Nevada Department of Transportation

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Characterization of Unbound Materials for Mechanistic-Empirical Pavement Design for NDOT Districts 2 and 3

July 2022

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16. Abstract
The resilient modulus is a critical engineering property used to characterize the unbound and subgrade materials in the AASHTO Mechanistic Empirical Pavement Design Guide (MEPDG) where a hierarchical approach is followed. Three levels of input are specified in the AASHTOWare® Pavement ME design software. This includes direct measurement from the laboratory testing offering the highest level of accuracy (i.e., Level 1), estimated values using correlations with materials properties (i.e., Level 2), and typical values offering the lowest level of accuracy (i.e., Level 3). The major objective of this study is to develop resilient modulus models for new design and rehabilitation projects for NDOT Districts 2 & 3 to be used in the MEPDG.

Unbound and subgrade materials were sampled from Districts 2 & 3 and various testing were conducted to determine numerous properties and characteristics including; materials classification (AASHTO and USCS), R-value, moisture-density relations, unconfined compressive strength, and resilient modulus. The resilient modulus test was conducted according to AASHTO T 307 procedure. The stress dependent resilient modulus models were developed for the unbound and subgrade materials. In summary, the stress dependent behavior of the resilient modulus for base and borrow materials in NDOT Districts 2 & 3 were found to fit very well the theta model. Meanwhile, the stress dependent behavior of the resilient modulus for the subgrade materials fitted very well both the universal model and Uzan model. The MEPDG procedure was used to determine the design resilient modulus for the new design projects. On the other hand, for the rehabilitation projects, a new approach based on the simulation of FWD testing was developed in this research and implemented to determine the design resilient modulus. It was observed that the design resilient modulus of the subgrade layer is independent of the pavement structure while the design resilient modulus of the borrow and base layers are dependent on the pavement structure.

Based on the analyses of the data generated from this research, two different resilient modulus models were developed; a) for new pavement design and b) for rehabilitation pavement design. The statistical analyses of the generated data indicated that the design resilient modulus of the subgrade layer for new and rehabilitation projects can be estimated based on the R-value or the unconfined compressive strength properties. However, the design resilient modulus of the borrow and base layers for new and rehabilitation projects can only be estimated based on the R-value. This leads to the conclusion that the unconfined compressive strength is not a good indicator of the strength properties of the borrow and base layers and a confined compressive strength must be measured.

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SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

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

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
		TEMPERATURE (exact degrees)		
^oC	Celsius	1.8C+32	Fahrenheit	^oF
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

*SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380.
(Revised March 2003)

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CHAPTER 1. INTRODUCTION

The American Association of State Highway and Transportation Officials (AASHTO) adopted the Mechanistic-Empirical Pavement Design Guide (MEPDG) as an interim pavement design standard in 2008 (1). The MEPDG is currently being implemented in the AASHTOWare®Pavement ME design software. The Nevada Department of Transportation (NDOT) already started the implementation of the MEPDG for the structural design of flexible pavements (2). The MEPDG conducts advanced mechanistic analysis of the pavement structure while taking into consideration the combined contributions of; traffic, climate, and materials properties. Currently, NDOT has a MEPDG Design Guide that covers the various parts of the design process including an extensive database on the properties and performance of asphalt concrete mixtures. The next logical step in the NDOT implementation process for MEPDG is to develop a database on the properties of unbound materials used in the base, subbase (borrow), and subgrade layers. Earlier NDOT project entitled; "Characterization of Unbound Materials (Soils/Aggregates) for Mechanistic-Empirical Pavement Design Guide (MEPDG)," developed resilient modulus models for unbound materials located within District 1 (3).

The MEPDG follows a hierarchical approach in defining the required engineering properties of the pavement structure. Three levels of input are specified: 1, 2, and 3. Level 1 offers the highest level of accuracy while level 3 offers the lowest level of accuracy. In the case of unbound materials used in base, subbase, and subgrade layers, the required engineering properties include the resilient modulus (Mr) and Poisson's ratio (μ). Additional unbound materials properties include Atterberg limits, gradation, conductivity, and coefficient of lateral pressure.

Since the impact of Poisson's ratio on the response of the pavement structure to climate and traffic loads is insignificant, this property is typically assumed with a reasonable accuracy. However, the impact of Mr on the response of the pavement structure to the combined actions of climate and traffic loads is highly significant, therefore, the Mr value of each pavement layer must be accurately specified. Level 1 requires the Mr property to be measured in the laboratory under repeated load triaxial (RLT) conditions, level 2 allows the determination of Mr through correlations with other empirical properties of the unbound materials such as the Resistance value (R-value) or the California Bearing Ratio (CBR), and basic properties of the unbound materials such as Atterberg limits, gradation, etc…, and level 3 allows the use of Mr default values.

While the RLT provides a fundamental approach to characterize the nonlinear stress-dependent behavior of unbound materials, the test itself is time-consuming and costly. In light of these issues, most state highway agencies have elected to implement level 2 input for unbound materials. Therefore, a well-defined fundamental approach must be followed to establish highly reliable relationships to determine the Mr property of unbound materials encountered throughout Nevada from other properties that can be practically and reliably measured.

1.1. Objective and Scope

The objective of this research study is to develop prediction models for the design resilient modulus values of unbound materials to be used for new and rehabilitation projects in NDOT Districts 2 & 3. In order to achieve this objective, the following tasks have been conducted:

- Collect base, subbase (borrow), and subgrade representative materials commonly used in NDOT Districts 2 & 3.
- Conduct laboratory testing of the collected materials to evaluate the following properties; sieve analysis, Atterberg limit, moisture density relationship, R-value, unconfined compressive strength, and resilient modulus.
- Develop models for the stress-dependent resilient modulus of unbound materials.
- Identify the design resilient modulus values for new and rehabilitation projects.
- Develop prediction models for estimating design resilient modulus of unbound materials in Nevada for new and rehabilitation projects.

In addition to the main objective identified for this current research project, another objective was identified and completed as follows:

- Use the data generated under the previous research effort on unbound materials from NDOT District 1 in combination with the data generated under the current research effort on unbound materials from NDOT Districts 2 & 3 to develop statewide models to predict the design resilient modulus for unbound materials used in new and rehabilitation projects.

CHAPTER 2. BACKGROUND

NDOT's goal is to implement the MEPDG through a phased approach, similar to many other agencies. This phased approach includes building material libraries and tying some of the inputs to their day-to-day practices to minimize deviations from current practice and maximize the use of historical information and data. One of the input categories to the MEPDG is the characterization of all unbound layers and subgrades. The input parameters for the unbound layers include: resilient modulus, Poisson's ratio, dry density, water content, gradation, Atterberg limits, etc. The resilient modulus is considered a key input parameter that has a significant impact on the structural responses of a pavement structure, and thus affects its performance and design.

2.1. Hierarchical Input Levels of the MEPDG

Table 2.1 summarizes the input parameters and how they are determined as recommended in the MEPDG Manual of Practice (1). Most of the input parameters are well defined and commonly measured by the agency on a day-to-day basis for various reasons. Performing the repeated load resilient modulus test, however, is expensive and time consuming. In addition, the process of determining the design resilient modulus has been widely debated. As such, many agencies have expended resources to determine an appropriate procedure to estimate the design Mr for specific site features and design strategy.

The Mr is a required input for all unbound granular materials and subgrades. The Mr values are used in the structural response computation models and have a significant effect on the pavement responses and modulus of subgrade reaction (k-value) computed internally. The Mr can be measured directly from laboratory testing, or obtained through correlations with other material strength properties. There are three different levels of inputs for Mr and consist of the following:

- *Input Level 1 – Project Specific Measured Values:*

  The level 1 resilient modulus for unbound granular materials and subgrade are determined from repeated load triaxial tests. The test standards recommended for use are: AASHTO T 307 and NCHRP 1-28A. The Mr is estimated using a generalized constitutive model (Equation 1). The k coefficients are determined by using linear or nonlinear regression analyses to fit the model to the laboratory test results. The input level 1 procedure is applicable to new design, reconstruction and rehabilitation design.

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

Where;

Mr:	resilient modulus, psi
θ:	bulk stress, psi
σ_1:	major principal stress, psi
σ_2:	intermediate principal stress, psi
σ_3:	minor principal stress/confining pressure, psi
τ_{oct}:	octahedral shear stress, psi
P_a:	normalizing stress (atmospheric pressure), psi
k_1,k_2,k_3:	regression constants (obtained by fitting resilient modulus test data to equation)

In earlier versions of Pavement ME Design, the regression coefficients (*k_1, k_2, k_3*) could be entered directly into the software. The program used a finite element model for calculating pavement responses within the various unbound layers based on the nonlinear regression coefficient to determine the stress dependent resilient modulus appropriate for the in-place stress condition. Version 1.0 excluded the finite element model and a user could no longer enter the regression coefficients from a repeated load triaxial resilient modulus test. Thus, the design resilient modulus is entered directly in the program which is determined external to the software and only the linear response is considered in calculating the critical pavement responses. The in-place stress condition is determined by the user which should represent the value at the critical condition – higher damage rate.

- *Input Level 2 – Correlations with Other Material Properties or Tests*

  While the repeated load triaxial resilient modulus test provides a fundamental approach to characterize the nonlinear stress dependent behavior of unbound materials, the test itself is time-consuming and costly. In light of these issues, most state highway agencies have elected to implement level 2 input for unbound materials. Many existing correlations can be used to estimate the resilient modulus, and the correlations can be direct or indirect.

  Table 2.2 summarizes the correlations included in the Pavement ME design software. For input level 2 design, the user can input a representative Mr or use the enhance integrated climatic model to adjust the Mr for seasonal effects or input an Mr for each month of the year.

- *Input Level 3 – Typical Values based on Soil Classification or Local Experience*

  In level 3, typical M_r values are specified for different types of unbound materials or soils. These typical values can represent the global defaults or represent local experience. The global values are built into the software, are dependent on soil classification, and represent the Mr at the optimum water content and maximum dry unit weight. These values should be used with caution as they represent approximate values. Levels 1 and 2 input are recommended to achieve more representative materials behavior.

The following summarizes the values and data sources for characterizing the unbound layers or materials used by most agencies that have completed or are in the process of implementing the Pavement M-E software. The default values used become important when completing the calibration and validation of the distress transfer functions to ensure consistency of use.

- <u>Design Resilient Modulus</u>: Many agencies have generated resilient modulus databases for the aggregate base materials commonly specified by the agency and soils that are predominantly encountered within the agency's jurisdictions. Other agencies use correlations to CBR, R-value, materials physical properties, and dynamic cone penetrometer test results.

- <u>Dry Density and Water Content</u>: The software asks for the maximum dry unit weight and optimum water content but the values depend on how the test specimens were prepared and/or the condition of the test specimens for the correlations that the agency is using to estimate the Mr. For example, some agencies use the CBR to estimate the design Mr. A few of these agencies have run soaked CBR tests and measured the resilient modulus at the dry density and water content from the soaked CBR test, while other agencies have measured the resilient modulus at the dry density and water content before the specimen is subjected to water soaking during the CBR test. How the correlation was developed defines the input values. It is important that the dry density and water content entered into the software to be consistent with the method used to define the correlation regardless of what other test is used.

- Poisson's Ratio: Poisson's ratio is identified as an insignificant input parameter in terms of the predicted cracking and distortion type distresses, and is generally estimated. However, Poisson's ratio does have an impact on the selection of the design resilient modulus of any unbound layer because it affects the vertical and horizontal stresses – this is called the Poisson's ratio effect. Therefore, a reliable estimate of the Poisson's ratio based on experience is desired.

- At-Rest Lateral Earth Pressure Coefficient: This input parameter is no longer needed since the selection of the design resilient modulus is not part of the input level 1 in the current version of the Pavement ME Design software. However, the at-rest earth pressure coefficient is important in defining the design resilient modulus. At-rest earth pressure coefficients can vary from 0.50 to well over 1.0 depending on the condition of the soil or aggregate base layers. The coefficient has an impact on the lateral stress condition, which in turn affects the design resilient modulus.

- Gradation and Atterberg Limits: Most agencies define the average gradation, plasticity limit, and liquid limit for the commonly used aggregate base layers and predominant soils found within the agency's jurisdictions. The local default values are typically compared to the global default values included in the Pavement ME Design software to determine the difference between the two sets of values. Sometimes differences in the physical properties will explain some of the differences between the global and local design resilient moduli.

- Soil-Water Characteristic Curve Parameters: Just about all agencies have used the global default values which are soil classification dependent.

- Specific Gravity: All agencies have simply used the global default value of 2.7 included in the current version of the Pavement ME Design software for all soil classifications.

- Saturated Hydraulic Conductivity: All agencies have used the global default value in their implementation and local calibration studies, which are soil classification dependent.

Table 2.1. Unbound Aggregate Base, Subbase, Embankment, and Subgrade Soil Input Parameters and Test Protocols for New and Existing Materials.

Design Type	Measured Property	Source of Data		Recommended Test Protocol and/or Data Source
		Test	Estimate	
New (lab samples) and existing (extracted materials)	Determine the average design resilient modulus for the expected in-place stress state from laboratory resilient modulus tests.	X		The generalized model used in MEPDG design procedure – see equation 1; AASHTO T 307 or NCHRP 1-28A
	At-Rest earth pressure coefficient		X	No national test standard; value used external to the software.
	Poisson's ratio		X	No national test standard, use default values included in the MEPDG.
	Maximum dry density	X		AASHTO T 180
	Optimum moisture content	X		AASHTO T 180
	Gradation	X		Gradation of the unbound aggregate or embankment soil measured in accordance with AASHTO T 88
	Atterberg Limits	X		Liquid limit measured in accordance with AASHTO T 89, and plastic limit and plasticity index determined in accordance with AASHTO T 90.
	Specific gravity	X		AASHTO T 100
	Saturated hydraulic conductivity	X		AASHTO T 215
	Soil water characteristic curve parameters	X		Pressure plate (AASHTO T 99), OR Filter paper (AASHTO T 180), OR Tempe cell (AASHTO T 100)
Existing material to be left in place	FWD backcalculated modulus	X		AASHTO T 256 and ASTM D 5858
	Poisson's ratio		X	No national test standard, use default values included in the MEPDG.

Table 2.2. Models Relating Material Index and Strength Properties to Mr (4).

Strength/Index Property	Model	Comments	Test Standard
CBR	$M_r = 2555(CBR)^{0.64}$ (TRL) Mr, psi	CBR = California Bearing Ratio, percent	AASHTO T193, "The California Bearing Ratio"
R-value	$M_r = 1155 + 555R$ (*20*) Mr, psi	R = R-value	AASHTO T190, "Resistance R-Value and Expansion Pressure of Compacted Soils"
AASHTO layer coefficient	$M_r = 30000\left(\frac{a_i}{0.14}\right)$ (*20*) Mr, psi	a_i = AASHTO layer coefficient	AASHTO Guide for the Design of Pavement Structures
PI and gradation*	$CBR = \frac{75}{1+0.728(wPI)}$ (see Appendix CC)	wPI = P200*PI P200= percent passing No. 200 sieve size PI = plasticity index, percent	AASHTO T27. "Sieve Analysis of Coarse and Fine Aggregates" AASHTO T90, "Determining the Plastic Limit and Plasticity Index of Soils"
DCP*	$CBR = \frac{292}{DCP^{1.12}}$	CBR = California Bearing Ratio, percent DCP =DCP index, mm/blow	ASTM D 6951, "Standard Test Method for Use of the Dynamic Cone Penetrometer in Shallow Pavement Applications"

*Estimates of CBR are used to estimate M_r.

2.2. Overview of Resilient Modulus Test

The resilient modulus is similar to the elastic modulus of a material and is defined as a ratio of deviatoric stress to resilient or elastic strain experienced under repeated loading conditions that aims to simulate traffic loading. Figure 2.1 shows a representation of the resilient modulus. The main reason for using the resilient modulus as the parameter for unbound bases and subgrades is that it represents a basic material property and can be used in mechanistic analyses to calculate pavement responses used to predict different distresses (i.e. rutting, cracking, and roughness).

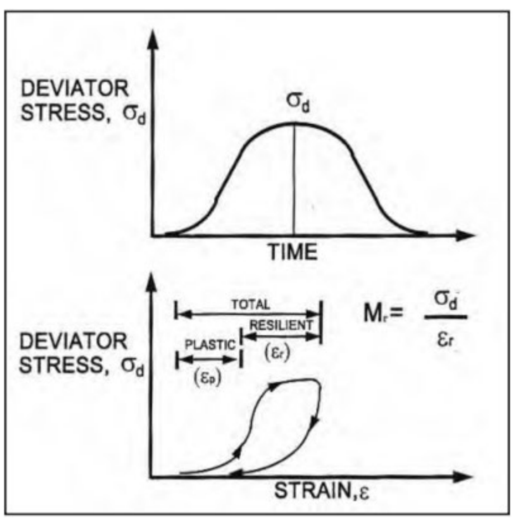


Figure 2.1. Definition of resilient modulus.

The resilient modulus test using the repeated load triaxial condition simulates traffic wheel loading on in-situ granular material by applying repeated or cyclic loads on compacted specimens. The stress levels applied to the specimens are dependent on the location of the material within the pavement structure. A confining pressure is also applied to the specimen that represents the overburden lateral pressure at a specific location in the pavement structure. The axial deviatoric stress consists of two components, the cyclic stress and a constant stress. The constant stress is typically equivalent to 10% of the total axial deviatoric stress.

The test procedure requires a compacted specimen using impact compaction methods. The specimen is then transferred into the triaxial chamber and the confining pressure is applied. The test is initiated by applying various levels of deviatoric stresses. Multiple confining pressures and deviatoric stresses are used during the testing process. The resilient modulus values are determined at each combination of confining pressure and deviatoric stress. The design resilient modulus value is established by determining the Mr value at the appropriate confining pressure and deviatoric stress level corresponding to the location of the materials within the pavement structure.

An earlier review of 30 state DOTs and other agencies specifications indicated that 22 out the 30 are currently using AASHTO T 307 test method for measuring the Mr of unbound materials.

2.3. Mr Models developed for NDOT District 1

As indicated earlier, in 2017 NDOT completed a research project entitled; "Characterization of Unbound Materials (Soils/Aggregates) for Mechanistic-Empirical Pavement Design Guide (MEPDG)." The objective of this research was to develop models to determine the design Mr values for unbound granular materials located throughout NDOT District 1 (3). The following models were recommended for inclusion in NDOT MEPDG Design Guide for flexible pavements:

- The design resilient modulus of the subgrade layer for new pavement designs can be predicted based on UCS or R-value from the following models.

$$\ln(Mr_{SG-New}) = 7.4514 + 0.0036*P\#200 - 0.0129*P\#3/8 + 0.0158*\gamma_d + 0.0973*UCS + 0.0311*PI$$

$$\ln(Mr_{SG-New}) = 3.1784 + 0.018*R\text{-value} + 0.0136*P\#40 + 0.0315*\gamma_d + 0.0433*PI$$

- The design resilient modulus of the subgrade layer for rehabilitation pavement designs can be predicted based on UCS or R-value from the following models.

$$\ln(Mr_{SG-Reh}) = 9.2335 + 0.0028*P\#200 - 0.0045*P\#3/8 - 0.0401*OMC + 0.0318*UCS + 0.0158*PI$$

$$\ln(Mr_{SG-Reh}) = 5.3982 + 0.0134*R\text{-value} + 0.0125*P\#40 - 0.0032*P\#3/8 + 0.0168*\gamma_d + 0.0177*PI$$

- The design resilient modulus of the base layer for new pavement and rehabilitation pavement designs can be predicted based on R-value from the following models.

$$\ln(Mr_{CAB-New}) = 7.3224 + 0.0366*R\text{-value} - 0.0656*P\#40 + 0.0256*P\#3/8 - 0.0893*OMC - 0.0270*H_{eq}$$

$$\ln(Mr_{CAB-Reh}) = 8.0140 + 0.0261*R\text{-value} - 0.0485*P\#40 + 0.0161*P\#3/8 - 0.0659*OMC - 0.0089*H_{eq}$$

- The design resilient modulus of the borrow layer for new pavement and rehabilitation pavement designs can be predicted based on R-value from the following models.

$$\ln (Mr_{BOR-New})=8.9671+0.0102*\text{R-value}+0.0123*P\#3/8 - 0.0743 * OMC - 0.0189 * H_{eq}$$

$$\ln (Mr_{BOR-Reh})=9.2304+0.0136*\text{R-value}-0.0229*P\#40+0.0079*P\#3/8 - 0.0661 * OMC - 0.0127 * H_{eq}$$

- The equivalent thickness (H_{eq}) is calculated for the layer being analyzed using the Equations below based on the depth of interest (D) for state of stress calculation.

$$H_{eqNew-CAB} = 2.2432 * D - 1.9263$$

$$H_{eqNew-Bor} = 1.3211 * D + 9.6409$$

$$H_{eqReh-CAB} = 2.399 * D - 1.7468$$

$$H_{eqReh-BOR} = 1.543 * D + 8.044$$

For example:

- New Design:
  - 5 inch of AC layer on top of 10 inch of CAB layer on top of SG.
  - Depth of interest for the CAB layer is at its quarter depth, D = 5 + 10/4 = 7.5 inch.
  - The equivalent thickness is:
    $H_{eqNew-CAB} = 2.2432 * 7.5 - 1.9263 = 14.90\ inch$
- Rehabilitation Design:
  - 5 inch of AC layer on top of 10 inch of CAB layer on top of SG.
  - Depth of interest for the CAB layer is at its quarter depth, D = 5 + 10/4 = 7.5 inch.
  - The equivalent thickness is:
    $H_{eqReh-CAB} = 2.399 * 7.5 - 1.7468 = 16.25\ inch$

CHAPTER 3. MATERIALS COLLECTION

This research evaluated different types of base, borrow, and subgrade materials from NDOT Districts 2 and 3 shown in Figure 3.1. The most common base material used by NDOT is Type 1 Class B. Table 3.1 summarizes the information on the collected base, borrow, and subgrade materials. Figure 3.2 shows the locations of the sampled materials within Districts 2 & 3. A total of 6 base, 5 borrow, and 6 subgrade materials were sampled from District 2 and a total of 4 base, 5 borrow, and 2 subgrade materials were sampled from District 3.

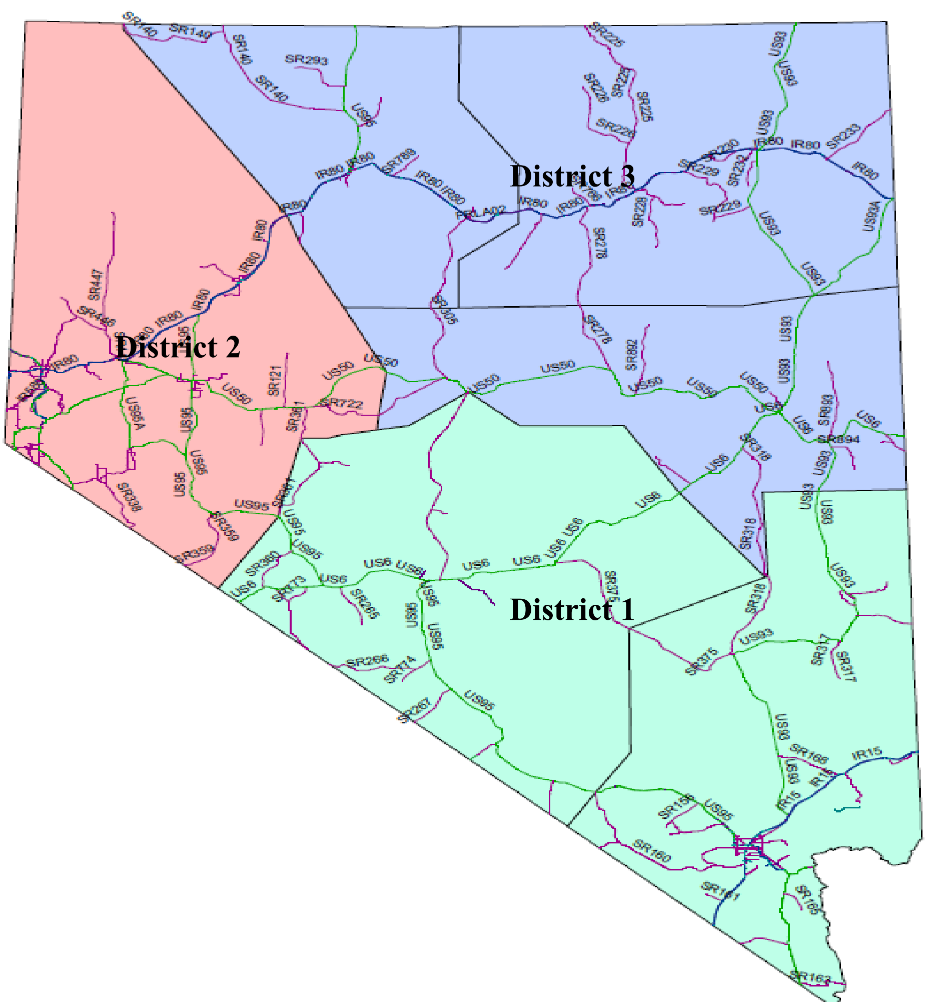


Figure 3.1. NDOT Districts boundaries.

Table 3.1 Collected Materials.

Source	District	Material	Source	District	Material
Lockwood	2	Base	Lemmon Dr.	2	Subgrade 1
		Borrow	Lemmon Dr.	2	Subgrade 2
Goni Pit	2	Base	Spaghetti Bowl	2	Subgrade
		Borrow	Sonoma Pit	3	Base
Spanish Springs	2	Base			Borrow
		Borrow	Carlin Pit	3	Base
Imlay Pit	2	Base	Vega Construction Shop	3	Base
		Borrow			Borrow
Trico Pit	2	Base A	Silver State Rock products	3	Base
		Base B			Borrow
		Borrow	Elko	3	Borrow 1
Fallon Big Dig	2	Subgrade 1	Elko	3	Borrow 2
Fallon Big Dig	2	Subgrade 2	Contract #3817	3	Subgrade
Kings Row	2	Subgrade	Contract #3824	3	Subgrade

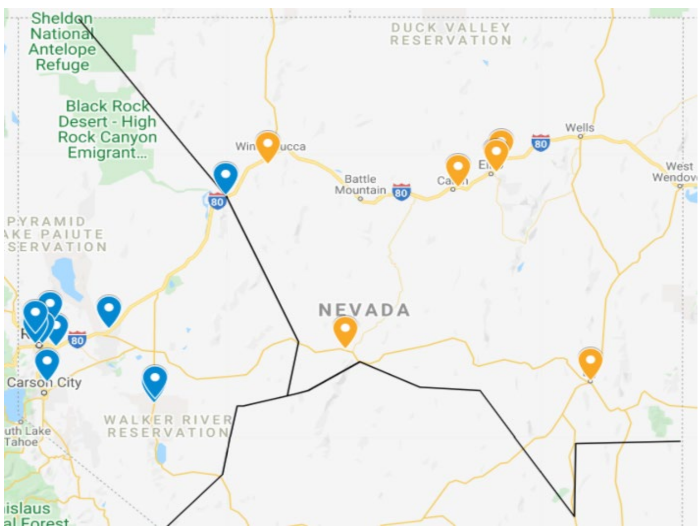


Figure 3.2. Locations of collected materials from Districts 2 and 3.

CHAPTER 4. LABORATORY TESTING

This chapter presents the laboratory testing of the base, borrow, and subgrade materials that were sampled from NDOT Districts 2 & 3. The materials were subjected to five groups of laboratory testing: Soil Classification, Moisture-density Relationship, Repeated Load Triaxial Resilient Modulus, Unconfined Compressive Strength, and Resistance Value "R-value". The following sections briefly describe the test methods and presents the data generated from each testing group.

4.1. Soil Classification Testing

The selected materials were classified using particle size analysis and Atterberg limits following both AASHTO and USCS systems which are widely used in practice. The particle size analysis for the aggregate and soil materials was conducted in accordance with NDOT test method Nev.T206 and ASTM D421 and D422 respectively. NDOT test methods Nev. T 210J, T 211J, and T 212J were used to determine the Liquid Limit (LL), Plastic Limit (PL), and Plasticity Index (PI) of the selected materials, respectively. The Materials Division Testing Manual for the NDOT test methods can be found online at: https://www.nevadadot.com/doing-business/about-ndot/ndot divisions /operations /materials-section/ materials-test-manual.

4.1.1. Particle Size Analysis of Base, Borrow, and Subgrade Materials

Aggregate from base and borrow materials were split into the sample size around 3000g and dried until to a constant weight at a temperature not exceeding 110°C. The dry aggregate was washed over sieve #10 and sieve #200. Retained materials on sieve #10, sieve #200, and washing vessel were transferred into a pan, dried at 110°C, and sieved through a set of sieves in a mechanical sieve shaker. Results of sieve analysis are summarized in Tables 4.1 – 4.4 and gradation curves are presented in Figures 4.1 – 4.4 for base and borrow materials. All base and borrow materials satisfied the NDOT specifications for Type 1 Class B aggregate type except Trico Pit A which exceeded the maximum limit for the #200 sieve.

Materials from subgrade samples were split into the required sample size and dried at 60°C. The dry material was pulverized by using a rubber head hammer. Washing was performed on sieve #10 and poured through sieve #200 until clear water appears. Retained materials on sieve #10 and sieve #200 were carefully transferred in to a pan and dried at a temperature of 60°C. The dry material was pulverized again and sieve analysis was done in a mechanical sieve shaker. The sieve analysis results for the subgrade are summarized in Table 4.5 and the gradation curves are presented in Figure 4.5.

Table 4.1. District 2 Base Materials Sieve Analysis Results.

Sieve Size	NDOT District 2 Base %Passing						NDOT Type 1 Base Specs	
	Lockwood	Goni Pit	Spanish Springs	Imlay Pit	Trico Pit A	Trico Pit B	Min	Max
1.5"	100.0	100.0	100.0	100.0	100.0	100.0	100	
1"	88.7	94.0	98.7	98.3	100.0	100.0	80	100
3/4 "	76.6	88.1	92.2	91.5	99.7	98.2		
1/2 "	72.4	78.3	75.0	78.6	90.8	73.6		
3/8 "	71.4	70.6	63.1	69.9	84.3	62.2		
#4	49.5	42.9	41.5	48.2	61.0	39.7	30	65
#8	37.6	26.6	29.3	33.0	45.5	26.9		
#10	35.4	23.9	26.9	29.9	42.2	25.1		
#16	28.9	17.6	21.9	23.8	35.5	19.7	15	40
#30	21.7	12.8	17.0	18.1	29.0	15.3		
#40	17.1	11.0	15.3	16.3	26.7	13.4		
#50	12.1	9.3	13.6	14.6	24.3	12.0		
#100	5.1	6.4	11.0	12.0	20.2	9.6		
#200	2.9	3.9	8.6	9.8	15.9	7.5	2	12

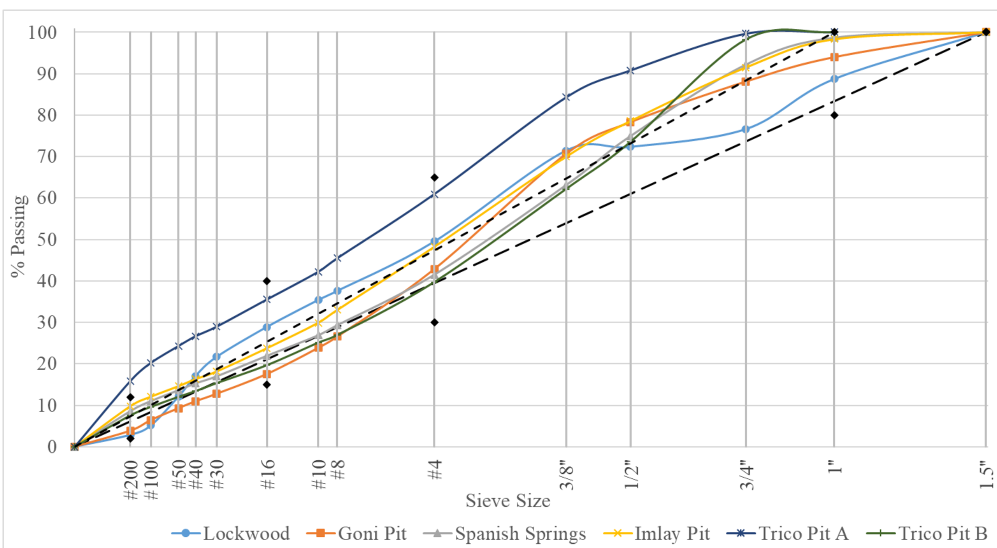


Figure 4.1. District 2 base materials gradation curves.

Table 4.2. District 3 Base Materials Sieve Analysis Results.

Sieve Size	NDOT District 3 Base %Passing				NDOT Type 1 Base Specs	
	Sonoma Pit	Carlin Pit	Vega	Silver State	Min	Max
1.5"	100.0	100.0	100.0	100.0	100	
1"	99.1	100.0	100.0	100.0	80	100
3/4 "	92.0	93.3	96.3	100.0		
1/2 "	77.4	78.4	79.9	97.3		
3/8 "	67.8	70.7	69.7	89.8		
#4	48.0	50.8	50.4	63.4	30	65
#8	36.7	38.2	37.5	44.5		
#10	34.1	35.7	34.5	40.4		
#16	28.3	29.9	27.3	31.5	15	40
#30	21.5	23.8	18.6	23.8		
#40	18.8	21.1	14.3	20.8		
#50	16.4	18.6	11.1	18.5		
#100	12.7	14.9	7.7	14.6		
#200	9.4	11.1	5.8	10.8	2	12

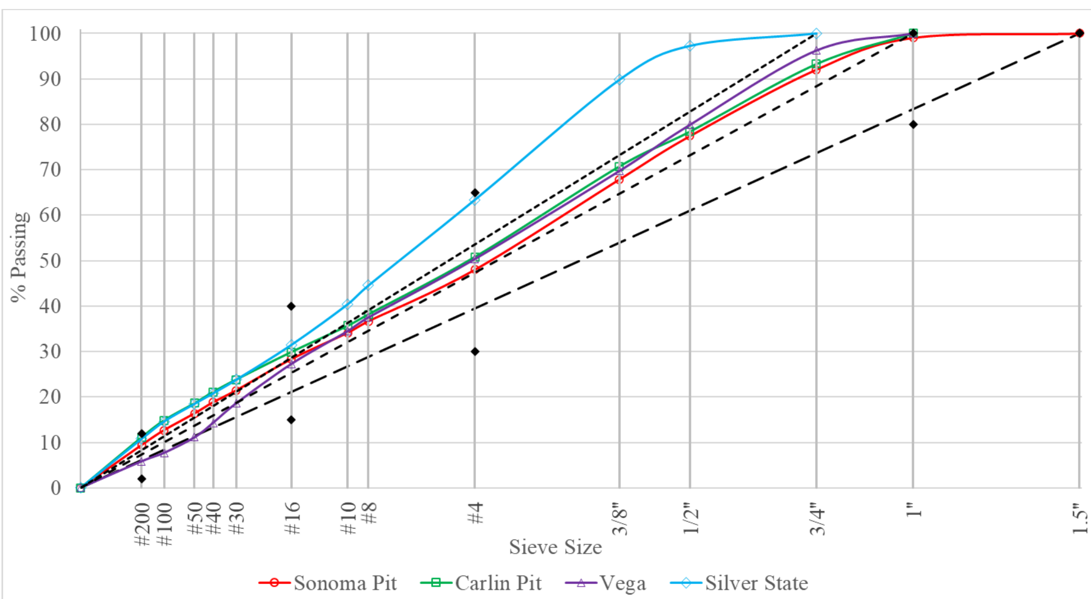


Figure 4.2. District 3 base materials gradation curves.

Table 4.3. District 2 Borrow Materials Sieve Analysis Results.

Sieve Size	District 2 Borrow % Passing					NDOT Specs
	Lockwood	Goni Pit	Spanish Springs	Imlay Pit	Trico Pit	
3"	100.0	100.0	100.0	100.0	100.0	100
2"	100.0	100.0	100.0	100.0	100.0	
1.5"	100.0	100.0	98.1	100.0	98.4	
1"	100.0	100.0	86.7	100.0	97.0	
3/4 "	97.4	98.4	80.3	100.0	96.1	
1/2 "	70.8	97.6	70.6	98.8	93.3	
3/8 "	53.2	96.6	64.1	93.4	92.4	
#4	32.4	92.4	50.0	55.9	87.7	
#8	23.4	78.6	39.7	40.2	71.3	
#10	22.1	74.5	37.4	37.8	65.6	
#16	18.5	61.6	32.3	32.2	52.4	
#30	15.0	49.2	26.7	26.9	41.7	
#40	13.0	44.0	24.7	24.6	36.8	
#50	10.9	39.0	22.7	22.3	32.0	
#100	7.7	29.2	18.7	16.4	25.8	
#200	6.0	17.2	13.2	11.7	19.5	

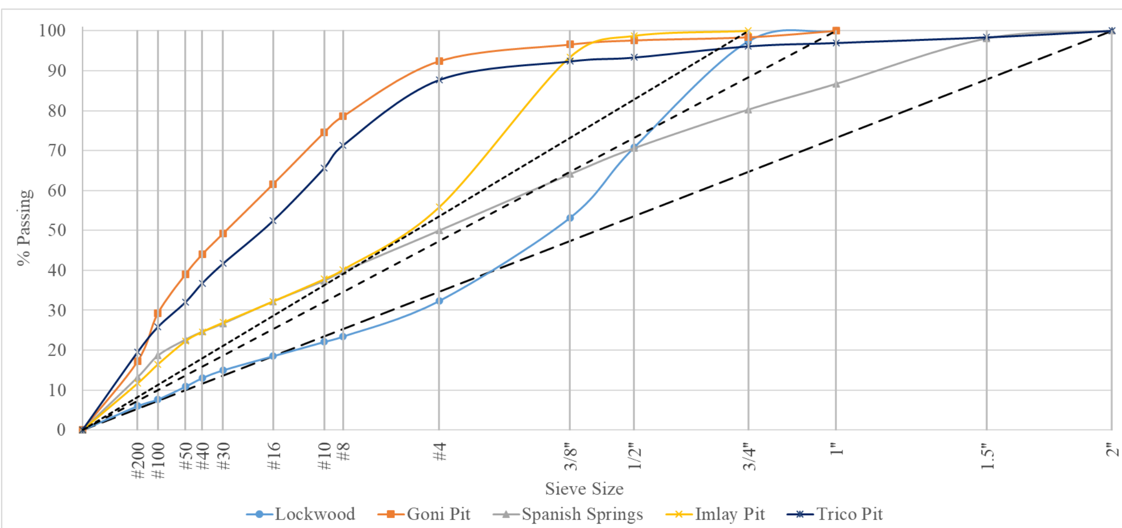


Figure 4.3. District 2 borrow materials gradation curves.

Table 4.4. District 3 Borrow Materials Sieve Analysis Results.

Sieve Size	District 3 Borrow % Passing					NDOT Specs
	Sonoma Pit	Vega	Silver State	Elko 1	Elko 2	
3"	100.0	100.0	100.0	100.0	100.0	100
2"	100.0	100.0	100.0	100.0	100.0	
1.5"	100.0	93.9	97.0	100.0	93.9	
1"	100.0	85.4	87.2	100.0	84.7	
3/4 "	100.0	79.7	81.7	100.0	78.0	
1/2 "	87.6	71.6	73.6	99.3	70.6	
3/8 "	78.7	65.8	68.7	93.2	65.9	
#4	53.1	50.2	53.6	71.1	56.0	
#8	35.0	37.6	39.9	54.4	47.5	
#10	32.0	34.3	36.2	50.7	45.5	
#16	22.9	27.2	26.7	41.3	39.5	
#30	16.2	18.8	15.4	31.6	32.7	
#40	14.0	14.6	10.6	27.7	29.5	
#50	12.6	11.5	7.1	24.3	26.6	
#100	11.0	8.4	4.4	19.1	21.4	
#200	9.4	6.3	3.5	14.1	15.6	

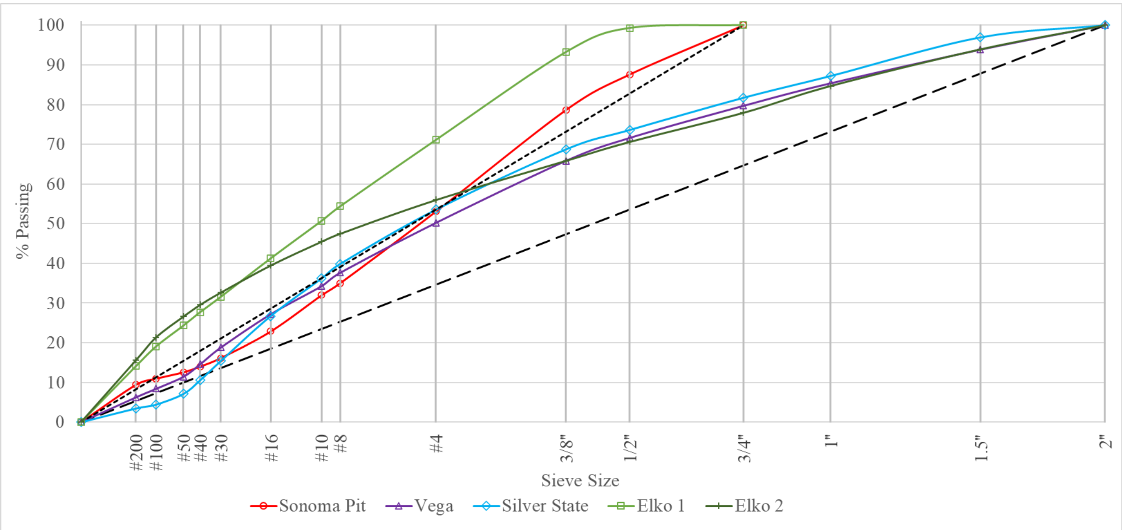


Figure 4.4. District 3 borrow materials gradation curves.

Table 4.5. Districts 2 and 3 Subgrade Materials Sieve Analysis Results.

Districts 2 and 3 Subgrade % Passing								
Sieve Size	3817	3824	Spag. Bowl	Fallon Big Dig1	Fallon Big Dig2	Kings Row	Lemmon Dr.1	Lemmon Dr.2
2.5"	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
2"	100.0	100.0	100.0	100.0	100.0	97.2	100.0	100.0
1.5"	100.0	99.0	97.2	100.0	100.0	97.2	100.0	100.0
1"	100.0	95.3	95.3	98.8	100.0	90.0	100.0	98.7
3/4 "	99.0	93.0	92.9	96.1	100.0	85.4	100.0	98.0
1/2 "	98.1	87.9	86.1	92.9	100.0	78.1	99.3	96.8
3/8 "	97.1	84.0	82.2	90.3	100.0	72.9	99.0	96.5
#4	92.2	71.8	73.0	80.5	100.0	62.1	95.3	95.8
#8	74.3	58.2	63.5	66.9	100.0	53.3	92.0	95.0
#10	68.2	55.6	61.2	63.3	100.0	50.9	91.3	94.6
#16	52.5	48.7	54.1	52.5	99.8	44.7	89.6	91.2
#30	35.4	41.8	43.1	40.4	96.4	36.6	84.7	84.4
#40	29.2	38.8	37.2	33.9	94.1	32.2	81.1	79.5
#50	23.4	36.1	32.0	27.2	91.8	27.7	77.0	73.6
#100	15.3	31.6	24.6	16.6	86.4	20.1	56.8	59.7
#200	11.0	22.3	17.0	9.4	78.1	14.0	36.0	42.2

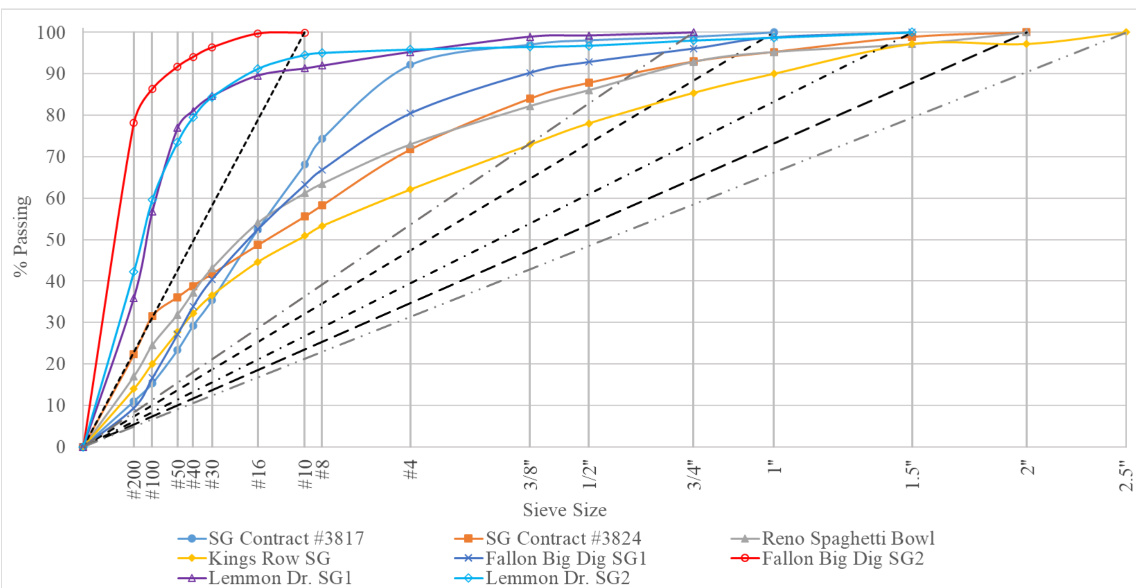


Figure 4.5. Districts 2 and 3 subgrade materials gradation curves.

4.1.2. Atterberg Limits

Atterberg limits typically refer to the liquid limit and the plastic limit, which are moisture content values that distinguish the boundaries of the consistency states of plastic soils. The liquid limit (LL) defines the boundary between the plastic state and the semi-liquid state, whereas the plastic limit (PL) defines the boundary between the semi-solid state and the plastic state. The plasticity index (PI) is the range at which the soil behaves as plastic, and is numerically defined as the difference between the LL and the PL. The LL, PL, and PI were obtained according to NDOT standards Nev. T210J and T211J/T212J, respectively.

The LL is the moisture content required to close the 13 mm groove on the Casagrande cup apparatus with 25 blows. To get this number of blows, three blow ranges are used to close the 13 mm groove: 25-35 blows, 20-30 blows, and 15-25 blows. A 100 g ± 15 g sample of materials passing the #40 sieve are obtained and mixed with 25 mL of water until uniform. If the desired consistency is not reached for the first range of blows, more water is added at increments of 1, 2, or 3 mL until testing can commence. The moisture contents from the three ranges are obtained and plotted against the number of blows, then the LL at 25 blows is obtained.

An 8 g sample was taken from the material used for the first blows range for PL testing. This sample is split to 1.5 to 2 g portions and hand-rolled on a glass plate until it forms a 3 mm diameter thread. This procedure is repeated until the thread crumbles at this diameter, and the PL is identified. Finally, the PI is obtained as the difference between the LL and the PL reported to the nearest 1%.

The testing apparatus (Casagrande cup and glass plate) used for LL and PL testing, and an example of the LL plot for the Spaghetti Bowl subgrade material are shown in Figures 4.6 and 4.7, respectively.

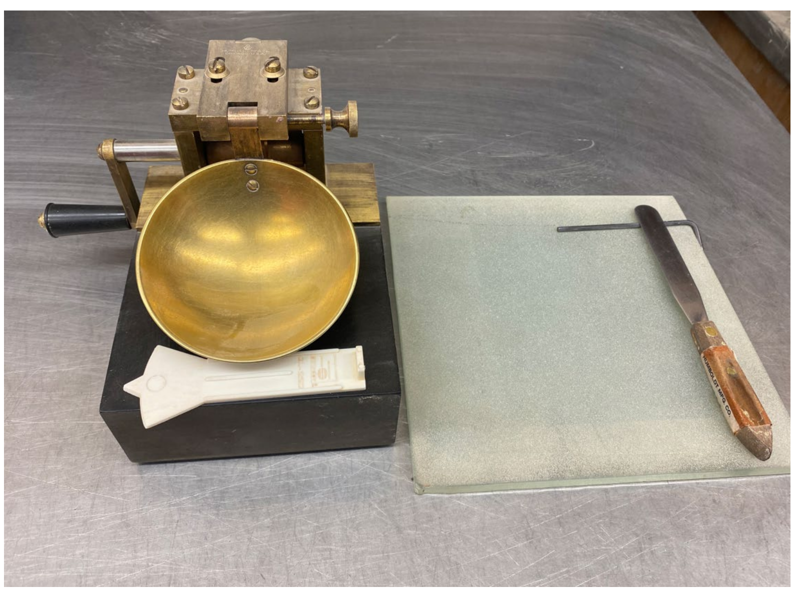


Figure 4.6. Atterberg limits testing apparatus.

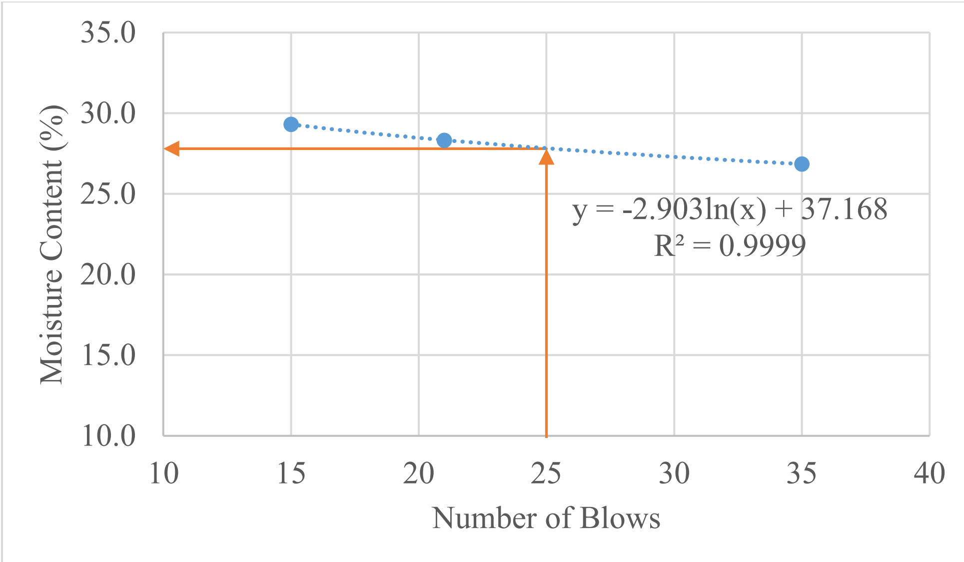


Figure 4.7. Spaghetti Bowl subgrade liquid limit plot.

Table 4.6 presents the Atterberg limits test results. Materials not shown in the table did not exhibit a LL or a PL.

Table 4.6. Atterberg Limits Test Results.

District	Source	Material	Liquid Limit (%)	Plastic Limit (%)	Plasticity Index (%)
2	Spanish Spring	Base	36.6	27.6	9
2	Spanish Spring	Borrow	34.8	23.4	11
2	Goni Pit	Borrow	24	22.6	2
2	Spaghetti Bowl	Subgrade	27.8	20.5	7
2	Fallon Big Dig 2	Subgrade	75.4	31.3	44
2	Kings Row	Subgrade	32.8	15.4	17
2	Lemmon Dr. 1	Subgrade	67.9	34.8	33
2	Lemmon Dr. 2	Subgrade	47.2	22.8	24
3	Silver State	Base	30.3	25.9	4
3	Sonoma Pit	Borrow	28.8	14.2	15
3	Elko 1	Borrow	29.3	24.3	5
3	Elko 2	Borrow	35.6	27.6	8

NDOT requires base materials to have a maximum LL of 35% and assigns PI limits based on the percent passing #200 sieve as shown in Table 4.7.

Table 4.7. NDOT PI Specifications for Base Materials.

P#200 (%)	4	5	6-8	9-11	12-15
Max. PI	12	9	6	4	3

The results show that all base materials pass the NDOT specifications except for the Spanish Springs source, which has 9% passing sieve #200 with a LL of 36.6% (greater than 35%) and a PI of 9% (greater than the 4% limit for 9% P#200).

4.1.3. Soil Classification

All materials were classified according to AASHTO and USCS classification systems. The procedures for AASHTO classification (from AASHTO M145) and USCS (from ASTM D2487) are shown in Tables 4.8 and 4.9, respectively.

Table 4.8. AASHTO Soil Classification.

General Classification	*Granular materials (35% or less passing No. 200 Sieve (0.075 mm))*							*Silt-clay Materials More than 35% passing No. 200 Sieve (0.075 mm)*			
Group Classification	*A—1*		*A—3*	*A—2*				*A—4*	*A—5*	*A—6*	*A—7*
	A—1—a	*A—1—b*		*A—2—4*	*A—2—5*	*A—2—6*	*A—2—7*				*A—7—5* *A—7—6*
(*a*) Sieve Analysis: Percent Passing											
(*i*) 2.00 mm (No. 10)	50 max										
(*ii*) 0.425 mm (No. 40)	30 max	50 max	51 min								
(*iii*) 0.075 mm (No. 200)	15 max	25 max	10 max	35 max	35 max	35 max	35 max	36 min	36 min	36 min	36 min
(*b*) Characteristics of fraction passing 0.425 mm (No. 40)											
(*i*) Liquid limit				40 max	41 min	40 max	41 min	40 max	41 min	40 max	41 min
(*ii*) Plasticity index	6 max		N.P.	10 max	10 max	11 min	11 min	10 max	10 max	11 min	11 min*
(*c*) Usual types of significant Constituent materials	Stone Fragments Gravel and sand		Fine Sand	Silty or Clayey Gravel Sand				Silty Soils		Clayey Soils	
(*d*) General rating as subgrade.	Excellent to Good							Fair to Poor			

* If plasticity index is equal to or less than (liquid Limit—30), the soil is A—7—5 (*i.e.* PL > 30%)
If plasticity index is greater than (Liquid Limit—30), the soil is A—7—6 (*i.e.* PL < 30%)

Table 4.9. USCS Classification Chart.

Criteria for Assigning Group Symbols and Group Names Using Laboratory Tests[A]				Soil Classification: Group Symbol	Soil Classification: Group Name[B]
COARSE-GRAINED SOILS More than 50 % retained on No. 200 sieve	Gravels (More than 50 % of coarse fraction retained on No. 4 sieve)	Clean Gravels (Less than 5 % fines[C])	Cu ≥ 4.0 and 1 ≤ Cc ≤ 3.0[D]	GW	Well-graded gravel[E]
			Cu < 4.0 and/or [Cc < 1 or Cc > 3.0][D]	GP	Poorly graded gravel[E]
		Gravels with Fines (More than 12 % fines[C])	Fines classify as ML or MH	GM	Silty gravel[E,F,G]
			Fines classify as CL or CH	GC	Clayey gravel[E,F,G]
	Sands (50 % or more of coarse fraction passes No. 4 sieve)	Clean Sands (Less than 5 % fines[H])	Cu ≥ 6.0 and 1.0 ≤ Cc ≤ 3.0[D]	SW	Well-graded sand[I]
			Cu < 6.0 and/or [Cc < 1.0 or Cc > 3.0][D]	SP	Poorly graded sand[I]
		Sands with Fines (More than 12 % fines[H])	Fines classify as ML or MH	SM	Silty sand[F,G,I]
			Fines classify as CL or CH	SC	Clayey sand[F,G,I]
FINE-GRAINED SOILS 50 % or more passes the No. 200 sieve	Silts and Clays Liquid limit less than 50	inorganic	PI > 7 and plots on or above "A" line[J]	CL	Lean clay[K,L,M]
			PI < 4 or plots below "A" line[J]	ML	Silt[K,L,M]
		organic	$\frac{\text{Liquid limit – oven dried}}{\text{Liquid limit – not dried}} < 0.75$	OL	Organic clay[K,L,M,N] Organic silt[K,L,M,O]
	Silts and Clays Liquid limit 50 or more	inorganic	PI plots on or above "A" line	CH	Fat clay[K,L,M]
			PI plots below "A" line	MH	Elastic silt[K,L,M]
		organic	$\frac{\text{Liquid limit – oven dried}}{\text{Liquid limit – not dried}} < 0.75$	OH	Organic clay[K,L,M,P] Organic silt[K,L,M,Q]
HIGHLY ORGANIC SOILS	Primarily organic matter, dark in color, and organic odor			PT	Peat

Tables 4.10 – 4.12 present the AASHTO and USCS classifications for the base, borrow, and subgrade soils, respectively.

Table 4.10. Base Materials Classifications.

Base	District	AASHTO	USCS
Lockwood	2	A-1-a	GW
Goni	2	A-1-a	GW
Imlay	2	A-1-a	GP-GM
Spanish Springs	2	A-2-4	GP-GM
TricoA	2	A-1-b	SM
TricoB	2	A-1-a	GP-GM
Sonoma	3	A-1-a	GW-GM
Carlin	3	A-1-a	GP-GM
Vega	3	A-1-a	GW-GM
Silver State	3	A-2-4	SP-SM

Table 4.11. Borrow Materials Classifications.

Borrow	District	AASHTO	USCS
Lockwood	2	A-1-a	GP-GM
Goni	2	A-1-b	SM
Imlay	2	A-1-a	GW-GM
Spanish Springs	2	A-2-6	GC
Trico	2	A-1-b	SM
Sonoma	3	A-2-6	GP-GC
Vega	3	A-1-a	GW-GM
Silver State	3	A-1-a	SP
Elko 1	3	A-2-4	SM
Elko 2	3	A-2-4	GM

Table 4.12. Subgrade Materials Classifications.

Subgrade	District	AASHTO	USCS
Spaghetti Bowl	2	A-2-4	SC
Kings Row	2	A-2-6	SC
Fallon Big Dig 1	2	A-2-4	SP-SM
Fallon Big Dig 2	2	A-7-5	CH
Lemmon Dr 1	2	A-7-5	SM
Lemmon Dr 2	2	A-7-6	SC
# 3817	3	A-2-4	SW-SM
# 3824	3	A-2-4	SM

4.2. Specific Gravity and Absorption

The specific gravity (G_s) is the ratio of the mass of a unit volume of a material to the mass of the same volume of water. The bulk dry, bulk saturated surface-dry (SSD), and apparent specific gravity values were calculated for each material. The test was done for both the coarse and fine portions of the materials, following AASHTO T85 and T84, respectively.

For the coarse aggregates, a sample mass depending on the NMAS was obtained and submerged in water for 16 to 19 hours, then dried to SSD condition using a damp towel and weighed. The SSD aggregates were then weighed underwater at 23 ± 1.7°C, and oven-dried to a constant mass at 110 ± 5°C to obtain the dry weight.

For the fine aggregates, a sample of minimum 1000 g mass was obtained and mixed with at least of 6% water by dry mass of the sample until uniform, then covered for 15-19 hours. The sample was then dried to SSD condition determined visually using the cone test, where after 25 light hammer drops, the cone is removed, and the fines should slump slightly. A 500 ± 5 g of the SSD sample was then added to a pycnometer with added water, and constant agitation was maintained for 15-20 minutes to let air voids out. The pycnometer was then filled to line mark and weighed. Finally, the sample was oven-dried to a constant mass at 110 ± 5°C and weighed.

The recorded masses from the procedures described above were used to calculate the specific gravities and absorption of the materials. The results are shown in Tables 4.13 – 4.17.

Table 4.13. District 2 Base Materials Specific Gravity and Absorption Results.

Base Source	Lockwood	Goni	Imlay	Spanish Springs	Trico A	Trico B
Coarse Gsb, Dry	2.642	2.605	2.594	2.639	2.161	2.526
Coarse Gsb, SSD	2.686	2.642	2.631	2.671	2.348	2.599
Coarse Gsa	2.763	2.705	2.694	2.726	2.657	2.726
Coarse Abs. (%)	1.7	1.4	1.4	1.2	8.6	2.9
Fine Gsb, Dry	2.578	2.632	2.473	2.471	2.222	2.558
Fine Gsb, SSD	2.644	2.663	2.560	2.550	2.395	2.621
Fine Gsa	2.760	2.717	2.709	2.684	2.686	2.731
Fine Abs. (%)	2.6	1.2	3.5	3.2	7.8	2.5

Table 4.14. District 2 Borrow Materials Specific Gravity and Absorption Results.

Borrow Source	Lockwood	Goni	Imlay	Spanish Springs	Trico
Coarse Gsb, Dry	2.630	-	2.571	2.595	-
Coarse Gsb, SSD	2.682	-	2.617	2.645	-
Coarse Gsa	2.775	-	2.695	2.732	-
Coarse Abs. (%)	2.0	-	1.8	1.9	-
Fine Gsb, Dry	2.456	2.509	2.487	2.340	1.765
Fine Gsb, SSD	2.577	2.576	2.568	2.450	2.058
Fine Gsa	2.793	2.689	2.708	2.629	2.498
Fine Abs. (%)	4.9	2.7	3.3	4.7	16.6

Table 4.15. District 3 Base Materials Specific Gravity and Absorption Results.

Base Source	Sonoma	Carlin	Vega	Silver State
Coarse Gsb, Dry	2.587	2.461	2.542	2.308
Coarse Gsb, SSD	2.621	2.508	2.569	2.417
Coarse Gsa	2.678	2.582	2.614	2.590
Coarse Abs. (%)	1.3	1.9	1.1	4.7
Fine Gsb, Dry	2.458	2.339	2.402	2.300
Fine Gsb, SSD	2.547	2.409	2.483	2.424
Fine Gsa	2.697	2.515	2.614	2.625
Fine Abs. (%)	3.6	3.0	3.4	5.4

Table 4.16. District 3 Borrow Materials Specific Gravity and Absorption Results.

Borrow Source	Sonoma	Vega	Silver State	Elko 1	Elko 2
Coarse Gsb, Dry	2.547	2.544	2.494	2.396	2.347
Coarse Gsb, SSD	2.599	2.569	2.535	2.505	2.454
Coarse Gsa	2.687	2.610	2.599	2.688	2.629
Coarse Abs. (%)	2.0	1.0	1.6	4.5	4.6
Fine Gsb, Dry	2.494	2.396	2.486	2.292	2.179
Fine Gsb, SSD	2.569	2.474	2.537	2.424	2.350
Fine Gsa	2.698	2.599	2.621	2.642	2.626
Fine Abs. (%)	3.0	3.3	2.1	5.8	7.8

Table 4.17. Subgrade Materials Specific Gravity and Absorption Results.

Subgrade Source	Sp. Bowl	Kings Row	Fallon Big Dig 1	Fallon Big Dig 2	Lemmon Dr. 1	Lemmon Dr. 2	#3817	#3824
District	2	2	2	2	2	2	3	3
Coarse Gsb, Dry	2.413	2.444	2.280	-	-	-	-	2.161
Coarse Gsb, SSD	2.516	2.538	2.397	-	-	-	-	2.337
Coarse Gsa	2.690	2.698	2.583	-	-	-	-	2.621
Coarse Abs. (%)	4.3	3.9	5.1	-	-	-	-	8.1
Fine Gsb, Dry	2.324	2.315	2.146	1.788	1.732	2.084	2.510	2.360
Fine Gsb, SSD	2.454	2.458	2.301	2.079	2.049	2.278	2.568	2.445
Fine Gsa	2.672	2.701	2.540	2.523	2.533	2.586	2.664	2.580
Fine Abs. (%)	5.6	6.2	7.2	16.3	18.3	9.3	2.3	3.6

4.3. Moisture-Density Relationship

Compaction is the densification of the material by rearranging the particles to fill voids through mechanical energy. Initially, adding water to the material will increase the density since it will make it easier for the particles to slip and fill the voids. However, maximum density is reached at the optimum moisture content (OMC), after which any addition of water will lead to a decrease in the density due to the displacement of particles. The objective of this test is to obtain the OMC and the corresponding maximum dry density (MDD).

The modified proctor test was conducted following Nev. T108D test method, where the material is screened over a 3/4" sieve, then compacted in a 6-inch mold using a 10 lb. rammer at an 18-inch drop height. Figure 4.8 shows the mold and rammer used for the test.

Figure 4.8. Modified Proctor equipment.

Compaction was done in 5 lifts with 56 blows per lift, with the final lift leaving the soil surface at about 0.25 inches above the top of the mold. A straightedge is used to level the surface, the weight after compaction is obtained, and the specimen is extruded for moisture content sampling vertically along the center of the specimen. The procedure is repeated at different moisture content levels, until a minimum of 4 points are obtained for plotting the Moisture-Density curve: one or two below the OMC, one close to the OMC, and one or two above the OMC.

Figures 4.9 – 4.11 show typical moisture-density relationship curves for a base, a borrow, and a subgrade materials, respectively.

After obtaining the OMC and MDD from the moisture-density curve, corrections are done to account for material screened over the 3/4" sieve if they were greater than 5%. The corrections are explained by the test method Nev. T108D for MDD (Equation 2), and for OMC (Equation 3).

$$MDD_{corrected} = \frac{MDD \times G}{MDD \times (1-P) + (G)(P)} \qquad (2)$$

$$OMC_{corrected} = [(1-P) \times 2] + P \times OMC \qquad (3)$$

Where;

- G= Mass per volume of coarse aggregates= Coarse aggregate G_{sa}*62.4 (pcf)
- P= percent passing 3/4" sieve (%)

Summary of the test results for the base, borrow, and subgrade materials are shown in Tables 4.18 – 4.20, respectively.

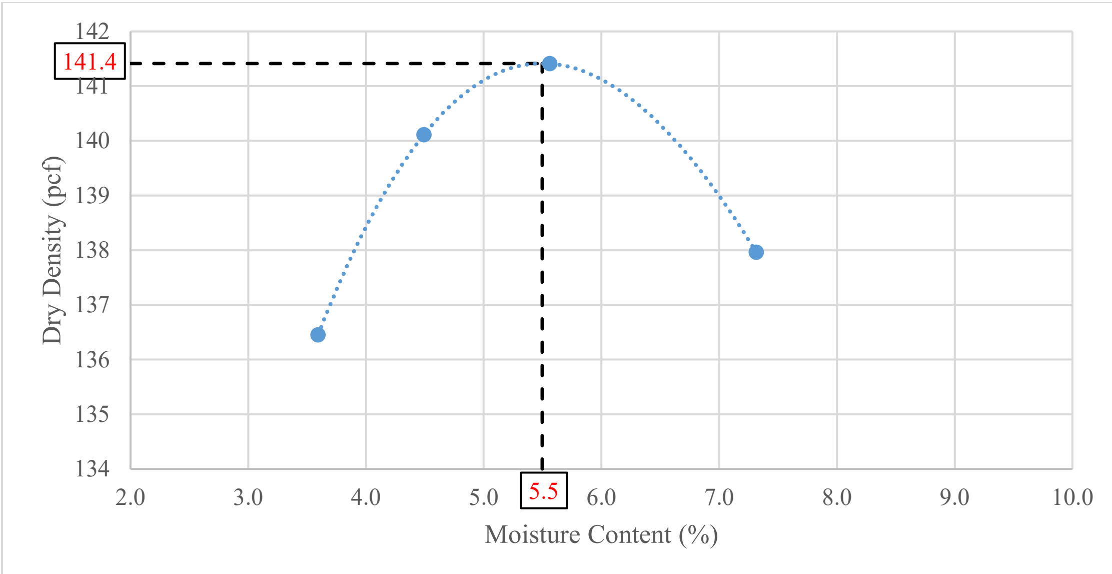


Figure 4.9. Imlay base moisture-density curve.

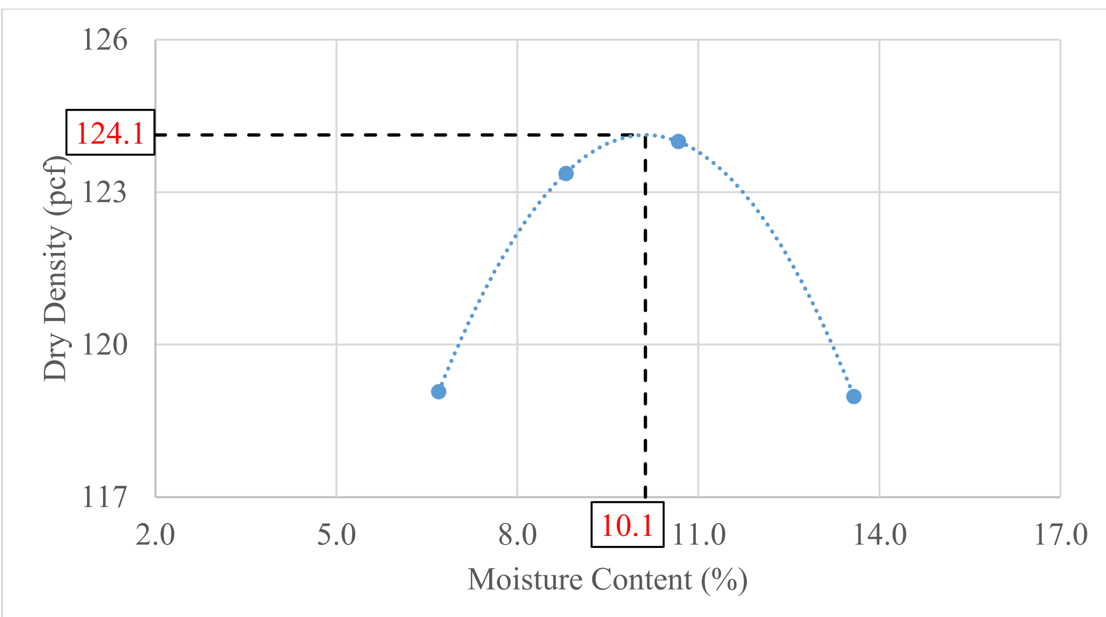


Figure 4.10. Elko borrow 1 moisture-density curve.

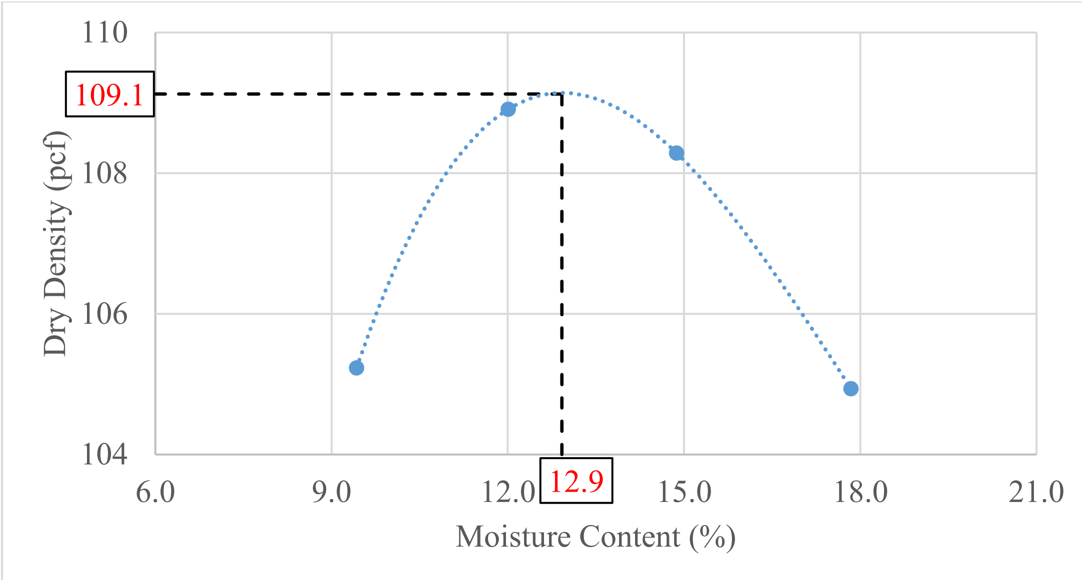


Figure 4.11. Fallon Big Dig subgrade 1 moisture-density curve.

Table 4.18. Base Materials Moisture-Density Relationship Results.

Source	District	OMC (%)	Corrected OMC (%)	MDD (pcf)	Corrected MDD (pcf)
Lockwood	2	8.7	7.2	135.3	142.5
Goni	2	7.1	6.5	131.2	134.7
Spanish Spring	2	6.3	5.9	139.6	141.6
Imlay	2	5.5	5.2	141.4	143.3
Trico A	2	10.6	10.6	123.4	123.4
Trico B	2	8.6	8.6	137.2	137.2
Sonoma	3	6.1	5.8	142.2	143.9
Carlin	3	5.7	5.5	134.5	136.0
Vega	3	5.2	5.2	135.3	135.3
Silver State	3	8.4	8.4	126.6	126.6

Table 4.19. Borrow Materials Moisture-Density Relationship Results.

Source	District	OMC (%)	Corrected OMC (%)	MDD (pcf)	Corrected MDD (pcf)
Lockwood	2	8.6	8.6	137.7	137.7
Goni	2	7.2	7.2	134.5	134.5
Spanish Spring	2	7.3	6.3	134.6	140.4
Imlay	2	6.8	6.8	141.0	141.0
Trico	2	22.2	22.2	96.7	96.7
Sonoma	3	5.6	5.6	139.9	139.9
Vega	3	5.6	4.9	135.6	140.4
Silver State	3	5.8	5.1	129.1	134.1
Elko 1	3	10.1	10.1	124.1	124.1
Elko 2	3	11.4	9.3	121.5	128.8

Table 4.20. Subgrade Materials Moisture-Density Relationship Results.

Source	District	OMC (%)	Corrected OMC (%)	MDD (pcf)	Corrected MDD (pcf)
Spaghetti Bowl	2	8.3	7.8	129.2	131.3
Kings Row	2	10.8	9.5	126.4	131.2
Fallon Big Dig 1	2	12.9	12.9	109.1	109.1
Fallon Big Dig 2	2	22.8	22.8	95.0	95.0
Lemmon Dr. 1	2	24.8	24.8	92.7	92.7
Lemmon Dr. 2	2	19.0	19.0	109.1	109.1
#3817	3	7.2	7.2	133.9	133.9
#3824	3	12.2	11.5	119.1	121.4

4.4. Unconfined Compressive Strength

This test was conducted according to ASTM D2166. The mold used for sample preparation has a 6-inch diameter and a 12-inch height. Samples were screened over a 3/4" sieve, water was added to reach the OMC and MDD, compacted in 10 lifts using a vibratory compactor, then extruded and transferred to the testing machine.

The test is strain-controlled where the samples are unconfined laterally and loaded axially at an axial strain rate of 0.5-2%/min. The UCS is defined as the highest load per unit area before failure. Figures 4.12 and 4.13 show a prepared UCS sample after extrusion, and after testing, respectively. Figures 4.14 – 4.16 show the stress-strain curves for Imlay base, Goni borrow, and subgrade #3817, respectively, as examples of the test results. Table 4.21 summarizes the UCS test results for all the materials tested.

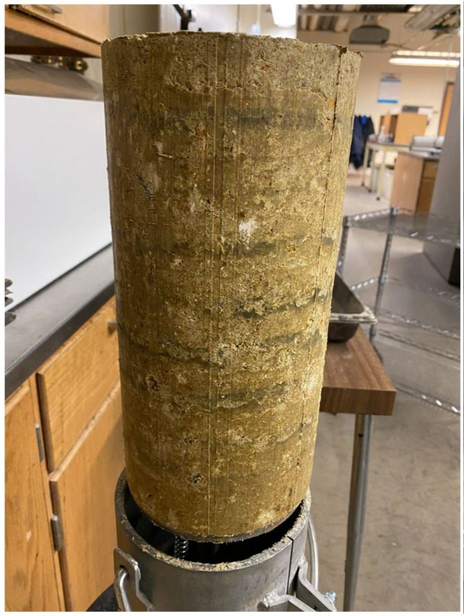


Figure 4.12. Extruded UCS sample. **Figure 4.13. UCS sample after testing.**

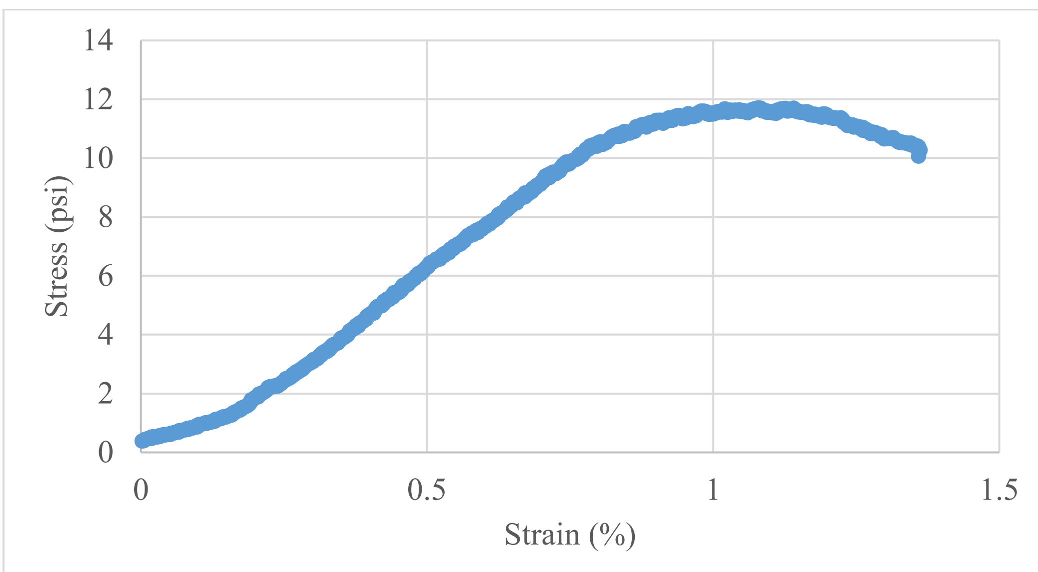


Figure 4.14. Imlay base UCS stress-strain curve.

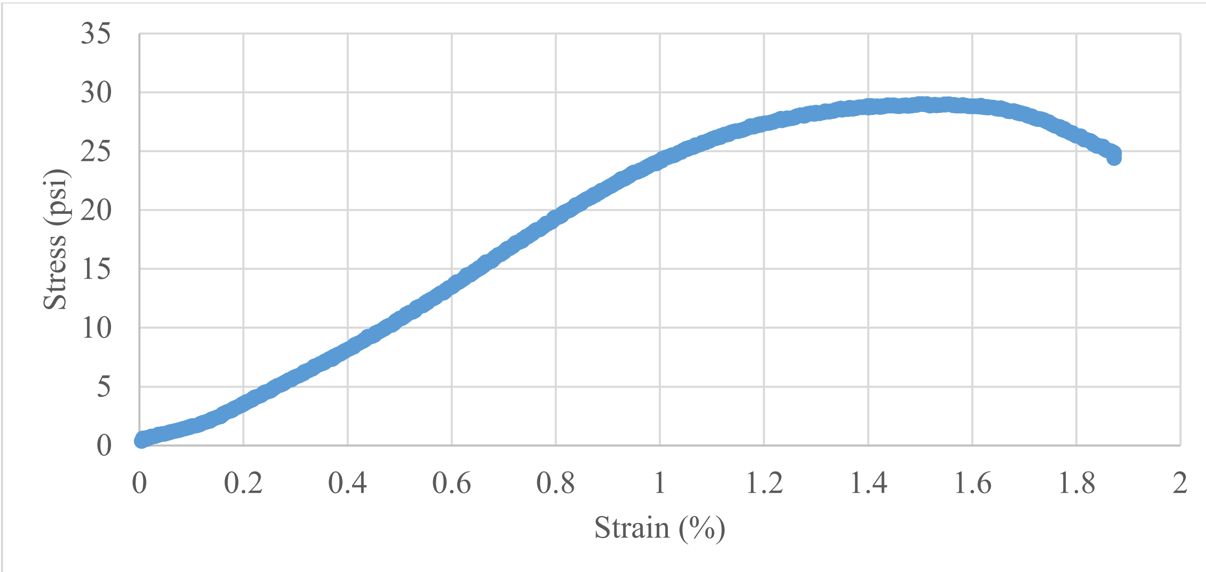


Figure 4.15. Goni borrow UCS stress-strain curve.

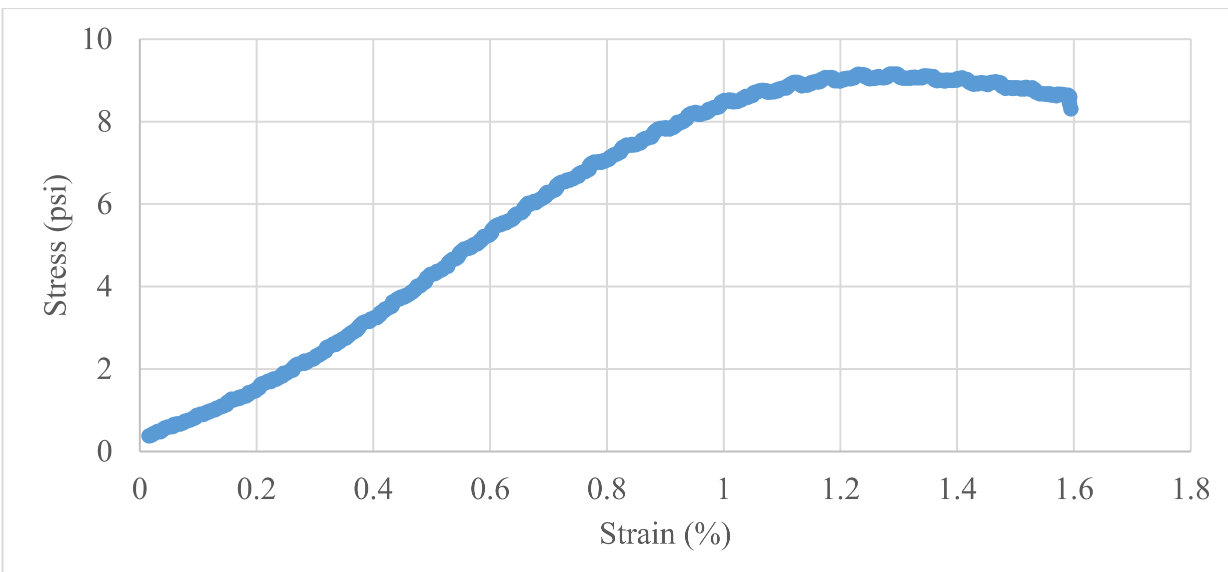


Figure 4.16. Subgrade #3817 UCS stress-strain curve.

Table 4.21. UCS Test Results.

Material	District	Source	UCS (psi)
Base	2	Lockwood	2.3
	2	Goni	4.9
	2	Spanish Spring	12.6
	2	Imlay	11.2
	2	Trico A	33.3
	2	Trico B	N.A.[1]
	3	Sonoma	13.1
	3	Carlin	10.2
	3	Vega	5.4
	3	Silver State	32.0
Borrow	2	Lockwood	N.A.[1]
	2	Goni	26.2
	2	Spanish Spring	25.9
	2	Imlay	13.4
	2	Trico	25.2
	3	Sonoma	13.9
	3	Vega	15.7
	3	Silver State	1.8
	3	Elko 1	N.E.M.[2]
	3	Elko 2	N.E.M.[2]
Subgrade	2	Spaghetti Bowl	56.4
	2	Kings Row	35.3
	2	Fallon Big Dig 1	14.4
	2	Fallon Big Dig 2	47.9
	2	Lemmon Dr. 1	54.4
	2	Lemmon Dr. 2	21.6
	3	#3817	8.1
	3	#3824	25.6

[1]Not applicable, sample crumbles when extruded
[2]Not enough material to conduct UCS test

4.5. Resistance Value (R-value) Test

The Resistance value (R-value) is an empirical measure of the strength of unbound materials. It represents the resistance of soils to deformation, defined as a function of the ratio of the applied vertical pressure to the generated horizontal pressure. This material property is used by NDOT for pavement design to characterize the strength of the unbound materials. The R-value for the tested materials was measured in accordance with NDOT test method Nev. T115D. Materials were split according to their gradation, and four 1200g samples were batched for the test, with one sample used as a guide for the three other Stabilometer samples. Different moisture contents were added to the samples and compaction was achieved in a 4-inch diameter by 5-inch height steel mold with a mechanical kneading compactor as shown in Figure 4.17. Specimens were compacted by applying 100 tamps at 200 psi foot pressure.

The compacted mold was then placed on an exudation device as shown in Figure 4.18, and load was applied at a rate of 2000 lb/min until exudation is achieved. The exudation pressure is then calculated by dividing the exudation load by the specimen's cross-sectional area. The specimens are covered and left in the mold for at least half an hour, then 200 mL of water was added to the specimen in the mold and left undisturbed for 16 to 20 hours to measure the expansion pressure. Following the expansion pressure testing, the specimens were forced into the Hveem Stabilometer, shown in Figure 4.19, where a vertical pressure of 160 psi was applied, and the horizontal pressure and displacement were recorded.

The Stabilometer R-value was calculated using Equation 4.

$$R - value = 100 - \frac{100}{\frac{2.5}{D} \times \left(\frac{P_v}{P_h} - 1\right) + 1} \tag{4}$$

Where;

- P_v= Vertical pressure (160 psi)
- P_h= Horizontal pressure (psi) at vertical pressure of 160 psi
- D= Turns displacement reading

The R-value was plotted against the exudation pressure for the three specimens and the resultant R-value was obtained from the graph at a 300-psi exudation pressure.

The testing was done by Wood Rogers Inc. and an example for the R-value versus exudation pressure graph is shown in Figure 4.20 for Silver State base material.

Figure 4.17. Kneading compactor.

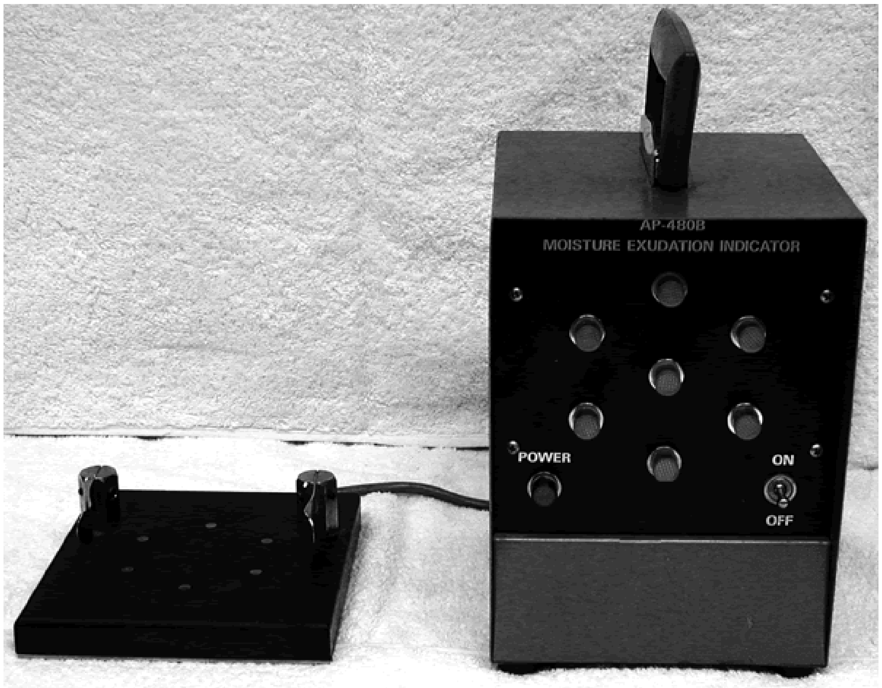
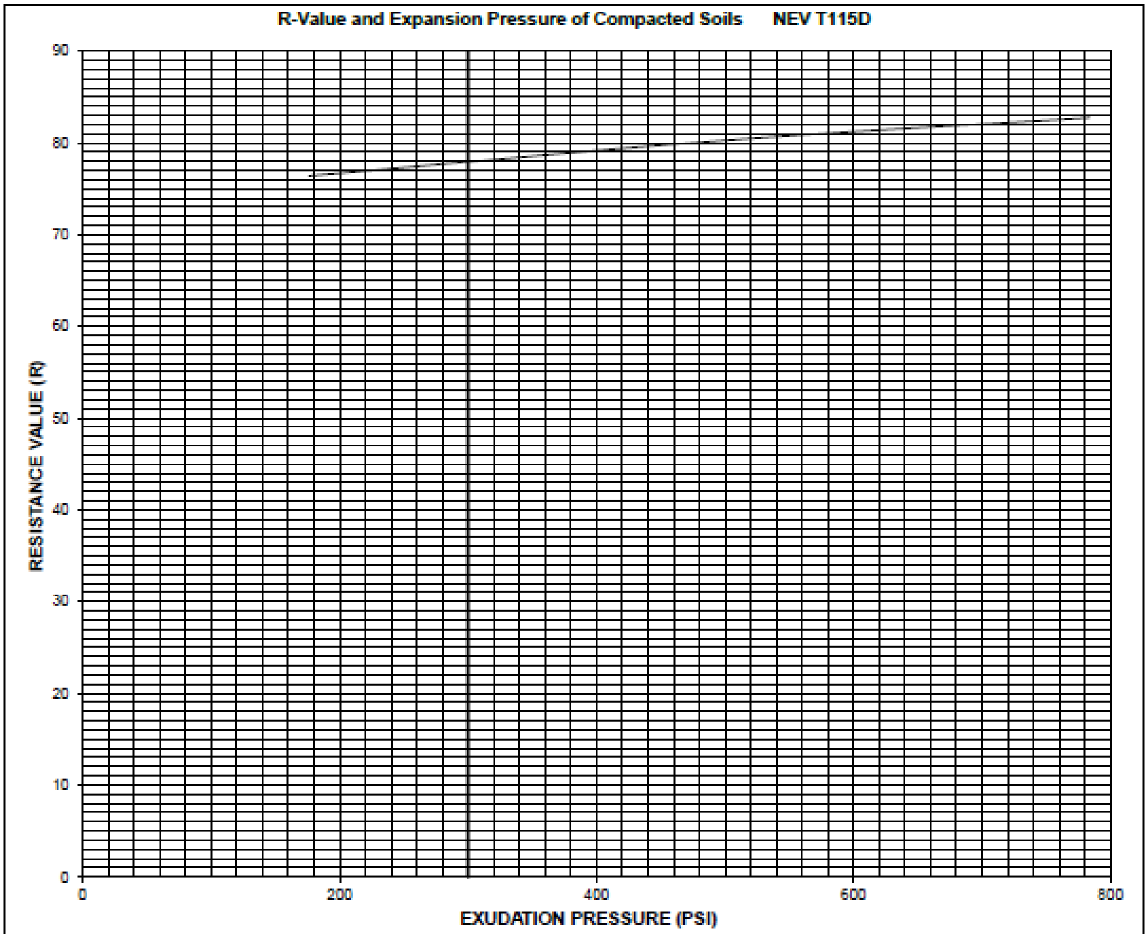


Figure 4.18. Exudation indicator device.

Figure 4.19. Hveem Stabilometer.



Lab Log #	Sample Source	Material	Expansion Pressure (psf) @ 300 (psi)	R-Value @ 300 (psi)
6062	Silver State Rock Products	Base	0	78

POINT #	WATER CONTENT (%)	DRY DENSITY (PCF)	EXUDATION PRESS. (PSI)	EXPANSION PRESS. (PSF)	RESISTANCE VALUE (R)
1	14.2	113.4	176	0	76
2	12.9	114.3	496	0	80
3	11.9	115.4	784	0	83
4					
5					

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Figure 4.20. R-value results for Silver State base material.

Tables 4.21 – 4.23 summarize the R-value test results for base, borrow, and subgrade materials, respectively. According to NDOT specifications, Type 1 base materials must have a minimum R-value of 70 and borrow materials require a minimum R-value of 45. The data show that base materials from Lockwood, Goni, Spanish Springs, and Vega had R-values less than 70, and hence failed the NDOT criterion. Also, Elko 2 borrow had an R-value of 38, which does not meet NDOT's minimum required R-value of 45.

Table 4.22. Base Materials R-value Test Results.

Source	Sample No	Dry Density (pcf)	Moist. (%)	Exud. Pressure (psi)	R Value	R Value Corr.	R-Value @300 psi Exud. Pres
Lockwood Base (District 2)	1	133.8	7.2	780	70.5	70.3	62
	2	132.7	8.6	496	66.8	66.7	
	3	130.9	10.4	281	61.4	61.1	
Goni Base (District 2)	1	125.7	8.6	751	58.8	59.2	51
	2	123.9	9.1	432	54.5	54.4	
	3	125.5	9.5	271	50.3	50.0	
Imlay Base (District 2)	1	122.1	7.1	602	76.4	75.4	74
	2	123.4	8.2	319	74.4	74.2	
	3	123.9	9.5	118	72.3	72.7	
Spanish Springs Base (District 2)	1	134.2	7.2	795	68.6	67.6	65
	2	132.0	7.4	312	65.5	65.3	
	3	125.8	8.4	151	63.9	63.6	
Trico A Base (District 2)	1	113.6	16.9	154	78.1	78.8	83
	2	114.9	16.5	229	80.9	80.5	
	3	116.0	16.1	317	83.5	83.2	
Trico B Base (District 2)	1	128.8	12.3	265	84.7	84.6	87
	2	128.0	11.6	286	86.2	86.2	
	3	127.4	10.8	315	87.6	87.4	
Sonoma Base (District 3)	1	126.0	8.1	450	77.3	76.8	79
	2	126.9	8.5	308	79.1	78.7	
	3	127.3	9.2	127	82.1	81.8	
Carlin Base (District 3)	1	126.4	7.8	113	67.5	66.9	70
	2	122.8	8.6	312	70.2	70.1	
	3	123.5	9.4	556	75.4	75.6	
Vega Base (District 3)	1	122.2	9.8	782	68.7	69.0	57
	2	121.4	10.7	477	62.4	62.3	
	3	120.1	11.8	261	56.4	55.8	
Silver State Base (District 3)	1	113.4	14.2	176	76.2	76.4	78
	2	114.3	12.9	496	80.4	80.2	
	3	115.4	11.9	784	83.3	82.7	

Table 4.23. Borrow Materials R-value Test Results.

Material	Sample No	Dry Density (pcf)	Moist. (%)	Exud. Pressure (psi)	R Value	R Value Corr.	R-Value @300 psi Exud. Pres
Goni Borrow (District 2)	1	128.4	11.2	240	70.4	69.6	77
	2	127.5	10.8	276	74.3	74.2	
	3	126.9	9.8	319	79.8	79.3	
Spanish Springs Borrow (District 2)	1	127.6	12.5	145	13.4	13.4	46
	2	130.4	9.7	308	48.3	48.2	
	3	132.9	8.1	409	69.3	69.0	
Sonoma Borrow (District 3)	1	127.4	9.5	487	80.7	80.2	64
	2	127.9	10.3	316	66.0	65.3	
	3	128.4	11.4	192	54.3	54.2	
Elko 1 Borrow (District 3)	1	113.6	15.6	111	41.4	42.2	63
	2	114.5	14.3	251	57.5	57.9	
	3	119.5	12.1	481	79.9	79.8	
Elko 2 Borrow (District 3)	1	113.5	16.6	180	27.8	27.7	38
	2	115.0	16.1	319	39.5	39.7	
	3	118.0	15.5	493	53.1	52.7	

Table 4.24. Subgrade Materials R-value Test Results.

Material	Sample No	Dry Density (pcf)	Moist. (%)	Exud. Pressure (psi)	R Value	R Value Corr.	R-Value @300 psi Exud. Pres
Spaghetti Bowl Subgrade (District 2)	1	120.7	12.6	227	52.8	52.8	59
	2	124.2	11.9	370	64.9	64.5	
	3	126.1	11.1	510	72.7	71.8	
Kings Row Subgrade (District 2)	1	116.5	16.6	234	17.2	16.6	20
	2	117.0	17.8	398	24.6	24.2	
	3	115.1	14.2	573	32.3	31.1	
Fallon BD 1 Subgrade (District 2)	1	116.8	12.1	473	83.2	83.9	74
	2	116.7	14.3	317	74.8	74.9	
	3	116.4	13.8	221	67.8	67.3	
Fallon BD 2 Subgrade (District 2)	1	83.0	34.5	751	32.4	31.8	13
	2	79.0	37.2	457	19.1	18.3	
	3	75.1	39.3	158	8.8	8.4	
	1	81.6	40.1	126	19.6	19.9	20

Material	Sample No	Dry Density (pcf)	Moist. (%)	Exud. Pressure (psi)	R Value	R Value Corr.	R-Value @300 psi Exud. Pres
Lemmon Dr. 1 Subgrade (District 2)	2	86.0	39.1	299	20.8	20.7	
	3	81.9	37.8	463	22.2	21.6	
Lemmon Dr. 2 Subgrade (District 2)	1	97.8	23.9	774	16.5	15.7	9
	2	97.2	26.3	455	10.7	10.3	
	3	95.1	28.4	240	8.5	8.3	
#3817 Subgrade (District 3)	1	126.0	9.1	569	75.0	75.0	75
	2	126.3	9.4	344	75.0	74.9	
	3	127.2	9.9	159	74.6	74.6	
#3824 Subgrade (District 3)	1	109.7	16.2	142	59.4	60.5	67
	2	112.7	14.6	467	73.5	73.7	
	3	114.4	12.8	753	83.7	83.6	

4.6. Resilient Modulus Repeated Load Triaxial Test

The Mr is an important property that represents the stress-dependent stiffness of unbound materials and is widely used in pavement analysis and design. The testing was done in accordance with AASHTO T307, which was identified as the most commonly used method in the literature review. The specimens are placed in a triaxial chamber and subjected to a dynamic cyclic loading sequence with a 0.1 sec loading time and a 0.9 sec resting period. Resilient (recoverable) strains of the specimens are measured while being subjected to different combinations of contact stresses, cyclic stresses, and confining pressures. The resilient strains are used along with the deviatoric stresses to calculate the Mr values at the different stress states. Base and subbase (borrow) materials are subjected to higher stress states than subgrade soils in the loading sequence due to their location in the pavement structure. Tables 4.24 and 4.25 show the loading sequence presented in the AASHTO T307 standard for base/subbase and subgrade materials, respectively.

4.6.1. Sample Preparation and Testing

A 4-inch diameter by 8-inch height mold was used for sample preparation. Materials were sieved over the 3/4” sieve to satisfy the maximum particle size requirement of AASHTO T307, where the minimum mold diameter has to be five times the maximum aggregate size. The optimum moisture content was added to the samples, mixed until uniform, then the samples were sealed for 16-48 hours. Specimens were compacted to 90% of the maximum dry density in 6 equal-mass lifts using a vibratory compactor as shown in Figure 4.21. Samples were carefully extruded and sealed by installing a membrane, filter papers, sandstones, and ‘O’ rings. Finally, sealed samples were transferred to the triaxial chamber and drainage tubes were connected, as shown in Figure 4.22.

Table 4.25. Testing Sequence for Base/Subbase Materials.

Sequence No.	Confining Pressure (psi)	Max. Axial Stress (psi)	Cyclic Stress (psi)	Contact Stress (psi)	No. of Load Applications
0	15	15	13.5	1.5	500-1000
1	3	3	2.7	0.3	100
2	3	6	5.4	0.6	100
3	3	9	8.1	0.9	100
4	5	5	4.5	0.5	100
5	5	10	9	1	100
6	5	15	13.5	1.5	100
7	10	10	9	1	100
8	10	20	18	2	100
9	10	30	27	3	100
10	15	10	9	1	100
11	15	15	13.5	1.5	100
12	15	30	27	3	100
13	20	15	13.5	1.5	100
14	20	20	18	2	100
15	20	40	36	4	100

Table 4.26. Testing Sequence for Subgrade Soils.

Sequence No.	Confining Pressure (psi)	Max. Axial Stress (psi)	Cyclic Stress (psi)	Contact Stress (psi)	No. of Load Applications
0	6	4	3.6	0.4	500-1000
1	6	2	1.8	0.2	100
2	6	4	3.6	0.4	100
3	6	6	5.4	0.6	100
4	6	8	7.2	0.8	100
5	6	10	9	1	100
6	4	2	1.8	0.2	100
7	4	4	3.6	0.4	100
8	4	6	5.4	0.6	100
9	4	8	7.2	0.8	100
10	4	10	9	1	100
11	2	2	1.8	0.2	100
12	2	4	3.6	0.4	100
13	2	6	5.4	0.6	100
14	2	8	7.2	0.8	100
15	2	10	9	1	100

Figure 4.21. Compaction with vibratory compactor.

Figure 4.22. Sealed sample in triaxial chamber.

Vacuum was applied through the drainage valves to ensure no leakage. The chamber was closed tightly and LVDTs were mounted outside of the chamber and connected to the load cell to measure axial deformation, as shown in Figures 4.23 and 4.24, respectively. The test was run by the software which controlled the loading patterns, and frequent checks were done to ensure that stresses and confining pressure were correct.

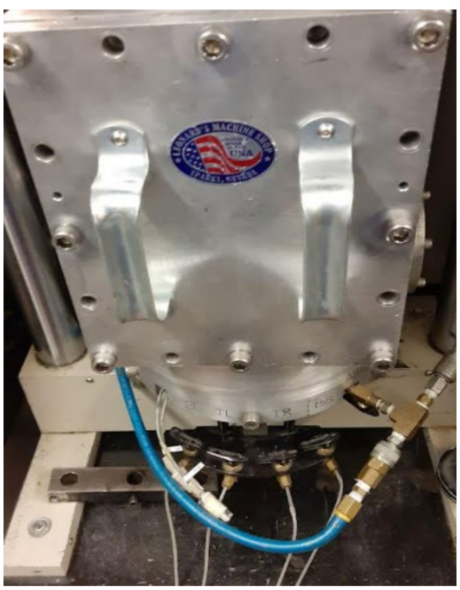

Figure 4.23. Closed chamber and drainage valves.

Figure 4.24. LVDTs connected outside the chamber.

4.6.2. Mr Models Development

The RLT test results were used to develop non-linear models relating the Mr of the unbound materials to the stress states. The constitutive models that best fit the tested materials were the Theta model (5) which describes the stress-hardening behavior, the Uzan, and Universal models (6). Although the Universal model (shown in Equation 1 previously) showed good correlations with most subgrade materials and many borrow materials, the Uzan model performed consistently better and hence was used later for the analysis. The Theta model (Equation 5) and Uzan model (Equation 6) are shown below.

Theta Model: $$Mr = K_1\theta^{K_2} \quad (5)$$

Uzan Model: $$Mr = K_1\theta^{K_2}\sigma_d^{K_3} \quad (6)$$

Where;

- θ= Bulk Stress (sum of the three principal stresses, psi)
- σ_d= Deviator Stress (psi)
- K_1, K_2, K_3= Regression Coefficients

For each loading sequence, the resilient strain values of the last five cycles were averaged to obtain the Mr value. The least squares method was used in Microsoft Excel to derive the coefficients for the constitutive models. The Carlin base Mr test results summary is shown in Table 4.26, along with the necessary parameters for the regression analysis. Figures 4.25 to 4.27 show the measured versus predicted Mr values for Carlin base, Goni borrow, and subgrade #3817, using the Theta model, the Uzan model, and the Universal model, respectively.

Table 4.27. Resilient Modulus Test Results Summary for Carlin Base Materials.

Sequence	Cyclic Axial Stress (psi)	Contact Stress (psi)	Confine Stress (psi)	Axial Resilient Modulus (psi)	Deviator Stress, σ_d (psi)	σ_1 (psi)	σ_3 (psi)	Bulk Stress, θ (psi)	Octahedral Shear Stress (psi)
0	13.5	1.5	14.4	32812	13.5	29.5	14.4	58.3	7.1
1	2.7	0.3	2.4	14986	2.7	5.4	2.4	10.3	1.4
2	5.4	0.6	2.4	15693	5.4	8.4	2.4	13.3	2.8
3	8.1	0.9	2.4	16910	8.1	11.4	2.4	16.3	4.2
4	4.5	0.5	4.4	18085	4.5	9.4	4.4	18.3	2.4
5	9.0	1.0	4.4	20297	9.0	14.4	4.4	23.2	4.7
6	13.5	1.5	4.4	21922	13.5	19.4	4.4	28.3	7.1
7	9.0	1.0	9.4	*26459*	9.0	19.4	9.4	38.2	4.7
8	18.0	2.0	9.4	29442	18.0	29.4	9.4	48.2	9.4
9	26.7	3.0	9.4	31135	26.7	39.1	9.4	58.0	14.0
10	9.0	1.0	14.4	30487	9.0	24.4	14.4	53.3	4.7
11	13.5	1.5	14.4	32223	13.5	29.4	14.4	58.3	7.1
12	26.7	3.0	14.4	*36342*	26.7	44.1	14.4	73.0	14.0
13	13.5	1.5	19.4	36119	13.5	34.4	19.4	73.2	7.1
14	18.0	2.0	19.4	38249	18.0	39.5	19.4	78.3	9.4
15	34.7	4.0	19.4	42256	34.7	58.1	19.4	97.0	18.2

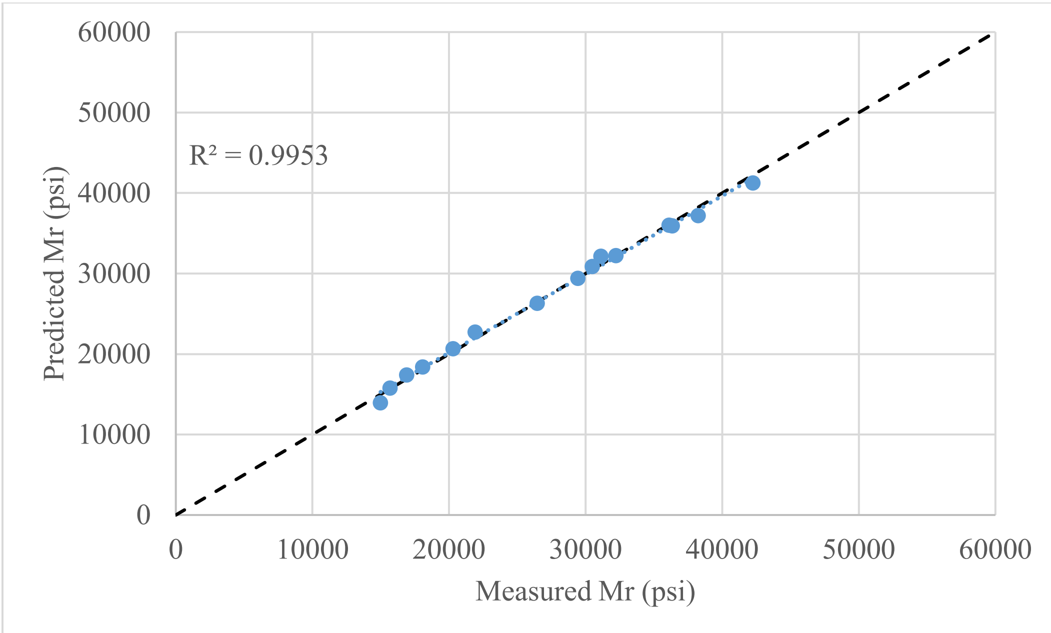

Figure 4.25. Carlin base materials Theta Model.

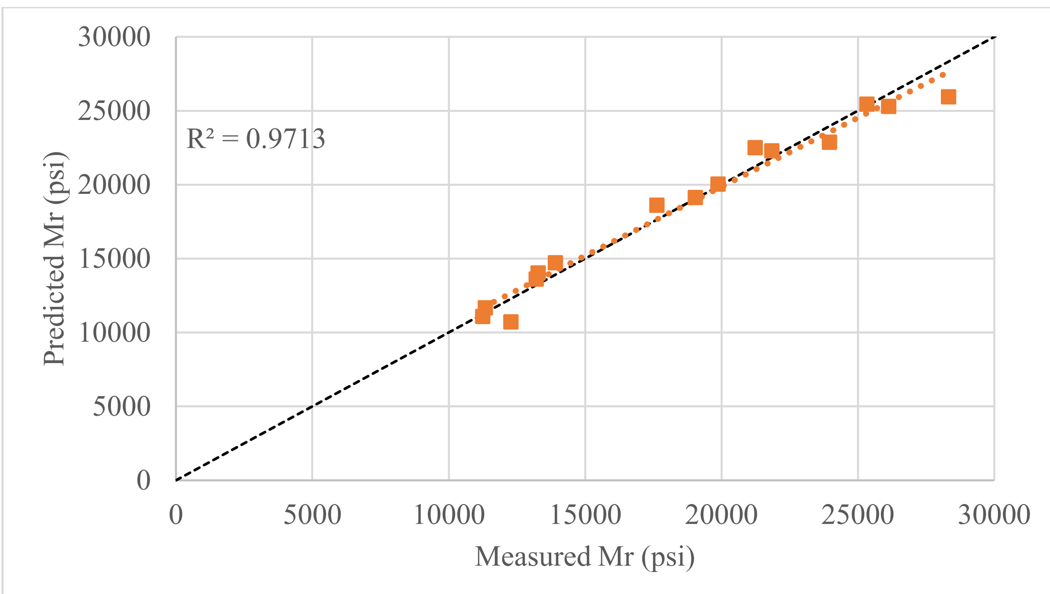

Figure 4.26. Goni borrow materials Uzan Model.

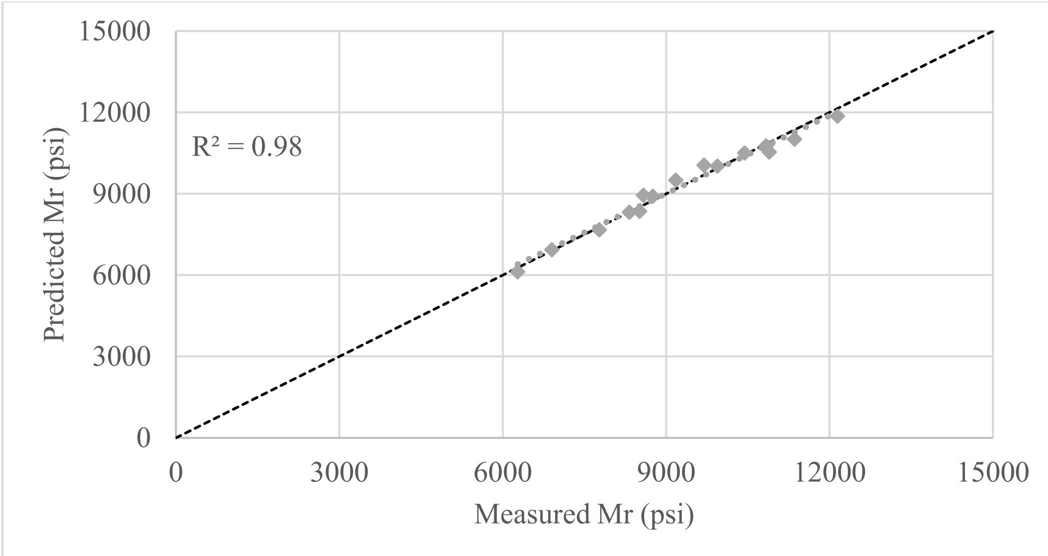

Figure 4.27. Subgrade #3817 Universal Model

Tables 4.27 – 4.29 summarize the three constitutive models' regression results for base, borrow, and subgrade materials, respectively. The best fit model for each material is also shown. It is worth to note that some materials showed better fit with Uzan model or Universal model, but the regression coefficient K_3 was positive, which means that the model does not really reflect the material behavior. This is because K_3 is the coefficient of the deviator stress (Uzan model), or the octahedral shear stress (Universal model), which represents stress softening behavior, and hence should be negative. Such cases are highlighted in the tables.

Figures 4.28 – 4.30 present the variation of the resilient modulus with the bulk stress for the base, borrow, and subgrade materials, respectively.

Table 4.28. Base Materials Constitutive Models Regression Results.

Model	Regression Coefficient	Base Source									
		District 2						District 3			
		Lockwood	Goni	Imlay	Spanish Springs	Trico A	Trico B	Carlin	Sonoma	Vega	Silver State
Theta	K_1	2990.0	1682.7	4178.2	4269.6	3330.1	2346.2	4512.8	3656.0	3474.0	3315.4
	K_2	0.531	0.545	0.507	0.325	0.451	0.515	0.484	0.524	0.456	0.455
	R^2	0.983	0.971	0.989	0.588	0.974	0.977	0.995	0.991	0.975	0.960
Uzan	K_1	3113.1	1653.1	4192.0	6307.4	3228.2	2508.7	4412.0	3702.6	3609.3	3625.5
	K_2	0.483	0.567	0.503	-0.135	0.488	0.432	0.512	0.508	0.406	0.342
	K_3	0.055	-0.026	0.004	0.524	-0.042	0.096	-0.033	0.018	0.058	0.130
	R^2	0.986	0.972	0.989	0.939	0.976	0.985	0.995	0.991	0.978	0.978
Universal	K_1	809.4	484.9	1087.8	536.4	754.9	597.8	1129.1	991.3	764.3	707.0
	K_2	0.462	0.516	0.476	-0.064	0.437	0.421	0.487	0.488	0.384	0.340
	K_3	0.282	0.121	0.127	1.608	0.060	0.395	-0.015	0.148	0.305	0.484
	R^2	0.991	0.973	0.990	0.974	0.975	0.993	0.994	0.993	0.986	0.989
Chosen Model		Theta	Uzan	Theta	Theta	Uzan	Theta	Theta	Theta	Theta	Theta

Table 4.29. Borrow Materials Constitutive Models Regression Results.

Model	Regression Coefficient	Borrow Source									
		District 2					District 3				
		Lockwood	Goni	Imlay	Spanish Springs	Trico	Elko 1	Elko 2	Vega	Silver State	Sonoma
Theta	K_1	2401.8	3413.1	3037.9	5922.7	1825.4	3538.9	6695.8	4427.6	2699.9	4092.4
	K_2	0.603	0.451	0.538	0.354	0.507	0.434	0.307	0.459	0.510	0.488
	R^2	0.988	0.944	0.979	0.854	0.972	0.976	0.896	0.987	0.979	0.984
Uzan	K_1	2462.8	3014.3	3062.5	4951.2	1697.2	3441.8	5876.8	4367.9	2552.5	3999.8
	K_2	0.575	0.587	0.529	0.551	0.589	0.470	0.476	0.476	0.585	0.515
	K_3	0.032	-0.152	0.011	-0.221	-0.093	-0.042	-0.196	-0.020	-0.088	-0.030
	R^2	0.989	0.970	0.979	0.935	0.979	0.978	0.977	0.987	0.985	0.985
Universal	K_1	802.5	805.8	852.5	1105.5	491.0	770.4	1116.8	1023.7	732.1	1025.4
	K_2	0.557	0.502	0.493	0.449	0.527	0.428	0.407	0.445	0.527	0.475
	K_3	0.189	-0.205	0.186	-0.383	-0.085	0.025	-0.421	0.058	-0.075	0.054
	R^2	0.991	0.949	0.982	0.883	0.972	0.976	0.940	0.987	0.980	0.984
Chosen Model		Theta	Uzan	Theta	Uzan	Uzan	Uzan	Uzan	Uzan	Uzan	Uzan

Table 4.30. Subgrade Materials Constitutive Models Regression Results.

Model	Regression Coefficient	Subgrade Source							
		District 2						District 3	
		Fallon Big Dig1	Fallon Big Dig2	Spaghetti Bowl	Kings Row	Lemmon Dr. 1	Lemmon Dr. 2	#3817	#3824
Theta	K_1	4465.6	7570.1	7226.2	10018.2	8112.5	10170.1	2546.0	6679.6
	K_2	0.242	0.055	0.197	0.212	0.063	0.086	0.470	0.243
	R^2	0.778	0.259	0.749	0.360	0.058	0.150	0.982	0.419
Uzan	K_1	4350.5	7369.0	7004.1	8836.4	7403.3	9371.8	2541.7	6098.5
	K_2	0.286	0.086	0.250	0.370	0.203	0.199	0.473	0.399
	K_3	-0.059	-0.038	-0.072	-0.201	-0.188	-0.148	-0.003	-0.215
	R^2	0.855	0.505	0.916	0.963	0.965	0.946	0.982	0.949
Universal	K_1	615.3	626.9	902.2	1532.5	822.3	1048.3	615.5	1123.3
	K_2	0.274	0.088	0.242	0.367	0.201	0.199	0.473	0.388
	K_3	-0.315	-0.296	-0.460	-1.455	-1.362	-1.104	-0.024	-1.475
	R^2	0.817	0.525	0.870	0.927	0.914	0.940	0.982	0.870
Chosen Model		Uzan	Uzan	Uzan	Uzan	Uzan	Uzan	Uzan	Uzan

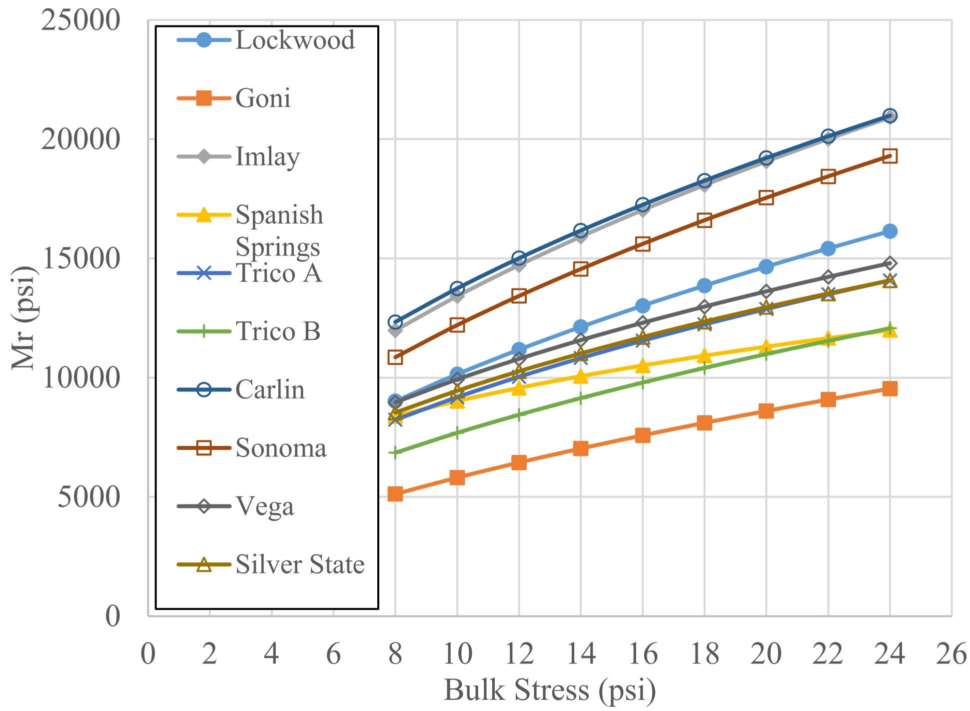

Figure 4.28. Variation of Mr with bulk stress for base materials.

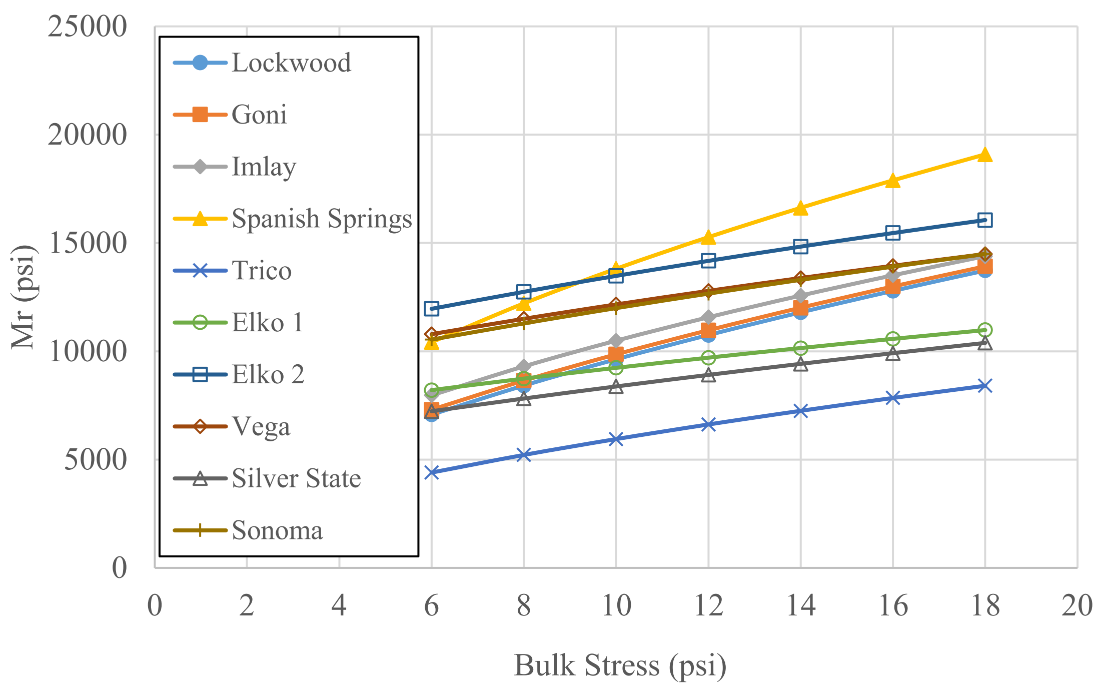

Figure 4.29. Variation of Mr with bulk stress for borrow materials.

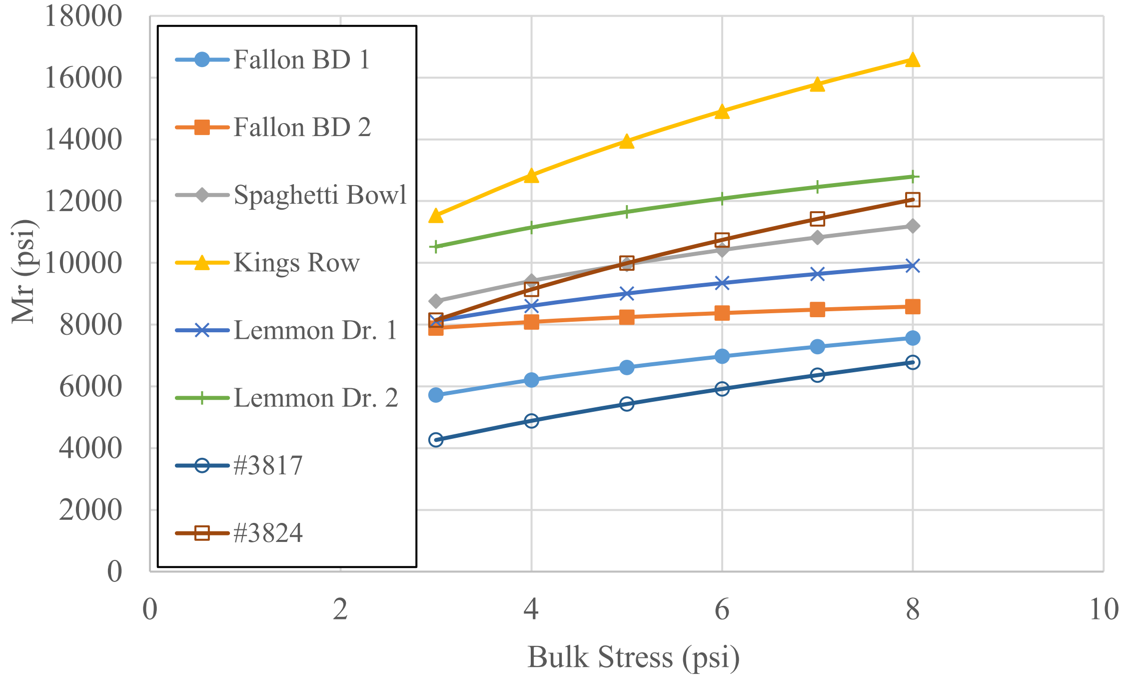

Figure 4.30. Variation of Mr with bulk stress for subgrade materials.

4.7. Test Results Comparison with NDOT Specifications

Before starting the analysis for determining the design Mr values, test results were checked against NDOT specifications to ensure that each material is correctly labeled as base or borrow. Tables 4.30 and 4.31 show this comparison for District 2 and District 3 base materials, respectively. As stated previously, borrow material from Elko 2 failed the R-value specification, and hence was excluded from further analysis. Similarly, all base materials failing any of the NDOT specifications (as highlighted in Tables 4.30 and 4.31) were excluded from base materials and treated as borrow materials for the development of Mr models, except for the Spanish Springs base. This material was excluded from the analysis since it showed an unexpected stress hardening behavior with the deviator stress, where its Mr increased with increasing deviator stress as shown in Figure 4.31. It is worth noting that the Mr results for the base materials that passed NDOT specifications fit the Theta model.

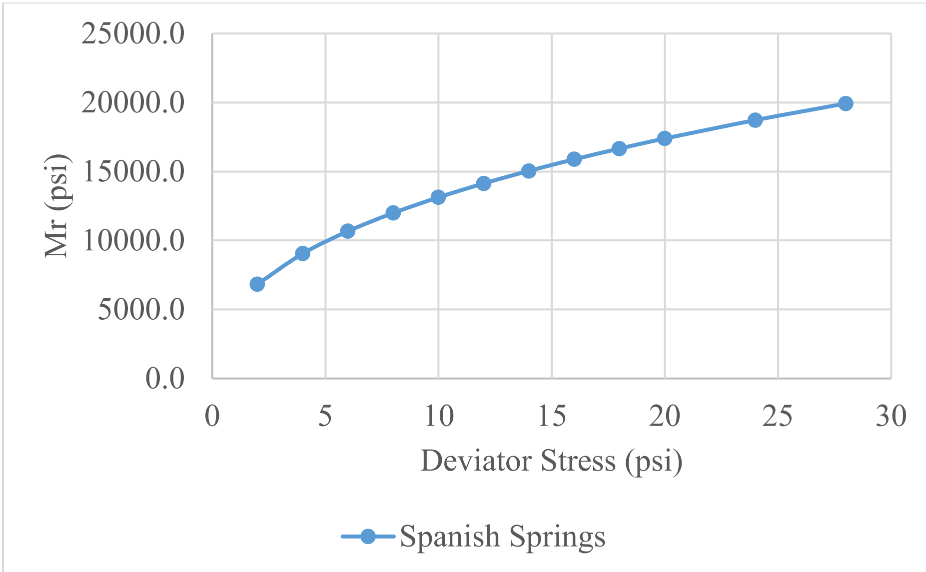

Figure 4.31. Variation of Mr with deviator stress for Spanish Springs base material.

Table 4.31. District 2 Base Materials Comparison with NDOT Specifications.

	Lockwood	Goni	Imlay	Spanish Springs	Trico A	Trico B	NDOT Specs	
							Min	Max
1.5"	100	100	100	100	100	100	100	-
1"	89	94	98	99	100	100	80	100
#4	50	43	48	42	61	40	30	65
#16	29	18	24	22	36	20	15	40
#200	3	4	10	9	16	8	2	12
R-value	62	51	74	65	83	87	70	-
L.L. (%)	N.A.	N.A.	N.A.	37	N.A.	N.A.	-	35
P.I. (%)	N.P.	N.P.	N.P.	9	N.P.	N.P.	-	4*

Table 4.32. District 3 Base Materials Comparison with NDOT Specifications.

	Sonoma Pit	Carlin Pit	Vega Pit	Silver State	NDOT Specs	
					Min	Max
1.5"	100	100	100	100	100	-
1"	99	100	100	100	80	100
#4	48	51	50	63	30	65
#16	28	30	27	31	15	40
#200	9	11	6	11	2	12
R-value	79	70	57	78	70	-
L.L. (%)	N.A.	N.A.	N.A.	30	-	35
P.I. (%)	N.P.	N.P.	N.P.	4	-	4*

*: Limit for material with 9-11% passing sieve #200

CHAPTER 5. DESIGN RESILIENT MODULUS FOR NEW PROJECTS

Proper characterization of the subgrade and unbound layers for structural design (new and rehabilitation) is essential since they significantly affect pavement performance. The Mr is the primary material property used to characterize these materials for flexible pavement design in the AASHTO 1993 Design Guide (1) and in the MEPDG developed under NCHRP project 1-37A (7) which is currently being implemented as the AASHTOWare® Pavement ME design software (8).

This chapter focuses on the determination of the unbound materials' Mr values for the design of new flexible pavements as recommended by the MEPDG. Establishing these Mr values is needed for the development of correlations between the Mr and other materials properties.

5.1. Procedure for Determination of Mr values for New Design

The steps to determine the Mr values for unbound layers (aggregate base, borrow materials and subgrade soil) using the results of the repeated load resilient modulus tests are listed and defined below. These steps are in accordance with the MEPDG Manual of Practice as well as in the final report for NCHRP project 1-37A for both flexible and rigid pavements.

1. Based on previous experience, a trial flexible pavement structure is assumed that can satisfy the requirements of traffic loads and available materials.
2. Use the trial pavement structure to calculate the at-rest stress state from the overburden pressures for the aggregate base layer, embankment, and/or subgrade. The at-rest stress state for the aggregate base layer and embankment are determined at their quarter depth, while the at-rest stress state for the subgrade is determined 18 inches into the subgrade. These material characterization depths are explained by Von Quintus et al in comparing laboratory resilient modulus values to backcalculated elastic layer modulus values. These depths are debatable but were selected for estimating the c-factor included in the 1993 AASHTO Design Guide, as well as in the MEPDG Manual of Practice.
3. Start with the subgrade or lowest unbound layer and move upward in the pavement structure to establish the design resilient modulus for all unbound material layers using a linear elastic layer program for calculating layer responses or stresses at the locations defined in step 2. Assume the Mr for the unbound layers above which the design Mr is being estimated.
4. For the design truck axle load and season, calculate the load-related vertical and horizontal stresses using a linear elastic layered program to be consistent with the Pavement ME Design pavement response program. The load-related stresses are calculated at the material/soil characterization depths listed in step 2.
5. Calculate the at-rest horizontal and vertical stresses from overburden at the same critical points or locations in the unbound layers used to calculate the load-related stresses. The at-rest vertical pressure (p_1) is calculated using Equation 7, while the at-rest horizontal stresses (p_2 and p_3) are calculated as using Equation 8.

$$p_1 = p_0 = (D_{HMA}\gamma_{HMA} + D_{Base}\gamma_{Base} + D_{Soil}\gamma_{Soil}) \quad (7)$$

$$p_2 = p_3 = p_0 K_0 \quad (8)$$

Where;

- p_0, p_1= At-rest vertical or overburden pressure from the layers above a specific point
- p_2, p_3= At-rest horizontal stress
- K_0= At-rest earth pressure coefficient
- D_{HMA}= Thickness of the AC layers
- D_{Base}= Thickness of the unbound aggregate base and/or embankment layers. If determining the at-rest stresses in the unbound base layer the point or depth into the base is ¼ of its thickness (see step 1)
- D_{Soil}= Point for computing at rest stress state in subgrade, 18 inches
- γ_{HMA}= Average in place density of the AC layers
- γ_{Base}= Average in place wet density of the unbound aggregate base and/or embankment layers
- γ_{Soil}= Average in place wet density of the subgrade soil

6. Superimpose the at-rest and load-related stresses in the vertical and horizontal directions. In other words, add the at-rest and load-related vertical stresses, and add the at-rest and load related horizontal stresses.
7. Superimpose the total stress state versus Mr calculated with the linear elastic layer theory and the repeated load Mr values versus stress state measured in the laboratory. The stress-state at which the elastic theory and laboratory Mr values are equal is the value to be used in the Pavement ME Design software for quasi-input level 1.
8. Check the design Mr determined for the lower unbound layers to be sure it is the same, as previously determined. This step can be an iterative process to determine a stable design Mr.

5.2. Identification of Mr Values for New Design of Typical NDOT Pavements

In this section, the unbound materials' Mr values for new flexible pavement design were identified using the same procedure followed in the research for District 1 (3). The typical NDOT sections were designed using the AASHTO 1993 design procedure (9) for three traffic level of low, medium, and high. The NDOT Pavement Structural Design Manual (10) was used as a reference for the input parameters as shown in Table 5.1.

As recommended by the NDOT manual, structural coefficients for the AC layer, base layer, and borrow layer were 0.35, 0.1, and 0.07, respectively. Two levels of subgrade strength were used: strong with a Mr of 14000 psi, and weak with a Mr of 8000 psi. The Mr for the base layer was kept constant at 26000 psi.

Pavements on weak subgrade were designed with and without a borrow layer. When incorporating the borrow layer as a subbase in the design, the Mr for the base, borrow, and subgrade was taken to be 26000 psi, 11250 psi, and 6800 psi, respectively. Tables 5.2 and 5.3 show the structures without and with borrow layer, respectively.

Table 5.1. Major Inputs for AASHTO 1993 Design.

Traffic Level	Design Traffic in Million ESALs (MESALs)	Reliability Level (%)	Initial Serviceability Index (pi)	Terminal Serviceability Index (pt)	Standard Deviation (S_o)
Low	5	85	4.2	2	0.45
Medium	15	90	4.2	2.5	0.45
High	30	95	4.2	2.5	0.45

Table 5.2. Pavement Structures without Borrow Materials.

Traffic Level	Subgrade Mr (psi)	Thickness (inch)	
		AC	Base
Low	14000	5	16
	8000	7	16
Medium	14000	7	18
	8000	9.5	18
High	14000	8	23
	8000	10.5	23

Table 5.3. Pavement Structures with Borrow Materials.

Traffic Level	Thickness (inch)		
	AC	Base	Borrow
Low	5.5	16	10
Medium	8.5	18	10
High	9.5	23	10

The 3D-Move analysis software (11) was used to calculate the load-induced principal stresses for a single wheel load of 9000 lb and a tire pressure of 100 psi, which is a typical truck tire pressure. Following the MEPDG procedure, the AC layer was subdivided into sublayers, as shown in Figure 5.1, to capture its viscoelastic behavior.

The AC layer was modeled as a viscoelastic material in the 3D-Move analysis software, where the modulus changes with temperature and frequency. A 100ºF median temperature and a vehicle speed of 45 mph were used for Districts 2 and 3 to calculate the dynamic modulus (E*) of the AC layer. E* master curves for Districts 2 and 3 were developed by using representative mean E* data for PG64-28NV mixtures. It should be noted that even-though the same binder grade is used in both districts, the E* master curves are different due to differences in aggregate sources and gradations. Tables 5.4 and 5.5 summarize the mean E* values for Districts 2 and 3, respectively. Figures 5.2 and 5.3 show the E* master curves for District 2 and 3, respectively.

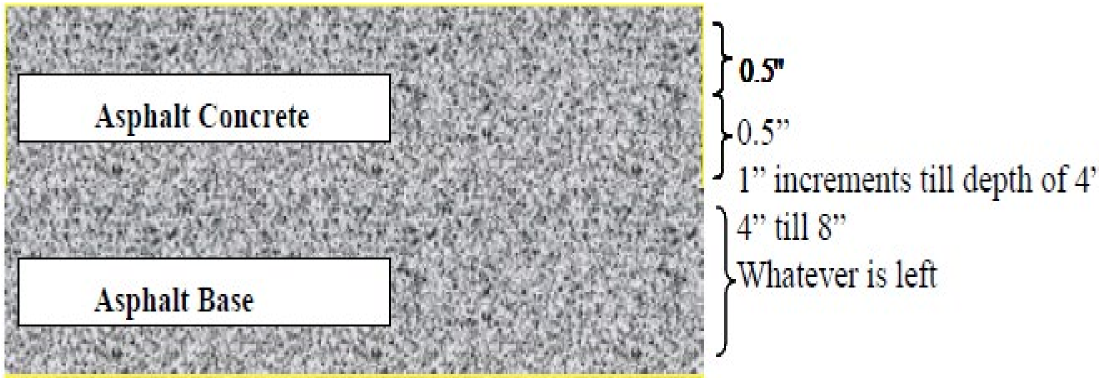

Figure 5.1. Sublayer thicknesses for the AC layer.

Table 5.4. Mean Dynamic Modulus Values for District 2 PG64-28NV Mixture.

Temperature (°F)	Frequency (Hz)					
	0.1	**0.5**	**1**	**5**	**10**	**25**
14	1631380	2008344	2164343	2500790	2632250	2792318
40	628946	885602	1008706	1324511	1472121	1685424
70	122675	212544	264370	436082	526218	678018
100	25282	41756	52208	97192	126317	183386
130	12340	17689	23032	34827	44416	71565

Table 5.5. Mean Dynamic Modulus Values for District 3 PG64-28NV Mixture.

Temperature (°F)	Frequency (Hz)					
	0.1	**0.5**	**1**	**5**	**10**	**25**
14	1727052	2107737	2263477	2595567	2723831	2878790
40	661937	934530	1066170	1385400	1528233	1751700
70	124687	213457	266323	442423	538683	706700
100	34902	54718	67373	118600	151013	222847
130	14977	20178	23423	39520	50332	74025

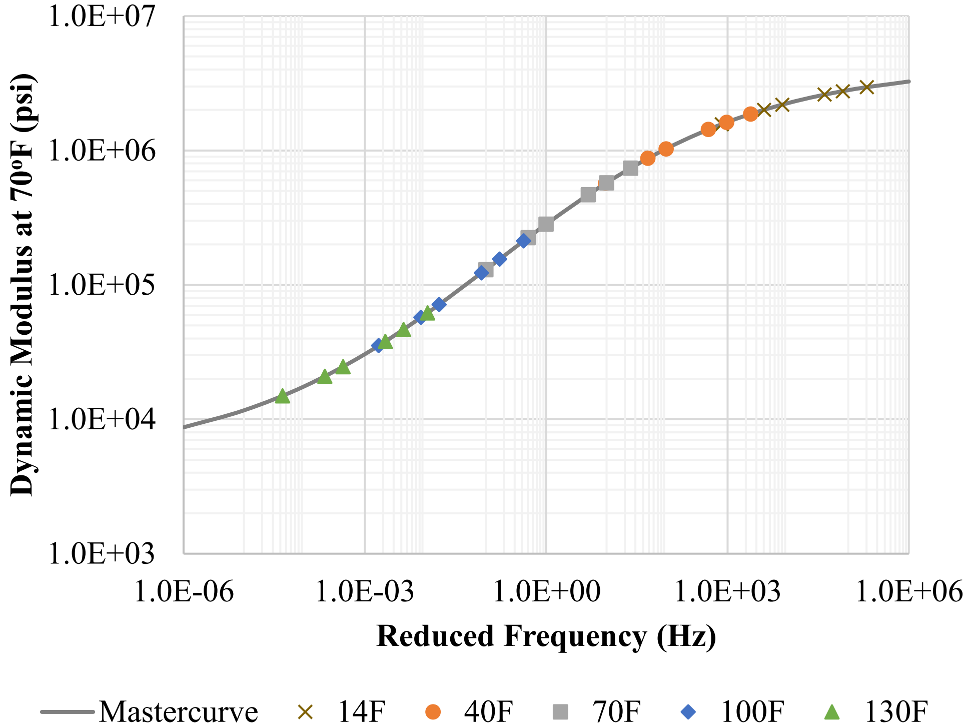

Figure 5.2. Dynamic modulus master curve for District 2 PG64-28NV mixture.

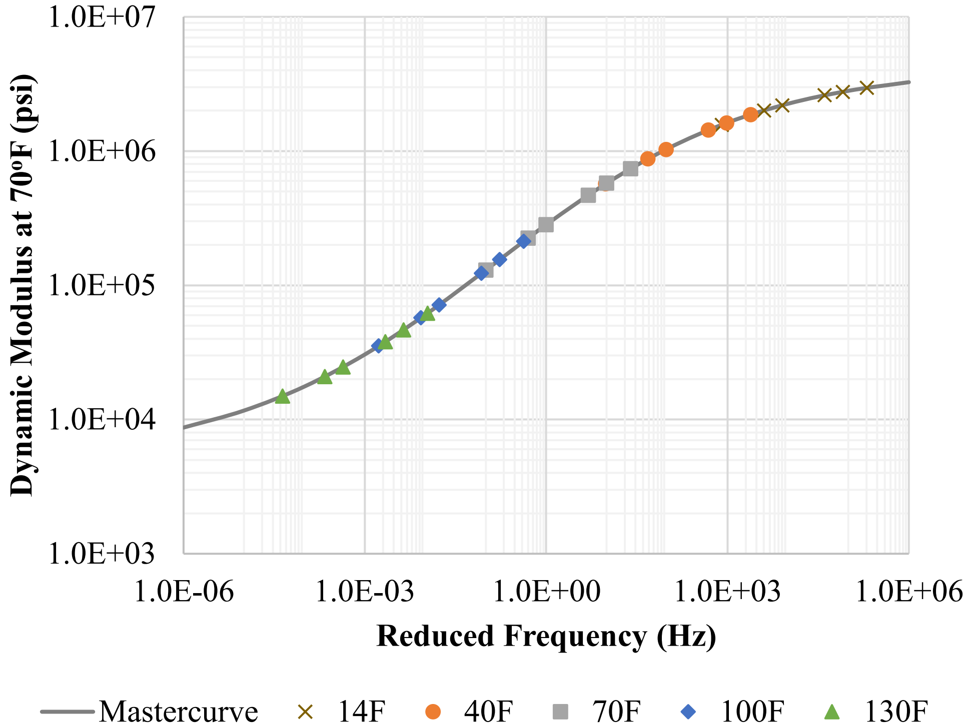

Figure 5.3. Dynamic modulus master curve for District 3 PG64-28NV mixture.

The loading frequency imparted by the moving vehicle changes with the depth of the AC layer. To obtain the frequency experienced by each AC sublayer, the method of equivalent thickness (MET) was used to transform the AC sublayers into equivalent thicknesses as shown in Figure 5.4.

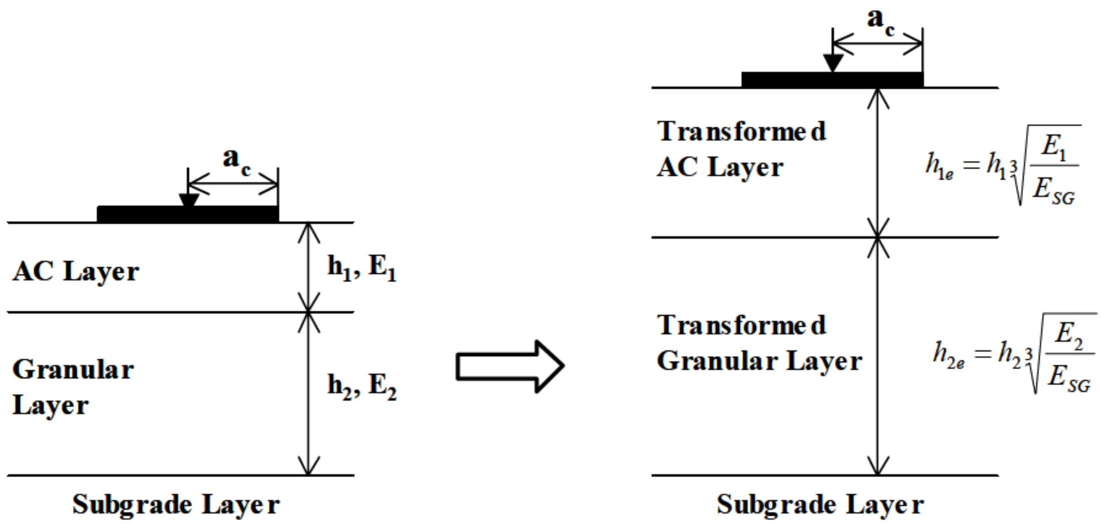

Figure 5.4. Equivalent thickness transformation using MET.

The pulse time was calculated using Equation 9. The vehicle speed used was 45 mph, and the effective length was calculated using the MEPDG procedure as shown in Figure 5.5. The frequency for each sublayer was calculated as the inverse of the pulse time, and the dynamic modulus master curve was used to obtain the E* values at the corresponding frequencies. Tables 5.6 and 5.7 summarize the procedure to calculate the E* values for the sublayers of a 5-inch AC layer for Districts 2 and 3, respectively.

$$t = \frac{L_{eff}}{17.6 v_s} \qquad (9)$$

Where;

- t= loading time (sec)
- L_{eff}= effective length (inch)
- v_s= velocity (mph)

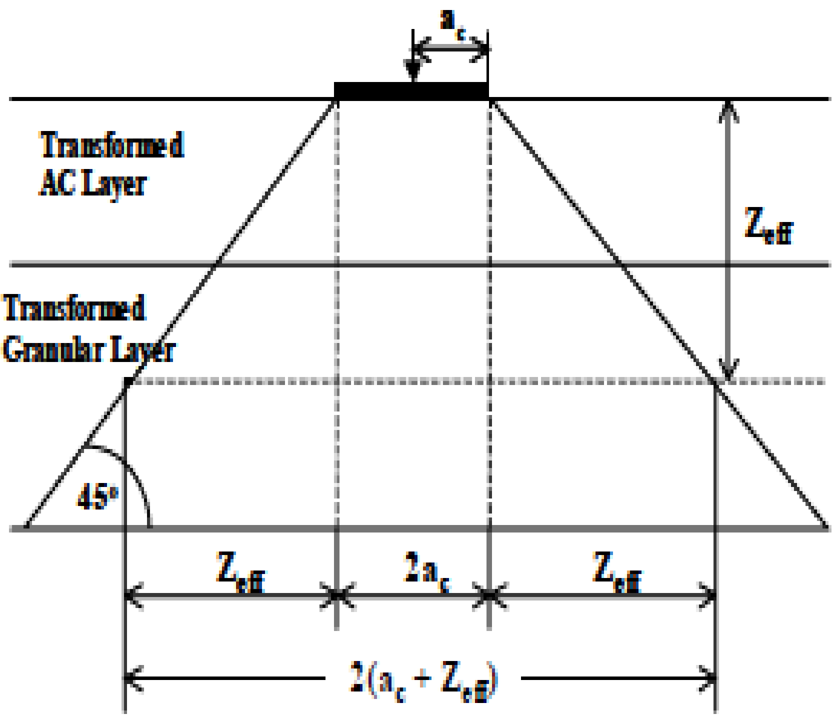

Figure 5.5. Effective length computation for single axle load configuration.

Table 5.6. Summary of Sublayers and E* Calculation for a 5-inch AC Layer for District 2.

AC Sublayers	Thickness (inch)	Z_{eff} (inch)	L_{eff} (inch)	Pulse time (sec)	Frequency (Hz)	E* (psi)
Sublayer 1	0.5	1.32	13.35	0.01685	59.34	258033
Sublayer 2	0.5	2.61	15.93	0.02012	49.71	242481
Sublayer 3	1	5.12	20.94	0.02644	37.82	220119
Sublayer 4	1	7.56	25.83	0.03261	30.66	204245
Sublayer 5	1	9.96	30.62	0.03866	25.87	192181
Sublayer 6	1	12.31	35.33	0.04460	22.42	182539

Table 5.7. Summary of Sublayers and E* Calculation for a 5-inch AC Layer for District 3.

AC Sublayers	Thickness (inch)	Z_{eff} (inch)	L_{eff} (inch)	Pulse time (sec)	Frequency (Hz)	E* (psi)
Sublayer 1	0.5	1.35	13.41	0.01693	59.05	277934
Sublayer 2	0.5	2.68	16.07	0.02029	49.29	261826
Sublayer 3	1	5.25	21.21	0.02679	37.33	238675
Sublayer 4	1	7.77	26.24	0.03313	30.18	222238
Sublayer 5	1	10.23	31.17	0.03936	25.41	209711
Sublayer 6	1	12.66	36.02	0.04548	21.99	199698

The subdivided AC layer was used in the 3D-Move analysis. The Poisson's ratio for the AC, base, borrow, and subgrade were assumed to be 0.3, 0.35, 0.4, and 0.45, respectively. The responses were obtained at the center and edge of the tire at the depths specified in step 2 previously. The principal stresses obtained from the 3D-Move analysis were used to calculate the octahedral normal and shear stresses (Equations 10 and 11). The octahedral stresses were used in Equations 12 and 13 to calculate the corresponding triaxial state of stresses (i.e., the deviatoric and confining stresses).

$$\sigma_{oct} = \frac{1}{3}(\sigma_1 + \sigma_2 + \sigma_3) \tag{10}$$

$$|\tau_{oct}| = \frac{1}{3}\sqrt{(\sigma_1 - \sigma_2)^2 + (\sigma_1 - \sigma_3)^2 + (\sigma_2 - \sigma_3)^2} \tag{11}$$

$$\sigma_d = \frac{3}{\sqrt{2}}|\tau_{oct}| \tag{12}$$

$$\sigma_c = \sigma_{oct} - \frac{\sigma_d}{3} \tag{13}$$

Where;

- σ_1= major principal stress
- σ_2= intermediate principal stress
- σ_3= minor principal stress
- σ_{oct}= octahedral normal stress
- τ_{oct}= octahedral shear stress
- σ_d= deviatoric stress
- σ_c= confining stress

Stresses from overburden were also converted into triaxial state of stress and superimposed to the load-induced stresses. The Theta model for base materials, the Uzan model for subgrade materials, and the best fitting model for the borrow materials, were used to calculate the Mr values. This iterative process continued until the error became less than one percent. The iterative process for a pavement structure with a 5-inch AC layer and a 16-inch base layer is shown in Tables 5.8 and 5.9. For this scenario, the new design Mr value for the base and subgrade layers were 19100 psi and 11750 psi, respectively.

The subgrade materials were divided into two categories depending on their Mr test results. Kings Row, Lemmon Dr. 2, Spaghetti Bowl, and #3824 subgrade materials were categorized as strong, whereas Lemmon Dr. 1, Fallon Big Dig 1, Fallon Big Dig 2, and #3817 subgrade materials were categorized as weak. Tables 5.10 – 5.12 summarize the Mr values for new design of structures with strong subgrade, weak subgrade, and weak subgrade with a borrow layer, respectively.

Due to limited sources of base and subgrade materials per District, the analysis was done for Districts 2 and 3 combined, while considering the different AC layer's E* values for each District. This means that the analysis with District 2 base materials used the E* values for District 2, whereas analysis with District 3 base materials used the E* values for District 3.

Table 5.8. Procedure for Obtaining Triaxial State of Stress.

Trial	Location	3-D Move Stress (psi)							Static (psi)	
		σ_1	σ_2	σ_3	τ_{oct}	σ_d	σ_{oct}	σ_c	σ_d	σ_c
Trial 1	CAB ct	18.35	-0.03	-0.04	8.66	18.38	6.09	-0.03	0.38	0.38
	CAB edg	15.48	-0.05	-0.23	7.36	15.62	5.07	-0.14	0.38	0.38
	SG ct	2.10	0.05	0.04	0.97	2.06	0.73	0.05	1.45	1.45
	SG edg	2.06	0.05	0.04	0.95	2.01	0.72	0.04	1.45	1.45
Trial 2	CAB ct	18.71	-0.08	-0.09	8.86	18.80	6.18	-0.09	0.38	0.38
	CAB edg	15.75	-0.10	-0.30	7.52	15.96	5.12	-0.20	0.38	0.38
	SG ct	2.09	0.05	0.04	0.96	2.05	0.73	0.04	1.45	1.45
	SG edg	2.05	0.05	0.04	0.94	2.00	0.71	0.04	1.45	1.45

Table 5.9. Procedure for Obtaining Mr Values.

Trial	Location	Total (psi)		Bulk Stress θ (psi)	Octahedral Shear Stress (psi)	Assumed Mr (psi)	Predicted Mr (psi)	Error (%)
		Σd	σc					
Trial 1	CAB ct	18.76	0.35	19.82	8.84	18000	18980	5.4
	CAB edg	16.00	0.25	16.74	7.54	18000	17420	3.2
	SG ct	3.51	1.49	7.99	1.65	11500	11770	2.4
	SG edg	3.46	1.49	7.94	1.63	11500	11780	2.4
Trial 2	CAB ct	19.18	0.30	20.07	9.04	19100	19100	0.0
	CAB edg	16.34	0.18	16.89	7.70	19100	17500	8.4
	SG ct	3.49	1.49	7.97	1.65	11750	11770	0.2
	SG edg	3.45	1.49	7.93	1.63	11750	11780	0.3

Table 5.10. Summary of Mr Values for New Design for Structures on Strong Subgrade.

Material Source		Low Traffic		Medium Traffic		High Traffic	
Base	Subgrade	Base	Subgrade	Base	Subgrade	Base	Subgrade
		Design Mr (psi)					
Imlay	Kings Row	19500	15000	15600	15400	13900	15950
Imlay	Lemmon Dr. 2	19100	11750	15200	12000	13650	12200
Imlay	Spaghetti Bowl	18950	10850	15050	11000	13550	11250
Imlay	#3824	18950	10800	15100	11100	13550	11500
Trico B	Kings Row	10700	15000	8550	15450	7600	15950
Trico B	Lemmon Dr. 2	10500	11750	8350	12000	7450	12200
Trico B	Spaghetti Bowl	10450	10850	8300	11050	7400	11250
Trico B	#3824	10450	10750	8300	11100	7450	11500
Carlin	Kings Row	19400	14950	15650	15350	14050	15850
Carlin	Lemmon Dr. 2	19000	11750	15250	11950	13750	12200
Carlin	Spaghetti Bowl	18850	10800	15150	11000	13700	11200
Carlin	#3824	18850	10750	15150	11050	13700	11450
Sonoma	Kings Row	17600	15000	13950	15450	12400	15950
Sonoma	Lemmon Dr. 2	17200	11750	13600	12000	12150	12250
Sonoma	Spaghetti Bowl	17050	10850	13450	11050	12100	11250
Sonoma	#3824	17050	10750	13450	11100	12100	11500
Silver State	Kings Row	12700	14900	10400	15350	9350	15800
Silver State	Lemmon Dr. 2	12450	11700	10150	11950	9200	12200
Silver State	Spaghetti Bowl	12350	10800	10100	10950	9150	11150
Silver State	#3824	12350	10650	10100	11000	9150	11400

Table 5.11. Summary of Mr Values for New Design for Structures on Weak Subgrade.

Material Source		Low Traffic		Medium Traffic		High Traffic	
Base	Subgrade	Base	Subgrade	Base	Subgrade	Base	Subgrade
		Design Mr (psi)					
Imlay	Lemmon Dr. 1	14950	9050	12500	9250	11800	9400
Imlay	Fallon Big Dig 1	14950	9050	12100	7500	11550	7650
Imlay	Fallon Big Dig 2	14800	8400	12350	8450	11700	8550
Imlay	#3817	14400	6900	12000	7050	11500	7350
Trico B	Lemmon Dr. 1	8350	9000	7000	9250	6550	9400
Trico B	Fallon Big Dig 1	8350	9000	6850	7500	6450	7650
Trico B	Fallon Big Dig 2	8250	8400	6950	8450	6500	8550
Trico B	#3817	8050	6950	6800	7100	6400	7350
Carlin	Lemmon Dr. 1	15000	9050	12650	9250	12000	9400
Carlin	Fallon Big Dig 1	15000	9050	12250	7450	11750	7600
Carlin	Fallon Big Dig 2	14850	8400	12500	8450	11900	8500
Carlin	#3817	14400	6850	12150	7000	11700	7250
Sonoma	Lemmon Dr. 1	13350	9050	11150	9250	10500	9400
Sonoma	Fallon Big Dig 1	13350	9050	10800	7500	10300	7650
Sonoma	Fallon Big Dig 2	13250	8400	11000	8450	10400	8550
Sonoma	#3817	12850	6900	10700	7100	10250	7350
Silver State	Lemmon Dr. 1	10100	9000	8650	9200	8200	9400
Silver State	Fallon Big Dig 1	10100	9000	8400	7400	8050	7600
Silver State	Fallon Big Dig 2	10000	8400	8550	8450	8100	8500
Silver State	#3817	9750	6850	8350	6950	8000	7200

Table 5.12. Summary of Mr Values for New Design for Structures with a Borrow Layer.

Material Source			Low Traffic			Medium Traffic			High Traffic		
Base	Borrow	Subgrade	Base	Borrow	Subgrade	Base	Borrow	Subgrade	Base	Borrow	Subgrade
			Design Mr (psi)								
Sonoma	Sonoma	Fallon BD1	15850	10350	7550	11850	10400	7750	11000	10750	7900
Sonoma	Sonoma	#3817	15800	10250	7250	11800	10350	7500	11000	10750	7800
Imlay	Spanish Springs	Fallon BD1	17600	9950	7550	13300	10500	7750	12350	11100	7900
Imlay	Spanish Springs	#3817	17550	9900	7250	13250	10450	7500	12350	11100	7800
Sonoma	Vega	Fallon BD1	15600	8600	7550	11650	8500	7750	10850	8750	7900
Sonoma	Vega	#3817	15600	8500	7250	11650	8500	7500	10850	8750	7800
Imlay	Goni	Fallon BD1	17250	7650	7550	13000	7850	7700	12150	8250	7900
Imlay	Goni	#3817	17200	7600	7250	12950	7800	7450	12150	8200	7750
Imlay	Goni	Fallon BD1	16700	5150	7600	12500	5100	7750	11850	5200	7900
Imlay	Goni	#3817	16650	5100	7250	12500	5050	7500	11850	5200	7800
Imlay	Lockwood Base	Fallon BD1	17400	8550	7600	13050	8500	7750	12200	8700	7900
Imlay	Lockwood	Fallon BD1	17300	8000	7550	13000	7900	7750	12150	8150	7900
Imlay	Imlay	Fallon BD1	17450	8800	7600	13100	8700	7750	12250	9000	7900
Imlay	Trico Base A	Fallon BD1	17300	7950	7550	13000	7950	7700	12150	8250	7900
Imlay	Trico	Fallon BD1	16650	5000	7500	12500	5000	7650	11850	5150	7850
Sonoma	Elko 1	#3817	15500	8150	7200	11600	8200	7450	10850	8450	7750
Sonoma	Silver State	#3817	15350	7200	7250	11500	7250	7500	10750	7550	7750
Sonoma	Vega	#3817	15850	10500	7250	11850	10600	7500	11000	10950	7800

CHAPTER 6. DESIGN RESILIENT MODULUS FOR REHABILITATION PROJECTS

Rehabilitation projects (i.e., overlay) are the most common type of construction for NDOT; hence, a relationship between the backcalculated and design modulus is needed for the implementation of the AASHTOWare® Pavement ME Design software. This chapter focuses on the methodology to obtain representative design Mr values for unbound materials for pavement rehabilitation projects. A stepwise mechanistic analysis approach was followed for determining the unbound materials' Mr values for rehabilitation design. The ILLI-PAVE 2005 finite element (FE) program was employed as an advanced structural model for computing stresses and deflection basins in typical Nevada pavements under representative tire loading (12). In comparison with other pavement analysis software, the main unique features that prompted the use of this program are:

- The inclusion of six different constitutive models allowing for the characterization of the non-linear (stress-dependent) Mr behavior of unbound materials under repetitive loading, unlike Linear Elastic Programs (LEP).
- The implementation of Mohr-Coulomb failure criteria (c and ϕ) for unbound materials.
- The significantly lower computational effort resulting from the use of axis-symmetric FE formulation.
- The ability to handle pavement structures with up to ten layers.

It should also be noted that the ILLI-PAVE program is the only model that allows the use of the constitutive models acquired from the AASHTO T307 test.

6.1. Procedure for Determination of Mr Values for Rehabilitation Design

The stepwise mechanistic approach for determining Mr values for rehabilitation design using ILLI-PAVE is summarized as follows.

1. Select Representative Pavement Structures: The analysis starts by establishing representative NDOT flexible pavement structures.
2. Pavement Layer Properties:
    i. Asphalt Concrete (AC): The AC layer was subdivided into sublayers in ILLI-PAVE to capture its viscoelastic behavior, and the appropriate E* master curve was used to assign a proper E* value for each sublayer depending on the temperature and frequency.
    ii. Crushed Aggregate Base (CAB), Borrow, and Subgrade (SG): The constitutive Mr models developed from the AASHTO T307 test as well as the Mohr-Coulomb failure criteria (c and ϕ) were used in ILLI-PAVE.
3. Pavement Responses: The unbound layers' Mr values are not constant at different locations within the respective layer. In other words, the stress dependency of the unbound materials results in a different Mr value at each location due to the changing state of stresses. Hence, assigning a Mr for the entire layer based on stresses at a specific location is questionable. In this study, surface deflection basins (i.e., vertical deflections at various radial distances from the applied loads) were generated for different pavement sections by applying the tire load on a circular plate using ILLI-PAVE. The generated surface deflection basins were then employed in a backcalculation analysis to identify the Mr for each pavement layer.

4. Establish the Mr Correlation Equations: Using the backcalculated moduli values for various types of unbound materials and pavement structures, correlations between Mr and other physical properties were developed and examined for their effectiveness.

6.2. Identification of Mr Values for Rehabilitation Design for NDOT Pavements

Flexible pavement structures used for the new design analysis were also used for this analysis. The AC layer was subdivided into sublayers as explained previously. The damaged E* master curve for the AC mix was used to simulate the in-situ condition of the AC layer in need for rehabilitation. Equation 14 was used to obtain the damaged E* values at different temperatures and frequencies, as shown in Tables 6.1 and 6.2 for Districts 2 and 3, respectively. The damage factor in the equation (d_{AC}) can be determined based on the condition of the AC layer as follows: a) Excellent condition, d_{AC} between 0.00 and 0.20, b) Good condition, d_{AC} between 0.20 and 0.40, c) Fair condition d_{AC} between 0.40 and 0.80, d) Poor condition d_{AC} between 0.80 and 1.20, and e) Very Poor condition d_{AC} greater than 1.20. In this research, a Fair condition was assumed for the existing AC layer and a damage value of 0.60 was selected for use in Equation 14.

Figures 6.1 and 6.2 present the master curves for the undamaged and damaged E* of the AC layer for a typical PG64-28NV mix for Districts 2 and 3, respectively. It should be noted that due to the use of the logarithmic scale, small differences between the damaged and undamaged E* master curves represent large changes in the actual E* value. The developed master curves were used to assign appropriate damaged E* values for each AC sublayer.

$$E^*_{dam} = 10^{\delta} + \frac{E^* - 10^{\delta}}{1 + e^{-0.3+5\times\log(d_{AC})}} \qquad (14)$$

Where;

- E^*_{dam}= damaged dynamic modulus
- δ= regression parameter
- d_{AC}= AC layer damage factor

The Theta model was used for the base materials, the Uzan model was used for the subgrade materials, and the better model was used for the borrow materials. The Poisson’s ratio values for the various layers and the subgrade strength categorization were the same as used in the new design analysis. The cohesion and friction angle for all unbound materials were estimated based on their corresponding USCS classification. The Falling Weight Deflectometer (FWD) was simulated in the ILLI-PAVE program by applying a circular load of 9000 lbs over a 5.35-inch radius.

Table 6.1. Damaged Dynamic Modulus Values for District 2 PG64-28NV Mixture.

Temperature (°F)	Frequency (Hz)					
	0.1	0.5	1	5	10	25
14	1312050	1614996	1740364	2010749	2116396	2245034
40	506447	712708	811640	1065436	1184062	1355482
70	99585	171807	213457	351453	423890	545884
100	21315	34554	42954	79105	102511	148375
130	10914	15213	19507	28986	36692	58510

Table 6.2. Damaged Dynamic Modulus Values for District 3 PG64-28NV Mixture.

Temperature (°F)	Frequency (Hz)					
	0.1	**0.5**	**1**	**5**	**10**	**25**
14	1388915	1694851	1820011	2086894	2189973	2314505
40	532939	752007	857799	1114347	1229135	1408723
70	101180	172519	215005	356527	433886	568912
100	29024	44949	55119	96288	122336	180066
130	13012	17191	19799	32735	41424	60465

Modulus-6.1 computer software was used to backcalculate the moduli for the various layers using the surface deflection basins obtained from ILLI-PAVE (13). An apparent rigid layer was introduced in the Modulus-6.1 software to capture the non-linearity of the unbound materials and avoid having compensation effects. The backcalculation process was considered complete when the deflection basins calculated by the Modulus-6.1 software closely matched the ILLI-PAVE ones, and the identified modulus values were assigned to the corresponding layers.

A sample calculation for a flexible pavement structure with 5-inch AC and 16-inch base material from Carlin on top of the #3824 subgrade material is presented in this section. Table 6.3 shows the forward calculated deflections by ILLI-PAVE and the corresponding backcalculated ones by Modulus-6.1. The absolute error was 0.61 and the E4/Stiff Layer ratio was 6. Figure 6.3 presents the comparison between the deflections obtained from forward calculation and backcalculation. The backcalculated layer moduli are shown in Table 6.4.

The results for this analysis are shown in Tables 6.5 and 6.6 for structures with strong and weak subgrade, respectively. Results for structures on weak subgrade with a borrow layer are shown in Tables 6.7 and 6.8 for low, and medium/high traffic, respectively.

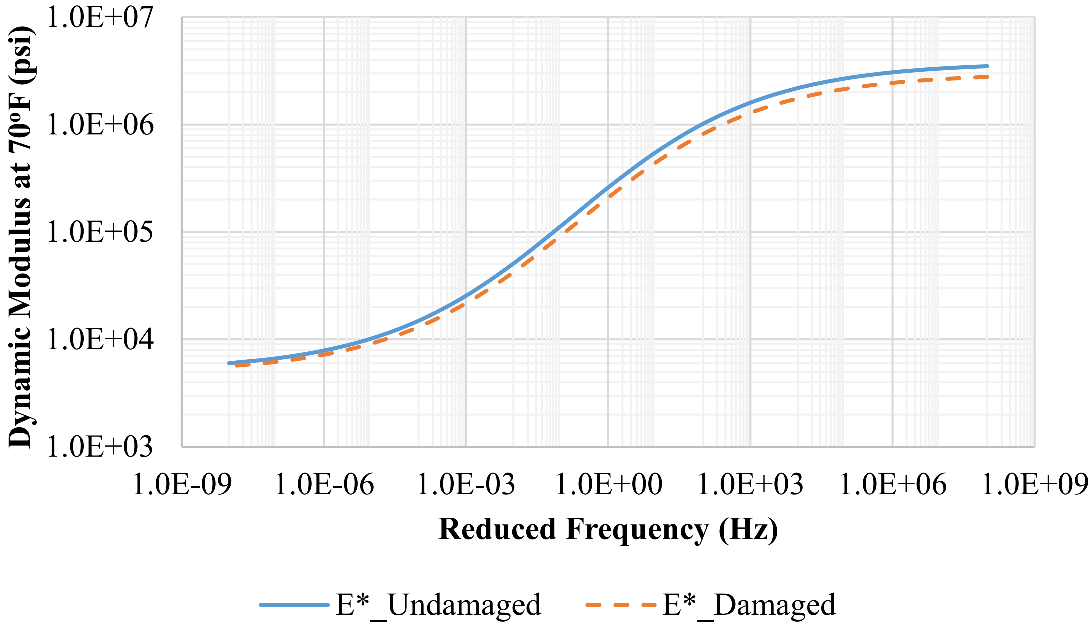

Figure 6.1. Undamaged and damaged dynamic modulus master curves for District 2 PG64-28NV mixture.

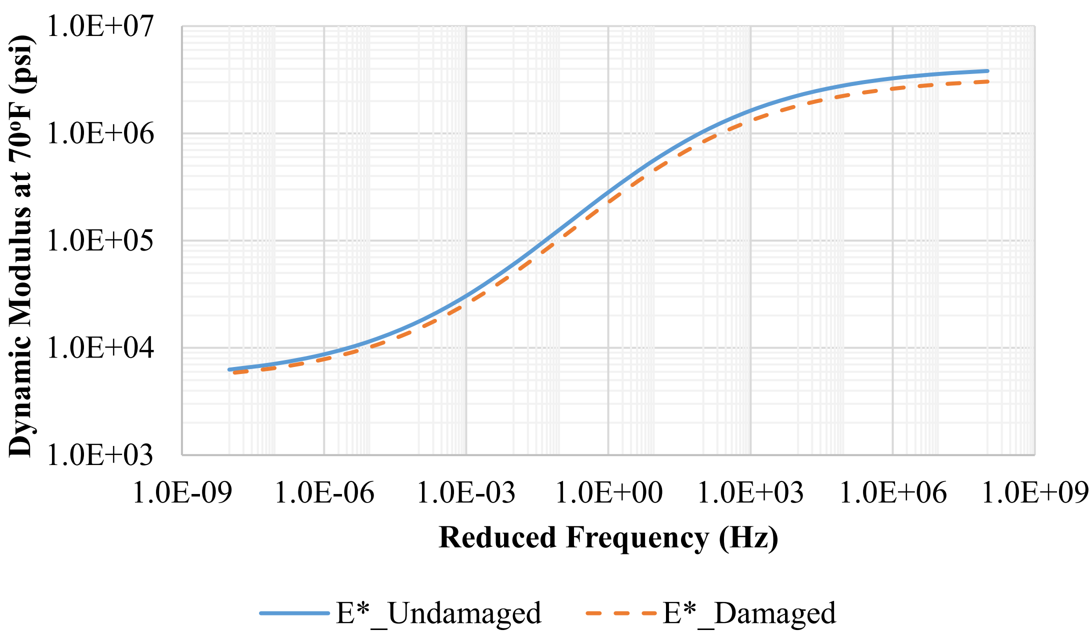

Figure 6.2. Undamaged and damaged dynamic modulus master curves for District 3 PG64-28NV mixture.

Table 6.3. Forward Calculated and Backcalculated Surface Deflections.

Radial Distance (inch)	Vertical Surface Deflections (mils)	
	ILLI-PAVE	Modulus-6.1
0	27.86	27.88
8	19.78	19.79
12	15.49	15.41
24	7.68	7.79
36	4.30	4.24
48	2.33	2.34
60	1.24	1.29

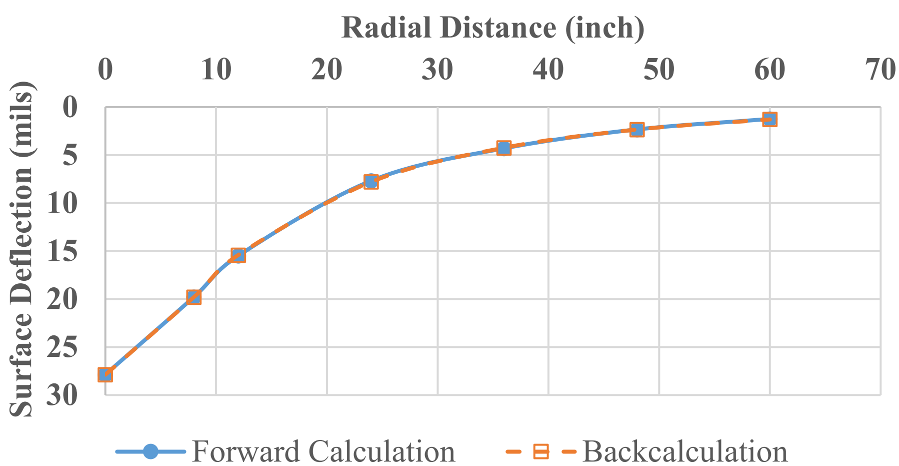

Figure 6.3. Comparison of Forward calculated and backcalculated Surface deflections.

Table 6.4. Backcalculated Layer Moduli.

Layer	AC	CAB	SG
Backcalculated Modulus (psi)	171200	18500	6800

Table 6.5. Summary of Mr Values for Rehabilitation Design for Structures on Strong Subgrade.

Material Source		Low Traffic			Medium Traffic			High Traffic		
Base	Subgrade	AC	Base	Subgrade	AC	Base	Subgrade	AC	Base	Subgrade
		Design Mr (psi)								
Imlay	Kings Row	160400	19100	9000	145400	18200	9000	143900	16200	8800
Imlay	Lemmon Dr. 2	161100	18500	7400	143300	18200	6900	142400	16200	6700
Imlay	Spaghetti Bowl	162500	18200	6800	146300	17500	6600	145100	15600	6500
Imlay	#3824	163200	18100	6800	146700	17400	6700	145600	15500	6600
Trico B	Kings Row	142300	13300	7000	140200	12600	7000	138300	10900	6200
Trico B	Lemmon Dr. 2	140400	13200	5900	137200	12800	5500	137200	10800	5000
Trico B	Spaghetti Bowl	142600	12900	5600	139000	12400	5300	138500	10500	4800
Trico B	#3824	143900	12700	5600	139200	12300	5300	139100	10500	4900
Carlin	Kings Row	168800	19400	9000	157200	18700	9000	156600	16500	8800
Carlin	Lemmon Dr. 2	169700	18800	7500	156900	18200	7200	155500	16400	6700
Carlin	Spaghetti Bowl	171900	18500	6800	157200	17900	6600	156500	16000	6500
Carlin	#3824	171200	18500	6800	157900	17800	6700	156900	15900	6600
Sonoma	Kings Row	169100	18100	8800	157300	17200	8700	156500	15100	8300
Sonoma	Lemmon Dr. 2	169000	17600	7000	156000	17100	6700	155500	15000	6300
Sonoma	Spaghetti Bowl	171000	17400	6400	158000	16500	6400	157100	14500	6100
Sonoma	#3824	170700	17300	6500	158200	16400	6500	157100	14500	6300
Silver State	Kings Row	151500	15400	8100	151500	14600	7900	148600	13300	6500
Silver State	Lemmon Dr. 2	150600	15100	6500	148000	14700	6200	147900	13100	5200
Silver State	Spaghetti Bowl	151000	15000	6000	150400	14200	5900	147900	12900	5000
Silver State	#3824	150300	14900	6000	150000	14200	6000	148100	12900	5000

Table 6.6. Summary of Mr Values for Rehabilitation Design for Structures on Weak Subgrade.

Material Source		**Low Traffic**			**Medium Traffic**			**High Traffic**		
Base	**Subgrade**	**AC**	**Base**	**Subgrade**	**AC**	**Base**	**Subgrade**	**AC**	**Base**	**Subgrade**
		Design Mr (psi)								
Imlay	Lemmon Dr. 1	138800	17700	6100	130500	16800	6100	131300	14900	6100
Imlay	Fallon Big Dig 1	143000	16500	5300	131300	15800	5400	131900	14300	5300
Imlay	Fallon Big Dig 2	139800	17500	5700	130600	16600	5800	131600	14700	5900
Imlay	#3817	146200	15700	5100	133300	14900	5400	133100	13700	5500
Trico B	Lemmon Dr. 1	131300	12600	5200	126000	12000	5200	129000	10100	5100
Trico B	Fallon Big Dig 1	135000	11800	4500	128100	11200	4600	130100	9500	4600
Trico B	Fallon Big Dig 2	131200	12600	4900	127400	11700	5000	130100	9800	4900
Trico B	#3817	136300	11400	4400	129300	10600	4600	131000	9200	4600
Carlin	Lemmon Dr. 1	149400	18100	6100	142400	17200	6200	143700	15200	6200
Carlin	Fallon Big Dig 1	155000	16700	5300	143100	16300	5300	143300	14700	5400
Carlin	Fallon Big Dig 2	151100	17900	5800	142000	17200	5800	144700	15000	5800
Carlin	#3817	158900	15900	5100	145900	15300	5400	144800	14100	5400
Sonoma	Lemmon Dr. 1	150300	16700	5900	141300	15900	6000	144000	13700	6000
Sonoma	Fallon Big Dig 1	155000	15500	5100	143400	14800	5200	144700	13100	5300
Sonoma	Fallon Big Dig 2	150000	16700	5600	142200	15700	5700	143400	13700	5700
Sonoma	#3817	157600	14800	5000	145100	14000	5300	145600	12700	5400
Silver State	Lemmon Dr. 1	141900	14600	5600	137900	14200	5500	139800	11300	5500
Silver State	Fallon Big Dig 1	144500	13600	4800	138700	13300	4900	141700	11000	5000
Silver State	Fallon Big Dig 2	141300	14600	5300	138500	13900	5200	139500	11400	5200
Silver State	#3817	148100	12900	4700	141000	12400	4900	141400	10900	5000

Table 6.7. Summary of Mr Values for Rehabilitation Design for Structures with a Borrow layer (Low Traffic).

Material Source			Low Traffic			
Base	Borrow	Subgrade	AC	Base	Borrow	Subgrade
			Design Mr (psi)			
Sonoma	Sonoma	Fallon BD1	169100	15200	8400	4000
Sonoma	Sonoma	#3817	172100	14900	8000	4100
Imlay	Spanish Springs	Fallon BD1	152400	16900	8000	4100
Imlay	Spanish Springs	#3817	155800	16500	7400	4200
Sonoma	Vega Base	Fallon BD1	164400	15700	7300	3900
Sonoma	Vega Base	#3817	170000	15000	7400	4000
Imlay	Goni	Fallon BD1	153900	16400	6400	4100
Imlay	Goni	#3817	158200	15700	6500	4100
Imlay	Goni Base	Fallon BD1	152200	16600	4100	4000
Imlay	Goni Base	#3817	154800	16000	4000	4000
Imlay	Lockwood Base	Fallon BD1	152300	17100	6500	4000
Imlay	Lockwood	Fallon BD1	153700	16800	6200	4000
Imlay	Imlay	Fallon BD1	153000	16900	7100	4000
Imlay	Trico Base A	Fallon BD1	152400	17000	6500	4000
Imlay	Trico	Fallon BD1	153000	16400	3900	3900
Sonoma	Elko 1	#3817	166500	15300	6800	3900
Sonoma	Silver State	#3817	166500	15300	6200	3900
Sonoma	Vega	#3817	168000	15600	8200	4100

Table 6.8. Summary of Mr Values for Rehabilitation Design for Structures with a Borrow layer (Medium and High Traffic).

Material Source			Medium Traffic				High Traffic			
Base	Borrow	Subgrade	AC	Base	Borrow	Subgrade	AC	Base	Borrow	Subgrade
			Design Mr (psi)							
Sonoma	Sonoma	Fallon BD1	143700	15200	7400	4400	143100	14100	6400	4300
Sonoma	Sonoma	#3817	145500	14800	7400	4500	144900	13600	6700	4600
Imlay	Spanish Springs	Fallon BD1	130700	16800	7000	4400	129900	15800	5500	4300
Imlay	Spanish Springs	#3817	132000	16300	6900	4600	130500	15600	5400	4600
Sonoma	Vega Base	Fallon BD1	143900	15300	6000	4200	142500	14400	4400	4400
Sonoma	Vega Base	#3817	144900	14900	6000	4300	143100	14100	4600	4500
Imlay	Goni	Fallon BD1	132200	16100	6000	4400	129800	15500	4400	4400
Imlay	Goni	#3817	133700	15400	6300	4400	131300	15100	4600	4600
Imlay	Goni Base	Fallon BD1	131400	16100	3900	4300	131400	14600	3900	4100
Imlay	Goni Base	#3817	133400	15500	4000	4400	132200	14300	4100	4300
Imlay	Lockwood Base	Fallon BD1	130700	16600	5900	4400	130200	15600	4300	4700
Imlay	Lockwood	Fallon BD1	131700	16100	6000	4300	131300	15200	4500	4600
Imlay	Imlay	Fallon BD1	132200	16300	6400	4400	129900	15600	4500	4700
Imlay	Trico Base A	Fallon BD1	130600	16700	5700	4400	130100	15600	4300	4700
Imlay	Trico	Fallon BD1	131500	16000	3900	4300	140000	14500	3700	4300
Sonoma	Elko 1	#3817	144300	14800	6000	4300	143000	14300	4000	4500
Sonoma	Silver State	#3817	146100	14300	6000	4200	143200	14000	4300	4300
Sonoma	Vega	#3817	144700	15200	7000	4400	142200	14800	4600	4500

CHAPTER 7. DEVELOPMENT OF MR PREDICTION MODELS

The goal of this analysis is to develop a prediction model for Mr value to be used in the design of flexible pavements as function of empirical and physical properties for the unbound materials. The properties considered in the development of the prediction model, included; R-value, unconfined compressive strength, materials passing sieves #200, #40, 3/8", maximum dry density, optimum moisture content, and plasticity index. In addition, the pavement equivalent thickness in terms of the base, borrow, or the subgrade layer were identified as critical parameters in the determination of the design Mr for unbound layers. The layer thicknesses above the base, borrow, and subgrade used for the state of stress calculations were transformed into equivalent thickness of base, borrow, or subgrade using the method of equivalent thickness (MET) as presented in Equations 15 – 17.

$$\mathbf{H}_{\mathbf{eq,\,CAB}} = \mathbf{h}_{\mathbf{AC}} \left(\frac{\mathbf{E}_{\mathbf{AC}} * (1 - \mathbf{\nu}_{\mathbf{SG}}{}^2)}{\mathbf{E}_{\mathbf{SG}} * (1 - \mathbf{\nu}_{\mathbf{AC}}{}^2)}\right)^{(1/3)} + \frac{\mathbf{h}_{\mathbf{CAB}}}{4} * \left(\frac{\mathbf{E}_{\mathbf{CAB}} * (1 - \mathbf{\nu}_{\mathbf{SG}}{}^2)}{\mathbf{E}_{\mathbf{SG}} * (1 - \mathbf{\nu}_{\mathbf{CAB}}{}^2)}\right)^{(1/3)} \qquad \mathbf{(15)}$$

$$\mathbf{H}_{\mathbf{eq,\,BOR}} = h_{AC} \left(\frac{E_{AC} * (1 - \nu_{SG}{}^2)}{E_{SG} * (1 - \nu_{AC}{}^2)}\right)^{(1/3)} + h_{CAB} * \left(\frac{E_{CAB} * (1 - \nu_{SG}{}^2)}{E_{SG} * (1 - \nu_{SG}{}^2)}\right)^{(1/3)} + \frac{\mathbf{h}_{\mathbf{BOR}}}{4} * \left(\frac{\mathbf{E}_{\mathbf{BOR}} * (1 - \mathbf{\nu}_{\mathbf{SG}}{}^2)}{\mathbf{E}_{\mathbf{SG}} * (1 - \mathbf{\nu}_{\mathbf{BOR}}{}^2)}\right)^{(1/3)} \qquad \mathbf{(16)}$$

$$\mathbf{H}_{\mathbf{eq,\,SG}} = h_{AC} \left(\frac{E_{AC} * \left(1 - \nu_{SG}{}^2\right)}{E_{SG} * (1 - \nu_{AC}{}^2)}\right)^{\left(\frac{1}{3}\right)} + h_{CAB} * \left(\frac{E_{CAB} * \left(1 - \nu_{SG}{}^2\right)}{E_{SG} * (1 - \nu_{SG}{}^2)}\right)^{\left(\frac{1}{3}\right)} + 18 \qquad \mathbf{(17)}$$

Where;

- $H_{eq,CAB}$= Equivalent thickness of the base layer
- $H_{eq,BOR}$= Equivalent thickness of the borrow layer
- $H_{eq,SG}$= Equivalent thickness of the subgrade layer
- h_{AC}= Thickness of the AC layer
- h_{CAB}= Thickness of the base layer
- h_{BOR}= Thickness of the subgrade layer
- E_{AC}= Modulus of the AC layer
- E_{CAB}= Resilient modulus of the base layer
- E_{BOR}= Resilient modulus of the borrow layer
- E_{SG}= Resilient modulus of the subgrade layer
- ν_{AC}= Poisson's ratio of the AC layer
- ν_{CAB}= Poisson's ratio of the base layer
- ν_{BOR}= Poisson's ratio of the borrow layer
- ν_{SG}= Poisson's ratio of the subgrade layer

7.1. Statistical Analysis

Multi-linear regression analysis was conducted using the computer software, Minitab (14). The models were checked for normal distribution of errors using the Anderson-Darling normality test (15) and for multi-collinearity using the variance inflation factors (VIFs) (16). It is important to mention that models failing the normality test (i.e., residuals are not normally distributed) would result in inability of conducting statistical tests, such as F-tests and t-tests.

The steps completed in this analysis were as follows:

1. All measured properties were included as prediction variables for preliminary analysis.
2. Variables were tested for correlations, and highly correlated variables were removed in order to avoid high VIFs.
3. The backward elimination method was used to identify the best fit model, where all remaining variables after step 2 were introduced into the Mr prediction model, then the insignificant variables (having a p-value greater than 0.05) were removed. This is an iterative process where the most insignificant variable (with the highest p-value) is removed first, and the model is re-established again until all insignificant variables are identified and removed.

The analysis was done to obtain three different sets of design Mr prediction models:

- General Models: R-value and UCS excluded from prediction variables.
- UCS Models: include UCS as a prediction variable but exclude the R-value.
- R-value Models: include R-value as a prediction variable but exclude the UCS.

The number of different material sources was not sufficient to develop separate models for Districts 2 and 3. Hence, the models for base, borrow, and subgrade materials were developed using the combined material sources from Districts 2 and 3. In addition, the database for District 1 unbound materials was included in a separate analysis to develop statewide models to predict the design Mr values for Nevada materials.

7.1.1. Models Development for Districts 2 and 3 Materials

This section presents the effort for developing design Mr values prediction models for Districts 2 and 3 materials. Table 7.1 shows the range of data that were used for the development efforts.

Typical residual and normality plots from Minitab are shown in Figures 7.1 and 7.2, respectively. The residual plot must show random distribution, such that no patterns exist, whereas the normality plot must be linear to satisfy the linear regression assumption. The data in Figures 7.1 and 7.2 indicate that both the random distribution and normality assumptions are satisfied.

Table 7.1. Range of Variables for Districts 2 and 3 Mr Models.

Parameters	Base		Borrow		Subgrade	
	Min	Max	Min	Max	Min	Max
R-value	70	87	46	83	9	75
UCS (psi)	10.2	32.0	1.8	33.3	8.1	56.4
P#200 (%)	7.5	11.1	2.9	19.5	9.4	78.1
P#40 (%)	13.4	21.1	10.6	44.0	29.2	94.1
P#4 (%)	39.7	63.4	32.4	92.4	62.1	100.0
P3/8" (%)	62.2	89.8	53.2	96.6	72.9	100.0
P3/4" (%)	91.5	100.0	76.6	100.0	85.4	100.0
P1" (%)	98.3	100.0	85.4	100.0	90.0	100.0
P1.5" (%)	-	-	93.9	100.0	97.2	100.0
Maximum dry density (pcf)	126.6	143.9	96.7	142.5	92.7	133.9
Optimum moisture content (%)	5.2	8.6	4.9	22.2	7.2	24.8
LL (%)	0.0	30.3	0.0	34.8	0.0	75.4
PI (%)	0.0	4.4	0.0	14.7	0.0	44.1
H_{eq} (New) (inch)	15.0	36.3	37.9	54.3	43.4	80.6
H_{eq} (Rehab) (inch)	17.5	37.9	44.9	65.4	49.9	91.6
Mr (New) (psi)	6,400	19,500	5,000	11,100	6,850	15,950
Mr (Rehab) (psi)	9,200	19,400	3,700	8,400	3,900	9,000

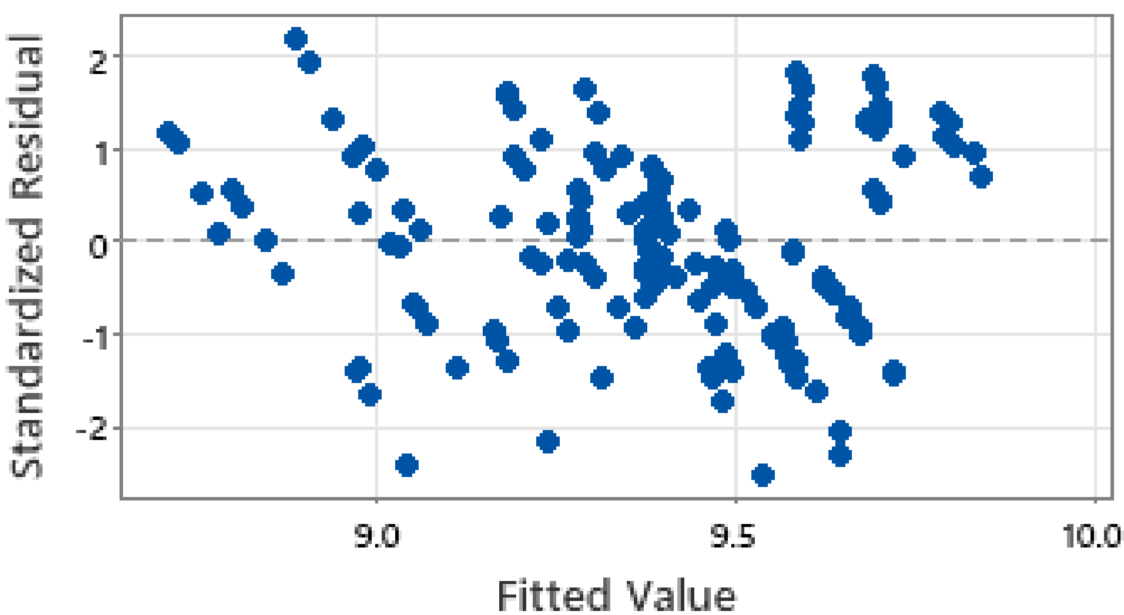

Figure 7.1. Typical prediction model residual plot for Districts 2 and 3 materials.

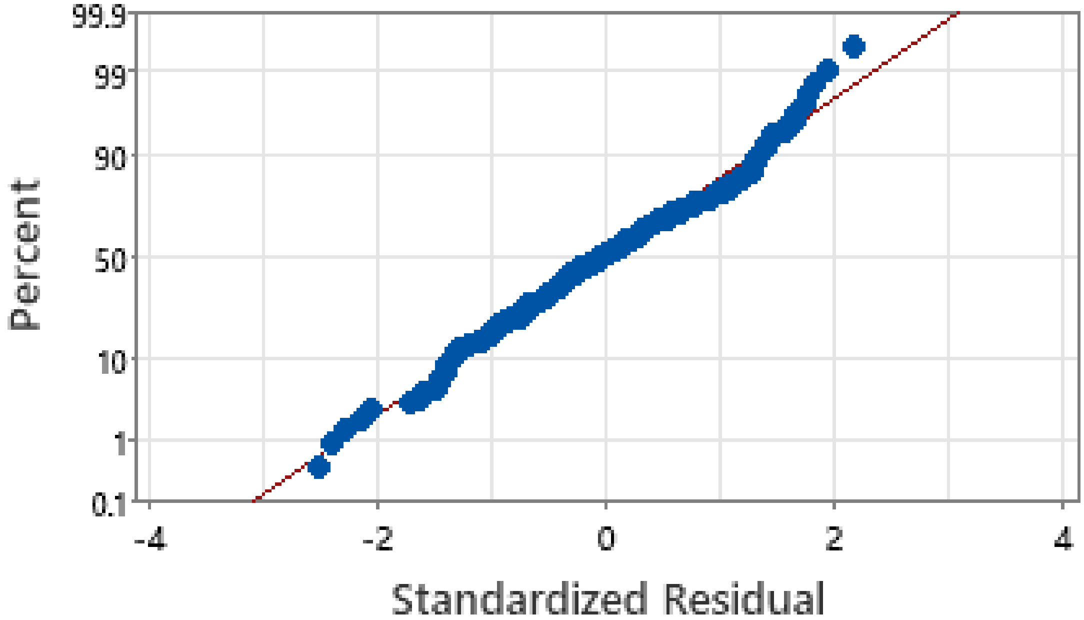

Figure 7.2. Typical prediction model normality plot for Districts 2 and 3 materials.

Based on the analysis of the data generated from this experiment, a correlation was found possible between the equivalent thickness (H_{eq}) and depth from pavement surface to the location where the state of stress was calculated (D) as shown in Figure 7.3. The depth of location for state of the stress calculation was defined in the MEPDG procedure (see step number 2 under Section 5.1 – for the aggregate base layer and embankment stresses are determined at their quarter depth, while for the subgrade, stresses are determined 18 inches into the subgrade). According to the MEPDG procedure, a trial pavement structure must be assumed in the design process. Therefore, using the assumed pavement structure, the depth to the state of stress calculation can be determined for each layer and used to calculate the equivalent thickness in terms of the layer being analyzed using Equations 15 to 17 (different equations for New and Rehabilitation designs and for CAB and Borrow materials). Once the equivalent thickness is computed from Equations 18 - 21, the resilient modulus of the layer being analyzed can be estimated from the models presented in and Table 7.3 and can be used as a Level 2 input for the AASHTOWare® Pavement ME Design software.

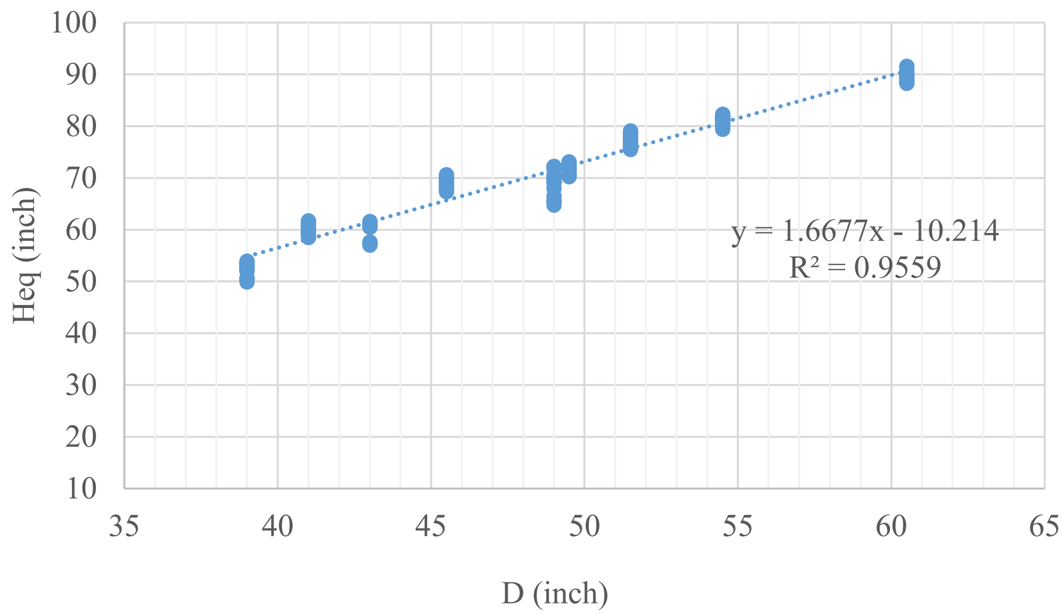

Figure 7.3. Correlation between H_{eq} and D for subgrade materials for Districts 2 and 3 for rehabilitation design.

$$H_{eq(CAB-New)} = 2.1806 \times D - 1.6 \quad (18)$$
$$H_{eq(CAB-Rehab)} = 2.3747 \times D - 0.8886 \quad (19)$$
$$H_{eq(BOR-Rehab)} = 1.6915 \times D + 5.2513 \quad (20)$$
$$H_{eq(SG-Rehab)} = 1.6677 \times D - 10.214 \quad (21)$$

Where;

- $H_{eq(CAB-New)}$= H_{eq} of the base layer for new design (inch)
- $H_{eq(CAB-Rehab)}$= H_{eq} of the base layer for rehabilitation design (inch)
- $H_{eq\ (BOR-Rehab)}$= H_{eq} of the borrow layer for rehabilitation design (inch)
- $H_{eq\ (SG-Rehab)}$= H_{eq} of the subgrade layer for rehabilitation design (inch)
- D= Depth to location for state of stress calculation in the corresponding layer (inch)

Table 7.2 presents the summary for the developed General Mr models. Table 7.3 presents the summary for the developed UCS Mr models. Table 7.4 presents the summary for the developed R-value Mr models. Examination of the data in Tables 7.2 – 7.4 leads to the following observations:

- Three General Mr models for base material in new designs were developed with similar prediction capabilities and are presented to allow more flexibility for NDOT to use the model with the more readily available properties.
- It was not possible to develop reliable models for estimating the design Mr for base material from the UCS property due to the extreme difficulties in measuring the UCS on unbound CAB materials.
- It was not possible to develop reliable models for estimating the design Mr for base materials from Districts 2 and 3 based the R-value property due to the extreme variability of the measured R-values on unbound base materials.
- The established models showed that the Mr for the unbound materials can be estimated very well by the General models. The inclusion of the UCS resulted in slightly lower R-square values except in the case of borrow materials in new design, where the UCS made it slightly better (i.e., from 71 to 72%).

Table 7.2. Summary of General Mr Models for Districts 2 and 3.

Ln (Mr)	Intercept	Heq (inch)	P1.5" (%)	P1" (%)	P3/4" (%)	P3/8" (%)	P#40 (%)
$Ln(Mr_{CAB-New})$ (1)	10.6832	-0.0272					
$Ln(Mr_{CAB-New})$ (2)	10.5101	-0.0272				0.0025	
$Ln(Mr_{CAB-New})$ (3)	14.4460	-0.02724			-0.0570		-0.0095
$Ln(Mr_{BOR-New})$	12.2800		-0.0647		0.0079		
$Ln(Mr_{SG-New})$	7.6220					-0.0268	
$Ln(Mr_{CAB-Rehab})$	12.0330	-0.0124			-0.0290		-0.0071
$Ln(Mr_{BOR-Rehab})$	13.1500	-0.0174	-0.0681	0.0184			
$Ln(Mr_{SG-Rehab})$	13.0340	-0.0035		-0.0493			0.0054

Table 7.2. Summary of General Mr Models for Districts 2 and 3 (Continued).

Ln (Mr)	P#200 (%)	OMC (%)	MDD (pcf)	PI (%)	R-square (%)	Norm.[1]	Multi-Col.[2]
$Ln(Mr_{CAB-New})$ (1)	0.0408	-0.1568		0.0141	97.00	Pass	Pass
$Ln(Mr_{CAB-New})$ (2)	0.0386	-0.1526			96.99	Pass	Pass
$Ln(Mr_{CAB-New})$ (3)	0.1204				97.00	Pass	Pass
$Ln(Mr_{BOR-New})$	0.0128		0.0167	0.0145	70.87	Fail	Pass
$Ln(Mr_{SG-New})$		0.0775	0.0250		93.10	Fail	Pass
$Ln(Mr_{CAB-Rehab})$	0.0811				91.33	Pass	Pass
$Ln(Mr_{BOR-Rehab})$			0.0102	0.0192	75.28	Fail	Pass
$Ln(Mr_{SG-Rehab})$			0.0032		76.45	Fail	Pass

[1]Normality; [2]Multi Collinearity

Table 7.3. Summary of UCS Mr Models for Districts 2 and 3.

Ln (Mr)	Intercept	Heq (inch)	P1.5" (%)	P1" (%)	P3/4" (%)	P#4 (%)	P#10 (%)
$Ln(Mr_{BOR-New})$	12.0400		-0.0614		0.0082		
$Ln(Mr_{SG-New})$	20.9140			-0.1376			0.0255
$Ln(Mr_{BOR-Rehab})$	9.6070	-0.0166					
$Ln(Mr_{SG-Rehab})$	15.8000	-0.00433		-0.0822		0.0129	

Table 7.3. Summary of UCS Mr Models for Districts 2 and 3 (Continued).

Ln (Mr)	OMC (%)	MDD (pcf)	PI (%)	UCS (psi)	R-square (%)	Norm.[1]	Multi-Col.[2]
$Ln(Mr_{BOR-New})$		0.0161	0.0139	0.0063	72.07	Fail	Pass
$Ln(Mr_{SG-New})$			-0.0158	0.0020	96.87	Fail	Pass
$Ln(Mr_{BOR-Rehab})$	-0.0274		0.0165	0.0054	68.73	Fail	Pass
$Ln(Mr_{SG-Rehab})$				0.0017	75.40	Fail	Pass

[1]Normality; [2]Multi Collinearity

Table 7.4. Summary of R-value Mr Models for Districts 2 and 3.

Ln (Mr)	Intercept	Heq (inch)	P1" (%)	P3/8" (%)	P#4 (%)	P#200 (%)
$Ln(Mr_{BOR-New})$	9.3440			-0.0250		
$Ln(Mr_{SG-New})$	9.8873	0.0027				0.0020
$Ln(Mr_{BOR-Rehab})$	8.4460	-0.0169	0.0170	-0.0171	0.0104	
$Ln(Mr_{SG-Rehab})$	9.2790	-0.0036				

Table 7.4. Summary of R-value Mr Models for Districts 2 and 3 (Continued).

Ln (Mr)	LL (%)	PI (%)	R-value	R-square (%)	Norm.[1]	Multi-Col.[2]
$Ln(Mr_{BOR-New})$	0.0150		0.0224	72.75	Pass	Pass
$Ln(Mr_{SG-New})$	-0.0017		0.0070	99.89	Fail	Pass
$Ln(Mr_{BOR-Rehab})$		0.0274	0.0076	77.90	Pass	Pass
$Ln(Mr_{SG-Rehab})$	-0.0074		0.0074	68.23	Pass	Pass

[1]Normality; [2]Multi Collinearity

Chapter 8. Conclusions and Recommendations

The major objective of this study is to develop a resilient modulus prediction model for unbound materials to be used for new design and rehabilitation projects in NDOT Districts 2 and 3. This objective was achieved by sampling and testing of different base, borrow, and subgrade materials from Districts 2 and 3. The classifications of materials were conducted according to AASHTO and UCSE systems. The maximum dry density and optimum moisture content relationships were obtained by conducting moisture-density tests for all materials. The resilient modulus and unconfined compressive strength tests were conducted on the evaluated materials at the optimum moisture content. Two different approaches were used to determine the design resilient modulus; a) for new design and b) for rehabilitation design.

Based on the generated data from the completed experiment and the statistical analyses, the following observations and conclusions can be made:

- The stress dependent behavior of the resilient modulus for the base and borrow material fits very well the Theta model.
- The stress dependent behavior of resilient modulus for the subgrade materials fits very well both the universal model and Uzan model.
- The design resilient modulus of base, borrow, and subgrade layers are significantly influenced by the pavement structure.

In addition to the primary objective of this research effort to develop prediction models for the design Mr for unbound materials from NDOT Districts 2 and 3, the research also developed statewide prediction models that combined the data generated from the previous research on materials from NDOT District 1 with the data generated on materials from Districts 2 and 3. The models developed based on the combined data are referred as "Statewide" models since they are applicable to materials sampled throughout the state of Nevada. Tables 8.1, 8.2, and 8.3 summarize the recommended models to predict design Mr values for base, borrow, and subgrade materials from Districts 2 and 3 combined and recommended models to predict design Mr values for materials from all NDOT Districts; 1, 2, and 3.

It should be noted that the equations to determine the Heq are different for the Districts 2 and 3 models and for the statewide models as summarized below.

For Districts 2 and 3 models, the following equations should be used:

$$H_{eq(CAB-New)} = 2.1806 \times D - 1.6$$
$$H_{eq(CAB-Rehab)} = 2.3747 \times D - 0.8886$$
$$H_{eq(BOR-Rehab)} = 1.6915 \times D + 5.2513$$
$$H_{eq(SG-Rehab)} = 1.6677 \times D - 10.214$$

For the Statewide models, the following equations should be used:

$$H_{eq(CAB-New)} = 2.1846 \times D - 1.4186$$
$$H_{eq(SG-New)} = 1.2921 \times D + 0.3671$$
$$H_{eq(CAB-Rehab)} = 2.4033 \times D - 1.4359$$
$$H_{eq(BOR-Rehab)} = 1.787 \times D + 2.0876$$
$$H_{eq(SG-Rehab)} = 1.6563 \times D - 9.5128$$

The following definitions of terms apply for both sets of equations:

- $H_{eq(CAB-New)}$= H_{eq} of the base layer for new design (inch)
- $H_{eq(CAB-Rehab)}$= H_{eq} of the base layer for rehabilitation design (inch)
- $H_{eq\ (BOR-Rehab)}$= H_{eq} of the borrow layer for rehabilitation design (inch)
- $H_{eq\ (SG-Rehab)}$= H_{eq} of the subgrade layer for rehabilitation design (inch)
- D= Depth to location for state of stress calculation in the corresponding layer (inch)

Since the developed models are based on statistical analyses of laboratory measured data, it is highly critical that they should be only applied within the ranges for the various parameters that were used in the analyses as summarized in Tables 8.4 and 8.5

Table 8.1. Models for the Design Mr of Base Materials.

Base Materials			
Source	**Model Type**	**Model**	**R-square (%)**
Districts 2 and 3	General	$Ln(Mr_{CAB-New}) = 10.6832 - 0.027232*H_{eq} + 0.04084 *P\#200 - 0.15677*OMC + 0.01407*PI$	97
		$Ln(Mr_{CAB-New}) = 10.5101 - 0.027223 *H_{eq} + 0.00248*P\#3/8 + 0.03859\ P\#200 - 0.15258*OMC$	97
		$Ln(Mr_{CAB-New}) = 14.446 - 0.027236 * H_{eq} - 0.05691 * P3/4 - 0.00942 * P\#40 + 0.12044 * P\#200$	97
		$Ln(Mr_{CAB-Rehab}) = 12.033 - 0.012366 * H_{eq} - 0.02901 * P\#\ 3/4 - 0.0071 * P\#40 + 0.08106 * P\#200$	91
Statewide	General	$Ln(Mr_{CAB-New}) = 12.90 - 0.028719 * H_{eq} - 0.0689 * P\#1 + 0.05984 * P\#3/4 - 0.01451 * P\#3/8 + 0.02666 * P\#40 + 0.04499 * P\#200 - 0.22317 * OMC$	93
		$Ln(Mr_{CAB-New}) = 6.539 - 0.028676*H_{eq} + 0.04216*P\#3/4 - 0.00911*P\#3/8 + 0.01466*P\#40 + 0.05763*P\#200 - 0.20135*OMC + 0.00541*MDD$	92
	R-value	$Ln(Mr_{CAB-New}) = 5.794 - 0.028672*H_{eq} + 0.03238*P\#3/4 - 0.002808*P\#4 + 0.11482*P\#200 - 0.26921*OMC + 0.02633*R\text{-}value$	97
		$Ln(Mr_{CAB-New}) = 5.461 - 0.028797*H_{eq} + 0.03077*P\#3/4 + 0.10733*P\#200 - 0.26853*OMC + 0.00262*MDD + 0.00893*PI + 0.02696*R\text{-}value$	97
	General	$Ln(Mr_{CAB-Rehab}) = 7.556 - 0.01168 * H_{eq} + 0.02689 * P\#\ 3/4 - 0.00995 * P\#\ 3/8 + 0.00829 * P\#40 + 0.04442 * P\#200 - 0.12585 * OMC + 0.00546 * MDD + 0.04769 * PI$	89
		$Ln(Mr_{CAB-Rehab}) = 8.108 - 0.011915 * H_{eq} + 0.02287 * P\#\ 3/4 - 0.007292 * P\#3/8 + 0.04454 * P\#200 - 0.12418 * OMC + 0.00392 * MDD + 0.0406 * PI$	88
	R-value	$Ln(Mr_{CAB-Rehab}) = 7.604 - 0.011713 * H_{eq} + 0.02089 * P\#\ 3/4 - 0.003264 * P\#\ 3/8 + 0.06318 * P\#200 - 0.15673 * OMC + 0.022 * PI + 0.01265 * R - value$	91

Table 8.2. Models for the Design Mr of Borrow Materials.

Borrow Materials			
Source	**Model Type**	**Model**	**R-square (%)**
Districts 2 and 3	General	$Ln(Mr_{BOR-New}) = 12.28 - 0.0647 * P\#1.5 + 0.00787 * P\#3/4 + 0.01279 * P\#200 + 0.01669 * MDD + 0.01454 * PI$	71
		$Ln(Mr_{BOR-Rehab}) = 13.15 - 0.0174 * H_{eq} - 0.0681 * P\#1.5 + 0.01836 * P\#1 + 0.01024 * MDD + 0.0192 * PI$	75
	UCS	$Ln(Mr_{BOR-New}) = 12.04 - 0.0614 * P\#1.5 + 0.00817 * P\#3/4 + 0.0161 * MDD + 0.01392 * PI + 0.00632 * UCS$	72
		$Ln(Mr_{BOR-Rehab}) = 9.607 - 0.01661 * H_{eq} - 0.02736 * OMC + 0.01648 * P\#1 + 0.00539 * UCS$	69
	R-value	$Ln(Mr_{BOR-New}) = 9.344 - 0.02498 * P\#3/8 + 0.01503 * LL + 0.02242 * R - value$	73
		$Ln(Mr_{BOR-Rehab}) = 8.446 - 0.01685 * H_{eq} + 0.01696 * P\#1 - 0.01712 * P\#3/8 + 0.01042 * P\#40 + 0.02744 * PI + 0.00759 * R - value$	78
Statewide	General	$Ln(Mr_{BOR-New}) = 9.75 - 0.0528 * P\#1.5 + 0.00866 * P\#4 - 0.02357 * P\#40 + 0.0576 * P\#200 + 0.02983 * MDD$	53
		$Ln(Mr_{BOR-Rehab}) = 6.745 - 0.02379 * H_{eq} - 0.00807 * P\#3/8 + 0.01511 * P\#4 - 0.03116 * P\#40 + 0.05823 * P\#200 + 0.02283 * MDD$	78
	R-value	$Ln(Mr_{BOR-New}) = 27.59 - 0.1943 * P\#1.5 - 0.0282 * P\#40 - 0.0603 * OMC + 0.02836 * LL - 0.0388 * PI + 0.0258 * R - value$	74
		$Ln(Mr_{BOR-New}) = 11.646 - 0.03607 * P\#1 - 0.03453 * P\#40 + 0.0408 * P\#200 - 0.1043 * OMC + 0.01973 * LL - 0.0291 * PI + 0.02831 * R - value$	74
		$Ln(Mr_{BOR-Rehab}) = 10.855 - 0.01915 * Heq - 0.02122 * P\#3/4 + 0.00877 * P\#3/8 - 0.03354 * P\#40 + 0.0772 * P\#200 - 0.1267 * OMC + 0.01573 * R\text{-}value$	85

Table 8.3. Models for the Design Mr of Subgrade Materials.

Subgrade Materials			
Source	**Model Type**	**Model**	**R-square (%)**
Districts 2 and 3	General	$\text{Ln}(\text{Mr}_{\text{SG-New}}) = 7.622 - 0.026788*P\#3/8 + 0.07752*OMC + 0.024975*MDD$	93
		$\text{Ln}(\text{Mr}_{\text{SG-Rehab}}) = 13.034 - 0.003485 * H_{eq} - 0.04932 * P\#1 + 0.005425 * P\#40 + 0.003188 * MDD$	77
	UCS	$\text{Ln}(\text{Mr}_{\text{SG-New}}) = 20.914 - 0.13762 * P\#1 + 0.025446 * P\#10 - 0.015851 * \text{PI} + 0.001972 * \text{UCS}$	97
		$\text{Ln}(\text{Mr}_{\text{SG-Rehab}}) = 15.8 - 0.004331 * H_{eq} - 0.08215 * P\#1 + 0.0129 * P\#4 + 0.001674 * UCS$	75
	R-value	$\text{Ln}(\text{Mr}_{\text{SG-New}}) = 9.8873 + 0.002691 * H_{eq} + 0.002009 * P\#200 - 0.016685 * LL + 0.007 * R - value$	99
		$\text{Ln}(\text{Mr}_{\text{SG-Rehab}}) = 9.279 - 0.00357 * H_{eq} - 0.007305 * LL + 0.00738 * R - value$	68
Statewide	General	$\text{Ln}(\text{Mr}_{\text{SG-New}}) = 11.436 - 0.003669*H_{eq} - 0.02942*P\#1 + 0.003102*P\#40 + 0.005167*MDD + 0.003689*PI$	67
		$\text{Ln}(\text{Mr}_{\text{SG-Rehab}}) = 11.204 - 0.007215 * H_{eq} - 0.02151 * P\#1 + 0.005381 * P\#40 - 0.02116 * OMC + 0.001836 * LL$	70
	UCS	$\text{Ln}(\text{Mr}_{\text{SG-New}}) = 11.362 - 0.002569*H_{eq} - 0.03114 * P\#1 + 0.004059 * P\#40 + 0.005963*\text{MDD} + 0.003279*UCS$	69
	R-value	$\text{Ln}(\text{Mr}_{\text{SG-New}}) = 9.7079 + 0.002468 * H_{eq} - 0.006447 * P\#1 - 0.002916 * P\#200 + 0.001894 * R - value$	93

Table 8.4. Range of Variables for Districts 2 and 3 Mr Models.

Parameters	Base		Borrow		Subgrade	
	Min	**Max**	**Min**	**Max**	**Min**	**Max**
R-value	NA	NA	46	83	9	75
UCS (psi)	NA	NA	1.8	33.3	8.1	56.4
P#200 (%)	7.5	11.1	2.9	19.5	9.4	78.1
P#40 (%)	13.4	21.1	10.6	44.0	29.2	94.1
P#4 (%)	39.7	63.4	32.4	92.4	62.1	100.0
P3/8" (%)	62.2	89.8	53.2	96.6	72.9	100.0
P3/4" (%)	91.5	100.0	76.6	100.0	85.4	100.0
P1" (%)	98.3	100.0	85.4	100.0	90.0	100.0
P1.5" (%)	-	-	93.9	100.0	97.2	100.0
Maximum dry density (pcf)	126.6	143.9	96.7	142.5	92.7	133.9
Optimum moisture content (%)	5.2	8.6	4.9	22.2	7.2	24.8
LL (%)	0.0	30.3	0.0	34.8	0.0	75.4
PI (%)	0.0	4.4	0.0	14.7	0.0	44.1
H_{eq} (New) (inch)	15.0	36.3	37.9	54.3	43.4	80.6
H_{eq} (Rehab) (inch)	17.5	37.9	44.9	65.4	49.9	91.6
Mr (New) (psi)	6,400	19,500	5,000	11,100	6,850	15,950
Mr (Rehab) (psi)	9,200	19,400	3,700	8,400	3,900	9,000

Table 8.5. Range of Variables for Statewide Mr Models.

Parameters	Base		Borrow		Subgrade	
	Min	**Max**	**Min**	**Max**	**Min**	**Max**
R-value	70	87	46	83	9	82
UCS (psi)	10.2	32.0	1.8	33.3	8.1	56.4
P#200 (%)	5.3	11.1	2.9	19.5	5.4	78.1
P#40 (%)	12.6	21.1	10.6	44.0	15.2	94.1
P#4 (%)	35.3	63.4	32.4	92.4	33.5	100.0
P3/8" (%)	54.1	89.8	53.2	99.9	52.5	100.0
P3/4" (%)	88.9	100.0	76.6	100.0	77.0	100.0
P1" (%)	98.3	100.0	85.4	100.0	83.5	100.0
P1.5" (%)	100.0	100.0	93.9	100.0	92.5	100.0
Maximum dry density (pcf)	126.6	147.5	96.7	143.2	92.7	139.2
Optimum moisture content (%)	3.5	8.6	4.9	22.2	6.1	24.8
LL (%)	0.0	30.3	0.0	34.8	0.0	75.4
PI (%)	0.0	4.4	0.0	14.7	0.0	44.1
H_{eq} (New) (inch)	15.0	36.3	37.9	54.3	43.4	80.6
H_{eq} (Rehab) (inch)	17.5	37.9	44.9	65.4	49.9	91.6
Mr (New) (psi)	6,400	27,250	5,000	20,400	6,850	15,950
Mr (Rehab) (psi)	9,200	22,900	3,700	15,500	3,900	9,000

CHAPTER 9. REFERENCES

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