outliers. Extreme outliers in backcalculated data may be indicative of anomalies in FWD testing or data processing, and therefore should be further investigated and potentially excluded from the analysis dataset used for development of the proposed relationships.

Based on the quantity, quality, and range analysis results, the research team concluded that the LTPP data are adequate for the development of laboratory-to-field relationships. However, the analysis dataset can be improved by filtering the data to reduce the impact of extraneous factors (e.g., large differences in moisture level) and to eliminate anomalies in the measured data. The recommended criteria for identifying the best possible dataset are detailed in the report.

In light of the above overarching conclusion, the research team proceeded with the preparation of a work plan for development of the proposed relationships. The research team first formulated the methodology to be used to develop the relationships. This methodology is predicated on the fact that the main reason layer moduli backcalculated from FWD tests do not agree with laboratory-measured resilient modulus values is that the homogeneous linearly elastic

theory underlying FWD backcalculation assumes that there is a single modulus value for the layer when in fact there is a near infinite variety of resilient modulus values for the material—a fact that is explicitly acknowledged in the laboratory resilient modulus testing protocols. Instead of "representative" values of stress states, what is needed is a weighted average of the stress states throughout the layer. Consequently, the proposed methodology is a non-point approach in which comparisons between nonlinear forward calculation and linear backcalculation analyses are used more holistically to define an "equivalent" homogeneous linear layer modulus that gives similar pavement responses as obtained from the nonlinear analysis. This approach eliminates the need for a single "representative" point estimate of stress state. Moreover, the equivalent layer modulus determined from this approach implicitly reflects a weighted average of stress state that directly incorporates the influences of pavement structure, loading magnitude, and material properties.

Having established the methodology, the research team formulated a work plan for development of the proposed relationships, which included the following six tasks:

1. Identify LTPP test sections to apply the methodology to.
2. Apply the methodology to the set of LTPP test sections.
3. Perform statistical analysis of the Task 2 results.
4. Prepare an interim report and participate in the panel meeting.
5. Develop the software tool.
6. Prepare and submit final deliverables.

The work plan effort was estimated to require 24-months to complete and $400,000 in funds.

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