TRUCK/PAVEMENT/ECONOMIC MODELING AND IN-SITU FIELD TEST DATA ANALYSIS APPLICATIONS – VOLUME 3: STIFFNESS AND MODULUS ESTIMATION FOR DIFFERENT SOIL TYPES USING FWD DEFLECTION DATA

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16. Abstract
In current U.S. practice, quality of subgrade in a pavement system is commonly evaluated using the degree of compaction in the field and comparing with the laboratory determined maximum dry density from Standard/Modified Proctor tests (AASHTO T-99/T-180) to confirm the degree of compaction. However density is inherently an indirect measurement of the subgrade quality. This report studies the use of nondestructive testing (NDT) devices, such as the Falling Weight Deflectometer (FWD), to directly and quickly measure subgrade and base stiffness and/or modulus. This study's main objective was assessment of material-specific stiffness and soil modulus of unbound granular soil materials using deflection data from 146 sections in ten states in the nationwide pavement database. In some cases, insufficient or unavailable in-situ soil data were supplemented with laboratory measurements. Calculation of stiffness and soil modulus was based on the linear elastic theory of granular soil material. To achieve high reliability of output results, establishment of the data screening procedures was another major concern in this study. Also, correlations between major engineering properties and stiffness or modulus of unbound granular materials were performed for validation of output results.

Statistics for modulus and stiffness of 11 types of subgrade soils are presented, including mean with 95% confidence interval, median, standard deviation, and interquartile range. Similar statistics are given for bases made from aggregate or aggregate mixed with soil. The subgrade modulus is then correlated with various engineering properties, including moisture content, maximum dry density, plasticity index, and grain size distribution.

Calculated mean stiffness and modulus values for base materials and coarse-grained soils agreed with typical previously published values, while those for fine-grained soils did not. For coarse-grained soils, modulus increased as moisture decreased, except below a threshold below which soil was too dry and modulus decreased. Well-graded soil had a higher modulus. The correlation analysis showed that for fine-grained soils, modulus was sensitive to the plasticity index, the weighted plasticity index, and number of fines. Stiffness and modulus for coarse-grained soils showed a good agreement and reliable relationship with other soil properties. Measured stiffness and modulus values in the pavement database exceeded the European standards, and all soils had been approved for construction.

For practical purposes, subgrade stiffness and soil modulus values at the 25th percentile could be considered as the minimum limiting criteria for AASHTO soil types A-1, A-1-a, A-1-b, A-2-4, and A-2-6. Similarly, base stiffness and base modulus values at the 25% percentile appear to be reasonable as a minimum criterion. A table of values is given.

17. Key Words
Subgrade stiffness, subgrade modulus, falling weight deflectometer (FWD)

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SI* (MODERN METRIC) CONVERSION FACTORS

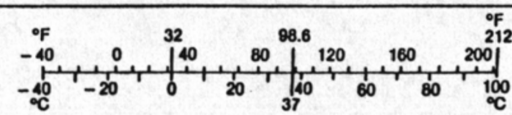
APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4	millimetres	mm
ft	feet	0.305	metres	m
yd	yards	0.914	metres	m
mi	miles	1.61	kilometres	km
		AREA		
in^2	square inches	645.2	millimetres squared	mm^2
ft^2	square feet	0.093	metres squared	m^2
yd^2	square yards	0.836	metres squared	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	kilometres squared	km^2
		VOLUME		
fl oz	fluid ounces	29.57	millilitres	mL
gal	gallons	3.785	litres	L
ft^3	cubic feet	0.028	metres cubed	m^3
yd^3	cubic yards	0.765	metres cubed	m^3
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams	Mg
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5(F-32)/9	Celcius temperature	°C

NOTE: Volumes greater than 1000 L shall be shown in m^3.

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimetres	0.039	inches	in
m	metres	3.28	feet	ft
m	metres	1.09	yards	yd
km	kilometres	0.621	miles	mi
		AREA		
mm^2	millimetres squared	0.0016	square inches	in^2
m^2	metres squared	10.764	square feet	ft^2
ha	hectares	2.47	acres	ac
km^2	kilometres squared	0.386	square miles	mi^2
		VOLUME		
mL	millilitres	0.034	fluid ounces	fl oz
L	litres	0.264	gallons	gal
m^3	metres cubed	35.315	cubic feet	ft^3
m^3	metres cubed	1.308	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.205	pounds	lb
Mg	megagrams	1.102	short tons (2000 lb)	T
		TEMPERATURE (exact)		
°C	Celcius temperature	1.8C + 32	Fahrenheit temperature	°F



* SI is the symbol for the International System of Measurement

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Truck/Pavement/Economic Modeling and In-Situ Field Test Data Analysis Applications – Volume 3: Stiffness and Modulus Estimation for Different Soil Types Using FWD Deflection Data

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1 Introduction

In current U.S. practice, quality of subgrade in a pavement system is commonly evaluated by the degree of compaction in the field. By obtaining in-situ density and moisture content using a field density measuring device, they can be compared with the laboratory determined maximum dry density from Standard/Modified Proctor tests (AASHTO T-99/T-180) to confirm the degree of compaction. There has been an issue in compaction quality control of subgrade solely based on the density-moisture content relationship. Even though density is a good indicator of the soils in the pavement system, it does not explain the overall performance of the compacted subgrade because density is inherently an indirect measurement of the subgrade quality. Due to the limited capability of this engineering property to estimate overall strength and performance of subgrade, this often results in more conservative specifications and pavement design. The nuclear density gauge, which is a widely used in-situ density measuring device, has several major drawbacks in field performance. Collecting measurements is a slow and labor-intensive process, and there are safety concerns and significant paperwork burdens due to its use of radioactive materials.

Stiffness or modulus of subgrade soils is the most representative characterization of the pavement foundation. Subgrade materials are typically characterized by their resistance to deformation under load, which is a measure of their strength. Because deflection measured from the compacted subgrade directly relates to the actual response of the subgrade under traffic load, evaluation of in-situ stiffness can clearly indicate the overall performance of the pavement system in a simpler and more direct manner with a higher reliability. Recent developments of nondestructive testing (NDT) devices such as Falling Weight Deflectometer (FWD) have made deflection measurement much easier and faster in response to a need for more practical and direct measurement of stiffness in the field.

This study's main objective was assessment of material-specific stiffness and modulus of soils and unbound granular materials using deflection data from the nationwide pavement database. Calculation of stiffness and soil modulus is rather simple and straightforward, since the approach made in this study was based on the linear elastic theory of granular soil material. To achieve high reliability of output results, establishment of the data screening procedures is another major concern in this study.

Also, correlations between major engineering properties and stiffness or modulus of unbound granular materials were performed for validation of output results.

2 The Falling Weight Deflectometer

The Falling Weight Deflectometer (FWD) is a widely accepted nondestructive testing method, and is commonly considered to provide estimates of material properties for levels of load similar to those exerted by vehicles. The FWD employs a mass falling on to a buffered circular load plate. These devices were primarily developed in Europe and have since become popular in the United States [Nunn, et al., 1997]. The FWD is so far the most effective NDT deflection device available to date because of its ability to perform fast testing, simulate wheel loads, apply heavy loads, and measure a multipoint deflection basin. Various attempts on how to evaluate deflection data by FWD have found that soil moduli determined from FWD deflections generally show good reliability and consistency.

3 Review of State DOT Specifications

An investigation on compaction requirements of different state DOTs in terms of moisture content and dry density was conducted to establish the current practice of compaction quality control. The compaction requirements were analyzed in terms of available AASHTO soil classifications and sieve analysis data. Based on the availability of Long Term Pavement Performance (LTPP) subgrade data for this study, a total of ten states were chosen for this investigation: Arizona, Arkansas, California, Colorado, Mississippi, Montana, Nevada, Ohio, Utah and Washington. State DOTs' specifications for embankment were mainly researched for this study purpose.

3.1 Requirements on Moisture Content

It is commonly known that moisture content control, especially for fine-grained soils, is a critical factor to achieve the desired quality of compaction. The moisture content requirements in compaction of subgrade or embankment from the ten states are summarized in Table 1.

Table 1. Moisture Content Requirements in Various State DOT Soil Compaction Specifications

States	Moisture Content (from OMC)	Remark
Arizona	Not Specified	MC near or below Optimum
Arkansas	Not Specified	Substantially that of OMC
California	Not Specified	
Colorado	- 2.0 % ~ 0%	Soil types A-2-6, A-2-7, A-4, A-6 ~ A-7
Mississippi	Not Specified	
Montana	+/- 2.0 %	
Nevada	Not Specified	
Ohio	+/- 3.0 %	From GB1: Plan Subgrades [Ohio Department of Transportation, 2005]
Utah	Not Specified	
Washington	+/- 3.0 %	

From Table 1, six of ten states did not specify any moisture content range for compaction control. The other states specified the moisture requirement in compaction in a range of 2-3% maximum. Some states' requirements on moisture content were dependent upon the material type to be compacted. For Instance, Colorado suggested the moisture content requirement on certain types of soils. This general lack of uniform standards suggests that no one value or range of moisture content could provide the best compaction, but rather an appropriate range of moisture content for compaction should be determined based on the type of the soil to be compacted. The state of Ohio provides the estimated optimum moisture content per different soil types in *Geotechnical Bulletin 1: Plan Subgrades*, a supplemental document to the state specifications [Ohio Department of Transportation, 2005].

3.2 Requirement on Soil Density

The compaction requirements based on the maximum dry density from the ten state DOT specifications are summarized in Table 2.

As can be seen from Table 2 below, most of states investigated adopted a minimum 95% of Standard Proctor maximum density for embankment or subgrade compaction. Colorado specified 100% of Standard Proctor maximum density for AASHTO soil types A-1, A-3, A-2-4 and A-2-5 to be compacted, and 95% for all other types. In Ohio DOT specifications, 102% of maximum dry density was required for the soils with the maximum dry unit weight between 100 pcf (1600 kg/m^3) and 105 pcf (1680 kg/m^3) and 100% for all other soils. Utah was the other exception, specifying 96% rather than 95%.

Table 2. Soil Compaction Requirements Based on Density in Various State DOT Specifications

States	Maximum Dry Density from AASHTO T-99	Remark
Arizona	95%	
Arkansas	95%	
California	95%	
Colorado	100% 95%	A-1, A-3, A-2-4, A-2-5 All others
Mississippi	95% 98%	Basement soils Design soils
Montana	95%	Earth embankment including all backfills
Nevada	95%	
Ohio	102% 100%	Maximum dry unit weight: 100 pcf (1600 kg/m^3) to 105 pcf (1680 kg/m^3) All others
Utah	96%	
Washington	95%	

From this investigation, it was confirmed that many, if not all, state agencies are still relying heavily on the density-moisture content relationship for the control of compacted subgrade quality.

4 European Practices on Stiffness

In European countries such as Germany and France, minimum elastic stiffness measured at the top of the subgrade is currently selected as the end-product requirement for the completed pavement foundation, in accordance with the minimum density requirement.

In Germany, the *Guideline for the standardization of the Structure of Traffic Bearing Surfaces* specifies the minimum surface modulus of the subgrade to be 45MPa (6,530 psi) at formation level when tested with a 300 mm (12 in) diameter static plate bearing test [Nunn, et al., 1997]. The construction method to achieve this requirement is dependent on the contractor's own responsibility and decision. The German standards also specify a surface modulus requirement at the top of the sub-base layer. According to the guideline, the subbase surface modulus for standard design is 120 MPa (17,400 psi) in the case of light traffic, and 150 MPa (21,750 psi) in the case of heavy traffic.

In France, the surface modulus requirement is also applied [Nunn, et al., 1997]. According to the Technical Guide for the Construction of Embankments and Capping Layers (1992), a minimum surface modulus of 50 MPa (7,250 Psi) is required for the short term and much higher modulus values are required for the long term. For both countries, specifications for the road foundation are performance-based and the elastic stiffness or modulus is the key factor.

United Kingdom currently uses California Bearing Ratio (CBR) as an index test to correlate with the modulus for the roadway formation, according to the Design Manual for Roads and Bridges [Great Britain Department for Transport, 1994]. Road design in the UK has been shifting from total empirical to two stage semi-empirical design considerations, and the first stage of the semi-empirical design procedure considers implementation of a stiffness requirement. To develop an end-product performance specification, various in-situ testing devices such as the portable dynamic plate bearing tester (PDPBT) to measure stiffness are currently under consideration.

5 Long Term Pavement Performance Program

The Long Term Pavement Performance (LTPP) program is the comprehensive database which contains almost every aspect of pavement performance of national highway systems. This program started as one of research tasks in the Strategic Highway Research Program (SHRP) by Transportation Research Board (TRB) of the National Research Council. Under the LTPP program, data were collected from major highway systems throughout the nation in advance of the development of specific data analysis objectives, and the data are available to the public. This study utilized FWD deflection data and other key parameters from the LTPP program for the subgrade stiffness analysis.

The LTPP test sections are divided into two study groups: General Pavement Studies (GPS) for in-service pavement sections; and Specific Pavement Studies (SPS) for sections that were newly constructed, maintained, or rehabilitated. Test sections in the SPS are more controlled sections for intensive and extensive studies of experimental design and construction features. Data were used from SPS sections in the ten states as listed in Table 3, as these were the states that included the most comprehensive subgrade data to the LTPP program.

The LTPP databases have been updated regularly and presently online release 19.0 is publicly available through the website at http://www.datapave.com. The version of LTPP database utilized in this study was Release 18.0, updated in July 2004. All the data collected and processed for Quality Control (QC) checks were put into a Microsoft Access 2000 file. The database was divided into modules containing sets of individual tables.

5.1 FWD Deflection Data in LTPP

In the LTPP program, regional contractors performed FWD testing to measure deflection on different pavement layers including subgrade, base, subbase and surface layers. With the identical test plan and condition for deflection testing, FWD testing was performed for different seasons, load levels, material types and other variable options. Deflection measurement data in the LTPP program consist of up to nine different geophone readings depending on the type of deflectometer. The majority of deflection data in LTPP have seven geophone readings, and only deflection data using seven geophones were utilized in this study.

Since GPS sections were constructed before the LTPP program was initiated, only SPS sections have FWD deflection data collected from the bare subgrade. Those available data from SPS sections in ten states were analyzed for stiffness and modulus. Table 3 summarizes the number of SPS sections in each state that contained deflection data from subgrade and were used for stiffness estimation.

Table 3. Summary of SPS Test Sections Investigated

State Number	State	Number of Sections Analyzed	AASHTO Soil Class Type Encountered
4	Arizona	26	A-1-a, A-1-b, A-2-4, A-2-6, A-4
5	Arkansas	12	A-1-a, A-2, A-2-4, A-3
6	California	16	A-1-b, A-2-4
8	Colorado	10	A-2-4, A-2-6, A-6
28	Mississippi	2	A-6
30	Montana	8	A-1, A-2-4, A-4
32	Nevada	23	A-2-4, A-4, A-6, A-7-6
39	Ohio	30	A-6, A-7-5
49	Utah	2	A-6
53	Washington	17	A-4
Total	**10 States**	**146**	

For deflection data from the base layer, a total of 63 sections in 9 states including Louisiana had deflection data directly obtained from the surface of the base layer. According to the soil description of base materials in the LTPP database, material types for selected base layers are predominately crushed stone, gravel and slag, and soil-aggregate mixture. Those data were utilized for estimating base stiffnesses and moduli.

6 Data Extraction and Screening

6.1 Extraction of Deflection & Soil Data

Since the LTPP database contained comprehensive information of almost every aspect of pavement performance, selecting appropriate types and ranges of data necessary for a specific research and analysis purpose was the first step in this study. Two key data types required for this study were 1) FWD deflection basin data from SPS test sections, and 2) engineering properties of soils. Table 4 summarizes LTPP modules and tables that have been selected and the relevant data extracted from them.

Table 4. LTPP Modules and Tables Utilized

LTPP Module	Table Designation	Description
Monitoring	MON_DEFL_DROP_DATA	FWD Deflection Data
Materials Testing	TST_SS01_UG01_UG02	Gradation Analysis with Wash Tests
	TST_SS02_UG03	Sieve Analysis with Hydrometer Tests
	TST_UG04_SS03	Atterberg Limits Tests of Subgrade
	TST_SS04_UG08	Classification & Soil Description
	TST_UG07_SS07_A	Modulus with Moisture Content
	TST_UG10_SS09	In-Situ Moisture Content
	TST_UG05_SS05	Standard Proctor Tests for Subgrade
	TST_SS08	In-Situ Moisture Content & Density
SPS	SPS#_SUBGRADE_PREP	Compaction, Stabilization of Subgrade
	SPS#_LAYER_THICKNESS	Layer Thickness of base layers

A limited quantity of information about the engineering properties of subgrade soils was available in LTPP database. Since material property information is essential to investigate various correlations with soil stiffness, this limitation induced a major constraint in this study. As previously described, in the current practice of compaction control, the three key soil parameters of concern are density, moisture content, and soil classification. In the LTPP program, those three soil parameters could be found from different tables in the testing module, as shown in Table 4. Unfortunately, only the representative values of moisture content and density data for individual sections of different states were available in the LTPP database at the time of this study. Also, information on subgrade soil classification based on the AASHTO soil classification system was available only for 60 percent of the test sections evaluated. Thus, both field and laboratory determined density and moisture data were extracted from LTPP tables and utilized in this study.

6.2 Screening of Deflection Data

FWD deflection data were carefully screened to increase the reliability and decrease the variability of analysis results. Unlike deflection basin data collected on a finished pavement surface, data collected on bare subgrade surface are typically less consistent due to the poor surface condition of the subgrade where the loading plate is placed and a possible shearing effect by the plate. The screening of deflection data included individually examining data for discrepancy that should be excluded from further analysis. The screening procedure followed was that introduced in the report FHWA-RD-01-113, “Back-calculation of Layer Parameters for LTPP Test Sections” [Von Quintus and Simpson, 2002]. All measured deflection basins were first normalized to the center load deflection (Geophone D0). Plots of normalized deflection basins were then individually examined and following types of basins were excluded in this analysis.

➢ Type I: Deflections measured at some of the sensors are greater than the center-load deflection (D1). Type I deflection basins generally have the greatest error terms, and elastic layer theory is generally not applicable. Figure 1 shows a typical plot of a deflection basin of this type.

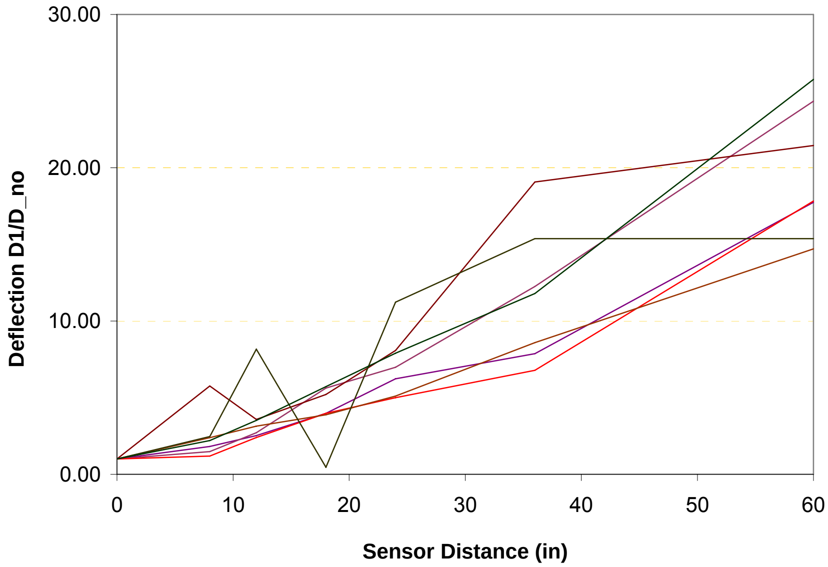

Figure 1. Type I Normalized Deflection Basin (1 in = 2.54 cm, 1 mil = 25.4 µm)

➢ Type II: Non-decreasing deflections from the center sensor are found to have errors. This type of deflection basin has more than one sensor deflection measurement which is still smaller than the center deflection, but higher than previous sensor measurement, resulting in non-decreasing pattern of the deflection basin, as shown in Figure 2.

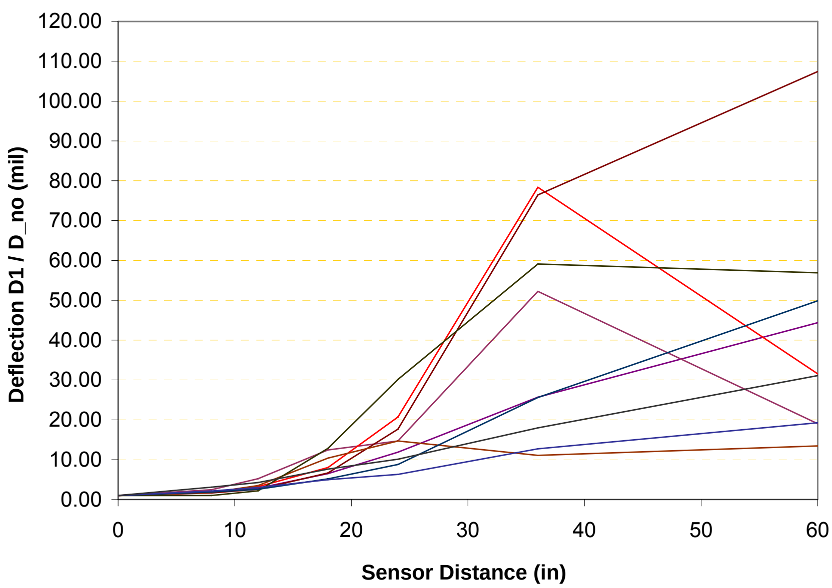

Figure 2. Type II Normalized Deflection Basin (1 in = 2.54 cm, 1 mil = 25.4 µm)

Also, deflection data from the sections where the subgrade was stabilized using lime, fly ash, or Portland cement were excluded, such as most test sections in Louisiana and Kansas.

6.3 Data Screening by Statistical Analysis

Further screening of deflection data was conducted with a statistical analysis using the software package SPSS version 13.0. First, the normality of data for each soil type was checked. According to the central limit theorem, a sampling distribution of means will be normally distributed when they are drawn from the same population. To determine if the distribution of deflection data is normal, the descriptive statistics Explore function in SPSS was utilized. The Explore function provides several ways of testing whether the normality of the data distribution has been met. Those options include skewness, kurtosis, the Kolmogorov-Smirnov test, and graphical methods such as histograms, quartile-by-quartile (Q-Q) plots, detrended Q-Q plots, and box plots. Also, outliers and extreme values were identified from box plots. Outliers can considerably impact the analysis results, especially when the sample size is relatively small. Since outliers are violations of normality, they were identified from the box plots and excluded for further analysis. Figure 3, Figure 4, and Figure 5 respectively show a typical histogram, Q-Q plot, and detrended Q-Q plot for AASHTO soil type A-1 as an example. Figure 6 shows a box plot of deflection data for different AASHTO soil types.

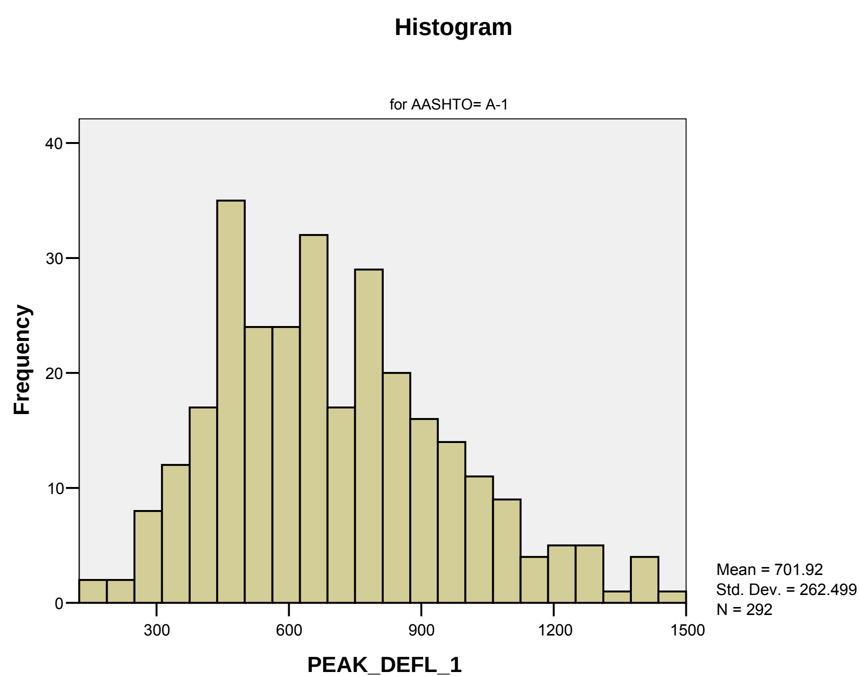

Figure 3. Histogram for deflection (PEAK_DEFL_1) data for A-1 soils (deflection in µm)

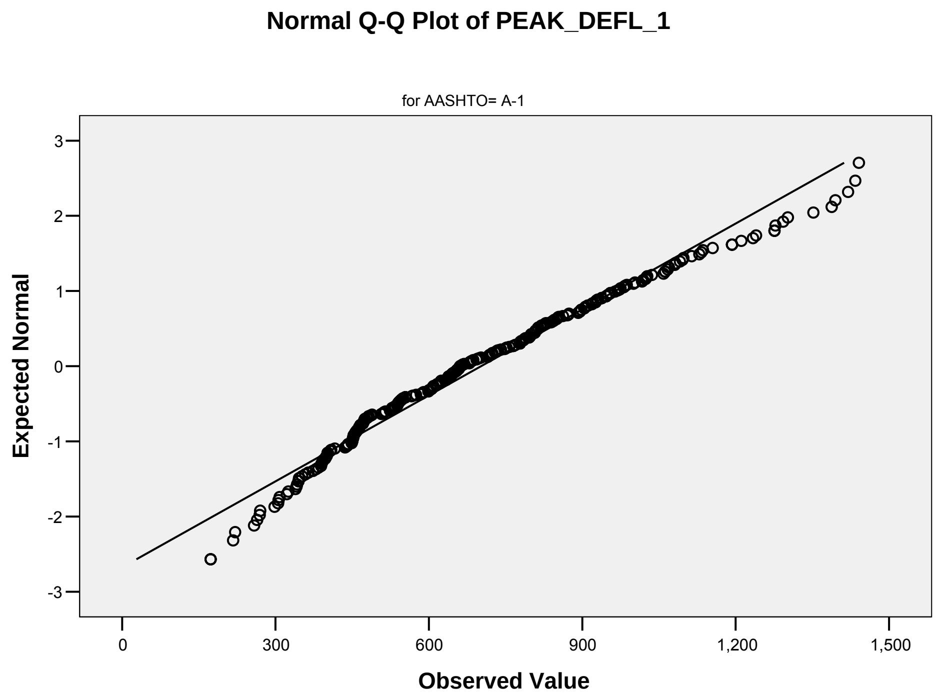

Figure 4. Q-Q plot of deflection data for A-1 soils (observed value of deflection in µm)

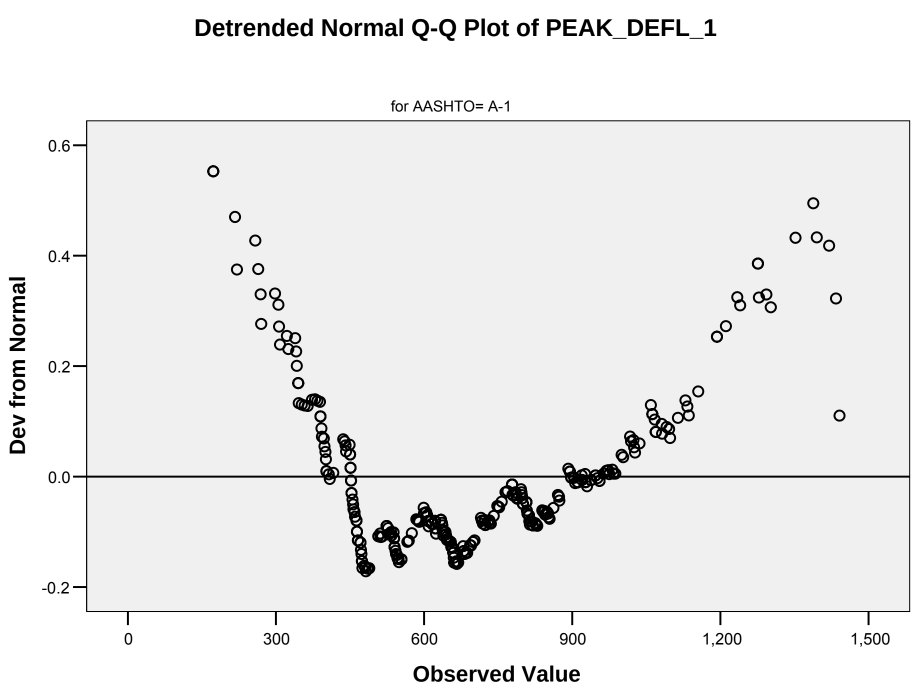

Figure 5. Detrended Q-Q plot of deflection data for A-1 soils (observed value of deflection in µm)

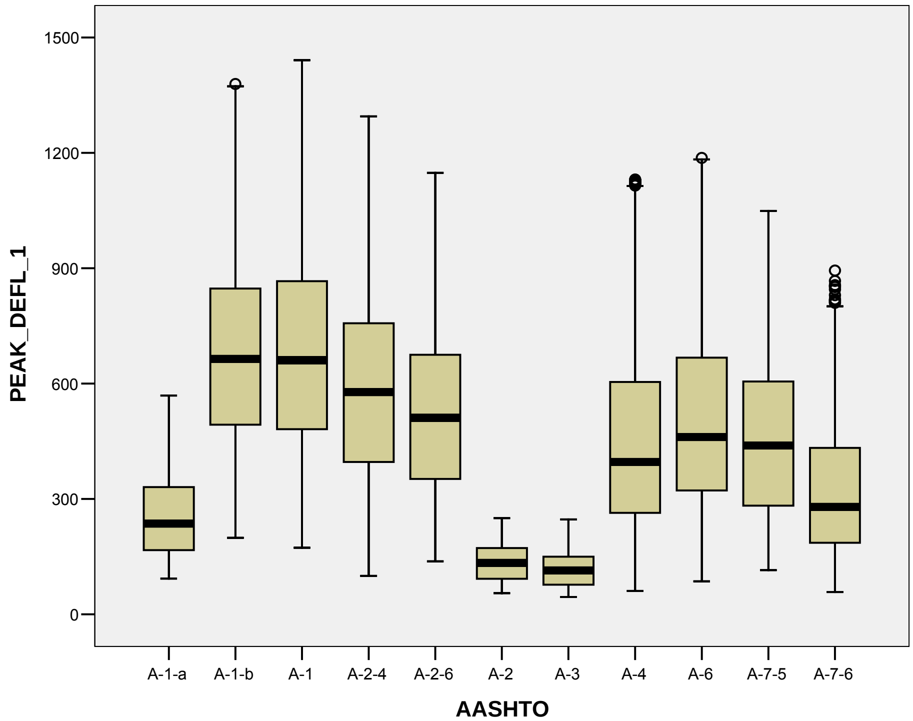

Figure 6. Box Plot of Deflection D1 (PEAK_DEFL_1) Data by Soil Type (deflection in µm)

It should be noted that only the center deflection D1 (PEAK_DEFL_1) was used for screening, since this center deflection data were used for actual stiffness and modulus calculation.

All soil types showed either a skewed distribution or uniform distribution. The same results were also found from the normality test by the Kolmogorov-Smirnov test, as shown in Table 5. In the Kolmogorov-Smirnov test, if the significance level of the test is less than 0.05, then it is unlikely the results fit a normal distribution. In Table 5, all of the significance values are well under 0.05, which indicate non-normally distributed data for all soil types.

Table 5. Kolmogorov-Smirnov test of normality of peak deflection (Geophone D1) distributions for different AASHTO soil types

	AASHTO	Kolmogorov-Smirnov		
		Statistic	df	Sig.
PEAK_DEFL_1	A-1-a	0.077	153	0.028
	A-1-b	0.047	1792	0.000
	A-1	0.065	292	0.004
	A-2-4	0.038	3582	0.000
	A-2-6	0.057	791	0.000
	A-2	0.104	148	0.000
	A-3	0.088	156	0.005
	A-4	0.098	3831	0.000
	A-6	0.083	3064	0.000
	A-7-5	0.103	139	0.001
	A-7-6	0.115	346	0.000

A normality check of data is necessary to perform more detailed statistical analysis using FWD deflection data, such as analysis of variance (ANOVA), because such an analysis method assumes a normal distribution of data. If applicable, ANOVA tests could provide more explanation of a relationship between different variables. If data is non-normally distributed, they have to be either transformed into a different form by an arithmetic transformation or non-parametric tests should be performed instead.

6.4 Calculation of Stiffness

Stiffness is defined as the ratio of the force to displacement. Field measured deflection under the applied load can be used to estimate soil stiffness and the elastic surface modulus, which is the equivalent modulus to be assigned to the whole medium beneath the level of testing.

The following equation, which is based on the half-space linear elastic theory by Boussinesq, was used to calculate soil stiffness and elastic surface modulus in this study.

$$K = \frac{P}{\delta} \qquad \text{(Equation 1)}$$

$$E_s = \frac{S \cdot (1 - \nu^2) \cdot K}{\pi \cdot r} = \frac{S \cdot (1 - \nu^2) \cdot P}{\pi \cdot r \cdot \delta} \qquad \text{(Equation 2)}$$

Where K = Soil stiffness
E_s = Surface modulus
S = Stress distribution factor, π/2 for a rigid plate, 2 for the uniform load distribution
P = Applied load pulse
r = Radius of loading plate
δ = deflection, and
ν = Poisson’s ratio

The magnitude of S depends on the stress distribution under the loading plate or on the ratio of the rigidity of the plate to that of the underlying medium. Under a very rigid plate deflections are the same over the plate area. Stress peak can be observed at the rim of the plate. Under a uniform load distribution, deflections in the load center will be higher than those at the rim of the plate. Using a very flexible plate, not only deflections but also stresses will decrease from the center towards the rim. For the modulus calculations in subgrade soils, a Poisson’s ratio of 0.4 was assumed for all cases to minimize additional variability in analysis.

Boussinesq’s equation is only applicable to single homogeneous layer. For a two-layer pavement system with a base layer over the subgrade, the concept of Odemark and Boussinesq was applied following the approach of Sargand, Edwards, and Salimath [2001]. Odemark developed an approximate method to transform a two-layer system into an equivalent system with the same modulus. This was also known as the “Method of Equivalent Thickness (MET)”. The concept of Odemark’s method is that stresses and strains below a layer depend only on the stiffness of that layer. If the structural capacity of the equivalent layer is unchanged, the stress and strain should be approximately unchanged, too, although thickness, modulus and Poisson’s ratio have changed. For calculation of response above the layer interface, the upper layer is treated as a half-space, and the lower layer is ignored [Kenis and Wang, 1997]. This method by Odemark has been validated against elastic layer theory by many researchers and can be used with the Boussinesq equation to determine pavement response below the layer interface.

Equation 3 approximates the deflection at the location directly under the loading plate on the surface of base [Sargand, Edwards, and Salimath, 2001].

$$\delta_{0,2} = 2(1-\nu^2)\frac{qr}{E_2 E_3}\left[E_3 + F_b(E_2 - E_3)\right] \qquad \text{(Equation 3)}$$

Where $\delta_{0,2}$ = Deflection on the surface of base
q = Loading pressure
E_2 = Base modulus
E_3 = Subgrade modulus, and
F_b = Boussinesq deflection factor, calculated using Equation 4 as follows:

$$F_b = \left[\sqrt{1+\left(\frac{h_e}{r}\right)^2} - \left(\frac{h_e}{r}\right)\right] \times \left[1 + \left(\left(\frac{h_e}{r}\right) \div \left(2(1-\nu^2)\right)\sqrt{1+\left(\frac{h_e}{r}\right)^2}\ )\right)\right] \qquad \text{(Equation 4)}$$

Where h_e = Equivalent thickness of subgrade to replace base thickness, h_2 in order to maintain the stiffness equivalent to that of the base, as determined in Equation 5.

$$h_e = h_2\left(\sqrt[3]{\frac{E_2}{E_3}}\right) \qquad \text{(Equation 5)}$$

Knowing the subgrade modulus value and FWD deflection obtained from the base top for individual section, the base modulus and stiffness were estimated by iterations of calculating this series of equations.

7 Analysis of Stiffness Estimation Results

7.1 Subgrade Stiffness and Modulus

Table 6 shows a number of valid measurements for each AASHTO soil type analyzed in this study. From the Table, the most frequently encountered AASHTO soil types for subgrade were A-1-b, A-2-4, A-4 and A-6. Each soil type had over 1,500 numbers of valid measurements. On the other hand, A-1-a, A-2, A-3, A-7-5 and A-7-6 soils were encountered from only one section each with approximately about 150 measurements except A-7-6 soil.

Individual measurement of FWD deflection was calculated for subgrade stiffness and modulus using the equation 1 and 2 in the previous chapter. Estimated stiffness and modulus values were grouped by each AASHTO soil type and descriptive statistics for analysis results were performed by the SPSS.

Analysis results of stiffness and modulus for LTPP subgrade soils by the SPSS were summarized for different AASHTO soil types and presented in Table 7 in English units and Table 8 in metric units.

Table 6. Summary of number of measurements for AASHTO soil types

AASHTO	No. of States	No. of Sections	Valid Cases
A-1-a	1	1	153
A-1-b	2	12	1,791
A-1	1	2	292
A-2-4	5	24	3,582
A-2-6	2	5	791
A-2	1	1	148
A-3	1	1	156
A-4	4	17	3,804
A-6	5	21	3,063
A-7-5	1	1	139
A-7-6	1	1	321

Table 7. SPSS Analysis Results of Subgrade Stiffness and Modulus by AASHTO Soil Types (English units).

Soil Type			A-1-a	A-1-b	A-1	A-2-4	A-2-6	A-2	A-3	A-4	A-6	A-7-5	A-7-6
Stiffness (lb/in)	Mean		340056	378317	342486	221350	268402	587820	695569	294782	234775	203835	330938
	95% Confidence Interval for Mean	Lower Bound	328092	372411	329099	219207	260026	579363	671484	291209	231138	188870	317113
		Upper Bound	352020	384224	355873	223493	276778	596278	719654	298355	238413	218800	344763
	5% Trimmed Mean		340838	375884	345220	220750	266200	587286	699741	292718	231155	201350	328095
	Median		340463	373691	367171	213947	246905	582245	682623	288127	227426	201422	333236
	Std. Deviation		74904	127457	116232	65410	120008	52065	152285	112403	102668	89231	125897
	Minimum		119893	120149	35692	35776	43233	486520	327786	32517	40470	46050	64158
	Maximum		511160	755694	647252	383434	545798	706410	1004672	622038	533412	438764	716849
	Range		391267	635545	611561	347658	502565	219890	676885	589520	492941	392714	652691
	Interquartile Range		104038	184800	159079	78044	195012	63481	208129	155830	147658	133199	143345
Skewness			-0.147	0.217	-0.408	0.283	0.346	0.105	-0.288	0.241	0.444	0.393	0.270
Kurtosis			0.215	-0.598	0.005	0.033	-0.932	-0.451	-0.077	-0.385	-0.347	-0.432	0.205
Modulus (ksi)	Mean		30.8	34.2	31.0	20.0	24.3	53.2	62.9	26.7	21.2	18.4	29.9
	95% Confidence Interval for Mean	Lower Bound	29.7	33.7	29.8	19.8	23.5	52.4	60.8	26.3	20.9	17.1	28.7
		Upper Bound	31.9	34.8	32.2	20.2	25.0	54.0	65.1	27.0	21.6	19.8	31.2
	5% Trimmed Mean		30.8	34.0	31.2	20.0	24.1	53.1	63.3	26.5	20.9	18.2	29.7
	Median		30.8	33.8	33.2	19.4	22.3	52.7	61.8	26.1	20.6	18.2	30.2
	Std. Deviation		6.8	11.5	10.5	5.9	10.9	4.7	13.8	10.2	9.3	8.1	11.4
	Minimum		10.8	10.9	3.2	3.2	3.9	44.0	29.7	2.9	3.7	4.2	5.8
	Maximum		46.3	68.4	58.6	34.7	49.4	63.9	90.9	56.3	48.3	39.7	64.9
	Range		35.4	57.5	55.3	31.5	45.5	19.9	61.2	53.3	44.6	35.5	59.1
	Interquartile Range		9.4	16.7	14.4	7.1	17.6	5.7	18.8	14.1	13.4	12.1	13.0
Skewness			-0.147	0.217	-0.408	0.283	0.346	0.105	-0.288	0.241	0.444	0.393	0.270
Kurtosis			0.215	-0.598	0.005	0.033	-0.932	-0.451	-0.077	-0.385	-0.347	-0.432	0.205

Table 8. SPSS Analysis Results of Subgrade Stiffness and Modulus by AASHTO Soil Types (metric units).

Soil Type			A-1-a	A-1-b	A-1	A-2-4	A-2-6	A-2	A-3	A-4	A-6	A-7-5	A-7-6
Stiffness (MN/m)	Mean		59.55	66.25	59.98	38.76	47.00	102.94	121.81	51.62	41.12	35.70	57.96
	95% Confidence Interval for Mean	Lower Bound	57.46	65.22	57.63	38.39	45.54	101.46	117.59	51.00	40.48	33.08	55.54
		Upper Bound	61.65	67.29	62.32	39.14	48.47	104.42	126.03	52.25	41.75	38.32	60.38
	5% Trimmed Mean		59.69	65.83	60.46	38.66	46.62	102.85	122.54	51.26	40.48	35.26	57.46
	Median		59.62	65.44	64.30	37.47	43.24	101.97	119.55	50.46	39.83	35.27	58.36
	Std. Deviation		13.12	22.32	20.36	11.46	21.02	9.12	26.67	19.68	17.98	15.63	22.05
	Minimum		21.00	21.04	6.25	6.27	7.57	85.20	57.40	5.69	7.09	8.06	11.24
	Maximum		89.52	132.34	113.35	67.15	95.58	123.71	175.94	108.94	93.41	76.84	125.54
	Range		68.52	111.30	107.10	60.88	88.01	38.51	118.54	103.24	86.33	68.77	114.30
	Interquartile Range		18.22	32.36	27.86	13.67	34.15	11.12	36.45	27.29	25.86	23.33	25.10
Skewness			-0.147	0.217	-0.408	0.283	0.346	0.105	-0.288	0.241	0.444	0.393	0.270
Kurtosis			0.215	-0.598	0.005	0.033	-0.932	-0.451	-0.077	-0.385	-0.347	-0.432	0.205
Modulus (MPa)	Mean		212.1	236.0	213.7	138.1	167.4	366.7	433.9	183.9	146.5	127.2	206.5
	95% Confidence Interval for Mean	Lower Bound	204.7	232.3	205.3	136.8	162.2	361.4	418.9	181.7	144.2	117.8	197.8
		Upper Bound	219.6	239.7	222.0	139.4	172.7	372.0	449.0	186.1	148.7	136.5	215.1
	5% Trimmed Mean		212.6	234.5	215.4	137.7	166.1	366.4	436.5	182.6	144.2	125.6	204.7
	Median		212.4	233.1	229.1	133.5	154.0	363.2	425.9	179.8	141.9	125.7	207.9
	Std. Deviation		46.7	79.5	72.5	40.8	74.9	32.5	95.0	70.1	64.1	55.7	78.5
	Minimum		74.8	75.0	22.3	22.3	27.0	303.5	204.5	20.3	25.2	28.7	40.0
	Maximum		318.9	471.5	403.8	239.2	340.5	440.7	626.8	388.1	332.8	273.7	447.2
	Range		244.1	396.5	381.5	216.9	313.5	137.2	422.3	367.8	307.5	245.0	407.2
	Interquartile Range		64.9	115.3	99.2	48.7	121.7	39.6	129.8	97.2	92.1	83.1	89.4
Skewness			-0.147	0.217	-0.408	0.283	0.346	0.105	-0.288	0.241	0.444	0.393	0.270
Kurtosis			0.215	-0.598	0.005	0.033	-0.932	-0.451	-0.077	-0.385	-0.347	-0.432	0.205

These summaries of descriptive statistics using SPSS included the standard deviations, mean values, minimum and maximum values, median, ranges, skew and kurtosis, confidence interval and the interquartile range (IQR) for both stiffness and modulus estimated in this study.

Based on the results in Table 7 and Table 8, the soil type A-3 was observed to have the highest mean stiffness and modulus values, 695,569 lb/in (121.8 MN/m) and 62.9 ksi (kip/in2) (433 MPa), while the soil type A-7-5 showed the lowest mean stiffness and modulus, 203,835 lb/in (35.7 MN/m) and 18.4 ksi (126 MPa).

To measure dispersion of data population from the mean values, the coefficient of variation (COV) for each soil type was estimated. The coefficient of variation is the ratio of the standard deviation to the mean values. Table 9 shows COV for each AASHTO soil type.

Table 9. Coefficient of Variation (COV) for AASHTO Soil Types

Soil Type	A-1-a	A-1-b	A-1	A-2-4	A-2-6	A-2	A-3	A-4	A-6	A-7-5	A-7-6
Coefficient of Variation	0.220	0.337	0.339	0.296	0.447	0.089	0.219	0.381	0.437	0.438	0.380

From Table 9, the COV for most of soil types ranged from 0.089 to 0.447. There was a wide dispersion of data distribution for several types of soils such as A-2-6, A-6 and A-7-5, which had the largest COVs.

Figure 7 and Figure 8 contain box plots of calculated stiffness and modulus for all AASHTO soil types. The box indicates the interquartile range (IQR) from the 25^{th} through 75^{th} percentiles of the distribution. Extreme values outside of the whiskers at the both bottom and the top of a plot are defined as outliers and they were removed before finalizing the analysis. The range between the bottom and the top whiskers indicates the distribution range of the analyzing values. The longer the length between both whiskers is, the more the stiffness and modulus values are widely scattered.

To examine the general acceptance of the estimated stiffness and modulus values, values obtained from this study were compared with the typical published resilient modulus values which are commonly accepted for design purposes. Figure 9 illustrates the typical modulus correlations to empirical soil properties and classification categories. Figure 9 is adapted from NAPA Information Series 117, “Guidelines for Use of HMA Overlays to Rehabilitate PCC Pavements”, 1994, and modified for the NCHRP Report 1-37A, “Guide for Mechanistic-Empirical Design of New and Rehabilitated Pavement Structures”, by ARA, Inc., ERES Consultants Division [ERES Consultants Division, 2004].

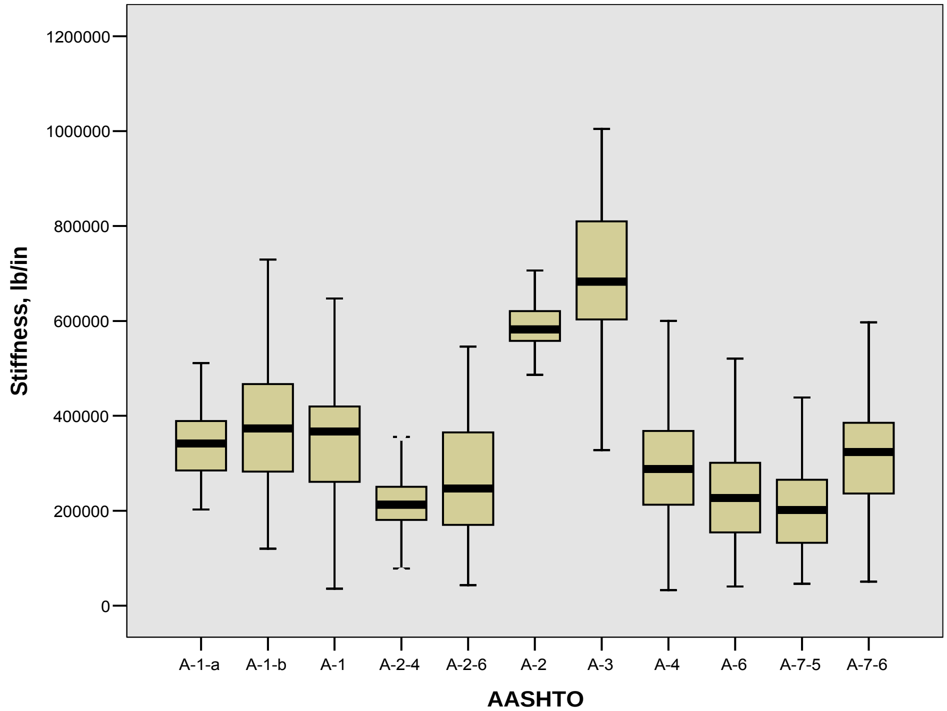

Figure 7. Box Plot of Calculated Subgrade Stiffness by Soil Types (100,000 lb/in = 17.5 MN/m)

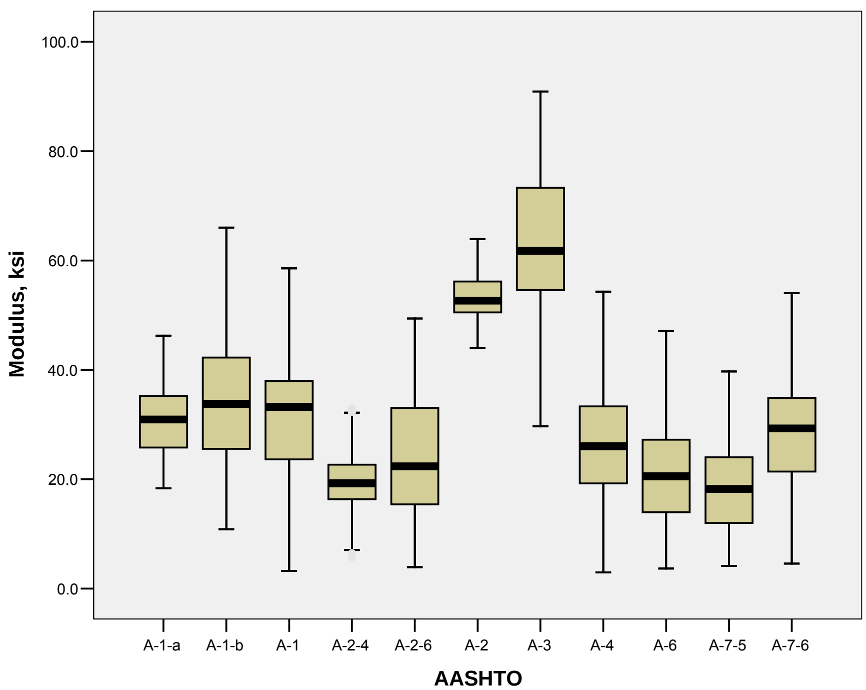

Figure 8. Box Plot of Calculated Subgrade Modulus by Soil Types (1 ksi = 6.89 MPa)

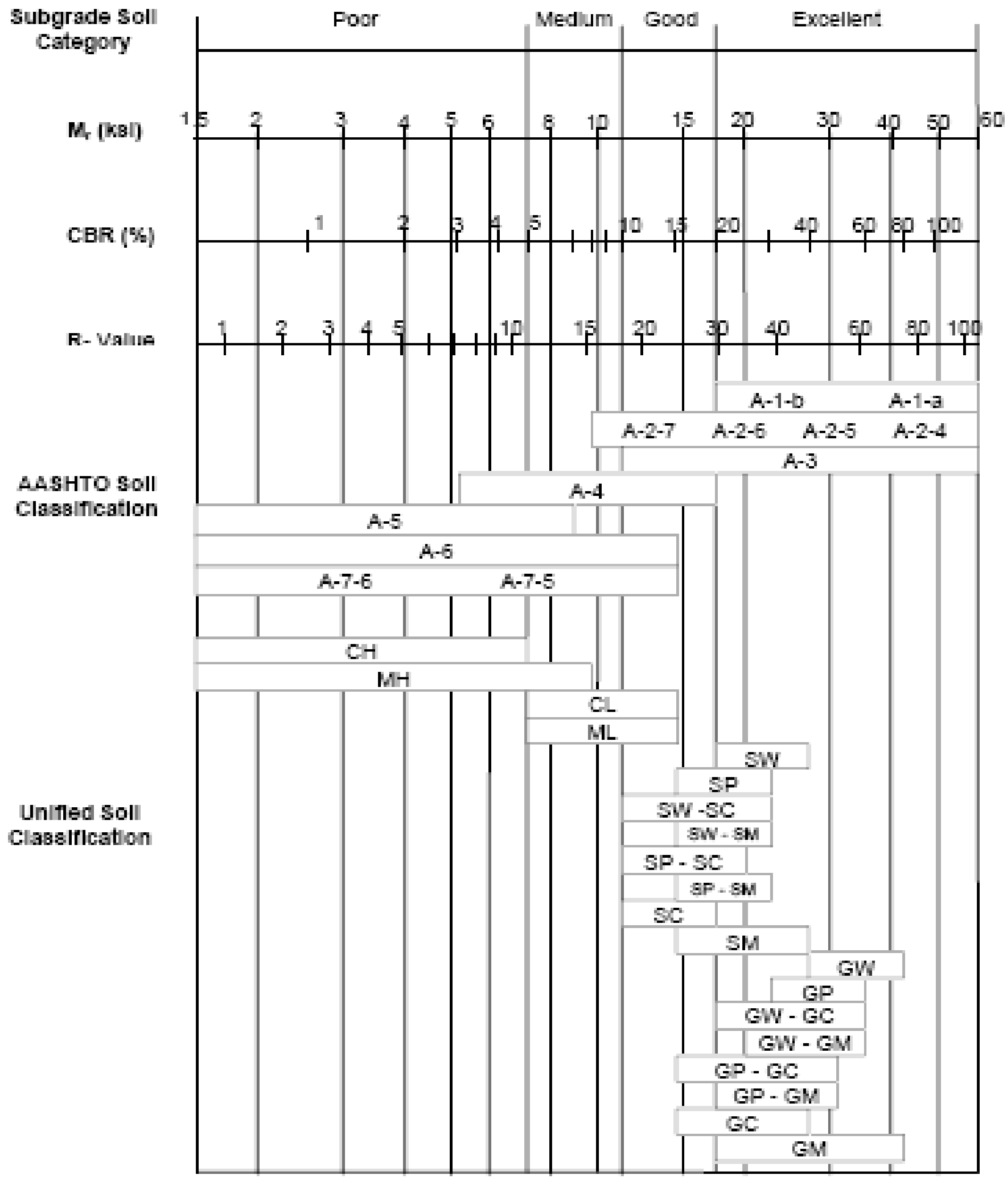

Figure 9. Typical Subgrade Modulus Correlations to Classification Categories (1 ksi = 6.89 MPa) [from ERES Consultants Division, 2004]

Table 10 (English units) and Table 11 (metric units) summarize the means, interquartiles (25th and 75th percentiles), minimum and maximum values, and typical published resilient moduli of subgrade soils approximately estimated from Figure 9. For comparison purposes, only the subgrade modulus for each soil type was shown in the table, since no published stiffness values were available.

Table 10. Summary of Subgrade Modulus by AASHTO Soil Types (English units).

Soil Type	Modulus (ksi)							
	Mean Modulus	Interquartile Range			Minimum	Maximum	Typical Published M_R*	
		25%	50%	75%			Min.	Max.
A-1-a	30.8	25.8	30.9	35.2	10.8	46.3	18	60
A-1-b	34.2	25.5	33.8	42.3	10.9	68.4	18	60
A-1	31.0	23.6	33.2	38.0	3.2	58.6	18	60
A-2-4	20.0	16.3	19.3	22.7	3.2	34.7	10	60
A-2-6	24.3	15.4	22.3	33.0	3.9	49.4	10	60
A-2	53.2	50.4	52.7	56.2	44.0	63.9	10	60
A-3	62.9	54.6	61.8	73.4	29.7	90.9	12	60
A-4	26.7	19.2	26.0	33.3	2.9	56.3	5	18
A-6	21.2	14.0	20.5	27.2	3.7	48.3	1.5	15
A-7-5	18.4	12.0	18.2	24.0	4.2	39.7	1.5	15
A-7-6	29.9	21.4	29.3	34.9	5.8	64.9	1.5	15

*Approximately estimated from Figure 9

Table 11. Summary of Subgrade Modulus by AASHTO Soil Types (metric units).

Soil Type	Modulus (MPa)							
	Mean Modulus	Interquartile Range			Minimum	Maximum	Typical Published M_R*	
		25%	50%	75%			Min.	Max.
A-1-a	212.1	177.7	213.2	242.8	74.8	318.9	124.1	413.7
A-1-b	236.0	176.1	232.9	291.4	75.0	471.5	124.1	413.7
A-1	213.7	162.6	229.1	261.8	22.3	403.8	124.1	413.7
A-2-4	138.1	112.6	132.7	156.4	22.3	239.2	68.9	413.7
A-2-6	167.4	106.1	154.0	227.8	27.0	340.5	68.9	413.7
A-2	366.7	347.8	363.2	387.4	303.5	440.7	68.9	413.7
A-3	433.9	376.1	425.9	506.0	204.5	626.8	82.7	413.7
A-4	183.9	132.7	179.5	229.6	20.3	388.1	34.5	124.1
A-6	146.5	96.2	141.5	187.8	25.2	332.8	10.3	103.4
A-7-5	127.2	82.7	125.7	165.8	28.7	273.7	10.3	103.4
A-7-6	206.5	147.2	201.9	240.4	40.0	447.2	10.3	103.4

*Approximately estimated from Figure 9 and converted to metric units

According to Table 10 and Table 11, the mean moduli for AASHTO soil types A-1, A-1-a, A-1-b, A-2-4, A-2-6, and A-2 were observed to be within the typical published subgrade modulus ranges. On the other hand, the mean moduli for soil types A-3, A-4, A-6, A-7-5, and A-7-6 were estimated to be greater than the typical modulus ranges, as indicated with the gray shading in the table. Those soil types which agreed with the typical modulus range are all coarse granular materials. Since this analysis was heavily dependent upon the raw FWD deflection data from the LTPP database, it implies that the testing method applied in this study could be sensitive to fine-grained subgrade materials. Furthermore, all other factors which could affect output of FWD testing but were not considered in this study might contribute to the erratic results, especially for fine-grained subgrade materials in stiffness and modulus estimation. Nevertheless, it could be generally concluded that stiffness and modulus estimation for coarse-granular subgrade materials showed good or acceptable results.

Based on the comparison results shown in above tables, the estimated modulus at the 25% of interquartile ranges generally showed a good agreement with the published values, with exceptions of A-4 and A-7-6. The modulus for A-7-6 was expected to be the lowest among other soil types, due to its high plasticity index based on the AASHTO classification system, but the modulus for A-7-6 was estimated to be the highest among fine-grained soils. This unrealistic estimation could be from incorrect testing or non-uniformity of subgrade materials for the tested section.

It was also noted that soil types tested from fewer testing sections showed relatively higher modulus values. As Table 6 illustrated, AASHTO soil types A-1-a, A-2, A-3, A-7-5 and A-7-6 were tested from only one LTPP test section for each soil type. Among those soil types, A-2, A-3, A-7-5 and A-7-6 soils were found to have values that were either close or over the highest limits of typical published values. This evidences that more FWD deflection data for the same types of soils should be analyzed to reinforce the results in this study.

As presented in Chapter 4, European countries such as Germany and France specify the minimum surface elastic modulus for verification of compacted subgrade in the pavement. Germany specifies the minimum surface modulus of the subgrade to be 45 MPa (6.5 Ksi), while France requires a minimum surface modulus of 50 MPa (7.3 Ksi). Those European specification requirements in terms of elastic stiffness were compared with the analysis results in this study. Among different AASHTO soil types, A-7-5 showed the lowest subgrade modulus of 12.0 ksi (82.7 MPa) at the 25% of the interquartile range, which is higher than the surface moduli specified either in Germany or France.

7.2 Base Stiffness and Modulus

Table 11 and Table 12 present the statistical summary of base stiffness and modulus estimated in this study in English and metric units, respectively. Based on various references and publications, the presumptive modulus for unbound granular base materials typically ranges from 10 ksi (69 MPa) to 160 ksi (1100 MPa) for base and from 10 ksi (69 MPa) to 100 ksi (690 MPa) for subbase. In this analysis, base moduli over 100 ksi (690 MPa) were regarded as outliers and excluded. Also, any base modulus value which was lower than the corresponding subgrade modulus was excluded in this analysis. Figure 10 and Figure 11 show histograms for base stiffness and base modulus, respectively. Table 13 summarizes base stiffness and modulus for each test section selected.

From Table 12 and 13, the mean base stiffness and the mean base modulus were 571,795 lb/in (100.14 MN/m) and 54 ksi (372.6 MPa), respectively. The mean base modulus estimated here fell within the presumptive modulus range.

Table 11. Summary of base stiffness and modulus results statistics (English units).

			Statistic	Std. Error
Base Stiffness (lb/in)	Mean		571795	12224
	95% Confidence Interval for Mean	Lower Bound	547757	
		Upper Bound	595833	
	5% Trimmed Mean		563165	
	Median		517647	
	Std. Deviation		234819	
	Minimum		174591	
	Maximum		1133933	
	Range		959342	
	Interquartile Range		342655	
	Skewness		0.578	0.1270
	Kurtosis		-0.536	0.2533
Base Modulus (ksi)	Mean		54.0	1.16
	95% Confidence Interval for Mean	Lower Bound	51.8	
		Upper Bound	56.3	
	5% Trimmed Mean		53.2	
	Median		48.9	
	Std. Deviation		22.2	
	Minimum		16.5	
	Maximum		107.2	
	Range		90.7	
	Interquartile Range		32.4	
	Skewness		0.578	0.1270
	Kurtosis		-0.536	0.2533

Table 12. Summary of base stiffness and modulus results statistics (metric units).

			Statistic	Std. Error
Base Stiffness (MN/m)	Mean		100.14	2.14
	95% Confidence Interval for Mean	Lower Bound	95.93	
		Upper Bound	104.35	
	5% Trimmed Mean		98.63	
	Median		90.65	
	Std. Deviation		41.12	
	Minimum		30.58	
	Maximum		198.58	
	Range		168.01	
	Interquartile Range		60.01	
	Skewness		0.578	0.1270
	Kurtosis		-0.536	0.2533
Base Modulus (MPa)	Mean		372.6	8.0
	95% Confidence Interval for Mean	Lower Bound	357.0	
		Upper Bound	388.3	
	5% Trimmed Mean		367.0	
	Median		337.4	
	Std. Deviation		153.0	
	Minimum		113.8	
	Maximum		739.0	
	Range		625.2	
	Interquartile Range		223.3	
	Skewness		0.578	0.1270
	Kurtosis		-0.536	0.2533

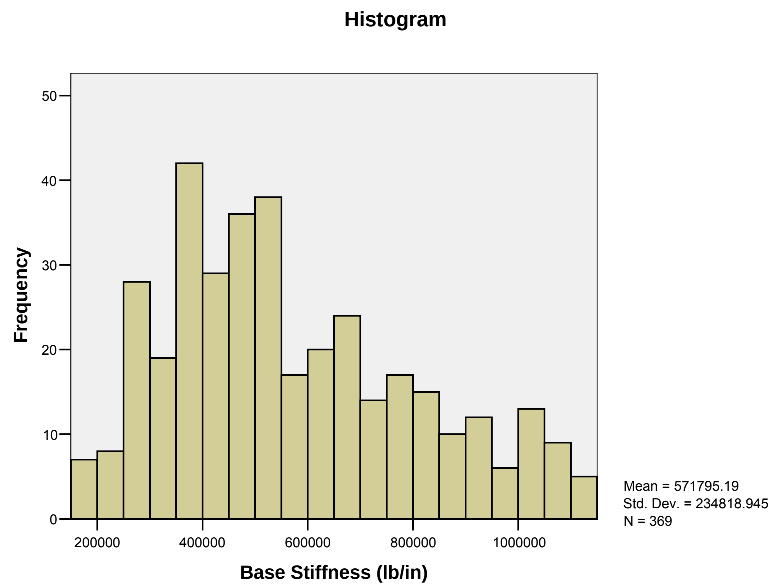

Figure 10. Histogram of base stiffness.

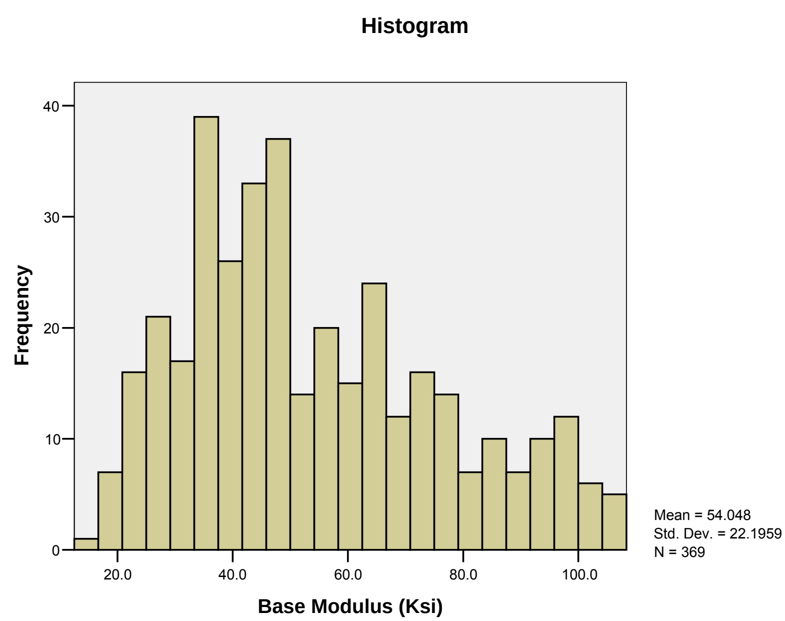

Figure 11. Histogram of base modulus.

Table 13. Summary of base stiffness and modulus for individual test sections.

State	SHRP_ID	M_Type	Base Stiffness		Base Modulus	
			(lb/in)	(MN/m)	(ksi)	(MPa)
AZ (4)	114	Crushed Stone, Gravel or slag	549760	96.28	52.0	358.3
	117	Crushed Stone, Gravel or slag	663866	116.26	62.8	432.7
	118	Crushed Stone, Gravel or slag	659861	115.56	62.4	430.0
	119	Crushed Stone, Gravel or slag	493087	86.35	46.6	321.4
	120	Crushed Stone, Gravel or slag	427531	74.87	40.4	278.6
	213	Crushed Stone, Gravel or slag	1098817	192.43	103.9	716.1
	214	Crushed Stone, Gravel or slag	678344	118.80	64.1	442.1
	215	Crushed Stone, Gravel or slag	494805	86.65	46.8	322.5
	216	Crushed Stone, Gravel or slag	435458	76.26	41.2	283.8
	221	Crushed Stone, Gravel or slag	757660	132.69	71.6	493.8
	222	Crushed Stone, Gravel or slag	495307	86.74	46.8	322.8
	223	Crushed Stone, Gravel or slag	665977	116.63	63.0	434.0
	224	Crushed Stone, Gravel or slag	580127	101.60	54.8	378.1
AR (5)	113	Crushed Stone, Gravel or slag	720428	126.17	68.1	469.5
	114	Crushed Stone, Gravel or slag	814716	142.68	77.0	531.0
	117	Crushed Stone, Gravel or slag	877639	153.70	83.0	572.0
	118	Crushed Stone, Gravel or slag	867129	151.86	82.0	565.1
	119	Crushed Stone, Gravel or slag	982449	172.05	92.9	640.3
	120	Crushed Stone, Gravel or slag	551699	96.62	52.1	359.6
	121	Crushed Stone, Gravel or slag	450856	78.96	42.6	293.8
CA (6)	201	Crushed Stone, Gravel or slag	727541	127.41	68.8	474.2
	202	Crushed Stone, Gravel or slag	779592	136.53	73.7	508.1
	203	Crushed Stone, Gravel or slag	609023	106.66	57.6	396.9
	204	Crushed Stone, Gravel or slag	685708	120.09	64.8	446.9
	209	Crushed Stone, Gravel or slag	838127	146.78	79.2	546.2
	210	Crushed Stone, Gravel or slag	696039	121.90	65.8	453.6
	211	Crushed Stone, Gravel or slag	956330	167.48	90.4	623.3
	212	Crushed Stone, Gravel or slag	1049659	183.82	99.2	684.1
	811	Crushed Stone, Gravel or slag	620473	108.66	58.6	404.4
	812	Crushed Stone, Gravel or slag	450802	78.95	42.6	293.8
CO (8)	215	Soil-Agg. Mix (Coarse-Grained)	593756	103.98	56.1	387.0
LA (22)	114	Crushed Stone, Gravel or slag	427028	74.78	40.4	278.3
	117	Crushed Stone, Gravel or slag	371334	65.03	35.1	242.0
	118	Crushed Stone, Gravel or slag	575347	100.76	54.4	375.0
	119	Crushed Stone, Gravel or slag	778266	136.30	73.6	507.2
	120	Crushed Stone, Gravel or slag	487438	85.36	46.1	317.7
NV (32)	101	Soil-Agg. Mix (Fine-Grained)	575112	100.72	54.4	374.8
	102	Soil-Agg. Mix (Fine-Grained)	612689	107.30	57.9	399.3
	105	Soil-Agg. Mix (Fine-Grained)	803705	140.75	76.0	523.8
	106	Soil-Agg. Mix (Fine-Grained)	955713	167.37	90.3	622.9
	108	Soil-Agg. Mix (Fine-Grained)	512537	89.76	48.4	334.0
	109	Soil-Agg. Mix (Fine-Grained)	485154	84.96	45.9	316.2

Table 13 continued.

State	SHRP_ID	M_Type	Base Stiffness		Base Modulus	
			(lb/in)	(MN/m)	(ksi)	(MPa)
OH (39)	101	Crushed Stone, Gravel or slag	489005	85.64	46.2	318.7
	102	Crushed Stone, Gravel or slag	275045	48.17	26.0	179.3
	105	Crushed Stone, Gravel or slag	256451	44.91	24.2	167.1
	107	Crushed Stone, Gravel or slag	342403	59.96	32.4	223.1
	109	Crushed Stone, Gravel or slag	373361	65.39	35.3	243.3
	201	Crushed Stone, Gravel or slag	572583	100.27	54.1	373.2
	202	Crushed Stone, Gravel or slag	363800	63.71	34.4	237.1
	204	Crushed Stone, Gravel or slag	735809	128.86	69.6	479.5
	209	Crushed Stone, Gravel or slag	784640	137.41	74.2	511.4
	210	Crushed Stone, Gravel or slag	510668	89.43	48.3	332.8
	211	Crushed Stone, Gravel or slag	264118	46.25	25.0	172.1
	902	Crushed Stone, Gravel or slag	264334	46.29	25.0	172.3
UT (49)	803	Soil-Agg. Mix (Coarse-Grained)	614907	107.69	58.1	400.7
	804	Soil-Agg. Mix (Coarse-Grained)	371922	65.13	35.2	242.4
WA (53)	202	Crushed Stone, Gravel or slag	617078	108.07	58.3	402.2
	203	Crushed Stone, Gravel or slag	469924	82.30	44.4	306.3
	204	Crushed Stone, Gravel or slag	551564	96.59	52.1	359.5
	209	Crushed Stone, Gravel or slag	355843	62.32	33.6	231.9
	210	Crushed Stone, Gravel or slag	355729	62.30	33.6	231.8
	211	Crushed Stone, Gravel or slag	276397	48.40	26.1	180.1
	212	Crushed Stone, Gravel or slag	421608	73.83	39.9	274.8

As can be seen from the equation 3 in Section 6.4, the Method of Equivalent Thickness (MET), which was used for the base modulus estimation, is heavily dependent upon the subgrade modulus as well as the layer thickness of subgrade and base. Since the subgrade modulus at the 25% interquartile range was reasonably acceptable compared to the mean modulus value, the same logic was applied for the base stiffness and modulus. Percentile values, including the interquartile ranges, for both base stiffness and base modulus were estimated and are presented in Table 14.

Table 14. Summary of base stiffness and modulus by percentile ranges.

		Percentiles						
		5	10	25	50	75	90	95
Base Stiffness	(lb/in)	252723	289810	387415	517647	730071	935055	1028862
	(MN/m)	44.26	50.75	67.84	90.65	127.85	163.75	180.17
Base Modulus	(ksi)	23.9	27.4	36.6	48.9	69.0	88.4	97.3
	(MPa)	164.7	188.9	252.5	337.4	475.8	609.4	670.6

The base stiffness and modulus at the 25% of interquartile range were 387,415 lb/in (67.8 MN/m) and 36.6 ksi (252.5 MPa), respectively. By comparing with the subbase surface modulus requirement specified in the German standards, this base modulus at 25% of the interquartile range appears to be reasonable.

From the LTPP database, three different base material types were specified for each test section: 1) crushed stone, gravel or slag, 2) coarse-grained soil-aggregate mixture, and 3) fine-grained soil-aggregate mixture. The majority of the base material type was of the first type. No other detailed information of each base material type was available in the LTPP database. Since soil gradation requirement for the base material is crucial and key to justifying the performance of the base layer, no further attempt to consider any variability in the soil particle size and material characteristics could be made in this study.

8 Correlations with Material Engineering Properties

For a correlation study of stiffness and modulus with other engineering properties of subgrade soils, another set of SPSS analyses was performed. Subgrade stiffness and modulus were estimated for each test section of the different states. The same data screening procedure as earlier described in stiffness estimation per AASHTO soil types was applied for this analysis. Since the grouping category for this correlation study was the test section instead of the AASHTO soil type, normality for each test section was checked individually and additional outliers within the deflection data of the test section were identified and removed.

Table 15 presents averaged stiffness and modulus values for individual test sections of different states. Only test sections with available AASHTO soil classification for subgrade materials were analyzed in this study. Classification of fine and coarse grained materials in the table was based on the percentage passing the no.200 sieve from the sieve analysis data and AASHTO soil types. AASHTO soil types A-1, A-2, and A-3, which have less than 35% of fine contents passing no.200 sieve, were classified as coarse-grained soils. All others were classified as fine-grained soils.

Engineering properties of subgrade soils were extracted from the LTPP testing modules, as described in Chapter 5. It should be noted that most of material property data utilized in this study were laboratory-determined, since in-situ testing data were generally not available in the LTPP database.

All test sections were classified as either fine- or coarse-grained material type and the representative subgrade modulus for each test section was plotted with different material properties to investigate any noticeable correlations for particular soil types.

Table 15. Subgrade Stiffness and Modulus by Individual Test Section

State	Test Section ID	AASHTO Soil Class	Fine/Coarse	Subgrade Stiffness		Subgrade Modulus	
				(lb/in)	(MN/m)	(ksi)	(MPa)
AZ (4)	113	A-1-b	Coarse	449,693	78.75	40.7	280.5
	114	A-2-4	Coarse	512,501	89.75	46.4	319.7
	115	A-1-b	Coarse	308,532	54.03	27.9	192.5
	116	A-1-b	Coarse	478,081	83.72	43.3	298.3
	117	A-1-b	Coarse	433,843	75.98	39.3	270.7
	118	A-2-6	Coarse	434,794	76.14	39.3	271.3
	119	A-1-b	Coarse	381,047	66.73	34.5	237.7
	120	A-1-b	Coarse	441,628	77.34	40.0	275.5
	122	A-1-b	Coarse	514,067	90.03	46.5	320.7
	123	A-1-b	Coarse	421,142	73.75	38.1	262.7
	124	A-1-b	Coarse	471,522	82.58	42.7	294.2
	160	A-1-a	Coarse	257,665	45.12	23.3	160.7
	213	A-2-4	Coarse	143,226	25.08	13.0	89.4
	214	A-2-4	Coarse	215,292	37.70	19.5	134.3
	216	A-2-4	Coarse	287,437	50.34	26.0	179.3
	217	A-2-4	Coarse	211,057	36.96	19.1	131.7
	220	A-1-b	Coarse	267,215	46.80	24.2	166.7
	222	A-2-6	Coarse	331,238	58.01	30.0	206.6
	223	A-2-4	Coarse	375,268	65.72	34.0	234.1
	224	A-4	Fine	242,959	42.55	22.0	151.6
	260	A-4	Fine	223,186	39.09	20.2	139.2
	261	A-2-4	Coarse	265,013	46.41	24.0	165.3
AR (5)	113	A-2	Coarse	573,175	100.38	51.9	357.6
	117	A-2-4	Coarse	656,150	114.91	59.4	409.3
	118	A-2-4	Coarse	378,219	66.24	34.2	236.0
	119	A-2-4	Coarse	588,938	103.14	53.3	367.4
	121	A-1-a	Coarse	350,134	61.32	31.7	218.4
	124	A-3	Coarse	689,358	120.73	62.4	430.1
CA (6)	202	A-2-4	Coarse	207,511	36.34	18.8	129.5
	203	A-1-b	Coarse	194,500	34.06	17.6	121.3
	204	A-2-4	Coarse	206,948	36.24	18.7	129.1
	206	A-2-4	Coarse	178,669	31.29	16.2	111.5
	207	A-2-4	Coarse	189,198	33.13	17.1	118.0
	210	A-2-4	Coarse	192,252	33.67	17.4	119.9
	211	A-2-4	Coarse	209,105	36.62	18.9	130.5
	212	-	-	198,462	34.76	18.0	123.8
	811	A-2-4	Coarse	215,395	37.72	19.5	134.4
	812	A-2-4	Coarse	196,082	34.34	17.7	122.3
	A805	A-2-4	Coarse	230,580	40.38	20.9	143.9
	A806	A-2-4	Coarse	217,661	38.12	19.7	135.8
CO (8)	213	-	-	181,303	31.75	16.4	113.1
	214	-	-	229,960	40.27	20.8	143.5
	215	A-6	Fine	223,007	39.05	20.2	139.1
	216	-	-	152,405	26.69	13.8	95.1
	218	A-6	Fine	126,156	22.09	11.4	78.7
	219	A-2-4	Coarse	129,202	22.63	11.7	80.6
	221	A-6	Fine	171,606	30.05	15.5	107.1
	222	A-2-6	Coarse	121,431	21.27	11.0	75.8
	223	A-2-4	Coarse	212,224	37.17	19.2	132.4
	224	A-6	Fine	95,914	16.80	8.7	59.8
MS (28)	806	A-6	Fine	300,835	52.68	27.2	187.7

Table 15 continued.

State	Test Section ID	AASHTO Soil Class	Fine/Coarse	Subgrade Stiffness		Subgrade Modulus	
				(lb/in)	(MN/m)	(ksi)	(MPa)
MT (30)	116	A-2-4	Coarse	57,669	10.10	5.2	36.0
	117	A-2-4	Coarse	88,182	15.44	8.0	55.0
	119	A-2-4	Coarse	82,778	14.50	7.5	51.6
	122	A-2-4	Coarse	57,982	10.15	5.2	36.2
	124	A-4	Fine	56,143	9.83	5.1	35.0
	805	A-1	Coarse	418,854	73.35	37.9	261.3
	806	A-1	Coarse	230,839	40.43	20.9	144.0
NV (32)	101	A-2-4	Coarse	302,273	52.94	27.4	188.6
	105	A-4	Fine	295,820	51.81	26.8	184.6
	106	A-4	Fine	325,374	56.98	29.4	203.0
	107	A-6	Fine	288,136	50.46	26.1	179.8
	109	A-4	Fine	388,067	67.96	35.1	242.1
	111	A-4	Fine	340,104	59.56	30.8	212.2
	201	A-2-4	Coarse	304,242	53.28	27.5	189.8
	204	A-4	Fine	358,749	62.83	32.5	223.8
	205	A-7-6	Fine	324,683	56.86	29.4	202.6
	206	A-4	Fine	299,816	52.51	27.1	187.0
	207	A-4	Fine	199,811	34.99	18.1	124.7
	210	A-4	Fine	291,375	51.03	26.4	181.8
	211	A-4	Fine	278,790	48.82	25.2	173.9
OH (39)	106	A-6	Fine	265,498	46.50	24.0	165.6
	107	A-6	Fine	275,139	48.18	24.9	171.6
	108	A-6	Fine	282,308	49.44	25.5	176.1
	110	A-6	Fine	192,332	33.68	17.4	120.0
	111	A-6	Fine	278,204	48.72	25.2	173.6
	159	A-6	Fine	102,117	17.88	9.2	63.7
	160	A-6	Fine	282,370	49.45	25.5	176.2
	202	A-6	Fine	286,170	50.12	25.9	178.5
	205	A-6	Fine	151,314	26.50	13.7	94.4
	207	A-6	Fine	251,336	44.02	22.7	156.8
	209	A-6	Fine	165,191	28.93	14.9	103.1
	210	A-6	Fine	149,168	26.12	13.5	93.1
	211	A-6	Fine	228,062	39.94	20.6	142.3
	809	A-7-5	Fine	203,835	35.70	18.4	127.2
	810	A-6	Fine	161,503	28.28	14.6	100.8
UT (49)	803	A-6	Fine	370,879	64.95	33.6	231.4
	804	A-6	Fine	412,255	72.20	37.3	257.2
WA (53)	259	A-4	Fine	164,209	28.76	14.9	102.4
	801	A-4	Fine	412,025	72.16	37.3	257.0
	802	A-4	Fine	321,436	56.29	29.1	200.5
	A809	A-4	-	90,549	15.86	8.2	56.5
	A810	A-4	Fine	114,407	20.04	10.4	71.4

8.1 Subgrade Modulus vs. Moisture Content

The moisture content of subgrade soils is probably the most influential factor to determine the subgrade modulus accurately. Ideally, in-situ measurement of moisture content directly from the compacted subgrade soil at the time of FWD testing would provide a clearer picture of the correlation between the subgrade modulus and the moisture content. Figure 12 and Figure 13 show a plot of the subgrade modulus as calculated based on elastic theory versus moisture content for coarse- and fine-grained soils, respectively.

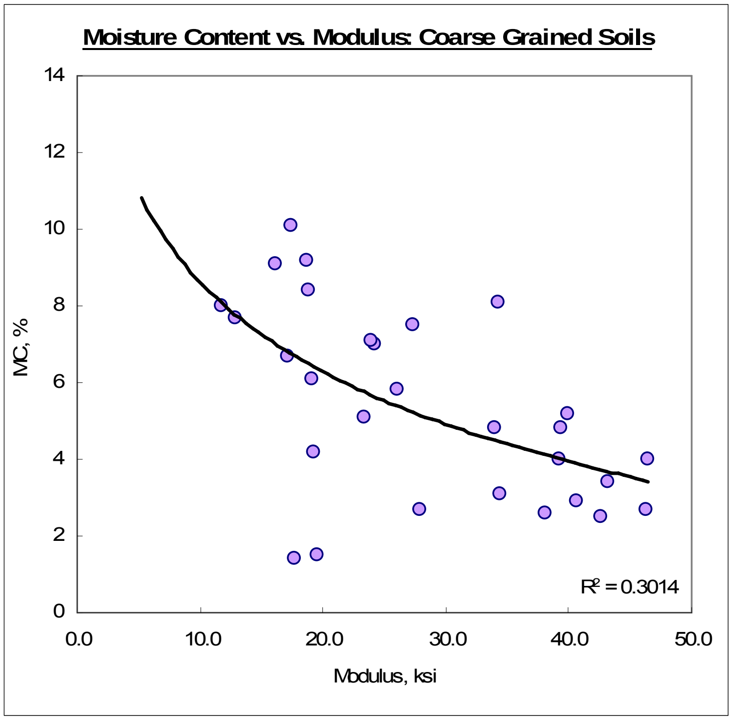

Figure 12. MC (Moisture Content) versus subgrade modulus for coarse-grained soils (1 ksi = 6.89 MPa)

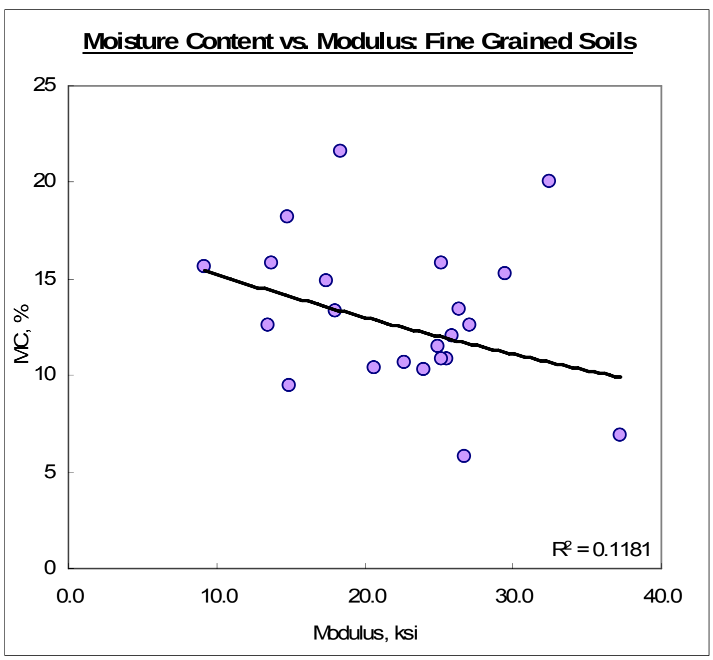

Figure 13. MC (Moisture Content) versus subgrade modulus for fine-grained soils (1 ksi = 6.89 MPa)

From Figure 12, it could be seen that the subgrade modulus for coarse granular soils generally increased as moisture content decreased to around 4%. However the two driest readings, at about 2% moisture content, had significantly lower modulus than those at around 3-4% moisture content. This trend can also be seen in Figure 14, which is a plot of the difference between optimum moisture content and natural moisture content versus subgrade modulus. The modulus of coarse-grained soils increased as the soil became drier. For fine-grained soils, no such noticeable correlation was found in this study.

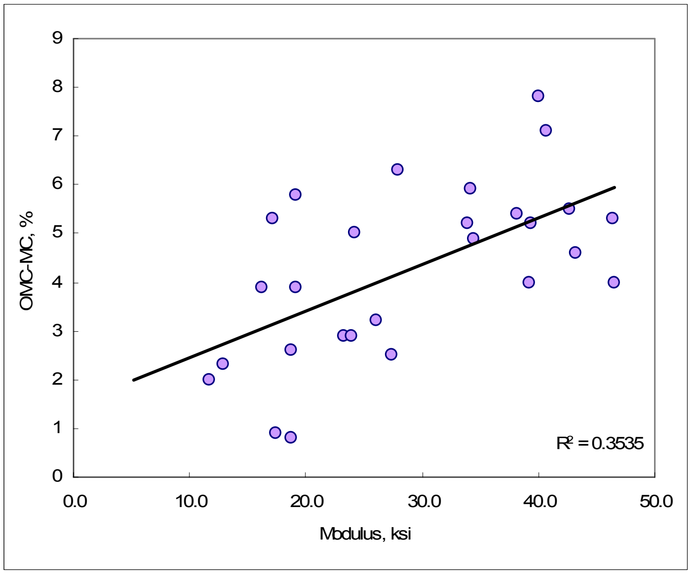

Figure 14. OMC-MC (Optimum Moisture Content – Natural Moisture Content) versus subgrade modulus for coarse-grained soils (1 ksi = 6.89 MPa)

8.2 Subgrade Modulus vs. Maximum Dry Density

The dry density of soils is another key parameter in correlating with subgrade modulus. Like moisture content data, not enough dry density data were available in the LTPP database. Therefore, the maximum dry density values from the LTPP material testing module TST_UG05_SS05 for the standard Proctor tests were utilized to examine the general trend of modulus variation by the dry density.

Figure 15 and Figure 16 present plots between the subgrade modulus and the maximum dry density for coarse- and fine-grained soils, respectively. Again, coarse-grained soils showed a stronger correlation of modulus increase with the increased maximum dry density.

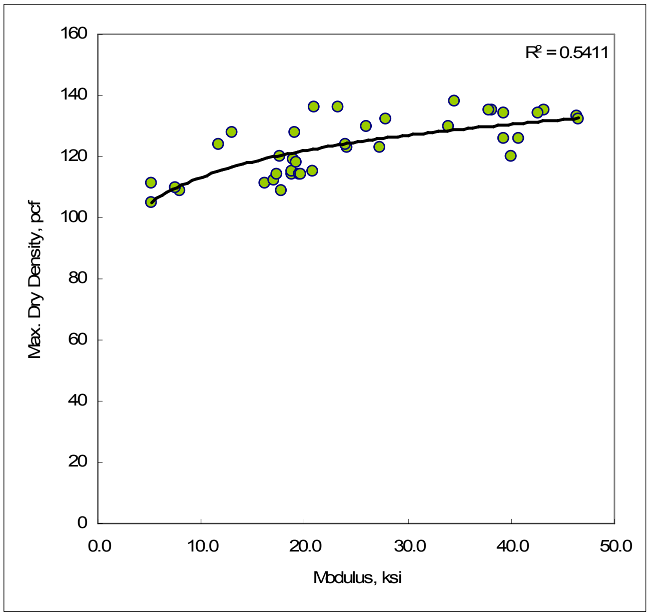

Figure 15. Maximum dry density versus subgrade modulus of coarse-grained soils (1 ksi = 6.89 MPa; 1 pcf = 1 kg/m³)

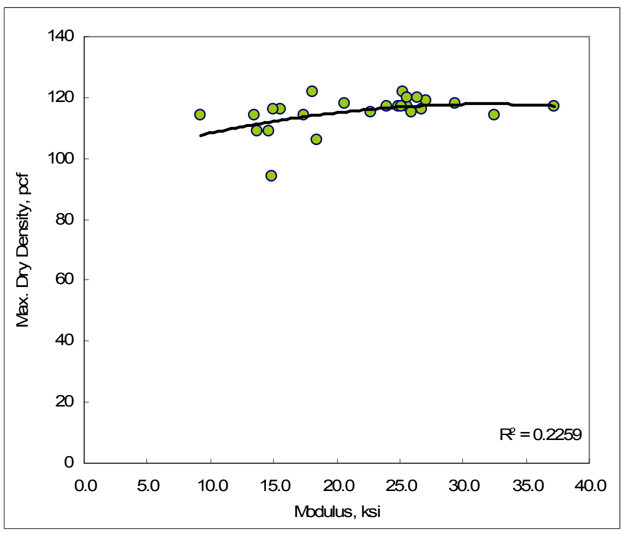

Figure 16. Maximum dry density versus subgrade modulus of fine-grained soils (1 ksi = 6.89 MPa; 1 pcf = 1 kg/m³)

8.3 Subgrade Modulus vs. Plasticity Index

Plasticity index (PI) is another key soil engineering property, especially for fine-grained soils because fine- and coarse-grained soils are classified based on this property in addition to grain size distribution. A correlation between plasticity index and the subgrade modulus was examined for fine-grained soils only, as plotted in Figure 17.

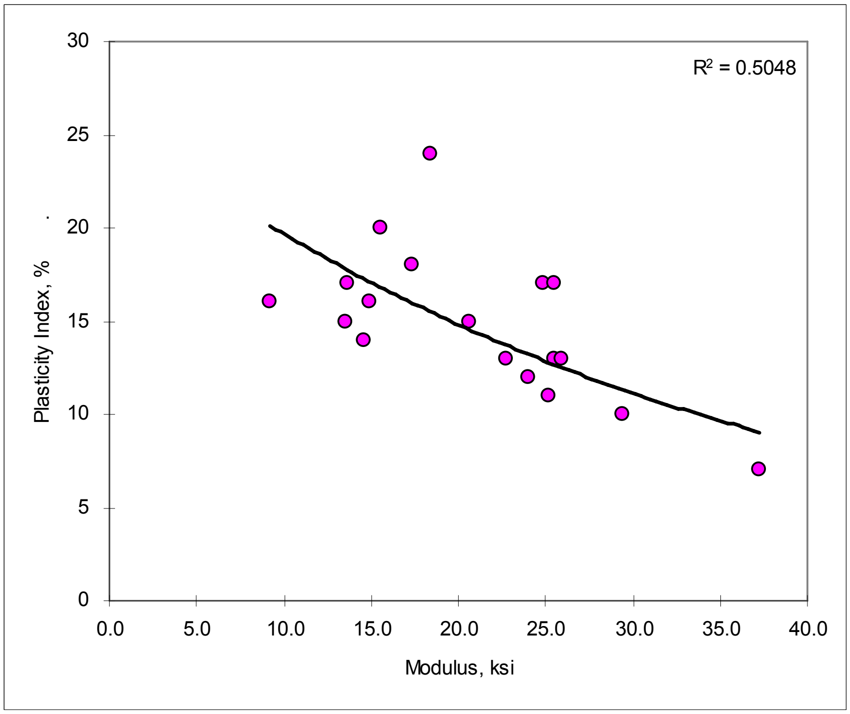

Figure 17. Plasticity index versus subgrade modulus for fine-grained soils (1 ksi = 6.89 MPa)

The subgrade modulus had a relatively clear relationship with PI, showing a decrease of the modulus with increasing PI. It is commonly known that higher plasticity of the subgrade soil causes instability of the subgrade, especially when water infiltrates the soil.

In addition to plasticity, the fine content of subgrade soils can be another controlling factor in determining the subgrade modulus. In general, the fine content of soils is determined by the percentage passing the No. 200 sieve from the sieve analysis.

In the NCHRP Report 1-37A "Guide for Mechanistic-Empirical Design of New and Rehabilitated Pavement Structures", by ERES Consultants Division [ERES Consultants Division, 2004], a weighted plasticity index, termed wPI, was used for soils with a PI>0 by multiplying two index properties of soils, plasticity index (PI) and the fine content percentage passing No. 200 sieve, which characterize the fine grained soils.

$$wPI = \text{Fraction Passing No. 200} \times \text{Plasticity Index} = P_{200} \times PI$$

with P_{200} as a decimal and PI in %

This wPI was calculated and plotted together with the subgrade modulus, as presented in Figure 18. Again, the subgrade modulus tends to decrease exponentially with increased wPI index.

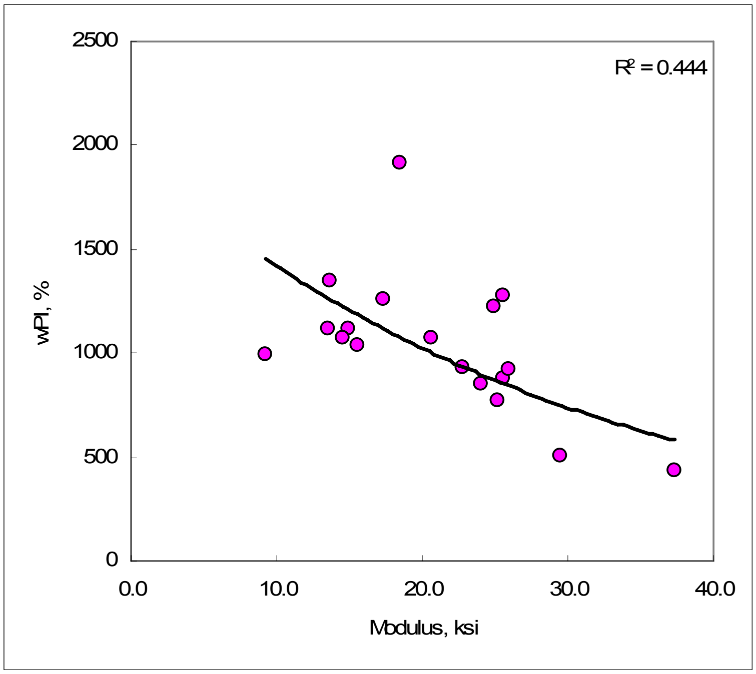

Figure 18. wPI (weighted plasticity index) versus subgrade modulus of fine-grained soils (1 ksi = 6.89 MPa)

8.4 Subgrade Modulus vs. Grain Size Distribution

A relationship between subgrade modulus and grain size distribution was examined for both coarse- and fine-grained soils. For each soil type, the percentages of soil particles passing No. 200, 40, 10, and 4 sieves were plotted versus the subgrade modulus. Figure 19 and Figure 20 present plots of grain size distribution to the subgrade modulus for coarse- and fine-grained soils, respectively.

For coarse-grained soils, trend lines for individual sieves showed increased modulus with less percent passing on larger opening sieves. In other words, the higher soil modulus would be expected when more soil particles are retained in the larger opening size sieves. The variation in the soil modulus was especially sensitive with the percent change of soil particles passing the No. 40 sieve, compared to other sieves. The percent change of soil particles passing No. 200 sieve had no influence on soil modulus variation when the percent passing was less than approximately 30%.

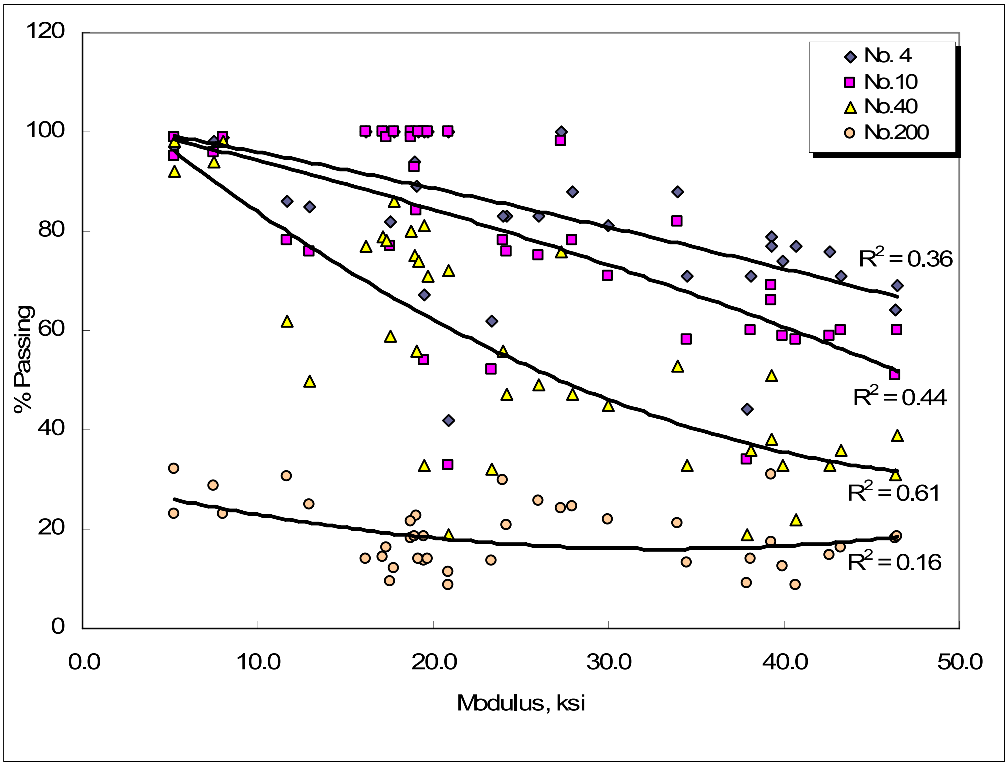

Figure 19. Grain size distribution versus subgrade modulus for coarse-grained soils (1 ksi = 6.89 MPa)

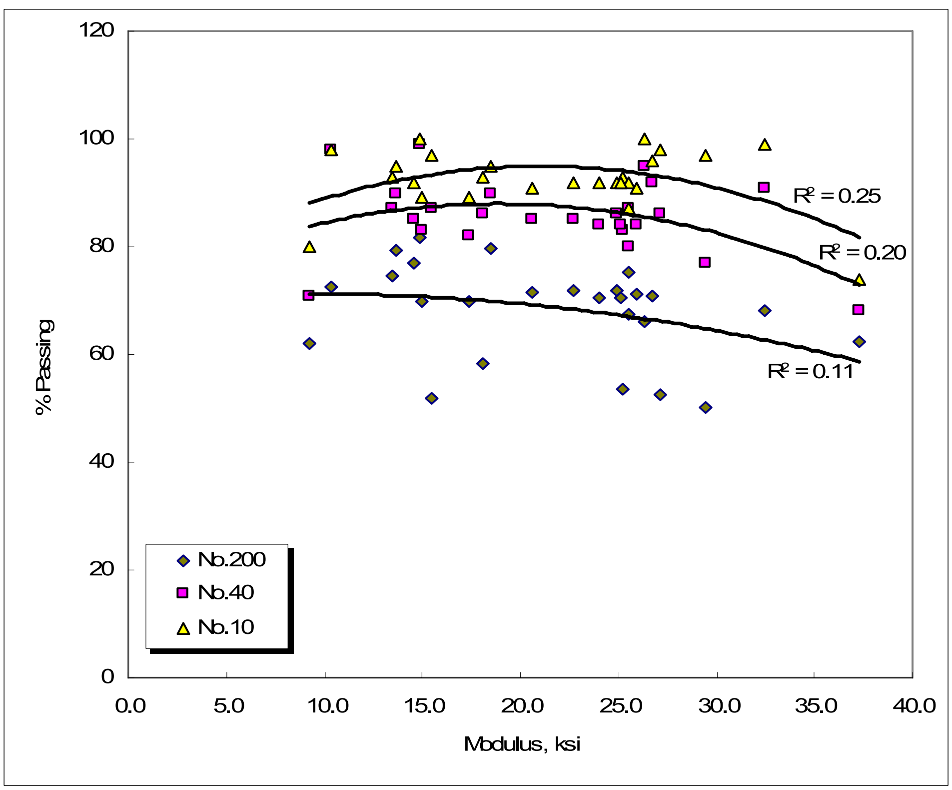

Figure 20. Grain size distribution versus subgrade modulus for fine-grained soils (1 ksi = 6.89 MPa)

Figure 19 also illustrated that well-graded soil distribution tends to have higher soil modulus values. The right side of the plot indicated well-graded soil particle distribution and the corresponding soil modulus was the highest. The left side of the plot showed poorly-graded soil distribution with lower soil modulus values.

In Figure 20, no clear correlation between soil modulus and grain size distribution of fine-grained soils was observed. Since the fine content of these soils passing no.200 sieve was more than 50% in all cases, sieves with larger mesh opening sizes had no effect or control on soil modulus variation. As previously discussed, the influence on soil modulus by the percent of soil particles passing the No. 200 sieve could be found from the dependence of subgrade modulus on wPI shown in Figure 18.

9 Summary and Conclusions

9.1 General Summary of Study

The current study was conducted to estimate soil stiffness and subgrade modulus for different subgrade soil types using falling weight deflectometer (FWD) deflection data from the LTPP studies. As a viable alternative for current compaction control based on the maximum dry density, subgrade stiffness and modulus can illustrate overall performance of pavement subgrade.

In this study, selected state DOT compaction specifications in terms of the maximum dry density and moisture content and current practices of subgrade preparation requirement by several European countries were reviewed. After a brief description of the Long Term Pavement Performance Program (LTPP), more detailed procedures of data selection and extraction from the LTPP database were presented. Data screening on center-deflection D1 data was performed based on the validation of elasticity on measured deflection basins. More in-depth analysis for data screening was performed using the statistical software package SPSS to identify the distribution of data per soil type and the outliers to be removed. From the screened data, stiffness and elastic moduli for different AASHTO soil types were estimated. Various statistical analyses were performed to estimate the appropriate ranges of stiffness and modulus for different soils, and those values were compared with the published typical values.

Representative stiffness and modulus values were estimated for individual test sections from different states that were evaluated in this study. Modulus values for each test section were correlated with available engineering property data of the sections to validate the output results in this study.

9.2 Conclusions

Based on the results obtained in this investigation, the following conclusions can be made:

- The screening procedure of raw deflection data was essential to improve the quality and reliability of the results. Considering the large variation of in-situ deflection data, this procedure had to be carefully performed.
- Even after the careful data screening procedures, FWD deflection data in the LTPP database were highly inconsistent and irregular, as skewed or uniform distribution of data indicated during the statistical analysis. This might be due to the inherent nature of FWD deflection data.
- Estimated stiffness and modulus of coarse-grained soils fell within the acceptable range of published typical values given in other references. These coarse grained soil types

included A-1, A-1-a, A-1-b, A-2, A-2-4, and A-2-4 under the AASHTO soil classification system.

- Calculated stiffness and modulus for fine-grained soils did not agree with the typical published values from other references.
- Calculated mean base stiffness and modulus were 571795 lb/in (100 MN/m) and 54 ksi (373 MPa), respectively, which fall well within the typical published values for unbound granular base materials.
- Due to unavailability or insufficiency of in-situ measurement data of soil properties, laboratory determined soil property data had to be substituted to make correlations with estimated subgrade modulus, reducing the reliability of the resulting analysis.
- The subgrade modulus for coarse-grained soils increased as the soil became drier, but sharply decreased when soil became too dry.
- A correlation between plasticity index and the subgrade modulus for fine-grained soil indicated that soil modulus was sensitive to the plasticity index. The similar results were found from correlation of the subgrade modulus with the weighted plasticity index. The results implied that both plasticity and amount of fines in fine-grained soils highly influenced the subgrade modulus.
- For coarse-grained soils, the higher soil modulus would be expected when larger soil particles are retained more in the large opening size sieves. Also, the soil modulus was higher when the soil was well-graded.
- Overall, stiffness and modulus estimated for coarse-grained soils showed a good agreement and reliability with other soil properties.
- For practical purposes, subgrade stiffness and soil modulus values at the 25^{th} percentile could be considered as the minimum limiting criteria for AASHTO soil types A-1, A-1-a, A-1-b, A-2-4, and A-2-6. Similarly, base stiffness and base modulus values at the 25% percentile appear to be reasonable as a minimum criterion.
- The stiffness and modulus for both subgrade and base were over the minimum requirement specified in the European standards. This result also satisfies the fact that all deflection data for subgrade and base analyzed in this study were from pavement sections with acceptable and approved compaction during construction.
- For all other AASHTO soil types, more detailed examination of individual deflection data and studies on field test history might be needed for further evaluation.

9.3 Implementation

The main objective of this study is to draw initial estimation of elastic stiffness and modulus for various unbound granular subgrade and base materials using FWD deflection data as performance-based criteria for compaction quality assurance and quality control (QA/QC).

As stated in the previous chapters, not enough supporting information such as subgrade preparation histories, compaction rates achieved, extensive data of in-situ density-moisture measurement by the nuclear density gauge, etc. was available in the LTPP database. For this reason, the basic assumption made in this study was that all subgrades in the LTPP program were prepared in accordance with the minimum compaction requirement of state DOTs' specifications.

In pavement engineering, the interquartile range (IQR) is often used instead of the confidence interval to identify outliers and estimate a statistically meaningful range of field measured data, due to a major drawback of unknown mean and standard deviation of population in confidence interval estimation.

In Table 10 and Table 11, the 25%, 50% and 75% interquartile ranges (IQR) of the estimated stiffness and the modulus of subgrade soils were presented as well as the mean, minimum and the maximum values. By comparing those statistical categories with the typical published values in Figure 9, 25% of IQR, the lowest limit of the box plots in Figure 7 and Figure 8 provided the most reliable values amongst other statistical categories. At this early stage of stiffness estimation as a compaction control parameter, these values at 25% of IQR should be generally interpreted as the minimum achievable limit of the subgrade stiffness. As a summary, subgrade stiffness and modulus at 25% IQR are presented in Table 16.

Table 16. Summary of Subgrade Stiffness and Modulus at 25% interquartile range

Soil Type	Stiffness at 25% IQR		Modulus at 25% IQR	
	(lb/in)	(MN/m)	(ksi)	(MPa)
A-1-a	284894	49.9	25.8	177.7
A-1-b	282292	49.5	25.5	176.1
A-1	260630	45.7	23.6	162.6
A-2-4	180517	31.6	16.3	112.6
A-2-6	170054	29.8	15.4	106.1
A-2	557422	97.7	50.4	347.8
A-3	602934	105.6	54.6	376.2
A-4	212741	37.3	19.2	132.7
A-6	154185	27.0	14.0	96.2
A-7-5	132521	23.2	12.0	82.7

The minimum achievable limit would imply that those subgrade stiffness and modulus values can be expected to be reasonably achieved if compaction work during subgrade preparation is practiced as required in the state DOT's specifications. For AASHTO soil types A-1, A-1-a, A-1-b, A-2-4, and A-2-6, which are all coarse-grained soils, stiffness and modulus values at 25% IQR should have higher reliability. For soil types A-2, A-3, A-4, A-6, and A-7-5, on the other hand, values were close to or slightly over the highest limit of the typical published ranges, even though most of those values were still within the ranges. Therefore, values for those soil types have low reliability and should be interpreted with a caution. Analysis results for A-7-6 were inconclusive and no recommendation was made for this soil type in this stage of the study.

To determine more practical stiffness based criteria for compaction quality control, additional correlative studies with data from other testing methods will be necessary. Since the density-moisture content relationship currently used in compaction control is determined by laboratory testing, modulus from laboratory tests should be compared with results in this study. Also, correlations with elastic modulus by backcalculation and interpretation of Dynamic Cone Penetrometer (DCP) data will enhance the reliability and practicability of the results in this study.

10 References

1. American Association of State Highway and Transportation Officials (AASHTO), (1993) *Guide for design of pavement structures*, Vol. II, Joint Task Force on Pavements, Highway Subcommittee on Design, Washington DC, 1993.
2. Chai, G., and N. Roslie, "The Structural Response and Behavior Prediction of Subgrade Soils Using Falling Weight Deflectometer in Pavement Construction", *3rd International Conference on Road and Airfield Pavement Technology*, April 1998.
3. Collop, A.C., R.J. Armitage, and N.H. Thom, "Assessing Variability of In Situ Pavement Material Stiffness Moduli" *ASCE Journal of Transportation Engineering*, Vol. 127, No. 1, Jan/Feb 2001, pp. 74-81.
4. ERES Consultants Division of ARA, Inc., Guide for Mechanistic-Empirical Design of New and Rehabilitated Pavement Structures, National Cooperative Highway Research Program report NCHRP1-37A, March 2004. Online at http://www.trb.org/mepdg/guide.htm (accessed March 28, 2006).
5. George, K.P., M. Bajracharya, and R. Stubstad, "Subgrade Characterization Employing The Falling Weight Deflectometer." *Transportation Research Record.* 1849, Transportation Research Board, Washington, D.C., 2004.
6. Great Britain Department for Transport, Design Manual for Roads and Bridges (DMRB) Volume 8, Great Britain Department for Transport, Highways Agency, London , October 1994.
7. "Guide for Mechanistic-Empirical Design of New and Rehabilitated Pavement Structures" Part 2. Design Input – NCHRP Final Report, March 2004.
8. Haegeman, W., "In Situ Assessment of Stiffness of a Road Sand Embankment" *Proceedings of 6th International Conference, Bearing Capacity of Roads, Railways and Airfields*, Vol. 2, 2002, pp. 629-635.
9. Kenis, W. J., and Wang, W., *Analysis of Pavement Structural Variability*, Final Report FHWA-RD-97-072; 3C4A, Federal Highway Administration, McLean, VA,1997.
10. National Asphalt Pavement Association, Guidelines For Use of HMA Overlays to Rehabilitate PCC Pavements, Pavement Consultancy Services, National Asphalt Pavement Association, Series 117, 1994.
11. Newcomb, D.E. and B. Birgisson, "Measuring In Situ Mechanical Properties of Pavement Subgrade Soils" *NCHRP Synthesis of Highway Practice 278*, Transportation Research Board, Washington DC, 1999.
12. Nunn, M.E., A. Brown, D. Weston, and J.C. Nicholls, "Design of Long Life Flexible Pavements for Heavy Traffic", TRL Report 250, Transportation Research Laboratory, United Kingdom, 1997.
13. Ohio Department of Transportation, Division of Production Management, Office of Geotechnical Engineering, "Plan Subgrades", Geotechnical Bulletin GB 1, Ohio Department of Transportation, Columbus OH, June 29, 2005, available online at http://www.dot.state.oh.us/geotechnical/Docs/GB1%2006-29-05.pdf#search=%22Ohio%20Geotechnical%20Bulletin%201%3A%20Plan%20Subgrades%22, accessed August 23, 2006.
14. Ooi, P.S.K., and J. Pu, "Use of Stiffness for Evaluating Compactness of Cohesive Pavement Geomaterials." *Transportation Research Record.* 1849, Transportation Research Board, Washington, D.C., 2003, pp. 11-19.
15. Ooi, P.S.K. and Jianping Pu, "Evaluating Compaction of Tropical Soils Using Soil Stiffness" *Proceedings of 6th International Conference, Bearing Capacity of Roads, Railways and Airfields*, Vol. 2, 2002, pp. 1143-1150.
16. Rahim, A., and K.P. George, "Falling Weight Deflectometer for Estimating Subgrade Elastic Moduli" *Journal of Transportation Engineering*, Vol. 129, No. 1, January 1, 2003, pp 100-107.

17. Salem, H., F.M. Bayomy, and M.G. Al-Taher, "Prediction of Seasonal Variation of Subgrade Resilient Modulus Using LTPP Data." *Transportation Research Record.* 1849, Transportation Research Board, Washington, D.C., 2003.
18. Sargand, S.M., W. Edwards, and S. Salimath, Evaluation of Soil Stiffness Via Non-Destructive Testing, Report for the Ohio Department of Transportation and Federal Highway Administration, Report No. FHWA/OH-2000/004, Ohio Research Institute for Transportation and the Environment, Ohio University, Athens, Ohio, June 2001.
19. Sargand, S.M., W. Edwards, and H. Kim, *Determination of Pavement Layer Stiffness on the Ohio SHRP Test Road Using Non-Destructive Testing Techniques*, Report for the Ohio Department of Transportation and Federal Highway Administration, Report Number FHWA/OH-2002/031, Ohio Research Institute for Transportation and the Environment, Ohio University, Athens, Ohio, 2002.
20. Von Quintus, H.L., and A. L. Simpson, "Back-Calculation of Layer Parameters for LTPP Test Sections: Volume II, Layered Elastic Analysis for Flexible and Rigid Pavements, FHWA-RD-01-113, Federal Highway Administration, McLean, VA, October 2002.

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