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Development of Models to Estimate Modulus and Permanent Deformation of Texas Bases

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PERMANENT DEFORMATION OF TEXAS BASES

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by

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CHAPTER 1 – INTRODUCTION

The performance of flexible pavements depends on many factors such as structural adequacy, properties of materials used, traffic loading, climatic conditions and construction practices. Some of the distresses experienced in flexible pavements can be traced to the problems encountered in base materials (Hall et al., 2001). Resilient modulus and permanent deformation test results of compacted unbound pavement layers are key inputs to the new generations of mechanistic-empirical design programs such as MEPDG and TexME. For a Level 1 (most rigorous) design, the resilient modulus and permanent deformation parameters of unbound granular materials and subgrade layers are determined through laboratory cyclic triaxial tests. These tests in general measure the stiffness of cylindrical specimens that are exposed to a number of repeated axial stresses and confining pressures. Various constitutive models exist in the literature to relate modulus parameters to the state of stress (Puppala, 2008). Several factors such as moisture content, gradation and density impact the modulus and permanent deformation values.

1.1 Problem Statement

The determination of laboratory resilient modulus and permanent deformation parameters requires substantial time and resource. The estimation of resilient modulus and permanent deformation with a model using index properties of the material would be a much simpler and more economical way of characterizing different bases. The selection of reasonable models will enable TXDOT Pavement Engineers to carry out the design rapidly and with confidence.

1.2 Objectives

A number of models exist to estimate resilient modulus of bases from their index parameters and their moisture-density characteristics; however, not many models have been developed to estimate permanent deformation parameters as a function of these parameters. This research study is addressing four objectives. The first objective is to study the influence of moisture content and index parameters of granular base materials on resilient modulus of Texas bases. The second objective is to evaluate the existing models to predict resilient modulus and permanent deformation parameters as a function of aggregate properties and index parameters of bases. The third objective is to propose improved models that characterize Texas materials better. The last objective consists of the development of a model to estimate the permanent deformation parameters as a function of the index properties and moisture content. The work carried out to accomplish the four objectives included the following items:

a) Four representative granular base materials with different aggregate qualities were tested for resilient modulus and permanent deformation at three different moisture contents in order to understand the influence of moisture on properties of granular base materials.

b) The results from the laboratory test were compared with the results obtained from several prediction models suggested in the literature.

c) Based on the results from Items a and b, new predictive models for estimating resilient modulus and permanent deformation parameters as a function of the index parameters and moisture-density properties of the bases are recommended.

1.3 Organization of Report

This report consists of five chapters. Chapter two includes a concise background of the resilient modulus and permanent deformation testing and constitutive models. Chapter three provides a brief explanation of the laboratory testing methodology followed in this study. Chapter four describes the methodology to evaluate the existing models to predict resilient modulus and permanent deformation as a function of index properties and also presents new models developed during this study for resilient modulus and for permanent deformation. Finally, Chapter five provides a summary of results, recommendations and conclusions of this study.

CHAPTER 2 – BACKGROUND

The mechanical response of subgrades and bases can be influenced by a variety of factors. These include:

- the shape, size and mechanical properties of the individual soil particles;
- the configuration of the pavement structure;
- the inter-granular stresses and stress history; and
- the variation in soil moisture content and density.

These factors generally contribute to nonlinear, time-dependent characteristics, as well as anisotropic and nonhomogeneous material properties (Selvadurai, 1979). The nonlinear behavior of a geomaterial is important for the analytical design and evaluation of pavements. The resilient modulus (MR) tests are commonly used to measure the stiffness of geomaterials. Resilient modulus test in general measures the stiffness of a cylindrical specimen that is subjected to numerous repeated axial loads and confining pressures. Mathematically, resilient modulus at a given state of stress is defined as:

$$Mr = \frac{\sigma_d}{\varepsilon_{axial}} \tag{2.1}$$

where $\sigma_d = \sigma_1 - \sigma_3 =$ deviator stress, σ_1, $\sigma_3 =$ major and minor principal stresses, and ε_{axial} = recovered axial strain.

The selection of an appropriate design modulus for base, subbase and/or subgrade has long been complicated by various test and analysis problems (Witzack, 2004). The procedure for conducting MR tests has been under continuous modification. AASHTO has adopted several test protocols (e.g., T292-91, T294-92, TP46-94 and T307-03). The so-called NCHRP 1-28A

(Andrei et al, 2004) protocol is also gaining popularity. These approaches differ in the specimen size, compaction method, loading time, stress sequence and the type and location of displacement transducers. A number of proposed resilient modulus models that have been used to study and understand the behavior of base and subgrade materials are presented in Table 1. The accuracy and reasonableness of this model are extremely important for successfully combining laboratory and field results.

Dunlap (1963) developed a relationship for resilient modulus using confining pressure σ_c, but he did not consider the effect of deviatoric stress, σ_d. On the other hand, Mossadeh and Witczak (1981) proposed a relationship using the deviator stress, $\sigma_{d,}$ without considered the confining pressure. Seed et al. (1967) suggested a relation where the bulk stresses, θ, was used to estimate the resilient modulus.

May and Witczak (1981) proposed a more complex model that used the deviatoric stress, σ_d, and bulk stresses θ (see Table 2.1). Witczak and Uzan (1988) replaced the deviatoric stress, σ_d, from the previous models with the octahedral shear stress, τ_{oct}. This model is known as k_1-k_3 model or universal model. NCHRP Project 1-28A (Hallin, 2001) proposed another three-coefficient mathematical expression that uses the bulk stresses, θ and octahedral shear stress, τ_{oct}, to describe the state of stress (see Table 2.1).

Table 2.1 – Summary of Proposed Resilient Modulus Models

Model Number	Reference	Equation
1	Dunlap (1963)	$Mr = k_1 \left(\frac{\sigma_c}{P_a}\right)^{k_2}$
2	Seed et al. (1967)	$Mr = k_1 \left(\frac{\theta}{P_a}\right)^{k_2}$
3	Moossazadeh and Witczak (1981)	$Mr = k_1 \left(\frac{\sigma_d}{P_a}\right)^{k_2}$
4	May and Witczak (1981)	$Mr = k_1 Pa \left(\frac{\theta}{P_a}\right)^{k_2} \left(\frac{\sigma_d}{P_a}\right)^{k_3}$
5	Witczak and Uzan (1988)	$Mr = K_1 \ P_a \left(\frac{\theta}{P_a}\right)^{K_2} \left(\frac{\tau_{OCT}}{P_a}\right)^{K_3}$
6	Itani (1990)	$Mr = k_1 P_a \left[\frac{\theta}{3}\right]^{k_2} {\sigma_d}^{k_{3a}} \ {\sigma_3}^{k_{3b}}$
7	Feliberti (1991)	$Mr = k_1 \theta^{k_2} (\varepsilon_a)^{k_3}$
8	Pezo (1993)	$Mr = k_1 \theta^{k_2} {\sigma_c}^{k_3}$
9	Thompson and Elliot (1985)	$Mr = k_1 + k_{3a}(k_2 - \sigma_d)$ when $\sigma_d < k_2$ $Mr = k_1 + k_{3b}(\sigma_d - k_2)$ when $\sigma_d > k_2$
10	Ni et al. (2002)	$Mr = k_1 \left(\frac{\sigma_c}{P_a} + 1\right)^{k_2} \left(\frac{\sigma_d}{P_a} + 1\right)^{k_3}$
11	Hallin (2001) (a.k.a. MEPDG Model)	$Mr = k_1 P_a \left(\frac{\theta}{P_a}\right)^{k_2} \left(\frac{\tau_{OCT}}{P_a} + 1\right)^{k_3}$
12	Dai et al. (2002)	$Mr = k_1 \theta^{k_2} {\sigma_d}^{k_3}$
Key:	σ_d = deviatoric stress. σ_c = confining pressure $\theta = \sigma_1 + \sigma_2 + \sigma_3 =$ bulk stress $\tau_{oct} = \frac{1}{3}\sqrt{[(\sigma 1 - \sigma 2)^2 + (\sigma 1 - \sigma 3)^2 + (\sigma 2 - \sigma 3)^2]} =$ octahedral shear stress σ_1 = major principal stress; σ_2, σ_3 = minor principal stresses. P_a= atmospheric pressure k_1 , k_2 and k_3 = regression coefficients.	

Many factors affect the moduli of unbound pavement materials. Some are inherent to the materials themselves; others are associated with the environment in which the materials exist or the loading or stress conditions to which they are subjected. The most important factors, aside from stress conditions, are the moisture, density and material characteristics (gradation or fines content, angularity, plasticity).

Monismith et al. (1967) noted that the modulus of a fully saturated material may be as much as 50% less than that of the same soil in a partially saturated condition. Chou (1977) suggested that the general trend of decreasing modulus with increasing moisture content was much less significant when effective stress conditions rather than total confining pressures are used as the basis of comparison.

Thompson and Robnett (1976) studied the effect of degree of saturation on resilient modulus of typical Illinois fine-grained soils. For degree of saturation (S_r) ranging from 50 to 100%, and densities corresponding to 95 and 100% of AASHTO T-99 compaction, they obtained the relationships given in Equation 2.2.

$$Mr\ (in\ ksi) = 32.9 - 0.334\ S_r \tag{2.2}$$

Rada and Witczak (1981) noted that the reduction in stiffness of granular materials with increasing moisture content was especially significant at degrees of saturation in excess of 80–85%, where a rapid loss of stiffness occurs with increasing saturation. However, the magnitude of this effect varied from one material to another.

Noureldin (1994) conducted an investigation of (among other things) the effect of changes in moisture content on the backcalculated moduli of granular base and subgrade materials. He found that an increase in the base moisture content from 5% to 9% corresponded to a 22% reduction in the modulus.

Ksaibati et al. (2000) looked at the effect of moisture content on backcalculated moduli for base and subgrade materials in Florida. They observed modulus changes of up to 96% as the moisture content varied, with the magnitude of the change depending on the deflection testing device (FWD or Dynaflect) used to obtain the data.

Edris and Lytton (1976) used soil suction, which is related to moisture content and saturation, along with the internal stress state of the soil. The general trend for the modulus was an increase with increasing suction up to a point, above which it became constant. Titus-Glover and Fernando (1995) also used suction (as well as moisture content and saturation) in their development of regression models to predict the coefficients for Model 5 in Table 2.1. The set of models selected as being best included the suction term as a variable for k_1, but not for k_2 or k_3.

Witzack et al. (2000) found general relationships of the form presented in Equation 2.3:

$$\log \frac{M_r}{M_{rref}} = k_w * (m - m_{ref}) \tag{2.3}$$

with M_{rref} being the resilient modulus at a reference moisture state represented by m_{ref}, and m being the moisture state associated with M_r. They considered both gravimetric moisture content and degree of saturation as the variables used to characterize moisture state (m), and recommended the use of the degree of saturation. They also recommended the use of the laboratory optimum condition for the reference values. Witczak et al. developed the modified model presented as Equation 2.4 because the laboratory dataset on which Equation 2.3 composed entirely of test results within ±30% of optimum, whereas field data indicate that lesser degrees of saturation often occur in practice.

(2.4)

$$\log \frac{M_r}{M_{rref}} = a + \frac{b-a}{1 + EXP\left(\beta + k_s * (S - S_{opt})\right)} \qquad (2.4)$$

where

$a = \min(\log(M_r / M_{ropt}))$
$b = \max(\log(M_r / M_{ropt}))$
$\beta = \ln(-b / a)$

Tables 2.2 through 2.4 show different types of models that have been used to analyze moisture and index properties in terms of resilient modulus for different types of materials. The models presented are functions of *k*-parameters. As an example, Table 2.2 contains the general form of the constitutive model developed by Witczak and Uzan (1988). Based on that equation, several models are proposed to predict the *k*-parameters as listed in Table 2.2, such as Malla and Joshi (2008), Malla and Joshi (2007) and Mohammed (1999). In some cases, the models are specific to either coarse-grained or fine-grained soils. In other cases, the model applies to both material types.

Table 2.3 and 2.4 present different constitutive equations developed by May and Witczak (1981) and Witczak (2002), respectively, to determine resilient modulus. This last model is the one used by MEPDG. Similarly, different models to predict the nonlinear parameters k have been proposed for each of these constitutive models. To evaluate these models, their estimated resilient moduli were compared with those obtained from laboratory testing. The most promising models were Malla and Joshi (2008) using Witczak and Uzan (1988) constitutive model and Yau and Von Quintus (2002) with Witczak (2002) constitutive model.

Permanent deformation is one of the most important types of load-associated distresses occurring in flexible pavement systems. To predict rutting of pavements under traffic loading, the contribution from both the granular base and subgrade soil are critical. One of the issues that have not been fully addressed is the influence of moisture on the behavior of granular base and subgrade soils in terms of permanent deformation. Barksdale (1972) performed a study looking for the behavior of different bases and found that the accumulated permanent strain was proportional to the logarithm of the number of load cycles as shown below

$$\varepsilon_p = a + b * (\log \mathrm{N}) \tag{2.5}$$

where a and b are regression parameters and N is the number of load cycles. Sweere (1990) proposed a model in the form of.

$$\varepsilon_p = a * N^b \tag{2.6}$$

Even though researchers have developed different models trying to correlate static or cyclic loadings, strain, stress and number of cycles to rutting parameters, models to estimate the permanent deformation as function of index parameters of geomaterials do not seem to exist.

Table 2.2 – Witczak and Uzan (1988) Model to Predict Resilient Modulus as a Function of Aggregate Properties and Index Parameters

<table>
<tr><td colspan="3">

$$\boldsymbol{Mr = K_1\ P_a \left(\frac{\theta}{P_a}\right)^{K_2} \left(\frac{\tau_{OCT}}{P_a}\right)^{K_3}}$$

where:
$\theta = \sigma_1 + \sigma_2 + \sigma_3$, Bulk stresses
Pa = Atmospheric pressure
K_1, K_2 and K_3 = Regression coefficients
$\tau_{oct} = \frac{1}{3}\sqrt{[(\sigma 1 - \sigma 2)^2 + (\sigma 1 - \sigma 3)^2 + (\sigma 2 - \sigma 3)^2]}$, Octahedral shear stress
σ_1 = Major principal stresses
σ_2, σ_3 = Intermediate principal stresses
</td></tr>
<tr><td>**Malla and Joshi (2008)**</td><td>

Coarse- grained samples CU<600
$\text{Log K1} = -0.64428 - 0.00773 * \text{MC} - 0.62335 * \text{DDR} + 0.02531 * \text{S3} - 0.01504 * \text{S1}_{\text{HALF}} - 0.00694 * \text{SN200} + 0.00469 * \text{SILT} + 0.00033564 * \text{CU} - 0.00432 * \text{CC}$
$\text{K2} = -0.74167 + 0.00804 * \text{MC} + 0.00035328 * \text{DD} + 0.00713 * \text{S1}_{\text{HALF}} - 0.00401 * \text{SN40} + 0.00459 * \text{FSAND} - 0.000156 * \text{CU} + 0.00166 * \text{CC}$
$\text{K3} = -0.90585 - 0.00186 * \text{MC} + 0.00021603 * \text{MAXDD} + 0.01777 * \text{S2} - 0.01830 * \text{S1} + 0.00528 * \text{SN10} - 0.00531 * \text{SN200}$

Coarse- grained samples CU<20
$\text{Log K1} = 0.50635 - 0.00945 * \text{OMC} - 0.70408 * \text{DDR} - 0.00784 * \text{SN200} + 0.00716 * \text{SILT} + 0.00775 * \text{CLAY} - 0.00470 * \text{CU} - 0.01280 * \text{CC}$
$\text{K2} = 0.39366 + 0.00769 * \text{OMC} + 0.00036161 * \text{DD} - 0.00026109 * \text{MAXDD} - 0.00352 * \text{SN40} + 0.00414 * \text{FSAND} - 0.01338 * \text{CLAY} + 0.01099 * \text{CU}$
$\text{K3} = 1.06845 - 0.00356 * \text{MC} - 0.57787 * \text{DDR} - 0.01942 * \text{S3} + 0.01379 * \text{S1}_{\text{HALF}} - 0.00073415 * \text{SN80} - 0.00359 * \text{CU}$
</td><td>

- MC = Specimen moisture content
- DDR = Dry density ratio
- S3 = Percent passing #3” sieve
- S1 = Percent passing #1”sieve
- S1_{HALF}= Percent passing # $1\frac{1}{2}$” sieve
- DD = Dry density
- SN40 = Percent passing #40 sieve
- SN10 = Percent passing #10 sieve
- FSAND = Percent fine sand
- SN200 = Percent passing #200 sieve
- CU = Uniformity coefficient
- CC = Coefficient of curvature
- MAXDD = Maximum dry density
- SILT = Percent of silt
- CLAY = Percent of clay
</td></tr>
<tr><td>**Malla and Joshi (2007)**</td><td>

$\text{Log K1} = -9.85454 - 0.01714 * \text{OMC} - 0.00078852 * \text{DD} + 0.11588 * \text{S1}_{\text{HALF}} - .00616 * \text{SN10} + 0.00279 * \text{FSAND}$
$\text{k2} = -1.15403 + 0.03198 * \text{OMC} + 5.69990 * \text{DDR} - 0.04336 * \text{S1}_{\text{HALF}} + 0.01404 * \text{SN40} + 0.00476 * \text{CSAND} - 0.00649 * \text{FSAND}$
$\text{K3} = 0.22460 - 0.02071 * \text{OMC} - 0.00010179 * \text{MAXDD} - 0.00046354 * \text{SN10} - 0.00682 * \text{SN40} + 0.00936 * \text{FSAND}$
</td><td>

- OMC = Optimum moisture content
- DD = Dry density
- MAXDD = Maximum dry density
- S1_{HALF} = Percent passing $1\frac{1}{2}$” sieve.
- SN10 = Percent passing #10 sieve
- SN40 = Percent passing #40 sieve
- FSAND = Percent fine sand
</td></tr>
<tr><td>**Mohammad (1999)**</td><td>

$\text{Log K1} = -0.679 + 0.0922 * \text{w} + 0.00559 * \gamma_d + 3.54 * D_c + 2.47 * D_m + 0.00676 * \text{LL} + 0.0116 * \text{PL} + 0.022 * \text{SAND} + 0.0182 * \text{SILT}$
$\text{Log K2} = -0.887 + 0.0044 * \text{w} + 0.00934 * \gamma_d + 0.264 * D_c + 0.305 * D_m + 0.00877 * \text{LL} + 0.00665 * \text{PL} + 0.0116 * \text{SAND} + 0.00429 * \text{SILT}$
$\text{LogK3} = -0.638 + 0.00252 * \text{w} + 0.00207 * \gamma_d + 0.61 * D_c + 0.152 * D_m + 0.000497 * \text{LL} + 0.00416 * \text{PL} + 0.00311 * \text{SAND} + 0.00143 * \text{SILT}$
</td><td>

- w = Moisture content
- γ_d = Dry density
- D_c = Degree of compaction
- D_m= Degree of moisture
- LL = Liquid limit
- PL = Plastic limit
</td></tr>
</table>

Table 2.3 – May and Witczak (1981) Model to Predict Resilient Modulus as a Function of Aggregate Properties and Index Parameters

$$\boldsymbol{Mr = K_1 P_a \left(\frac{\theta}{P_a}\right)^{K_2} \left(\frac{\sigma_d}{P_a}\right)^{K_3}} \quad \text{or,} \quad \boldsymbol{Mr = K_1 P_a \left(\frac{\sigma_d}{P_a}\right)^{K_3}}$$ where: $\theta = \sigma_1 + \sigma_2 + \sigma_3$, Bulk stresses; Pa = Atmospheric pressure; K_1, K_2 and K_3 = Regression coefficients; $\sigma_d = \sigma_1 - \sigma_3$, Deviator stress		
Santha (1994)	**Coarse Grained Soils** $$\text{Log K1} = 3.479 - 0.07 * \text{MC} + 0.24 * \text{MCR} + 3.681 * \text{COMP} + 0.011 * \text{SILT} + 0.006 * \text{CLAY} - 0.025 * \text{SW} - 0.039 * \text{DEN} + 0.004 * \left(\frac{\text{SW}^2}{\text{CLAY}}\right) + 0.003 * \left(\frac{\text{DEN}^2}{\text{S40}}\right)$$ $$\text{Log K2} = 6.044 - 0.053 * \text{MOIST} - 2.076 * \text{COMP} + 0.0053 * \text{SATU} - 0.0056 * \text{CLAY} + 0.0088 * \text{SW} - 0.0069 * \text{SH} - 0.027 * \text{DEN} + 0.012 * \text{CBR} + 0.003 * \left(\frac{\text{SW}^2}{\text{CLAY}}\right) - 0.31 * \left(\frac{\text{SW} + \text{SH}}{\text{CLAY}}\right)$$ $$\text{Log K3} = 3.752 - 0.068 * \text{MC} + 0.309 * \text{MCR} - 0.006 * \text{SILT} + 0.0053 * \text{CLY} - 0.026 * \text{SH} - 0.033 * \text{DEN} - 0.0009 * \left(\frac{\text{SW}^2}{\text{CLAY}}\right) + 0.00004 * \left(\frac{\text{SATU}^2}{\text{SH}}\right) - 0.0026 * (\text{CBR} * \text{SH})$$ **Fine Grained Soils** $$\text{Log K1} = 19.813 - 0.045 * \text{MOIST} - 0.131 * \text{MC} - 9.171 * \text{COMP} + 0.037 * \text{SILT} + 0.015 * \text{LL} - 0.016 * \text{PI} - 0.021 * \text{SW} - 0.052 * \text{DEN} + 0.00001(\text{S40} * \text{SATU})$$ $$\text{K3} = 10.274 - 0.09 * \text{MOIST} - 1.06 * \text{MCR} - 3.471 * \text{COMP} + 0.0088 * \text{S40} - 0.0087 * \text{PI} + 0.014 * \text{SH} - 0.046 * \text{DEN}$$	- MC = Moisture Content - MOIST = Optimum moisture content - MCR = Ratio of MC and MOIST - COMP = Percent compaction - SATU = Percent saturation - S40 = Percent passing #40 sieve - CLAY = Percent of clay - SILT = Percent of silt - SW = Percent of swell - SH = Percent shrinkage - DEN = Maximum dry unit weight - CBR = California bearing ratio - LL = Liquid limit - PL = Plastic limit
Titus-Glover and Fernando (1995)	$$\text{K1} = 28659 - 417.297 * \text{PL} - 5706.38 * \text{G}_{\text{sb}} + 12780 * \theta_{\text{w}} - 75.443 * \text{N40} - 5462.069 * \tan\emptyset + 58.975 * \text{N}_{\text{40N}} * \text{U}_{\text{N}} + 256.002 * \text{N}_{\text{40N}} * \tan\emptyset_{\text{N}} * \varepsilon\text{rN}$$ $$\text{K2} = -0.127927 + 0.515759 * \text{g}_{\text{sb}} - 0.084802\text{w} + 0.00027 * {\text{N}_{\text{40N}}}^2 - 0.009607 * \text{LL}_{\text{NWN}} - 0.192586 * \text{LL}_{\text{N}} * \tan\emptyset_{\text{N}} + 0.003981 * {\text{LL}_{\text{N}}}^2$$ $$\text{K3} = 1.807384 - 0.181851 * \varepsilon\text{r} - 2.808291 * \text{LL}_{\text{N}} * \text{W}_{\text{N}} - 0.016342 * \text{LL}_{\text{N}} * \varepsilon_{\text{r}}$$	- LL = Liquid limit - PL = Plastic limit - G_{sb} = Specific gravity of soil binder - θw = Volumetric moisture content - tanØ = tangent of friction angle - N40 =Percent passing number 40 - εr= Dialectic constant - N_{40N} = Normalized N40 = N40 - 57.215 - $\tan Ø_N$ = Normalized tanØ = tanØ - 0.92877 - U_N = Normalized suction = U – 2.12231 - εrN = Normalized dialectic constant = ε_r -12.5981 - LL_N = Normalized liquid limit = LL – 28.667 - W_N = Normalized gravimetric moisture content = W – 13.451

Table 2.4 – Hallim (2001) MEPDG Model to Predict Resilient Modulus as a Function of Aggregate Properties and Index Parameters

<table>
<tr><td colspan="3">

$$\boldsymbol{Mr = K_1\ P_A \left(\frac{\theta}{P_a}\right)^{K_2} \left(\frac{\tau_{OCT}}{P_a} + 1\right)^{K_3}}$$

where:
$\theta = \sigma_1 + \sigma_2 + \sigma_3$, Bulk stresses
Pa = Atmospheric pressure
K_1, K_2 and K_3 = Regression coefficients
$\tau_{oct} = \frac{1}{3}\sqrt{[(\sigma 1 - \sigma 2)^2 + (\sigma 1 - \sigma 3)^2 + (\sigma 2 - \sigma 3)^2]}$, Octahedral shear stress
σ_1 = Major principal stresses
σ_2, σ_3 = Intermediate principal stresses
</td></tr>
<tr><td>

Yao and Von Quintus (2002)
</td><td>

For Crushed Gravel
$k_1 = -0.8282 - 0.0065 * P\frac{3}{8} + 0.0114 * LL + 0.0004 * PI - 0.0187 * Wopt + 0.0036 * Ws + 0.0013 * \gamma s - (2.6 * 10 - 6) * \left(\frac{\gamma 2opt}{P40}\right)$
$k_2 = 4.9555 - 0.0057 * LL - 0.0075 * PI - 0.0470 * Ws - 0.0022 * \gamma opt + (2.8 * 10 - 6) * (\gamma 2opt/P40)$
$k_3 = -3.514 + 0.0016 * \gamma s$

For Uncrushed Gravel
$k_1 = -1.8961 + 0.0014 * \gamma s - 0.1184 * (Ws/Wopt)$
$k_2 = 0.4960 - 0.0074 * P200 - 0.0007 * \gamma s + 1.6972 * (\gamma s/\gamma opt) + 0.1199 * (Ws/Wopt)$
$k_3 = -0.5979 + 0.0349 * Wopt + 0.0004\gamma opt - 0.5166(Ws/Wopt)$
For coarse-grained sand soils
$K1 = 3.2868 - 0.0412 * P_{3/8} + 0.0267 * P_4 + 0.0137 * CLAY + 0.0083 * LL - 0.0379 * W_{opt} - 0.0004 * \gamma_s$
$K2 = 0.5670 + 0.0045 * P_{3/8} - 2.98X10^{-5} * P_4 - 0.0043 * SILT - 0.0102 * CLAY - 0.0041 * LL + 0.0014 * W_{opt} - 3.41X10^{-5} - 0.4582 * \left(\frac{\gamma_s}{\gamma_{opt}}\right) + 0.1779 * \left(\frac{W_c}{W_{opt}}\right)$
$K3 = -3.5677 + 0.1142 * P_{\frac{3}{8}} - 0.0839 * P_4 - 0.1249 * P_{200} + 0.1030 * SILT + 0.1191 * CLAY - 0.0069 * LL - 0.0103 * W_{opt} - 0.0017 * \gamma_S + 4.3177 * \left(\frac{\gamma_s}{\gamma_{opt}}\right) - 1.1095 * \left(\frac{W_c}{W_{opt}}\right)$

For fine-grained silt soils
$K1 = 1.0480 + 0.0177 * CLAY + 0.0279 * PI - 0.0370 * Wc$
$K2 = 0.5094 - 0.0286 * PI$
$K3 = -0.2218 + 0.0047 * CLAY + 0.0849 * PI - 0.1399 * Wc$
</td><td>

- $P_{3/8}$ = Percentage passing sieve #3/8 sieve
- P_4 = Percentage passing #4 sieve
- CLAY = Percent of clay
- SILT = Percent of silt
- P_{40} = Percentage passing #40 sieve
- P_{200} = Percent passing #200 sieve
- Wc = Moisture content of specimen, %
- W_{opt} = Optimum moisture content of the soil, %
- γ_s = Dry density of the sample
- γ_{opt} = Optimum dry density
- LL = Liquid limit
- PL = Plastic limit
- PI = Plastic Index
</td></tr>
</table>

CHAPTER 3 – TESTING METHODOLGY

3.1 Instrumentation

Test protocols followed to carry out resilient modulus and permanent deformation tests are Included in Appendix A. Figure 3.1 shows the components used for conducting these tests. A servo-dynamic system manufactured by MTS® was used. A top actuator is used to apply the dynamic axial loading sequence to the specimen being tested. A rigid triaxial cell was used as shown in Figure 3.2. The load cell is placed inside the triaxial chamber to minimize the inaccurate load readings due to friction. Four to six proximetors are placed on the middle one-third to one-half of the specimen height. Linear Variable Differential Transformers (LVDTs) can be used to measure deformations of the specimen, if desired.

3.2 Specimen Preparation

Figure 3.3 contains a flowchart of the activities involved in specimen preparation. These activities are further illustrated in Figure 3.4. The material is dried and mixed according to a specified gradation obtained from sieve analysis and water is added to achieve target moisture content. The soil-water mixture is allowed to mellow for 24 hrs in a sealed container. A 6 in. diameter and 12 in. high specimen is then compacted in 6 lifts following Tex-113-E. The specimen is extruded, measured and weighed to determine its density and is cured for another 24 hrs while covered with a membrane.

Figure 3.5 illustrates the compaction process. The first two layers are compacted first. Either three (120º apart) or two (180º apart) L-shaped metal pieces are placed on top of the second layer. The third and fourth layers of material are then compacted. Two or three additional metal pieces are placed on top of the fourth layer. Finally, two additional layers are compacted.

The top and bottom platens are attached to the specimen using a Jade stone grout. After the grout cures, vacuum grease is applied to platens to avoid any air intrusion during testing. O-rings are used to seal the membrane. Figure 3.6 shows the specimen ready for testing. Magnets and another set of metal piece are attached to embedded metal pieces to act as the proximetor targets.

The loading sequences used during testing are shown in Table 3.1. These load sequences are similar to those proposed by the NCHRP 1-28A study with some modifications. Based on a careful analysis of the strength requirements of Tex-117-E, the load sequences highlighted in red were found to be too excessive for Texas bases. After several iterations, a confining pressure of 10 psi and cyclic stress of 20 psi were selected for permanent deformation.

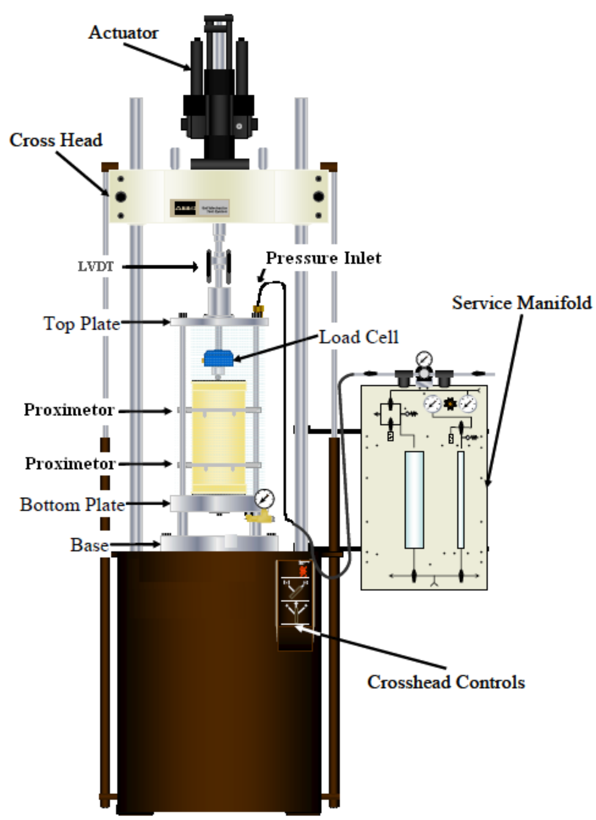


Figure 3.1 – MTS® Load Unit

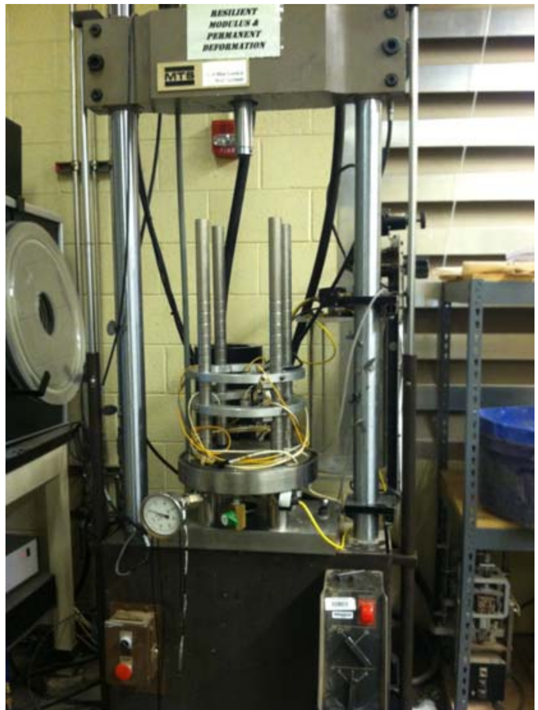


Figure 3.2 – MTS® System

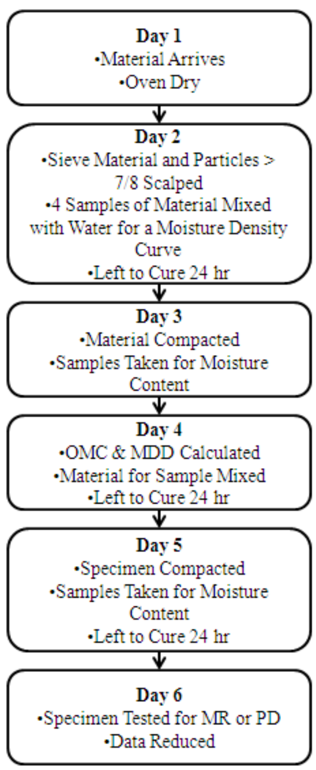


Figure 3.3 – Specimen Preparation Process

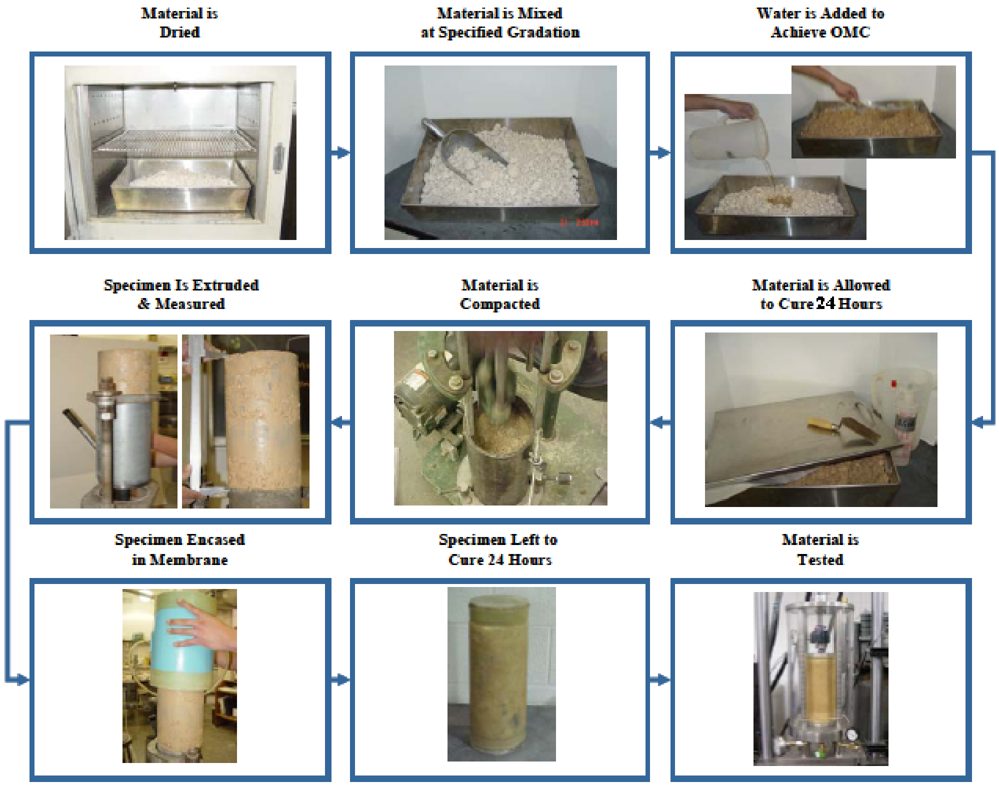


Figure 3.4 – Specimen Preparation

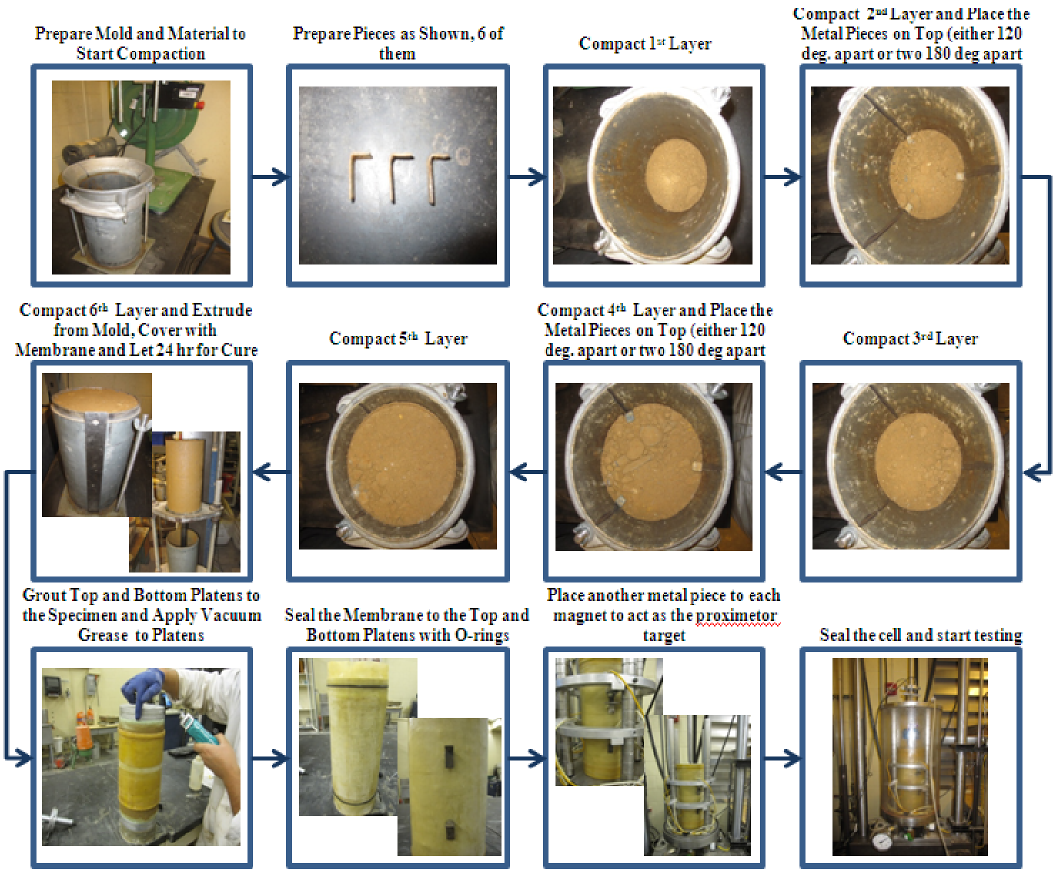


Figure 3.5 – Proximetor and Specimen Installation

Figure 3.6 – Proximetor Installation

Table 3.1 – Resilient Modulus Test Sequence Used in This study

Sequence	Confining Pressure		Contact Stress		Cyclic Stress		Maximum Stress		Nrep.
	KPa	psi	KPa	psi	KPa	psi	KPa	psi	
Preconditioning	103.5	15.0	20.7	3.0	20.7	3.0	41.4	6.0	100
1	20.7	3.0	4.1	0.6	10.4	1.5	14.5	2.1	100
2	41.4	6.0	8.3	1.2	20.7	3.0	29.0	4.2	100
3	69.0	10.0	13.8	2.0	34.5	5.0	48.3	7.0	100
4	103.5	15.0	20.7	3.0	51.8	7.5	72.5	10.5	100
5	138.0	20.0	27.6	4.0	69.0	10.0	96.6	14.0	100
6	20.7	3.0	4.1	0.6	20.7	3.0	24.8	3.6	100
7	41.4	6.0	8.3	1.2	41.4	6.0	49.7	7.2	100
8	69.0	10.0	13.8	2.0	69.0	10.0	82.8	12.0	100
9	103.5	15.0	20.7	3.0	103.5	15.0	124.2	18.0	100
10	138.0	20.0	27.6	4.0	138.0	20.0	165.6	24.0	100
11	20.7	3.0	4.1	0.6	41.4	6.0	45.5	6.6	100
12	41.4	6.0	8.3	1.2	82.8	12.0	91.1	13.2	100
13	69.0	10.0	13.8	2.0	138.0	20.0	151.8	22.0	100
14	103.5	15.0	20.7	3.0	207.0	30.0	227.7	33.0	100
15	138.0	20.0	27.6	4.0	276.0	40.0	303.6	44.0	100
16	20.7	3.0	4.1	0.6	62.1	9.0	66.2	9.6	100
17	41.4	6.0	8.3	1.2	124.2	18.0	132.5	19.2	100
18	69.0	10.0	13.8	2.0	207.0	30.0	220.8	32.0	100
19	103.5	15.0	20.7	3.0	310.5	45.0	331.2	48.0	100
20	138.0	20.0	27.6	4.0	414.0	60.0	441.6	64.0	100
21	20.7	3.0	4.1	0.6	103.5	15.0	107.6	15.6	100
22	41.4	6.0	8.3	1.2	207.0	30.0	215.3	31.2	100
23	69.0	10.0	13.8	2.0	345.0	50.0	358.8	52.0	100
24	103.5	15.0	20.7	3.0	517.5	75.0	538.2	78.0	100
25	138.0	20.0	27.6	4.0	690.0	100.0	717.6	104.0	100
26	20.7	3.0	4.1	0.6	144.9	21.0	149.0	21.6	100
27	41.4	6.0	8.3	1.2	289.8	42.0	298.1	43.2	100
28	69.0	10.0	13.8	2.0	483.0	70.0	496.8	72.0	100
29	103.5	15.0	20.7	3.0	724.5	105.0	745.2	108.0	100
30	138.0	20.0	27.6	4.0	966.0	140.0	993.6	144.0	100

3.3 Materials Used

Four unbound granular base materials were primarily used to develop the models. The materials were sampled from Austin, Bryan, Paris, and Pharr Districts. These bases are representative of a range of typical materials used in Texas. Since limestone aggregates are the most predominant type of aggregates used throughout TxDOT, two bases (Austin and Bryan) were selected with this type of aggregate. The other two base materials were caliche from Pharr and sandstone from Paris. These tests were supplemented with three additional materials from

three ongoing construction projects. These materials are named Loop 480 from Laredo District, IH 35 from Waco District and SH 21 from Bryan District.

Table 3.2 shows the results from sieve analyses as per Tex-110-E (dry sieve) and Tex-111-E (wet sieve) for the seven materials. Figure 3.7 and 3.8 shows the gradation curves of these materials respectively. The gradation curves from the dry and wet sieves are significantly different, especially for materials that are finer than No. 40 sieve.

Table 3.2 – Gradation of Materials

a) Dry Sieve Analysis

Sieve Size	Particle Diameter (mm)	Primary Materials				Supplementary Materials		
		Austin	Bryan	Paris	Pharr	Laredo (Loop 480)	Waco (IH 35)	Bryan (SH21)
1.75 in.	63.5	100	100	100	100	100	100	100
1.5 in.	44.4	100	100	100	100	100	100	100
1 in.	25.4	100	100	100	100	100	100	100
7/8 in.	22.4	95	94	94	94	89	70	69
3/8 in.	9.52	66	64	62	65	65	45	47
#4	4.75	49	48	45	48	51	35	36
#40	0.425	22	25	23	21	30	18	13
#100	0.15	11	9	8	7	14	7	6
#200	0.075	6	2	2	3	8	2	2

b) Wet Sieve Analysis

Sieve Size	Particle Diameter (mm)	Primary Materials				Supplementary Materials		
		Austin	Bryan	Paris	Pharr	Laredo (Loop 480)	Waco (IH 35)	Bryan (SH21)
1.75 in.	63.5	100	100	100	100	100	100	100
1.5 in.	44.4	100	100	100	100	100	100	100
1 in.	25.4	100	100	100	100	100	100	100
7/8 in.	22.4	91	89	91	95	86	84	85
3/8 in.	9.52	71	72	62	67	68	56	53
#4	4.75	54	57	47	51	57	46	48
#40	0.425	33	36	24	29	41	32	28
#100	0.15	28	26	11	19	26	21	18
#200	0.075	24	14	8.5	14	22	12	10

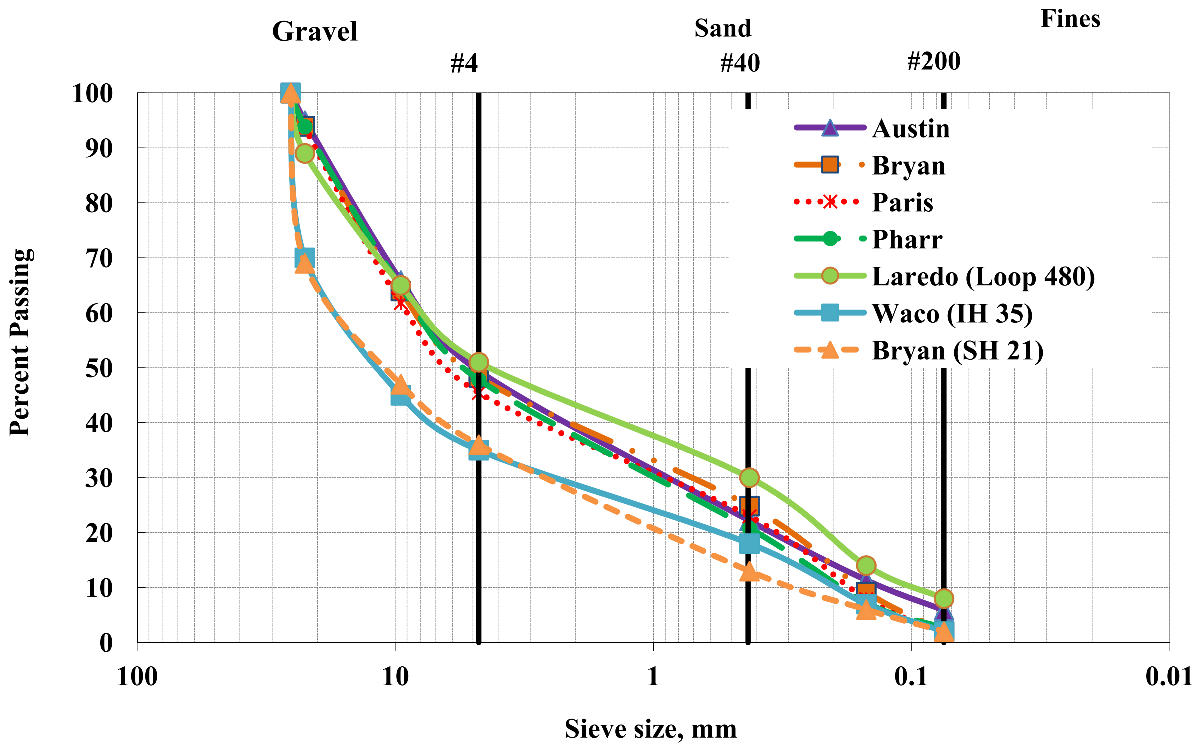


Figure 3.7 – Dry Sieve Grain Size Distribution for Texas Materials

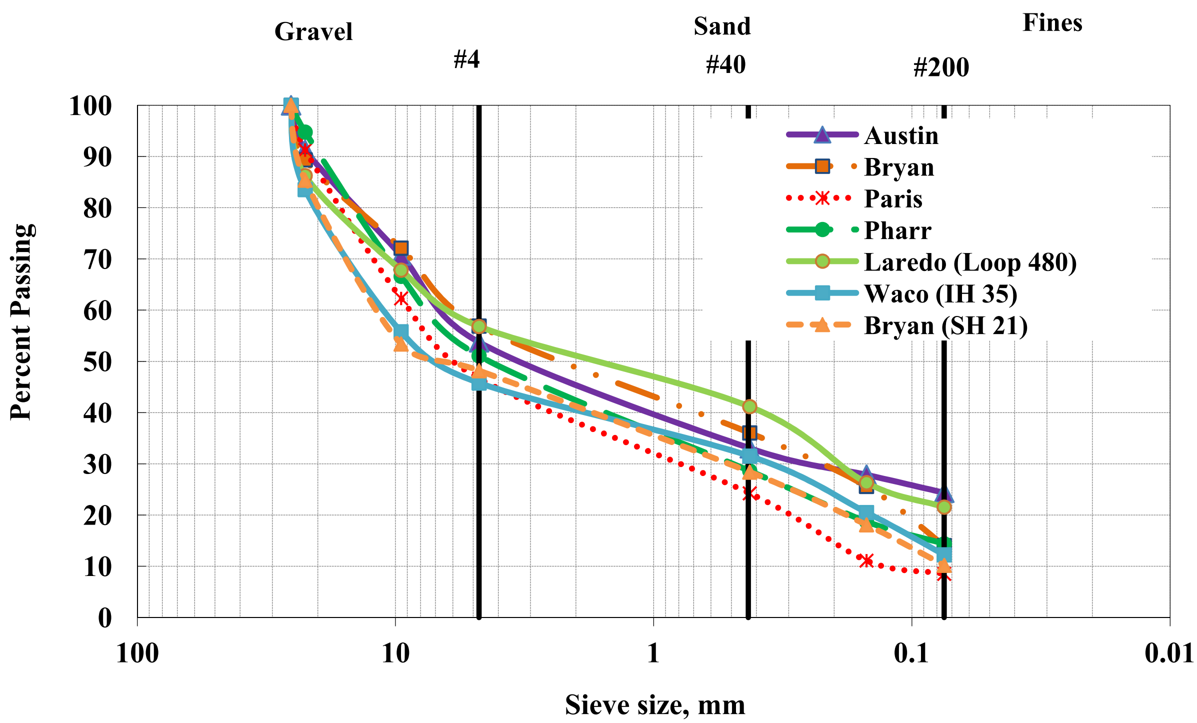


Figure 3.8 – Wet Sieve Grain Size Distribution for Texas Materials

The Atterberg limits obtained as per Tex-104-E, Tex-105-E and Tex-106-E are presented for all four materials in Table 3.3.

Table 3.3 – Atterberg Limits

Tests		Primary Materials				Supplementary Materials		
		Austin	Bryan	Paris	Pharr	Laredo (Loop 480)	Waco (IH 35)	Bryan (SH21)
Tex-104-E	**Liquid Limit, %**	25	11	NP	16	18	17	20
Tex-105-E	**Plastic Limit, %**	12	22	NP	9	14	8	11
Tex-106-E	**Plasticity Index, %**	13	11	NP	3	4	9	9

Table 3.4 contains the constituents of the bases as well as their classification as per Unified Soil Classification System (USCS). The optimum moisture content (OMC) and maximum dry density (MDD) obtained as per Tex-113-E for each material is also reflected in this table.

Table 3.4 – Index and Moisture Density Properties of Materials Used in Testing

Base	Type of Material	USCS Classification	Constituents, %			Optimum Moisture Content, %	Max Dry Density, pcf
			Gravel	Sand	Fines		
Pharr	Caliche	GW	62.8 (48.9)*	35.2 (36.7)	2.0 (14.4)	13.2	117.1
Paris	Sandstone	GW	61.1 (53.3)	37.4 (38.2)	1.5 (8.5)	6.4	135.3
Bryan	Limestone	GW	63.0 (43.1)	35.4 (42.8)	1.6 (14.1)	6.8	134.0
Austin	Limestone	GW	59.2 (46.3)	36.0 (29.3)	4.8 (14.6)	8.7	131.9
Laredo (Loop 480)	Gravel	SW	49.0 (43.2)	43.0 (35.2)	8.0 (21.6)	6.8	137.8
Waco (IH 35)	Limestone	GW	65.0 (54.2)	33.1 (33.6)	2.0 (12.2)	6.5	136.3
Bryan (SH 21)	Limestone	GW	64.0 (51.8)	34.0 (38.0)	2.0 (10.2)	7.5	138

* Numbers in parentheses are calculated from wet sieve analyses.

3.4 Resilient Modulus Test Results

The laboratory test matrix is shown in Table 3.5. The four primary base materials were tested at three nominal moisture contents of OMC -1.5%, OMC and OMC +1.5%. The supplementary bases were only tested at OMC. Tests were carried on duplicate specimens for each base material for both resilient modulus and permanent deformation testing to insure repeatability of results. All materials were tested using both proximetors and LVDTs.

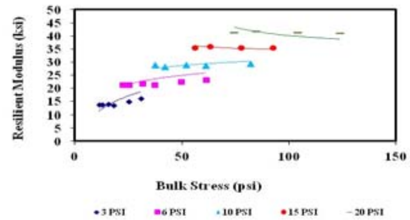
Typical MR results for Paris material at the OMC are shown in Figure 3.9 with the LVDTs and proximetors. The results for other materials are included in Appendix B. Some differences in the patterns of the results are apparent. The k_1-k_3 parameters obtained from Uzan and Witczak model (Model No. 5 in Table 2.1) and MEPDG model (Model No. 11 in Table 2.1) are also shown in the figure. These parameters from different models and different deformation measuring devices are different.

Table 3.5 – Laboratory Test Matrix

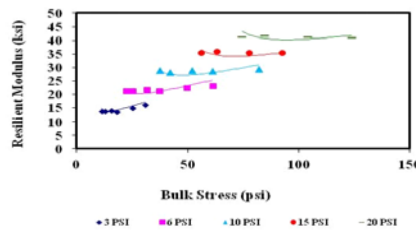
Base	Laboratory Test	Test Conditions		
		OMC -1.5%	OMC	OMC +1.5%
Austin	PD	X	X	X
	MR	X	X	X
Paris	PD	X	X	X
	MD	X	X	X
Pharr	PD	X	X	X
	MR	X	X	X
Bryan	PD	X	X	X
	MR	X	X	X
Laredo (Loop 480)	PD		X	
	MR		X	
Waco (IH 35)	PD		X	
	MR		X	
Bryan (SH 21)	PD		X	
	MR		X	

Description:	Paris 6%					
Before Testing:			**Field Conditions:** MC:		6.00%	
OMC:	6.5%					
Diameter:	6.1 in.				MEPDG Model	Uzan and Witczak (1988) Model
Height:	11.9 in.					
Gage Length:	11.9 in.			k_1 =	1011	712
Volume:	348.4 in.^{3}			k_2 =	0.83	0.81
Wet Density:	142.4 pcf			k_3 =	-0.73	-0.29
Dry Density:	134.3 pcf			R^2 =	0.975	0.986
Dry Mass:	27.1 lb.					

Cycle No.	Axial Strain (%)	Bulk Stress (psi)	Oct Stress (psi)	Resilient Modulus (ksi)	MEPDG Model Predicted Modulus (ksi)	Uzan and Witczak (1988) Model Predicted Modulus (ksi)
1	0.01	11.18	1.03	14	11	15
2	0.02	12.62	1.71	14	12	14
3	0.04	15.53	3.08	14	14	14
4	0.06	18.13	4.31	14	15	14
5	0.10	24.91	7.50	15	17	16
6	0.13	30.70	10.23	16	19	17
7	0.01	22.19	0.00	21	21	22
8	0.03	25.06	3.33	21	20	21
9	0.05	31.35	6.30	22	22	20
10	0.08	37.17	9.04	21	23	21
11	0.13	49.42	14.81	23	25	23
12	0.18	61.17	20.35	23	26	25
13	0.02	37.34	3.46	29	28	29
14	0.04	41.93	5.62	28	28	28
15	0.07	52.10	10.42	29	29	27
16	0.10	61.21	14.71	29	29	28
17	0.17	82.11	24.56	30	30	31
18	0.02	55.95	5.16	36	36	37
19	0.04	62.90	8.44	36	36	35
20	0.08	77.32	15.24	36	35	34
21	0.13	92.25	22.28	36	35	35
22	0.03	74.36	6.77	41	43	43
23	0.05	84.46	11.53	42	42	41
24	0.10	104.06	20.77	41	40	40
25	0.15	123.81	30.08	41	39	42



a) MEPDG MODEL

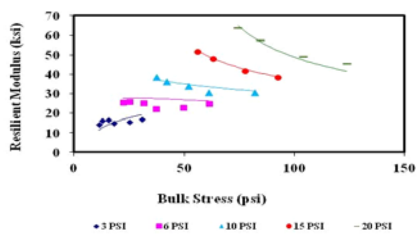


b) Uzan and Witczak (1988) Model

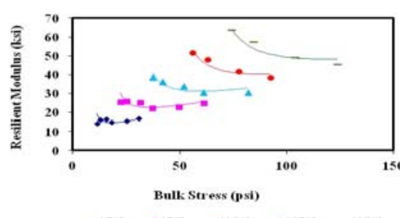
a) Results with LVDTs

Description:	Paris 6%					
Before Testing:			**Field Conditions:** MC:		6.00%	
OMC:	6.5%					
Diameter:	6.1 in.				MEPDG Model	Uzan and Witczak (1988) Model
Height:	11.9 in.					
Gage Length:	4.0 in.			k_1 =	1170	361
Volume:	348.4 in.^{3}			k_2 =	1.15	1.24
Wet Density:	142.4 pcf			k_3 =	-1.40	-0.61
Dry Density:	134.3 pcf			R^2 =	0.979	0.981
Dry Mass:	27.1 lb.					

Cycle No.	Axial Strain (%)	Bulk Stress (psi)	Oct Stress (psi)	Resilient Modulus (ksi)	MEPDG Model Predicted Modulus (ksi)	Uzan and Witczak (1988) Model Predicted Modulus (ksi)
1	0.01	11.18	1.03	15	11	19
2	0.02	12.62	1.71	17	12	16
3	0.03	15.53	3.08	17	14	15
4	0.06	18.13	4.31	15	15	15
5	0.10	24.91	7.50	16	18	15
6	0.12	30.70	10.23	17	19	17
7	0.01	22.19	0.00	26	28	30
8	0.02	25.06	3.33	26	24	26
9	0.05	31.35	6.30	25	25	23
10	0.08	37.17	9.04	22	25	23
11	0.13	49.42	14.81	23	26	24
12	0.17	61.17	20.35	25	26	26
13	0.01	37.34	3.46	38	37	41
14	0.03	41.93	5.62	36	36	35
15	0.06	52.10	10.42	34	35	32
16	0.10	61.21	14.71	31	33	31
17	0.16	82.11	24.56	31	31	33
18	0.02	55.95	5.16	52	52	53
19	0.03	62.90	8.44	48	48	45
20	0.07	77.32	15.24	42	43	41
21	0.12	92.25	22.28	39	39	40
22	0.02	74.36	6.77	64	65	64
23	0.04	84.46	11.53	58	57	54
24	0.08	104.06	20.77	49	47	49
25	0.13	123.81	30.08	45	42	48



a) MEPDG MODEL



b) Uzan and Witczak (1988) Model

b) Results with Proximeters

Figure 3.9 – Typical Results from MR Test

The extracted parameters from all tests with the LVDTs and proximetors are reported in Tables 3.6 and 3.7, respectively. The best way to compare the results is by calculating the representative lab MR modulus by using a set of prescribed octahedral and bulk stresses. Values recommend by the MEPDG (i.e. 31 psi for bulk stress and 7.5 psi for octahedral stress) were used in this study. For the MEPDG model, the representative MR moduli are 20 ksi and 22 ksi with the LVDTs and proximetors, respectively.

The variations in the representative modulus, MR, with moisture content measured with Proximetors and LVDTs for Paris material are shown in Figure 3.10. In both cases, MR values increases with the decrease in moisture content within the range of moisture contents considered in this study. The differences between the MR values with LVDTs and Proximetors increase as the material becomes stiffer (i.e. as moisture content decreases).

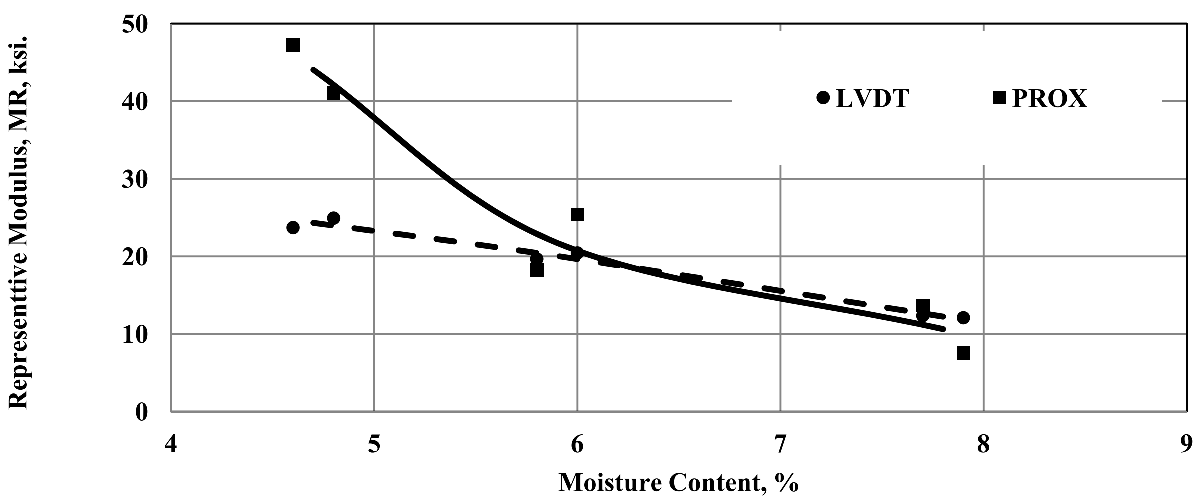


Figure 3.10 – Variations in Representative Resilient Modulus Results Using LVDTs and Proximetors

Table 3.6 – Resilient Modulus Results Using LVDT System

Material	Moisture Content %	Dry Density, pcf	*MEPDG Parameters*					*Uzan and Witczak Parameters*				
			k_1	k_2	k_3	*MR*, ksi	R^2	k_1	k_2	k_3	*MR*, ksi	R^2
Paris OMC	6.0	134.3	1011	0.83	-0.73	20.4	0.98	531	0.90	-0.33	19.1	0.99
Paris OMC	6.1	135.4	988	0.82	-0.75	19.7	0.97	509	0.89	-0.34	18.3	0.98
Paris OMC -1.5%	4.6	133.3	1172	0.66	-0.42	23.7	0.97	790	0.71	-0.20	22.6	0.99
Paris OMC -1.5%	4.8	132.9	1251	0.75	-0.62	24.9	0.97	712	0.81	-0.29	23.3	0.99
Paris OMC +1.5%	7.7	134.2	640	0.42	-0.10	12.4	0.97	522	0.49	-0.10	11.8	0.95
Paris OMC +1.5%	7.9	133.4	622	0.43	-0.10	12.1	0.96	511	0.51	-0.10	11.8	0.93
Pharr OMC	13.2	118.6	707	0.74	-0.87	12.6	0.97	324	0.82	-0.36	11.2	0.98
Pharr OMC	13.3	118.8	730	0.74	-0.82	13.3	0.98	356	0.79	-0.33	11.8	0.97
Pharr OMC-1.5%	11.0	117.0	997	0.92	-0.94	19.8	0.95	419	1.00	-0.42	17.2	0.99
Pharr OMC-1.5%	10.6	117.6	782	0.73	-0.83	14.1	0.96	358	0.82	-0.37	12.4	0.94
Pharr OMC+1.5%	**Too Wet To Test**											
Pharr OMC+1.5%												
Bryan OMC	6.2	135.2	1208	0.77	-0.71	23.5	0.96	615	0.85	-0.32	21.1	0.99
Bryan OMC	7.0	135.2	1197	0.77	-0.73	23.1	0.96	610	0.84	-0.32	20.8	0.98
Bryan OMC-1.5%	5.1	133.0	1570	0.62	-0.60	28.6	0.92	889	0.70	-0.29	26.8	0.97
Bryan OMC-1.5%	5.1	132.3	1312	0.67	-0.49	26.0	0.95	798	0.74	-0.24	23.9	0.99
Bryan OMC+1.5%	7.9	134.9	1022	0.89	-1.04	19.0	0.95	398	0.99	-0.45	16.6	0.98
Bryan OMC+1.5%	8.3	133.9	922	0.65	-0.66	16.8	0.95	550	0.66	-0.23	15.4	0.91
Austin OMC	8.4	132.7	1159	0.79	-0.66	23.4	0.97	653	0.82	-0.27	21.2	0.96
Austin OMC	8.5	132.8	1025	0.80	-0.88	19.0	0.98	477	0.85	-0.35	16.7	0.96
Austin OMC-1.5%	6.9	130.6	1529	0.67	-0.49	30.3	0.98	992	0.69	-0.24	28.7	0.99
Austin OMC-1.5%	6.8	130.6	1766	0.60	-0.49	33.2	0.95	1067	0.67	-0.23	30.2	0.99
Austin OMC+1.5%	**Too Wet To Test**											
Austin OMC+1.5%												
SH 21 OMC	7.3	137.8	1407	0.89	-1.26	23.9	0.94	477	0.99	-0.52	20.8	0.92
SH 21 OMC	7.7	137.5	1382	0.92	-1.44	22.3	0.96	404	1.02	-0.57	18.7	0.91
IH 35 OMC	6.5	137.2	1367	0.86	-1.21	23.2	0.96	456	1.00	-0.53	20.2	0.97
IH 35 OMC	6.3	136.2	1350	0.90	-1.00	25.7	0.92	916	0.70	-0.23	26.5	0.99
Loop 480 OMC	6.5	137.9	827	0.79	-0.46	18.1	0.99	566	0.82	-0.20	17.6	0.99
Loop 480 OMC	6.6	138.0	951	0.84	-0.88	18.2	0.98	441	0.92	-0.37	16.5	0.97

Table 3.7 – Resilient Modulus Results Using Proximeters

Material	Moisture Content %	Dry Density, pcf	MEPDG Parameters					Uzan and Witczak Parameters				
			k_1	k_2	k_3	*MR*, ksi	R^2	k_1	k_2	k_3	*MR*, ksi	R^2
Paris OMC	6.0	134.3	1170	1.15	-1.40	22.8	0.98	361	1.24	-0.61	20.2	0.98
Paris OMC	6.1	135.4	942	1.17	-1.45	18.2	0.93	355	1.27	-0.59	20.0	0.96
Paris OMC -1.5%	4.6	133.3	2256	0.85	-0.68	47.2	0.98	1293	0.89	-0.30	45.2	0.98
Paris OMC -1.5%	4.8	132.9	2157	0.96	-1.11	41.1	0.97	837	1.04	-0.50	37.4	0.99
Paris OMC +1.5%	7.7	134.2	693	0.45	-0.10	13.7	0.89	448	0.45	-0.10	9.9	0.97
Paris OMC +1.5%	7.9	133.4	452	0.23	-0.10	7.6	0.59	368	0.30	-0.10	7.2	0.30
Pharr OMC	13.2	118.6	664	0.63	-0.10	15.0	0.86	398	0.80	-0.26	12.7	0.90
Pharr OMC	13.3	118.8	803	0.53	-0.45	14.6	0.90	480	0.62	-0.22	13.0	0.93
Pharr OMC-1.5%	11.0	117.0	1004	1.21	-1.28	21.5	0.97	333	1.29	-0.57	18.8	1.00
Pharr OMC-1.5%	10.6	117.6	976	1.10	-1.15	20.3	0.96	325	1.19	-0.60	17.4	0.94
Pharr OMC+1.5%	**Too Wet To Test**											
Pharr OMC+1.5%												
Bryan OMC	6.2	135.2	1348	0.89	-0.66	29.3	0.99	792	0.90	-0.30	27.9	0.98
Bryan OMC	7.0	135.2	1298	1.07	-1.33	24.5	0.93	697	1.05	-0.57	32.9	0.95
Bryan OMC-1.5%	5.1	133.0	2113	0.89	-1.14	37.7	0.89	763	1.00	-0.53	33.8	0.97
Bryan OMC-1.5%	5.1	132.3	2032	0.93	-0.94	40.6	0.94	871	1.01	-0.43	36.3	0.99
Bryan OMC+1.5%	7.9	134.9	1222	0.97	-2.22	14.8	0.98	384	0.99	-0.42	15.7	0.99
Bryan OMC+1.5%	8.3	133.9	1006	0.68	-0.40	20.8	0.97	693	0.83	-0.10	20.2	0.71
Austin OMC	8.4	132.7	1400	0.99	-1.00	28.5	0.86	601	1.10	-0.53	28.1	0.97
Austin OMC	8.5	132.8	1232	0.70	-0.87	21.3	0.86	679	0.84	-0.39	24.3	0.86
Austin OMC-1.5%	6.9	130.6	2074	1.23	-1.75	37.1	0.88	1562	0.82	-0.35	53.6	0.86
Austin OMC-1.5%	6.8	130.6	2571	0.90	-1.32	42.9	0.89	1080	1.07	-0.52	50.1	0.92
Austin OMC+1.5%	**Too Wet To Test**											
Austin OMC+1.5%												
SH 21 OMC	7.3	137.8	2003	1.15	-1.88	32.0	0.85	394	1.32	-0.77	26.0	0.79
SH 21 OMC	7.7	137.5	1836	0.98	-1.38	31.7	0.78	505	1.17	-0.58	26.3	0.83
IH 35 OMC	6.5	137.2	2190	1.20	-1.31	45.9	0.97	606	1.26	-0.66	35.6	0.96
IH 35 OMC	6.3	136.2	2080	1.18	-1.50	39.7	0.94	497	1.39	-0.66	32.1	0.98
Loop 480 OMC	6.5	137.9	1000	1.26	-1.63	19.2	0.98	295	1.38	-0.53	17.3	0.98
Loop 480 OMC	6.6	138.0	1049	1.14	-1.29	21.2	0.96	220	1.58	-0.73	17.2	0.96

3.5 Permanent Deformation Results

Several permanent deformation tests were performed for each base material. These materials were tested at three nominal moisture contents (OMC and ±1.5%OMC). Figure 3.11 shows the results obtained from the Bryan material. For this particular material all moisture conditions could be tested; whereas for some other materials the specimens prepared wet of OMC experienced tertiary deformations prematurely. As the moisture content increases, the permanent deformation increases.

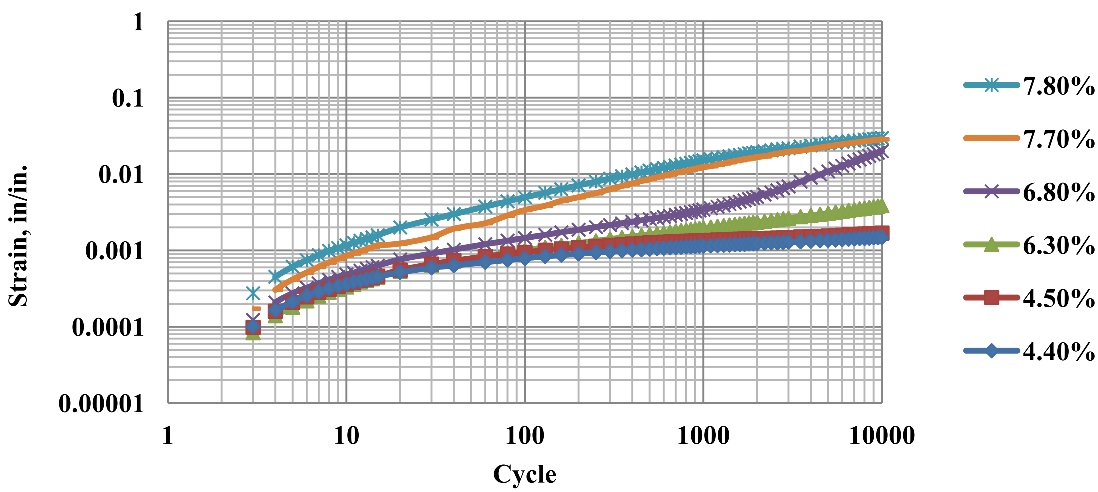


Figure 3.11 – Permanent Deformation Analysis Results for Bryan Base Material

Using the analysis results obtained after testing it is possible to estimate the parameters necessary for the rutting distress model. The total permanent deformation model requires the parameters α, defined as the rate of permanent deformation against the number of load applications, and μ, the permanent deformation parameter representing the constant of proportionality between permanent and elastic resilient strains. These parameters are involved in the permanent deformation model that calculates the progress of rutting with load repetition; all layers are modeled using a constitutive model in the form,

$$\varepsilon_p = \frac{\mu}{1-\alpha} \cdot \varepsilon_r \cdot N^{1-\alpha} \tag{3.1}$$

where ε_p is the accumulated permanent strain, ε_r is the resilient elastic strain, N is the load cycle number (Kenis, 1977). To estimate the rutting parameters α and μ the following relations are used:

$$\alpha = 1 - b \tag{3.2}$$

$$\mu = \frac{ab}{\varepsilon_r} \tag{3.3}$$

where, a is the intercept and b the slope of a log-log plot of permanent strain versus number of load repetitions. Tables 3.8 and 3.9 show the results obtained using the LVDTs and proximetors, respectively.

Table 3.8 – Permanent Deformation Results Using LVDT

Material	Moisture Content,%	Dry Density, pcf	Intercept a	Slope b	R^2	Resilient Strain ε_{res}	Permanent Strain ε_{perm}	Rutting Parameters	
								μ	α
Paris OMC	6.3%	134.8	0.000	0.28	1.00	0.001	0.004	0.07	0.72
Paris OMC	6.5%	135.1	0.000	0.36	1.00	0.001	0.006	0.06	0.64
Paris OMC -1.5%	4.4%	132.4	0.001	0.12	1.00	0.001	0.001	0.07	0.88
Paris OMC -1.5%	4.5%	133.1	0.001	0.10	0.99	0.001	0.002	0.07	0.90
Paris OMC +1.5%	7.8%	133.2	0.001	0.35	0.98	0.007	0.029	0.07	0.65
Paris OMC +1.5%	7.7%	133.2	0.001	0.43	0.98	0.005	0.028	0.05	0.57
Pharr OMC	12.8%	118.5	0.005	0.15	0.97	0.009	0.017	0.08	0.85
Pharr OMC	13.1%	118.3	0.004	0.14	0.98	0.007	0.013	0.08	0.86
Pharr OMC-1.5%	11.3%	116.6	0.001	0.09	0.99	0.001	0.002	0.07	0.91
Pharr OMC-1.5%	11.7%	117.1	0.001	0.20	0.99	0.002	0.005	0.08	0.80
Pharr OMC+1.5%	**Too Wet To Test**								
Pharr OMC+1.5%									
Bryan OMC	6.9%	134.8	0.000	0.26	0.96	0.001	0.002	0.07	0.74
Bryan OMC	6.9%	134.5	0.000	0.11	0.99	0.001	0.001	0.07	0.89
Bryan OMC-1.5%	5.1%	132.5	0.001	0.08	0.99	0.001	0.001	0.06	0.92
Bryan OMC-1.5%	5.3%	132.9	0.000	0.17	1.00	0.000	0.001	0.08	0.83
Bryan OMC+1.5%	7.8%	133.5	0.005	0.07	0.91	0.007	0.009	0.05	0.93
Bryan OMC+1.5%	8.1%	133.8	0.005	0.11	0.93	0.008	0.013	0.07	0.89
Austin OMC	8.5%	132.5	0.002	0.10	0.94	0.003	0.005	0.07	0.90
Austin OMC	8.8%	132.1	0.002	0.08	0.91	0.003	0.004	0.06	0.92
Austin OMC-1.5%	6.8%	131	0.001	0.10	0.98	0.001	0.002	0.07	0.90
Austin OMC-1.5%	7.0%	131.5	0.000	0.13	0.98	0.001	0.001	0.08	0.87
Austin OMC+1.5%	**Too Wet To Test**								
Austin OMC+1.5%									
SH 21 OMC	7.2%	137.7	0.004	0.09	0.981	0.005	0.008	0.06	0.91
SH 21 OMC	7.8%	137.5	0.004	0.09	0.95	0.005	0.008	0.06	0.91
IH 35 OMC	6.6%	136.8	0.002	0.07	0.95	0.002	0.003	0.06	0.93
IH 35 OMC	6.1%	137.1	0.001	0.09	0.98	0.001	0.002	0.06	0.91
Loop 480 OMC	7.0%	137.4	0.005	0.09	0.98	0.008	0.012	0.06	0.91
Loop 480 OMC	6.6%	137.7	0.003	0.09	0.96	0.005	0.008	0.06	0.91

Table 3.9 – Permanent Deformation Results Using Proximetor

Material	Moisture Content, %	Dry Density, pcf	Intercept a	Slope b	R^2	Resilient Strain ε_{res}	Permanent Strain ε_{perm}	Rutting Parameters μ	α
Paris OMC	6.3%	134.8	0.000	0.27	1.00	0.001	0.004	0.07	0.73
Paris OMC	6.8%	135.1	0.000	0.36	1.00	0.001	0.005	0.05	0.64
Paris OMC -1.5%	4.4%	132.4	0.001	0.13	0.99	0.002	0.003	0.07	0.87
Paris OMC -1.5%	4.5%	133.1	0.001	0.13	0.99	0.001	0.002	0.07	0.87
Paris OMC +1.5%	Too Wet To Test								
Paris OMC +1.5%									
Pharr OMC	12.8%	118.5	0.01	0.080	0.99	0.012	0.016	0.05	0.92
Pharr OMC	13.1%	118.3	0.01	0.038	0.99	0.008	0.009	0.03	0.96
Pharr OMC-1.5%	11.3%	116.6	0.00	0.109	1.00	0.002	0.002	0.06	0.89
Pharr OMC-1.5%	11.7%	117.1	0.00	0.152	0.98	0.003	0.005	0.07	0.85
Pharr OMC+1.5%	Too Wet To Test								
Pharr OMC+1.5%									
Bryan OMC	6.9%	134.8	0.000	0.26	0.96	0.001	0.003	0.06	0.74
Bryan OMC	6.9%	134.5	0.001	0.10	0.99	0.002	0.003	0.06	0.90
Bryan OMC-1.5%	5.1%	132.5	0.001	0.10	1.00	0.001	0.002	0.06	0.90
Bryan OMC-1.5%	5.3%	132.9	0.000	0.13	0.97	0.000	0.001	0.07	0.87
Bryan OMC+1.5%	Too Wet To Test								
Bryan OMC+1.5%									
Austin OMC	8.5%	132.5	0.002	0.119	0.93	0.004	0.006	0.07	0.88
Austin OMC	8.8%	132.1	0.002	0.096	0.91	0.003	0.005	0.06	0.90
Austin OMC-1.5%	6.8%	131	0.001	0.069	0.96	0.001	0.002	0.05	0.93
Austin OMC-1.5%	7.0%	131.5	0.000	0.165	0.99	0.001	0.001	0.07	0.84
Austin OMC+1.5%	Too Wet To Test								
Austin OMC+1.5%									
SH 21 OMC	7.2%	137.7	0.003	0.097	0.95	0.005	0.008	0.06	0.90
SH 21 OMC	7.8%	137.5	0.010	0.065	0.87	0.013	0.018	0.05	0.93
IH 35 OMC	6.6%	136.8	0.003	0.084	0.88	0.004	0.006	0.06	0.92
IH 35 OMC	6.1%	137.1	0.001	0.049	0.75	0.002	0.002	0.04	0.95
Loop 480 OMC	7.0%	137.4	0.007	0.072	0.91	0.009	0.013	0.05	0.93
Loop 480 OMC	6.6%	137.7	0.004	0.119	0.98	0.007	0.012	0.07	0.88

CHAPTER 4 – EVALUATION AND DEVELOMENT OF MODELS

The evaluation of existing models and developing new ones to predict MR and PD as a function of index properties were carried out in two stages. In the first stage, the results from the MR and PD tests carried out on the seven materials at their optimum moisture contents were related to the index properties of the materials. In that manner, the representative moduli and permanent deformation parameters at the optimum moisture content can be estimated. In the second stage, models to estimate the variations of these parameters with moisture content were evaluated and recommended.

After an initial evaluation of the applicability of the models presented in Table 2.1 to the practices of TxDOT, the models shown in Tables 4.1 and 4.2, corresponding to Malla and Joshi (2008) and Yau and Von Quintus (2002) were selected. Malla and Joshi (2008) models were developed from data collected using loading sequences recommended by AASHTO T-307. Yau and Von Quintus (2002) proposed different models for crushed and uncrushed gravel. These models were established using data collected according to the Long Term Pavement Performance Protocol P46.

Table 4.1 – Malla and Joshi (2008) Resilient Modulus Model

<table>
<tr><td colspan="2">

$$\boldsymbol{MR = k_1\ P_a \left(\frac{\theta}{P_a}\right)^{k_2} \left(\frac{\tau_{oct}}{P_a}\right)^{k_3}}$$

where:
$\theta = \sigma_1 + \sigma_2 + \sigma_3$, Bulk stresses
Pa = Atmospheric pressure
k_1, k_2 and k_3 = Regression coefficients
$\tau_{oct} = \frac{1}{3}\sqrt{[(\sigma 1 - \sigma 2)^2 + (\sigma 1 - \sigma 3)^2 + (\sigma 2 - \sigma 3)^2]}$, Octahedral shear stress
σ_1 = Major principal stresses
σ_2, σ_3 = Intermediate principal stresses
</td></tr>
<tr><td>

Coarse- grained samples CU<600

$$\text{Log } k_1 = -0.64428 - 0.00773 * \text{MC} - 0.62335 * \text{DDR} + 0.02531 * \text{S3} - 0.01504 * \text{S1}_{\text{HALF}} - 0.00694 * \text{SN200} + 0.00469 * \text{SILT} + 0.00033564 * \text{CU} - 0.00432 * \text{CC}$$

$$k_2 = -0.74167 + 0.00804 * \text{MC} + 0.00035328 * \text{DD} + 0.00713 * \text{S1}_{\text{HALF}} - 0.00401 * \text{SN40} + 0.00459 * \text{FSAND} - 0.000156 * \text{CU} + 0.00166 * \text{CC}$$

$$k_3 = -0.90585 - 0.00186 * \text{MC} + 0.00021603 * \text{MAXDD} + 0.01777 * \text{S2} - 0.01830 * \text{S1} + 0.00528 * \text{SN10} - 0.00531 * \text{SN200}$$
</td><td>
- MC = Specimen moisture content
- DDR = Dry density ratio
- S3 = Percent passing 3" sieve
- S2 = Percent passing 2"sieve
- S1_{HALF}= Percent passing # $1\frac{1}{2}$" sieve
- DD = Dry density
- SN40 = Percent passing #40 sieve
- SN10 = Percent passing #10 sieve
- FSAND = Percent fine sand
- SN200 = Percent passing #200 sieve
- CU = Uniformity coefficient
- CC = Coefficient of curvature
- MAXDD = Maximum dry density
- SILT = Percent of silt
- CLAY = Percent of clay
</td></tr>
</table>

Table 4.2 – Yau and Von Quintus (2002) Resilient Modulus Model

<table>
<tr><td colspan="2">

$\boldsymbol{MR = k_1\ P_A \left(\frac{\theta}{P_a}\right)^{k_2} \left(\frac{\tau_{oct}}{P_a} + 1\right)^{k_3}}$

Where:

$\theta = \sigma_1 + \sigma_2 + \sigma_3$, Bulk stresses

Pa = Atmospheric pressure

k_1, k_2 and k_3 = Regression coefficients

$\tau_{oct} = \frac{1}{3}\sqrt{[(\sigma 1 - \sigma 2)^2 + (\sigma 1 - \sigma 3)^2 + (\sigma 2 - \sigma 3)^2]}$, Octahedral shear stress

σ_1 = Major principal stresses

σ_2, σ_3 = Intermediate principal stresses

</td></tr>
<tr><td>

For Crushed Gravel

$k_1 = -0.8282 - 0.0065 * \mathrm{P}\frac{3}{8} + 0.0114 * \mathrm{LL} + 0.0004 * \mathrm{PI} - 0.0187 * \mathrm{Wopt} + 0.0036 * \mathrm{Ws} + 0.0013 * \gamma\mathrm{s} - (2.6 * 10 - 6) * \left(\frac{\gamma 2\mathrm{opt}}{\mathrm{P40}}\right)$

$k_2 = 4.9555 - 0.0057 * \mathrm{LL} - 0.0075 * \mathrm{PI} - 0.0470 * \mathrm{Ws} - 0.0022 * \gamma\mathrm{opt} + (2.8 * 10 - 6) * (\gamma 2\mathrm{opt}/\mathrm{P40})$

$k_3 = -3.514 + 0.0016 * \gamma\mathrm{s}$

For Uncrushed Gravel

$k_1 = -1.8961 + 0.0014 * \gamma\mathrm{s} - 0.1184 * (\mathrm{Ws}/\mathrm{Wopt})$

$k_2 = 0.4960 - 0.0074 * \mathrm{P200} - 0.0007 * \gamma\mathrm{s} + 1.6972 * (\gamma\mathrm{s}/\gamma\mathrm{opt}) + 0.1199 * (\mathrm{Ws}/\mathrm{Wopt})$

$k_3 = -0.5979 + 0.0349 * \mathrm{Wopt} + 0.0004\gamma\mathrm{opt} - 0.5166(\mathrm{Ws}/\mathrm{Wopt})$

</td><td>

- $P_{3/8}$ = Percentage passing sieve #3/8 sieve
- P_4 = Percentage passing #4 sieve
- CLAY = Percent of clay
- SILT = Percent of silt
- P_{40} = Percentage passing #40 sieve
- P_{200} = Percent passing #200 sieve
- Wc = Moisture content of specimen, %
- W_{opt} = Optimum moisture content of the soil, %
- γ_s = Dry density of the sample
- γ_{opt} = Optimum dry density
- LL = Liquid limit
- PL = Plastic limit
- PI = Plastic Index

</td></tr>
</table>

Figure 4.1a compares the measured representative resilient moduli with those predicted using Malla and Joshi's model presented in Table 4.1. The measured and estimated moduli are reasonably correlated as judged by a standard error of estimate (SEE) of about 3 ksi. Similarly, the models proposed by Yau and Von Quintus (2002) were evaluated. The estimated moduli from the model for the crushed gravels compare well with the measured values with an SEE of 2.3 ksi (Figure 4.1b). The uncrushed gravels model is not as appropriate since the SEE is in excess of 3.5 ksi (Figure 4.1c).

As reflected in Figure 4.2, these three models are inappropriate for the data collected with the proximetors since the moduli calculated with the LVDTs and proximetors diverge as the materials become stiffer. As such, new models were developed for the data obtained with proximetors.

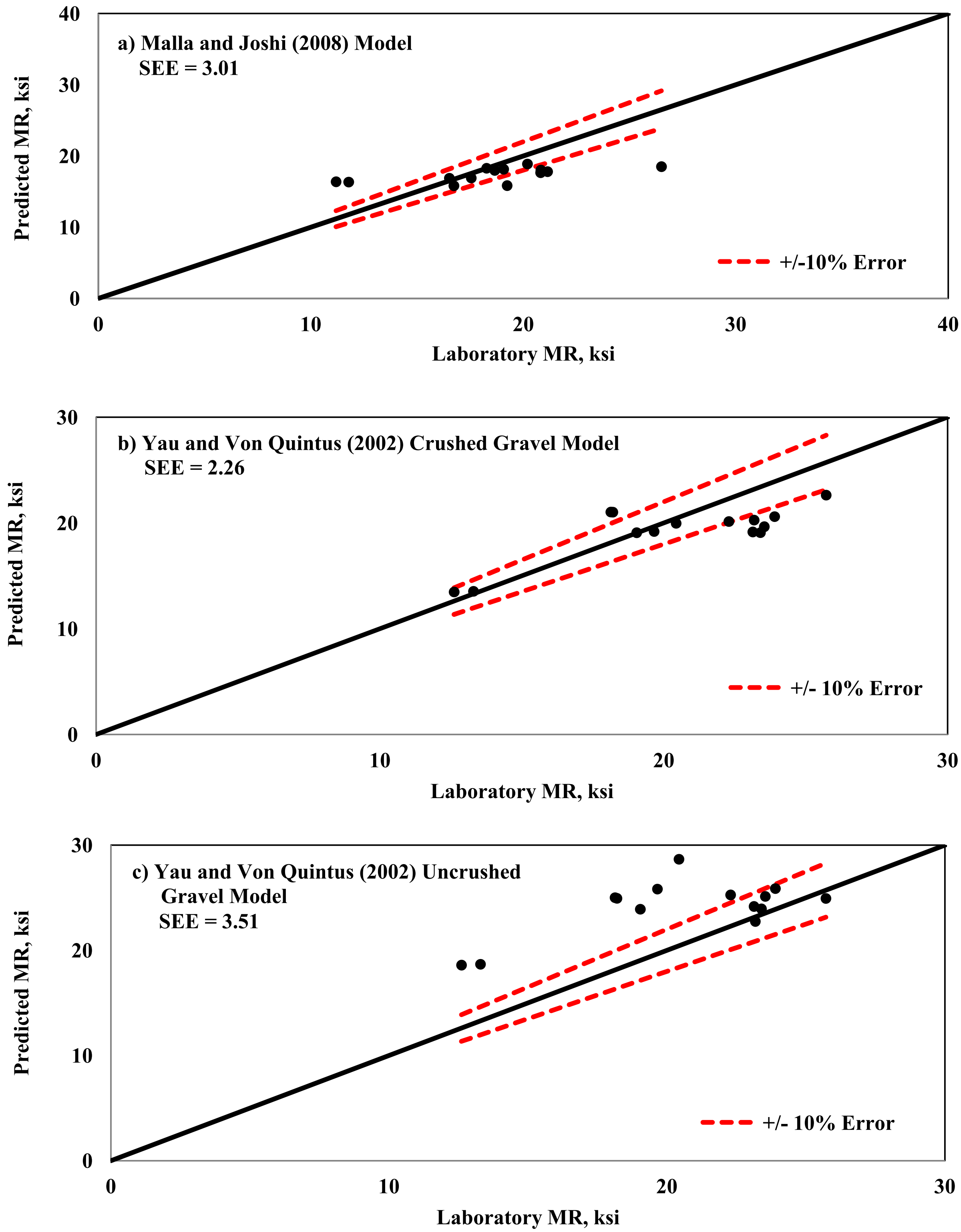


Figure 4.1 – Evaluation of Resilient Modulus Models from Data Using LVDT

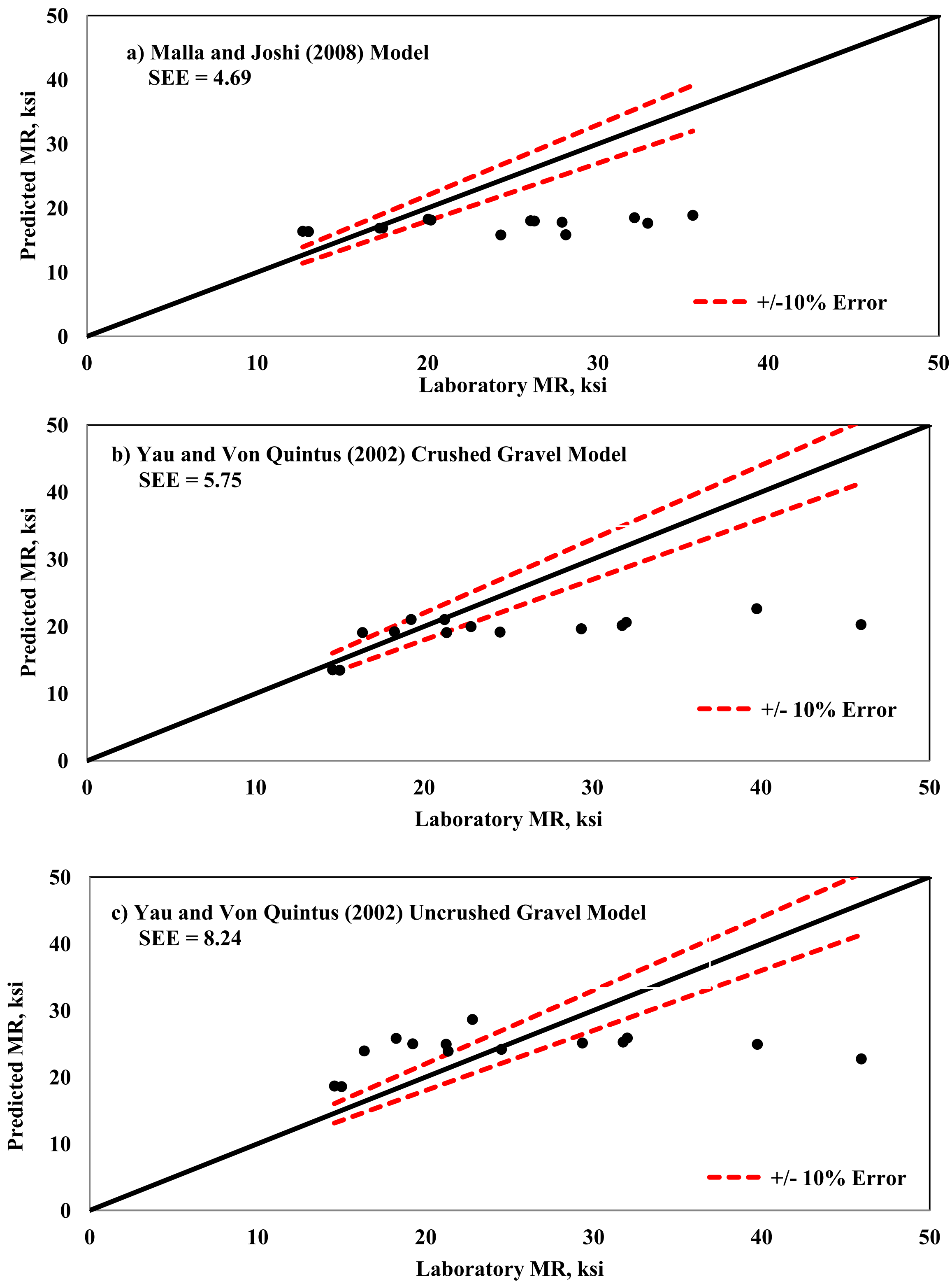


Figure 4.2 – Evaluation of Resilient Modulus Models for Data Obtained Using Proximeters

Multiple linear regression analyses with software package STATISTICA were carried out in order to identify the most appropriate soil indices as independent variables, and to determine the regression coefficients for those parameters. The dependent variables in these analyses were parameters k_1 through k_3 obtained from laboratory MR tests using either Witczak and Uzan model (Model 5 in Table 2.1) or the MEPDG model (Model 11 in Table 2.1). The β coefficients provide the relative contributions of each independent variable in the prediction of each of the dependent variables. Table 4.3 contains the β coefficients for each k-parameter obtained from the MEPDG model from MR tests using proximetors (as dependent variables) and index parameters using dry sieve gradations (as independent variables). The top five parameters that correlated best with each k parameter were used to develop the model. The optimal models for this situation are presented in Equations 4.1 through 4.3 along with the R^2 for each equation:

$$k_1 = 4629.095 - 54.585 \times P_{3/8} + 11.946 \times PL - 52.190 \times SMC + 0.775 \times P_{\#200} + 28.925 \times P_{CLAY} \; (R^2=0.92) \tag{4.1}$$

$$k_2 = -1.08644 + 0.00124 \times MDD - 0.04877 \times P_{coarse\text{-}sand} - 0.01828 \times P_{CLAY} + 0.00826 \times P_{\#40} - 0.00398 \times P_{fine\text{-}sand} \; (R^2=0.79) \tag{4.2}$$

$$k_3 = 19.4433 - 0.0041 \times MDD + 0.0154 \times P_{7/8} + 0.0361 \times PI - 3.2098 \times MCR - 10.2869 \times DDR \; (R^2=0.86) \tag{4.3}$$

where,

PI = Plasticity Index

PL = Plastic Limit

DDR = Dry Density Ratio

MCR = Moisture Content Ratio

MDD = Maximum Dry Density

SMC = Specimen Moisture Content

$P_{7/8}$ = Percentage Passing 7/8”

$P_{3/8}$ = Percentage Passing 3/8”

$P_{\#40}$= Percentage Passing #40

$P_{\#200}$= Percentage Passing #200

$P_{coarse\text{-}sand}$ = Percentage of Coarse Sand

$P_{fine\text{-}sand}$ = Percentage of Fine Sand

P_{CLAY} = Percentage of Clay

The MCR and DDR are included in these relationships to consider the inevitable small differences in the densities and moisture contents of the specimens nominally prepared at the OMC and MDD. For design purposes, these two values should be set as unity.

The predicted k values and representative resilient moduli obtained from the proposed relationships are compared in Figure 4.3 with those measured in the laboratory using the proximetors. The results from the proposed models are in good agreement with the measured ones.

Given that index properties vary depending on the sieve analysis method (wet sieve vs. dry sieve), a second set of relationships was developed based on wet sieve gradations. After identifying the most appropriate index properties as independent variables (see Appendix C for β coefficients), the optimal models for this case are presented in Equations 4.4 through 4.6.

$$k_1 = 15385.06 - 137.69 \times P_{7/8} - 56.91 \times P_{\#40} + 125.87 \times P_{CLAY} - 82.02 \times P_{coarse\text{-}sand} + 0.81 \times LL \quad (R^2=0.92) \tag{4.4}$$

$$k_2 = -0.8138 + 0.00166 \times MDD - 0.04325 \times P_{coarse\text{-}sand} - 0.00873 \times PI - 1.17211 \times DDR - 0.00152 \times P_{\#4} \quad (R^2=0.79) \tag{4.5}$$

$$k_3 = 21.5249 - 0.0045 \times MDD + 0.0291 \times P_{3/8} - 0.0710 \times P_{SILT} - 2.9459 \times MCR - 11.5521 \times DDR \quad (R^2=0.86) \tag{4.6}$$

where $P_{\#4}$= Percentage Passing #4 and P_{SILT} = Percentage of Silt.

Table 4.3 – β Coefficients for Different Index Parameters for Estimating MR k Parameters (Dry Sieve Analysis)

Parameter k_1			Parameter k_2			Parameter k_3		
Rank	**Index Property**	**β Coefficient**	**Rank**	**Index Property**	**β Coefficient**	**Rank**	**Index Property**	**β Coefficient**
1	Percent Passing 3/8" Sieve	-0.901	1	Maximum or Optimum Dry Density	0.612	1	Maximum or Optimum Dry Density	-0.860
2	Plastic Limit	0.209	2	Percent of Coarse Sand	-0.249	2	Percent Passing 7/8" Sieve	0.333
3	Specimen Moisture Content	-0.201	3	Percent of Clay	-0.176	3	Plastic Index	0.316
4	Percent Passing #200	-0.045	4	Percent Passing #40 Sieve	0.105	4	Ratio of MC and MOIST	-0.220
5	Percent of Clay	0.035	5	Percent Fine Sand	0.092	5	Dry Density Ratio	-0.158
6	Liquid Limit	-0.031	6	Percent of Sand	0.078	6	Percent Fine Sand	-0.031
7	Coefficient of Curvature	0.024	7	Percent Passing #4 Sieve	0.076	7	Percent of Silt	-0.026
8	Dry Density Ratio	-0.024	8	Percent Passing #200	0.067	8	Percent of Coarse Sand	0.024
9	Percent Fine Sand	0.024	9	Percent Passing 3/8" Sieve	0.066	9	Plastic Limit	-0.023
10	Dry Density of the Sample	-0.022	10	Coefficient of Curvature	-0.060	10	Percent Passing #40 Sieve	-0.021
11	Maximum or Optimum Dry Density	-0.018	11	Percent of Silt	0.060	11	Percent of Clay	-0.016
12	Percent Passing 7/8" Sieve	0.017	12	Percent Passing 7/8" Sieve	0.060	12	Percent of Sand	-0.016
13	Uniformity Coefficient	-0.016	13	Plastic Limit	0.050	13	Liquid Limit	0.014
14	Percent of Sand	0.015	14	Specimen Moisture Content	-0.020	14	Optimum Moisture Content	0.011
15	Plastic Index	0.012	15	Optimum Moisture Content	-0.019	15	Specimen Moisture Content	0.010
16	Ratio of MC and MOIST	-0.008	16	Uniformity Coefficient	0.007	16	Uniformity Coefficient	-0.009
17	Percent of Coarse Sand	-0.007	17	Plastic Index	0.003	17	Percent Passing #200	0.009
18	Percent Passing #4 Sieve	-0.006	18	Liquid Limit	-0.002	18	Percent Passing 3/8" Sieve	0.002
19	Percent of Silt	-0.003	19	Ratio of MC and MOIST	-0.002	19	Coefficient of Curvature	0.001
20	Optimum Moisture Content	0.000	20	Dry Density Ratio	-0.002	20	Percent Passing #4 Sieve	-0.001
21	Percent Passing #40 Sieve	0.000	21	Dry Density of the Sample	0.000	21	Dry Density of the Sample	0.000

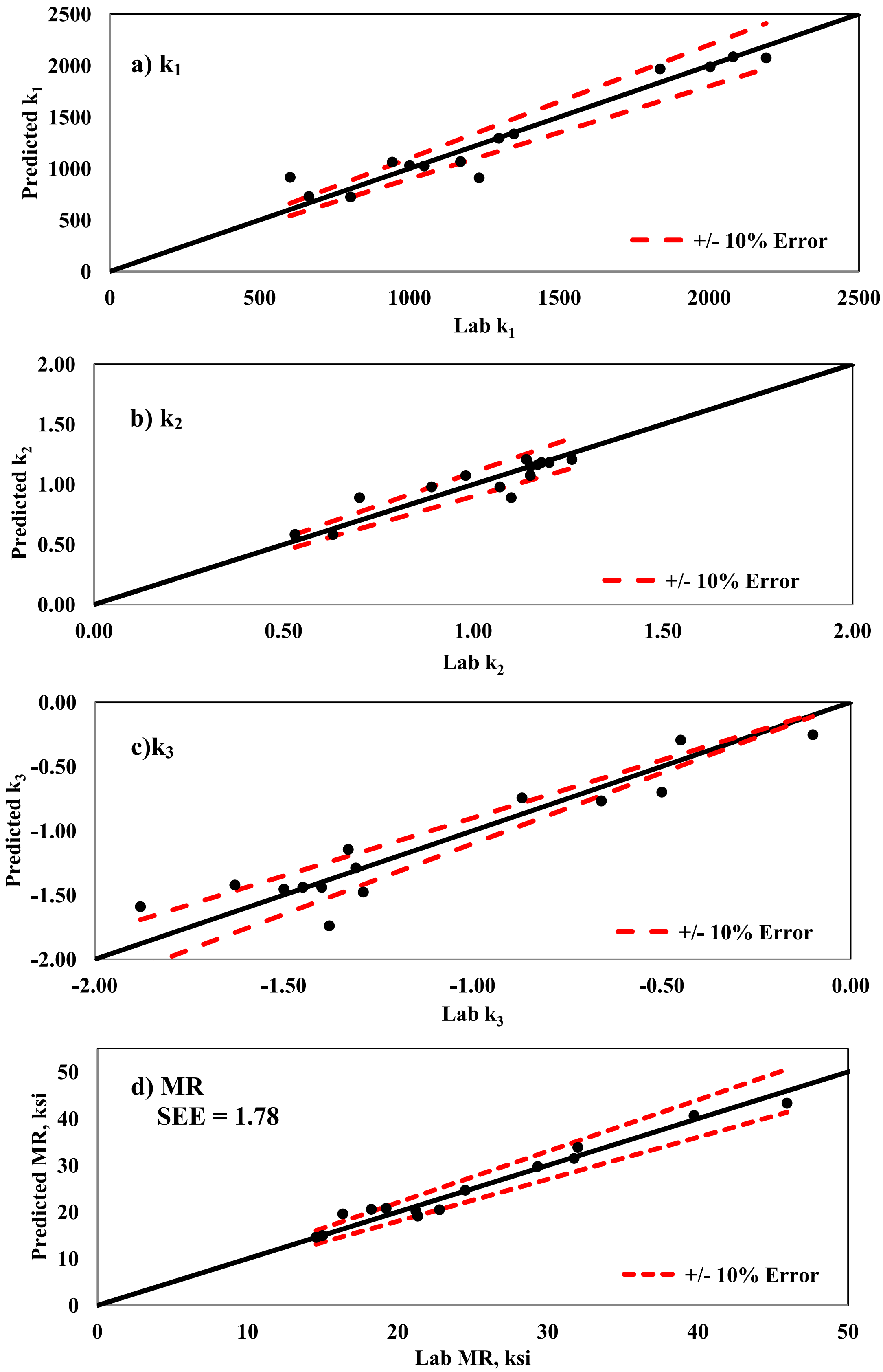


Figure 4.3 – Comparison of Lab and Predicted MR Parameters (Dry Sieve)

As reflected in Figure 4.4, these models perform slightly better than the models proposed for dry sieve analysis in Equations 4.1 through 4.3.

Since some of the index parameters used in developing the previous two sets of models are not available to TxDOT personnel under Item 247 specifications, another set of models following dry gradation were developed that uses only those parameters that TxDOT labs can provide. These models are shown in Equations 4.7 through 4.9. The optimal relationships developed with this constraint are (β coefficients are shown in Appendix C):

$$k_1 = 4182.233 - 47.479 \times P_{3/8} + 21.877 \times PL - 44.815 \times SMC - 5.362 \times LL + 92.951 \times CC \; (R^2=0.92) \tag{4.7}$$

$$k_2 = -1.70355 + 0.00131 \times MDD - 0.03245 \times P_{coarse\text{-}sand} + 0.00838 \times P_{\#40} - 0.00452 \times PL - 0.00258 \times CU \; (R^2=0.79) \tag{4.8}$$

$$k_3 = 19.4433 - 0.0041 \times MDD + 0.0154 \times P_{7/8} + 0.0361 \times PL - 3.2098 \times MCR - 10.2869 \times DDR \; (R^2=0.86) \tag{4.9}$$

where *LL* = Liquid Limit, *CC* = Coefficient of Curvature and *CU* = Uniformity Coefficient.

As reflected in Figure 4.5, these relationships are only slightly less representative of the measured values than the other two sets. It is also interesting that the R^2 values for all relationships are quite close.

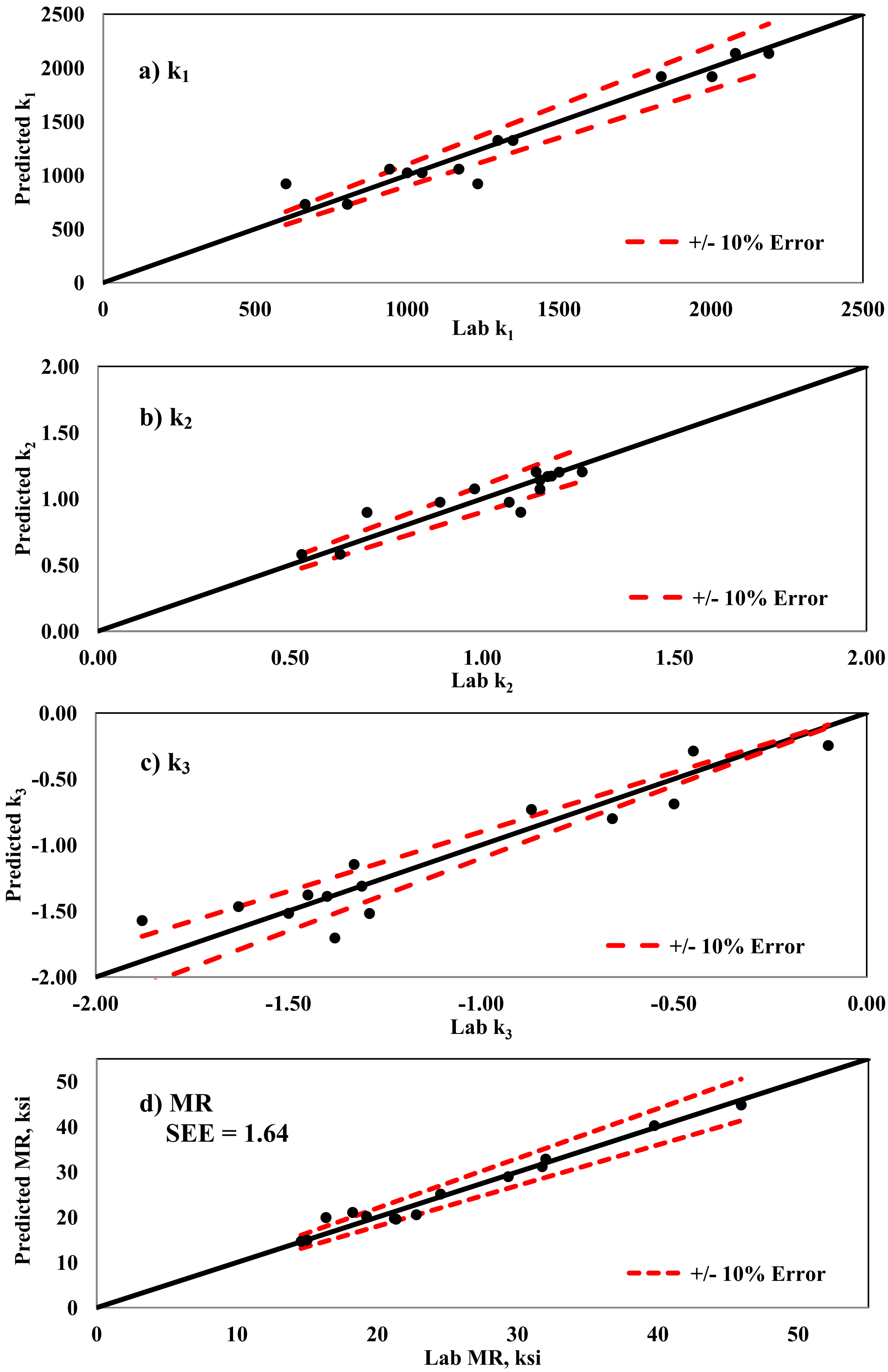


Figure 4.4 – Comparison of Lab and Predicted MR Parameters (Wet Sieve)

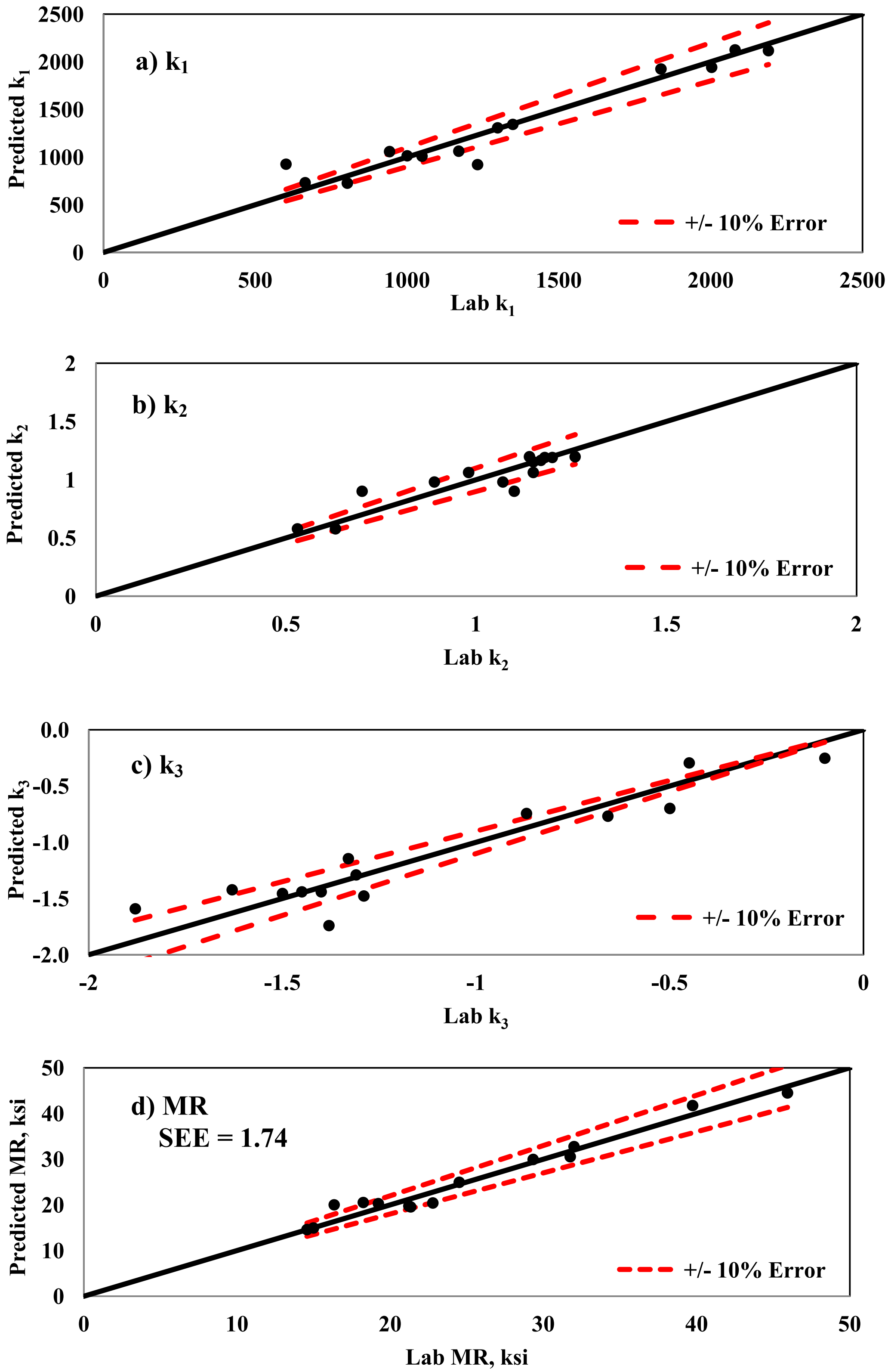


Figure 4.5 – Comparison of Lab and Predicted MR Parameters Using TxDOT Item 247 Index Parameters (Dry Sieve)

4.1 Influence of Moisture Content on Moduli

The models developed before can be used to estimate the moduli at OMC. To account for the variations in modulus with moisture content, a relationship proposed as a part of MEPDG by Witczak et al. (2000) was evaluated. The MEPDG relationship is in the form of:

$$\log \frac{M_R}{M_{Ropt}} = a + \frac{b-a}{1+\exp\left(\beta + K_S \cdot (S - S_{opt})\right)} \tag{4.10}$$

where M_R = representative resilient modulus at a degree of saturation S (decimal); M_{Ropt}= representative resilient modulus at the maximum dry density and optimum moisture content; S_{opt}= degree of saturation (in decimal) at the maximum dry density and optimum moisture content, (in decimal); a = minimum of log(M_R/M_{Ropt}); b = maximum of log(M_R/M_{Ropt}); β and k_S = regression parameters. The degree of saturation, which is used as the surrogate for moisture content in that relationship, can be readily calculated from the moisture content and dry density. The MEPDG recommended two separate sets of regression parameters for coarse-grained and fine-grained geomaterials as shown in Table 4.4.

Table 4.4 – Regression Parameters Proposed by MEPDG

MEPDG			
Type of Material	**a**	**b**	**k_s**
Coarse-Grained	-0.3123	0.3010	6.8157
Fine- Grained	-0.5934	0.3979	6.1324

Cary and Zapata (2010) proposed a more general form of Equation 19 by incorporating percent finer than No. 200 sieve (w, in decimal) and plasticity index of the materials (PI, in percent):

$$\log\left(\frac{M_R}{M_{Ropt}}\right) = \left(\alpha + \beta \times e^{-wPI}\right)^{-1} + \frac{\left(\delta+\gamma\times wPI^{0.5}\right)-\left(\alpha+\beta\times e^{-wPI}\right)^{-1}}{1+e^{\left(\ln\left(\frac{-\left(\delta+\gamma\times wPI^{0.5}\right)}{\left(\alpha+\beta\times e^{-wPI}\right)^{-1}}\right)+\left(\rho+\omega\times e^{-wPI}\right)^{0.5}\times\left(\frac{S-S_{opt}}{100}\right)\right)}} \tag{4.11}$$

where, α = -0.600, β = -1.87194, δ = 0.800, γ = 0.080, ρ = 11.96518, and ω = -10.19111.

To evaluate these models, the resilient modulus test results from the four primary materials are superimposed on the Cary and Zapata model (a.k.a. Zapata model) and MEPDG model in Figure 4.6. Based on Tables 3.2 and 3.3, the wPI ranges from zero to 0.6 from dry sieve analysis and zero and 3 from the wet sieve analysis. As such, the relationships based on wPI of zero and 3 are shown for the Zapata model. The experimental results lie between the MEPDG relationship and Zapata relationship with wPI = 3. Thus, both models were found suitable for establishing a relationship between modulus and moisture content.

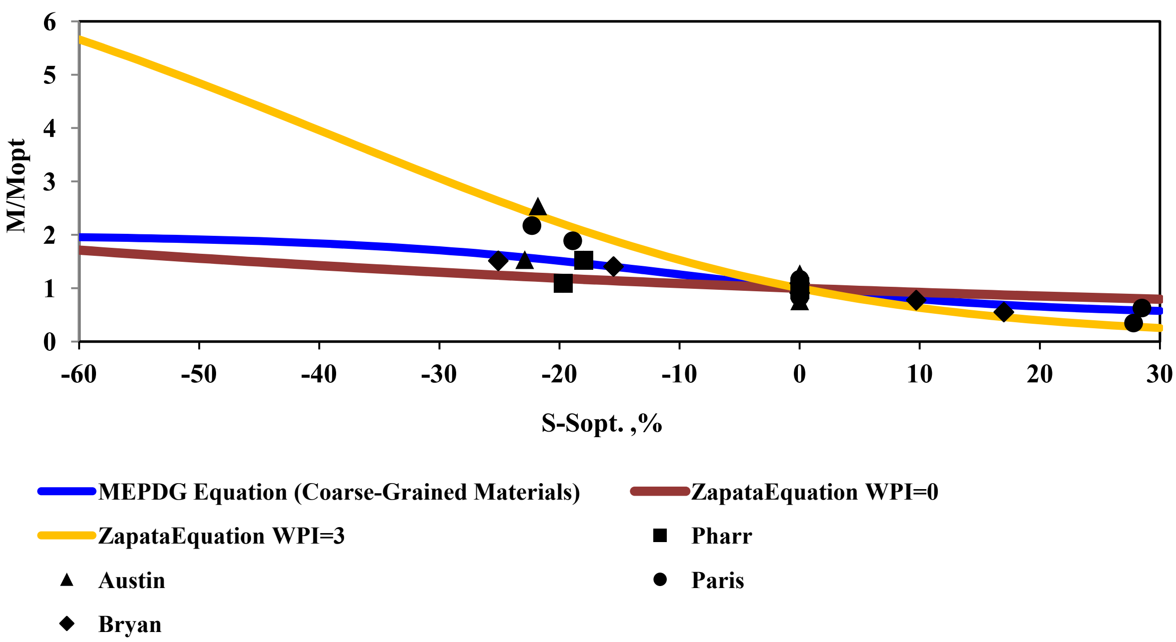


Figure 4.6 – Variations of Normalized Representative Modulus with Degree of Saturation

4.2 Permanent Deformation Model

Not many models have been developed to estimate permanent deformation parameters as a function of the index properties and moisture-density relationships. Thus, new sets of models were developed for permanent deformation parameters using the results obtained during this research.

The recommended constitutive model to predict permanent deformation is shown in Equation 4.12.

$$\varepsilon_p = \frac{\mu}{1-\alpha} \cdot \varepsilon_r \cdot N^{1-\alpha} \tag{4.12}$$

where ε_p is the accumulated permanent strain, ε_r is the resilient elastic strain, N is the load cycle number (Kenis, 1977).

Similar to the process followed for the resilient modulus test results, multiple linear regression analyses were carried out in order to identify the most appropriate soil indices as independent variables, and to determine the regression coefficients for those indices. The dependent variables in these analyses were the resilient strain ε_r, and the rutting parameters α and μ in order to determine predicted permanent strain. Table 4.5 shows the β coefficients for each index property that impacts the variables mentioned obtained from dry sieve analyses.

The proposed models for determining permanent deformation parameters are provided in Equation 4.13 through 4.15. These models were developed from dry sieve analysis.

$$\varepsilon_r = -0.254161 - 0.005961 \times SMC + 0.000124 \times MDD + 0.001604 \times P_{SILT} + 0.000466 \times PI - 0.065958 \times DDR \; (R^2 = 0.81) \tag{4.13}$$

$$\mu = 0.368006 - 0.005048 \times OMC + 0.010387 \times P_{coarse\text{-}sand} + 0.000364 \times CU + 0.000007 \times DDS - 0.429041 \times DDR \; (R^2 = 0.62) \tag{4.14}$$

$$\alpha = -3.168 + 0.00853\times LL - 0.03238\times P_{coarse\text{-}sand} + 1.07574\times MCR + 3.19948\times DDR + 0.0051\times P_{SILT}\ (R^2=0.92) \tag{4.15}$$

The estimated resilient strain ε_r, and the rutting parameters α and μ are compared with corresponding measured values in Figure 4.7. The proposed models seem to provide representative results.

Equations 4.16 through 4.18 are proposed models when wet sieve gradations are used (see Appendix C for β values).

$$\varepsilon_r = -0.13652 + 0.005496\times SMC + 0.000099\times MDD + 0.000406\times P_{\#40} - 0.125619\times DDR - 0.000128\times PI\ (R^2=0.79) \tag{4.16}$$

$$\mu = 0.223081 + 0.001528\times P_{\#200} - 0.002675\times P_{SILT} - 0.000589\times LL + 0.000028\times DDS - 0.227641\times DDR\ (R^2=0.57) \tag{4.17}$$

$$\alpha = -4.63907 + 0.04081\times P_{SILT} + 0.01816\times PI - 0.00882\times P_{3/8} + 1.18023\times MCR + 4.58772\times DDR\ (R^2= 0.88) \tag{4.18}$$

Figure 4.8 compares estimated resilient strain ε_r, and the rutting parameters α and μ with those obtained from laboratory tests. The SEE = 0.0029 for permanent strain is similar to the SEE obtained for the dry sieve models.

The most representative models found from only using parameters that are readily available to TxDOT labs (following Item 247 specifications) are shown in Equations 4.19 through 4.21.

$$\varepsilon_r = -0.1088492 + 0.003723 \times SMC + 0.000046 \times MDD - 0.003973 \times CC - 0.000308 \times P_{3/8} + 0.000148 \times CU \; (R^2=0.81) \tag{4.19}$$

$$\mu = 0.368006 - 0.005048 \times OMC + 0.010387 \times P_{coarse\text{-}sand} + 0.000364 \times CU + 0.000007 \times DDS - 0.429041 \times DDR \; (R^2=0.62) \tag{4.20}$$

$$\alpha = 1.069507 - 0.002334 \times MDD + 0.001909 \times DDS - 0.042877 \times P_{coarse\text{-}sand} + 0.006686 \times LL + 1.143634 \times MCR \; (R^2=0.94) \tag{4.21}$$

As reflected in Figure 4.9, these models are almost equally capable of estimating the permanent deformation parameters (as judged with their corresponding SEE values).

Table 4.5 – β Coefficients for Different Index Parameters for Estimating PD (Dry Sieve Analysis)

Parameter Resilient Strain			Parameter μ			Parameter α		
Rank	Index Property	β Coefficient	Rank	Index Property	β Coefficient	Rank	Index Property	β Coefficient
1	Specimen Moisture Content	3.487	1	Optimum Moisture Content	-1.374	1	Liquid Limit	0.576
2	Maximum or Optimum Dry Density	3.292	2	Percent of Coarse Sand	1.168	2	Ratio of MC and MOIST	0.402
3	Percent of Silt	0.795	3	Uniformity Coefficient	0.444	3	Percent of Silt	0.400
4	Plastic Index	0.490	4	Dry Density of the Sample	-0.337	4	Percent Passing 3/8" Sieve	-0.398
5	Dry Density Ratio	-0.118	5	Dry Density Ratio	-0.115	5	Dry Density Ratio	0.239
6	Percent Passing 7/8" Sieve	-0.100	6	Plastic Limit	-0.070	6	Plastic Index	0.044
7	Percent Passing 3/8" Sieve	-0.099	7	Percent Fine Sand	-0.069	7	Coefficient of Curvature	0.035
8	Percent of Sand	-0.096	8	Percent Passing #40 Sieve	-0.068	8	Percent Fine Sand	0.034
9	Percent Passing #4 Sieve	-0.095	9	Percent of Sand	-0.057	9	Percent Passing #40 Sieve	0.028
10	Coefficient of Curvature	0.092	10	Percent of Silt	-0.049	10	Uniformity Coefficient	0.028
11	Uniformity Coefficient	0.076	11	Percent Passing #4 Sieve	-0.048	11	Percent of Coarse Sand	-0.028
12	Percent Fine Sand	-0.074	12	Ratio of MC and MOIST	-0.046	12	Optimum Moisture Content	-0.021
13	Percent of Coarse Sand	-0.073	13	Percent of Clay	-0.046	13	Specimen Moisture Content	-0.021
14	Percent Passing #40 Sieve	-0.071	14	Percent Passing 3/8" Sieve	-0.041	14	Plastic Limit	0.020
15	Percent of Clay	-0.036	15	Percent Passing 7/8" Sieve	-0.040	15	Percent of Clay	0.018
16	Plastic Limit	-0.035	16	Coefficient of Curvature	0.030	16	Percent Passing 7/8" Sieve	0.014
17	Liquid Limit	0.031	17	Plastic Index	-0.028	17	Percent of Sand	0.013
18	Percent Passing #200	-0.031	18	Percent Passing #200	-0.026	18	Dry Density of the Sample	-0.008
19	Dry Density of the Sample	-0.019	19	Maximum or Optimum Dry Density	0.018	19	Maximum or Optimum Dry Density	-0.008
20	Ratio of MC and MOIST	-0.002	20	Specimen Moisture Content	-0.007	20	Percent Passing #200	-0.007
21	Optimum Moisture Content	0.000	21	Liquid Limit	-0.006	21	Percent Passing #4 Sieve	0.001

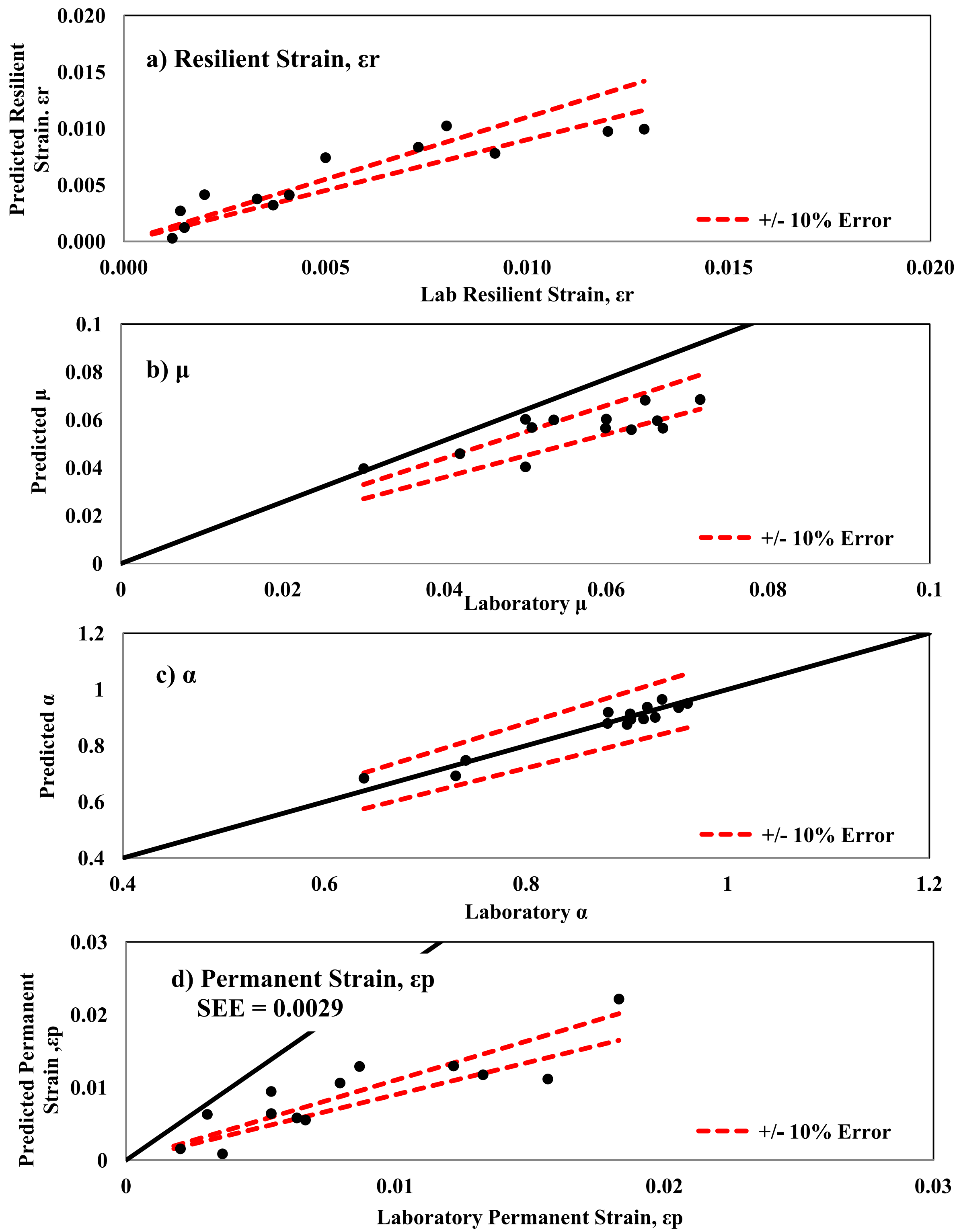


Figure 4.7 – Comparison of Lab PD and Predicted PD Parameters (Dry Sieve)

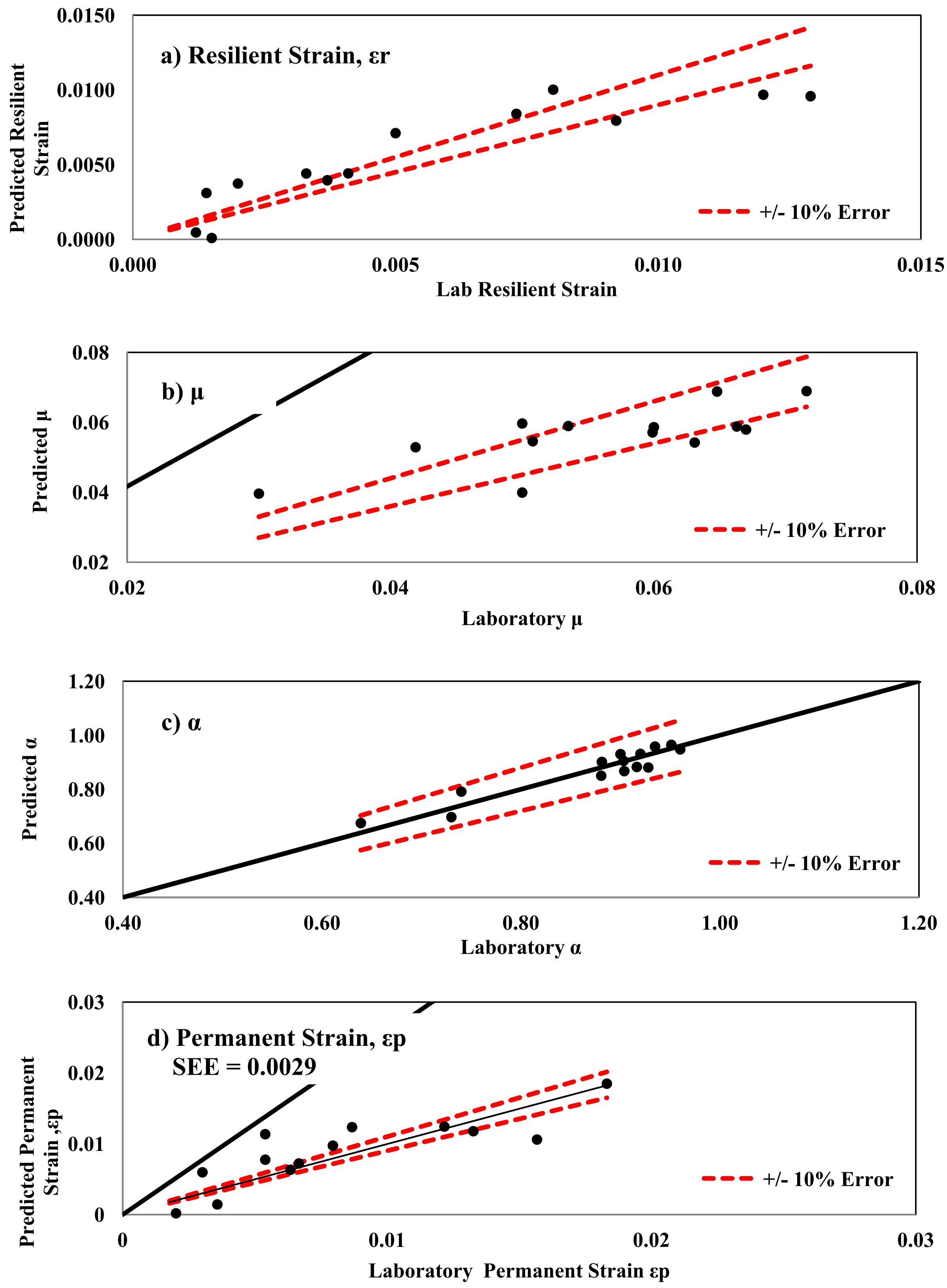


Figure 4.8 – Comparison of Lab PD and Predicted PD Parameters (Wet Sieve)

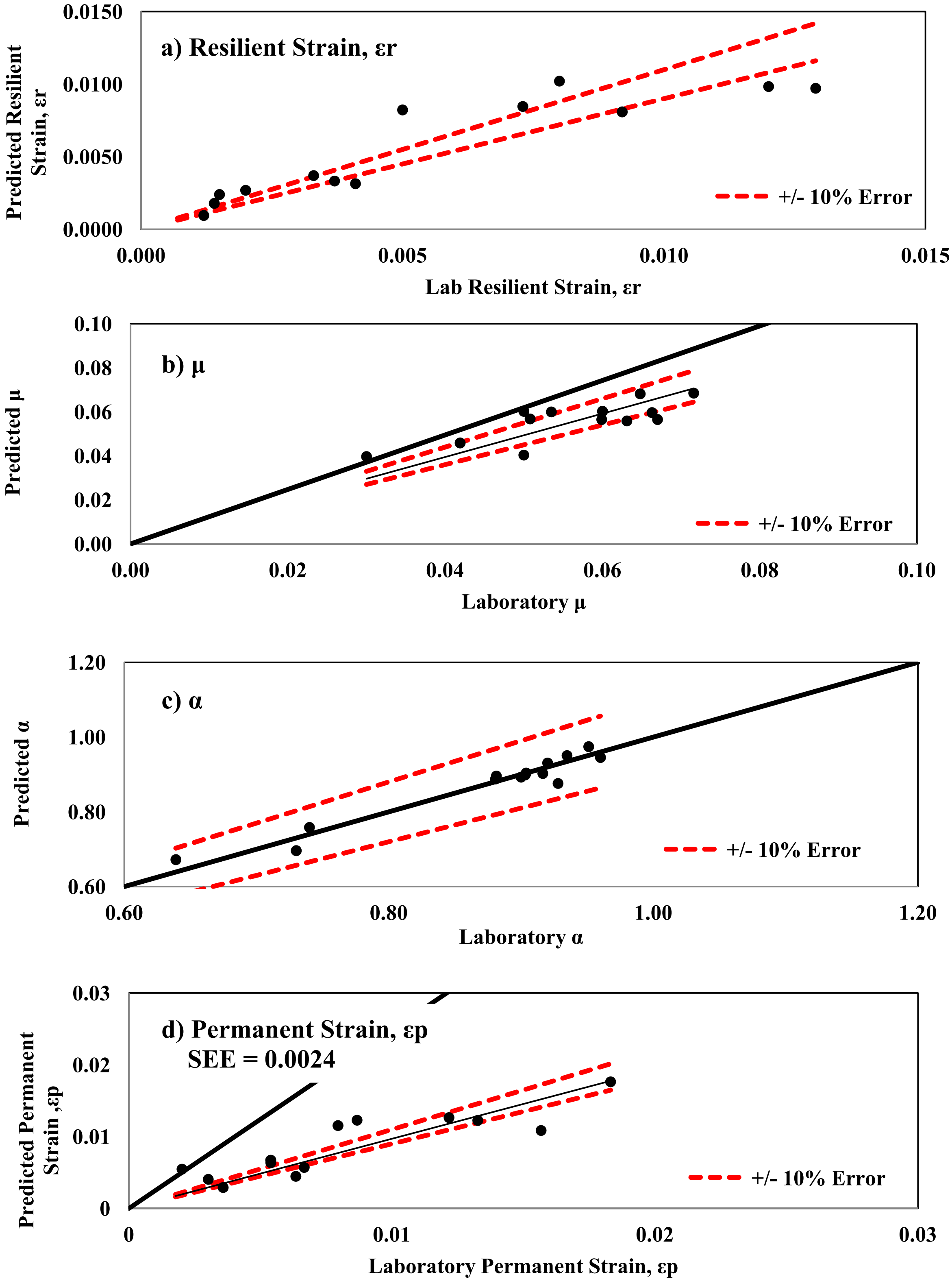


Figure 4.9 – Graphical Comparison of Lab MR and Predicted MR Following Item 247 Index Parameters (Dry Sieve)

4.3 Influence of Moisture Content on PD Parameters

The models presented before can be used to estimate the permanent deformation parameters at the OMC. Unlike for the MR tests, relating the permanent deformation parameters to the variation in moisture content was not feasible. Most specimens prepared wet of OMC did not survive the permanent deformation tests. As such, several sets of models were developed to estimate the variations in permanent deformation parameters at nominal moisture contents of OMC - 1.5%. These models are summarized in Table 5.1. The representativeness of these models can be inspected in Figures 4.10 through 4.12.

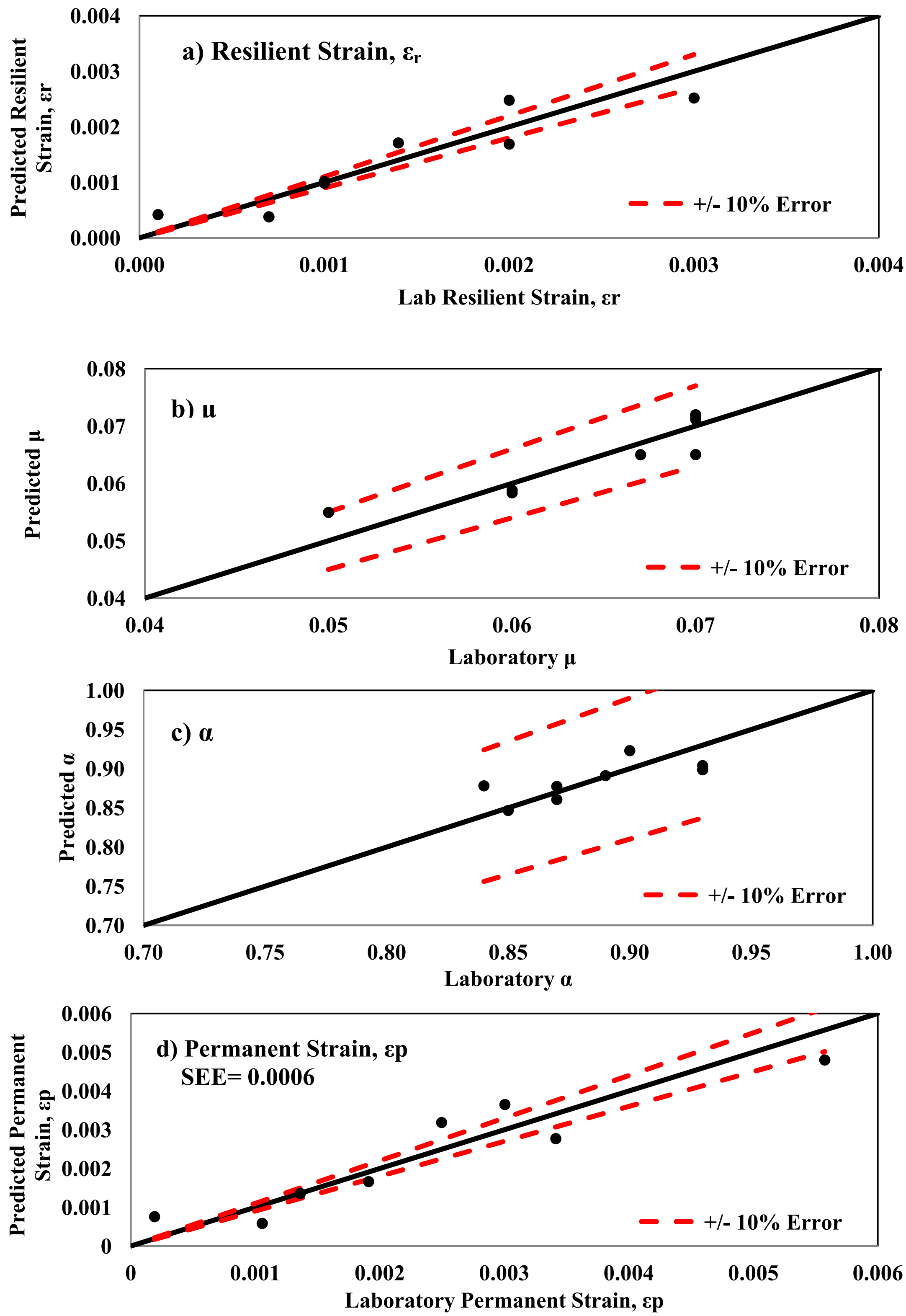


Figure 4.10 – Comparison of Lab PD and Predicted PD at -1.5%OMC (Dry Sieve)

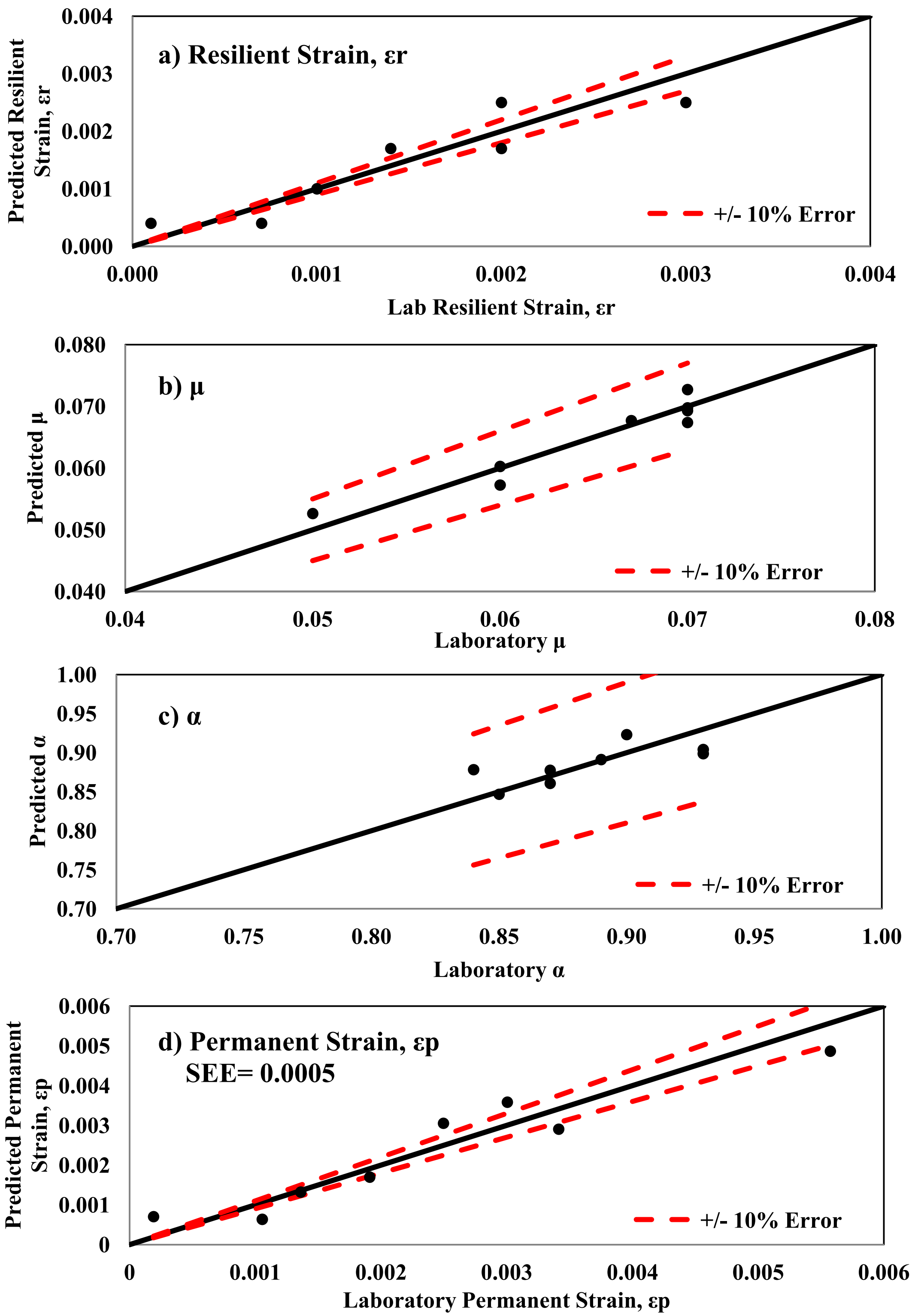


Figure 4.11 – Comparison of Lab PD and Predicted PD at -1.5%OMC (Wet Sieve)

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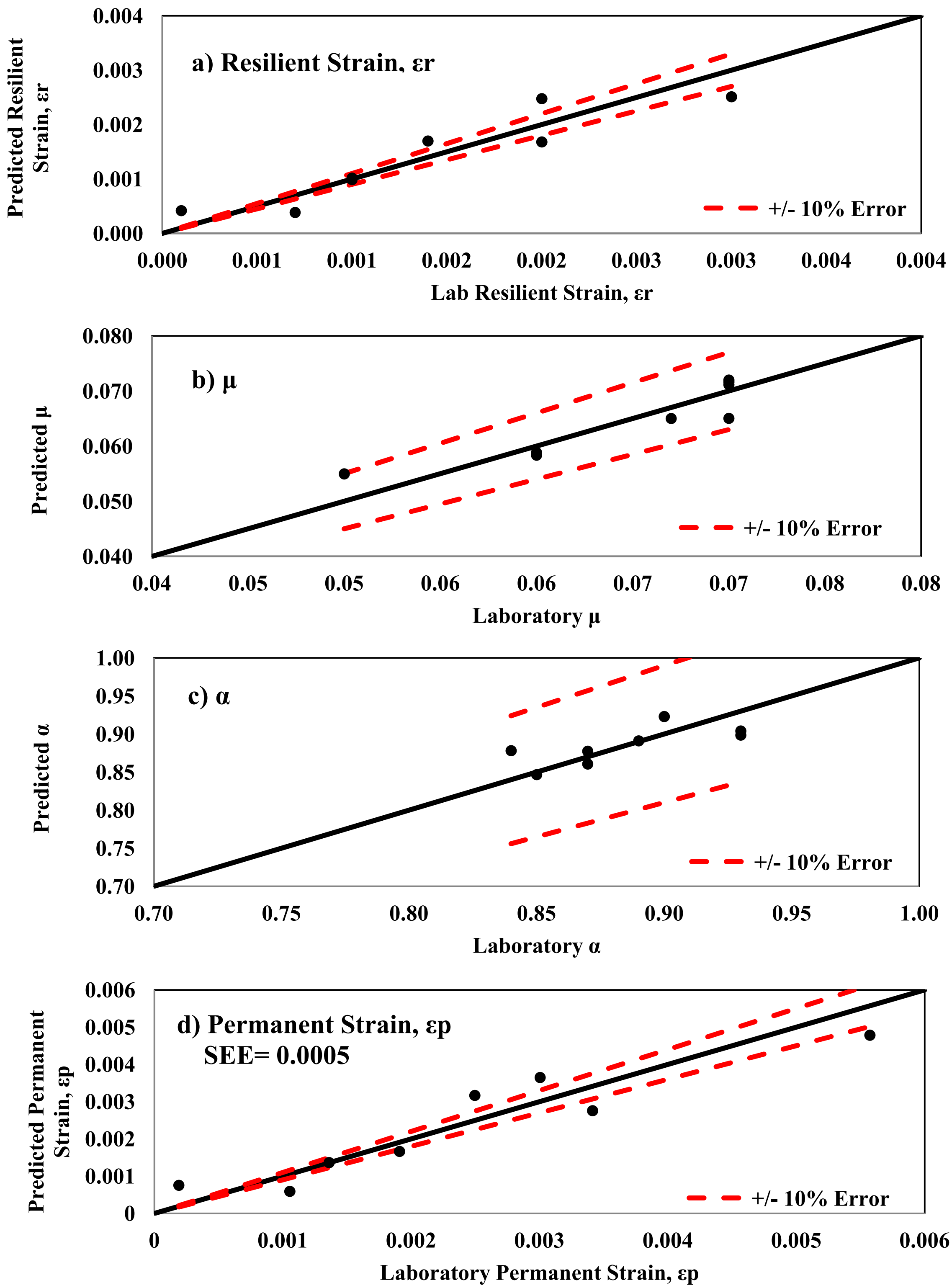

Figure 4.12 – Graphical Comparison of Lab MR and Predicted MR at -1.5% OMC Following Item 247 Index Parameters (Dry Sieve)

CHAPTER 5 – CONCLUSIONS AND RECOMMENDATIONS

In this report, several existing models for estimating the resilient modulus and permanent deformation parameters as a function of index properties and moisture-density parameters are evaluated and developed. Based on testing seven materials, the following recommendations can be made:

- Two existing models recommended by Malla and Joshi (2008) and Yau and Von Quintus (2002) are suitable for predicting the resilient modulus parameters at the optimum moisture contents. However, these models are not appropriate when measurements are made with proximetors.
- Three sets of models were developed for estimating the resilient modulus parameters at OMC when the proximetors are used. The main differences between the models stem from the method used for sieve analysis. These models that are summarized in Table 5.1 include:
    - index properties as per ASTM dry sieve analysis
    - index properties as per ASTM wet sieve analysis
    - index properties as per Tex-110-E dry sieve analysis
- To account for the variation in modulus with moisture content, relationships proposed by MEPDG (2000) and Cary and Zapata (2010) were evaluated. The MEPDG relationship for coarse aggregates seems to work reasonably well.
- As existing models for estimating permanent deformation parameters do not exist, three sets of models, similar to the MR models, were developed to estimate them. The developed models are presented in Table 5.2.

- Since a significant number of specimens tested wet of OMC did not survive the tests, it was not possible to develop a model to adjust the permanent deformation parameters with moisture content. As such, second sets of models were developed to estimate the permanent deformation parameters as a function of the index properties for nominal moisture contents of OMC – 1.5%. The developed models are presented in Table 5.3. It seems that it is imperative that most bases used in Texas should be maintained at optimum moisture content or drier during their performance lives to minimize excess rutting.

Table 5.1 – Recommended Models to Predict Resilient Modulus Parameters at Optimum Moisture Content

Name	Model	Parameters
Index Parameters from ASTM Dry Sieve $$MR = k_1 \ P_A \left(\frac{\theta}{P_a}\right)^{k_2} \left(\frac{\tau_{oct}}{P_a}+1\right)^{k_3}$$	$k_1 = 4629.095 - 54.585\times P_{3/8} + 11.946\times PL - 52.190\times SMC + 0.775\times P_{\#200} + 28.925\times P_{CLAY}$ $(R^2=0.92)$ $k_2 = -1.08644 + 0.00124\times MDD - 0.04877\times P_{coarse\text{-}sand} - 0.01828\times P_{CLAY} + 0.00826\times P_{\#40} - 0.00398\times P_{fine\text{-}sand}$ $(R^2=0.79)$ $k_3 = 19.4433 - 0.0041\times MDD + 0.0154\times P_{7/8} + 0.0361\times PI - 3.2098\times MCR - 10.2869\times DDR$ $(R^2=0.86)$	PI = Plasticity Index PL = Plastic Limit LL = Liquid Limit DDR = Dry Density Ratio MCR = Moisture Content Ratio MDD = Maximum Dry Density SMC = Specimen Moisture Content $P_{7/8}$ = Percentage Passing 7/8” $P_{3/8}$ = Percentage Passing 3/8” $P_{\#4}$= Percentage Passing #4 $P_{\#40}$= Percentage Passing #40 $P_{\#200}$= Percentage Passing #200 $P_{coarse\text{-}sand}$ = Percentage of Coarse Sand $P_{fine\text{-}sand}$ = Percentage of Fine Sand P_{CLAY} = Percentage of Clay P_{SILT} = Percentage of Silt CC = Coefficient of Curvature CU = Uniformity Coefficient
Index Parameters from Wet Sieve $$MR = k_1 \ P_A \left(\frac{\theta}{P_a}\right)^{k_2} \left(\frac{\tau_{oct}}{P_a}+1\right)^{k_3}$$	$k_1 = 15385.06 - 137.69\times P_{7/8} - 56.91\times P_{\#40} + 125.87 \times P_{CLAY} - 82.02\times P_{coarse\text{-}sand} + 0.81\times LL$ $(R^2=0.92)$ $k_2 = -0.8138 + 0.00166\times MDD - 0.04325\times P_{coarse\text{-}sand} - 0.00873\times PI - 1.17211\times DDR - 0.00152\times P_{\#4}$ $(R^2=0.79)$ $k_3 = 21.5249 - 0.0045\times MDD + 0.0291\times P_{3/8} - 0.0710\times P_{SILT} - 2.9459\times MCR - 11.5521\times DDR$ $(R^2=0.86)$	
Index Parameters from Tex-110-E Dry Sieve $$MR = k_1 \ P_A \left(\frac{\theta}{P_a}\right)^{k_2} \left(\frac{\tau_{oct}}{P_a}+1\right)^{k_3}$$	$k_1 = 4182.233 - 47.479\times P_{3/8} + 21.877\times PL - 44.815 \times SMC - 5.362\times LL + 92.951\times CC$ $(R^2=0.92)$ $k_2 = -1.70355 + 0.00131\times MDD - 0.03245\times P_{coarse\text{-}sand} + 0.00838\times P_{\#40} - 0.00452\times PL - 0.00258\times CU$ $(R^2=0.79)$ $k_3 = 19.4433 - 0.0041\times MDD + 0.0154\times P_{7/8} + 0.0361\times PL - 3.2098\times MCR - 10.2869\times DDR$ $(R^2=0.86)$	

Table 5.2 – Recommended Models to Predict Permanent Deformation Parameters at Optimum Moisture Content

Name	Model	Parameters
Index Parameters from ASTM Dry Sieve $\varepsilon_p = \frac{\mu}{1-\alpha} \cdot \varepsilon_r \cdot N^{1-\alpha}$	$\varepsilon_r = -0.254161 - 0.005961 \times SMC + 0.000124 \times MDD + 0.001604 \times P_{SILT} + 0.000466 \times PI - 0.065958 \times DDR$ ($R^2=0.81$) $\mu = 0.368006 - 0.005048 \times OMC + 0.010387 \times P_{coarse\text{-}sand} + 0.000364 \times CU + 0.000007 \times DDS - 0.429041 \times DDR$ ($R^2=0.62$) $\alpha = -3.168 + 0.00853 \times LL - 0.03238 \times P_{coarse\text{-}sand} + 1.07574 \times MCR + 3.19948 \times DDR + 0.0051 \times P_{SILT}$ ($R^2=0.92$)	PI = Plasticity Index PL = Plastic Limit LL = Liquid Limit DDR = Dry Density Ratio MCR = Moisture Content Ratio MDD = Maximum Dry Density SMC = Specimen Moisture Content $P_{7/8}$ = Percentage Passing 7/8" $P_{3/8}$ = Percentage Passing 3/8" $P_{\#4}$= Percentage Passing #4 $P_{\#40}$= Percentage Passing #40 $P_{\#200}$= Percentage Passing #200 $P_{coarse\text{-}sand}$ = Percentage of Coarse Sand $P_{fine\text{-}sand}$ = Percentage of Fine Sand P_{CLAY} = Percentage of Clay P_{SILT} = Percentage of Silt CC = Coefficient of Curvature CU = Uniformity Coefficient
Index Parameters from Wet Sieve $\varepsilon_p = \frac{\mu}{1-\alpha} \cdot \varepsilon_r \cdot N^{1-\alpha}$	$\varepsilon_r = -0.13652 + 0.005496 \times SMC + 0.000099 \times MDD + 0.000406 \times P_{\#40} - 0.125619 \times DDR - 0.000128 \times PI$ ($R^2=0.79$) $\mu = 0.223081 + 0.001528 \times P_{\#200} - 0.002675 \times P_{SILT} - 0.000589 \times LL + 0.000028 \times DDS - 0.227641 \times DDR$ ($R^2=0.57$) $\alpha = -4.63907 + 0.04081 \times P_{SILT} + 0.01816 \times PI - 0.00882 \times P_{3/8} + 1.18023 \times MCR + 4.58772 \times DDR$ ($R^2=0.88$)	
Index Parameters from Tex-110-E Dry Sieve $\varepsilon_p = \frac{\mu}{1-\alpha} \cdot \varepsilon_r \cdot N^{1-\alpha}$	$\varepsilon_r = -0.1088492 + 0.003723 \times SMC + 0.000046 \times MDD - 0.003973 \times CC - 0.000308 \times P_{3/8} + 0.000148 \times CU$ ($R^2=0.81$) $\mu = 0.368006 - 0.005048 \times OMC + 0.010387 \times P_{coarse\text{-}sand} + 0.000364 \times CU + 0.000007 \times DDS - 0.429041 \times DDR$ ($R^2=0.62$) $\alpha = 1.069507 - 0.002334 \times MDD + 0.001909 \times DDS - 0.042877 \times P_{coarse\text{-}sand} + 0.006686 \times LL + 1.143634 \times MCR$ ($R^2=0.94$)	

Table 5.3 – Recommended Models to Predict Permanent Deformation Parameters at 1.5% Dry of Optimum Moisture Content

Name	Model	Parameters
Index Parameters from ASTM Dry Sieve $\varepsilon_p = \frac{\mu}{1-\alpha}\cdot\varepsilon_r\cdot N^{1-\alpha}$	$\varepsilon_r = -2193.25 + 21.26\times P_{7/8''} + 6.09\times P_{\#40} + 14.28 \times P_{CLAY} - 3.74\times PL - 0.00134\times MCR$ ($R^2=0.83$) $\mu = -2.45737 - 0.00523\times LL + 0.49874\times MCR - 0.00696\times SMC + 0.10740\times P_{SILT} - 0.03342\times CU$ ($R^2=0.79$) $\alpha = 2.3678 + 0.002258\times PL + 0.22508\times MCR - 0.12817\times SMC + 0.089225\times OMC - 0.000744\times MDD$($R^2=0.52$)	PI = Plasticity Index PL = Plastic Limit LL = Liquid Limit DDR = Dry Density Ratio MCR = Moisture Content Ratio MDD = Maximum Dry Density SMC = Specimen Moisture Content $P_{7/8}$ = Percentage Passing 7/8” $P_{3/8}$ = Percentage Passing 3/8” $P_{\#4}$= Percentage Passing #4 $P_{\#40}$= Percentage Passing #40 $P_{\#200}$= Percentage Passing #200 $P_{coarse\text{-}sand}$ = Percentage of Coarse Sand $P_{fine\text{-}sand}$ = Percentage of Fine Sand P_{CLAY} = Percentage of Clay P_{SILT} = Percentage of Silt CC = Coefficient of Curvature CU = Uniformity Coefficient
Index Parameters from Wet Sieve $\varepsilon_p = \frac{\mu}{1-\alpha}\cdot\varepsilon_r\cdot N^{1-\alpha}$	$\varepsilon_r = -1660.52 + 7.05\times P_{7/8''} + 49.12\times P_{3/8''} - 85.11 \times P_{SAND} + 44.58\times P_{fine\text{-}sand} - 52.79\times P_{\#200}$ ($R^2=0.83$) $\mu = -4.39896 - 0.01013\times P_{\#200} - 0.17603\times MCR + 4.81548\times DDR + 0.00006\times DDS - 0.01345\times CU$ ($R^2=0.79$) $\alpha = 2.3678 + 0.002258\times PL + 0.22508\times MCR - 0.12817\times SMC + 0.089225\times OMC - 0.000744\times P_{CLAY}$($R^2=0.52$)	
Index Parameters from Tex-110-E Dry Sieve $\varepsilon_p = \frac{\mu}{1-\alpha}\cdot\varepsilon_r\cdot N^{1-\alpha}$	$\varepsilon_r = -1047.18 - 3.63\times P_{\#40''} + 16.96\times P_{7/8} + 1.43 \times PL + 0.0011\times MCR - 10.10\times P_{\#4}$ ($R^2=0.83$) $\mu = -0.49452 - 0.004023\times LL + 0.49874\times MCR - 0.00696\times SMC + 0.004015\times CU - 0.008029\times OMC$ ($R^2=0.79$) $\alpha = 2.36378 + 0.002258\times PL + 0.22508\times MCR - 0.12817\times SMC + 0.089225\times OMC - 0.000744\times MDD$($R^2=0.52$)	

CHAPTER 6 – REFERENCES

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Appendix A - Test Protocols

RECOMMENDED PERMANENT DEFORMATION AND RESILIENT MODULUS LABORATORY TEST PROTOCOLS FOR UNBOUND GRANULAR BASE/SUBBASE MATERIALS AND SUBGRADE SOILS

1. SCOPE

1.1 This test method describes the laboratory preparation and testing procedures for the determination of permanent deformation and resilient modulus (Mr) of unbound granular base/subbase materials and subgrade soils for pavement performance prediction. This test procedure has been adapted primarily from the standard test methods recommended by the National Cooperative Highway Research Program (NCHRP) Project 1-28A[1].

1.2 The methods described herein are applicable to laboratory-molded specimens of unbound granular base/subbase materials and subgrade soils.

1.3 In this test procedure, stress states used for permanent deformation and resilient modulus testing are based upon whether the specimen is located in the base/subbase or the subgrade. Specimen size for testing depends upon the maximum particle size of the material.

1.4 The values of permanent deformation and resilient modulus determined from these procedures are the measures of permanent deformation properties and the modulus of unbound granular base/subbase materials and subgrade soils with the consideration of their stress-dependency.

1.5 Resilient modulus values can be used with structural response analysis models to calculate the pavement structural response to wheel loads, and with the combination of permanent deformation properties and pavement design procedures to predict rutting performance.

2. REFERENCED DOCUMENTS

2.1 TxDOT Procedures:

- Tex-103-E Determining Moisture Content in Soil Materials
- Tex-104-E Determining Liquid Limits of Soils
- Tex-105-E Determining Plastic Limit of Soils
- Tex-106-E Calculating the Plasticity Index of Soils
- Tex-108-E Determining Specific Gravity of Soils
- Tex-110-E Particle Size Analysis of Soils
- Tex-113-E Laboratory Compaction Characteristics and Moisture-Density Relationship of Base Materials

[1] Comments are added when the two are different.

- Tex-114-E Laboratory Compaction Characteristics and Moisture-Density Relationship of Subgrade, Embankment Soils, and Backfill Material

Tex-117-E Triaxial Compression for Disturbed Soils and Base Materials

3. TERMINOLOGY

3.1 *Unbound Granular Base and Subbase Materials* – These include soil-aggregate mixtures and naturally occurring materials. No binding or stabilizing agent is used to prepare unbound granular base or subbase layers. These materials are classified as Type 1 and Type 2, as defined in Sections 3.3 and 3.4.

3.2 *Subgrade* – Subgrade soils may be naturally occurring or prepared and compacted before the placement of subbase and/or base layers. These materials are classified as Type 1, Type 2, and Type 3, as defined in Sections 3.3, 3.4, and 3.5.

3.3 *Material Type 1* - These include all unbound granular base and subbase materials and all untreated subgrade soils with maximum particle sizes greater than 3/8 in. (9.5 mm). All material greater than 1.0 in. (25 mm) shall be scalped off prior to testing. Prepare samples as per Tex-113-E unless otherwise directed. Materials classified as Type 1 shall be molded in a 6 in. (150 mm) diameter mold and shall be compacted as per Tex-113-E in 2-in. (50-mm) lifts.

3.4 *Material Type 2* – These include all unbound granular base and subbase materials and all untreated subgrade soils that have a maximum particle size less than 3/8 in (9.5 mm) and that meet the criteria of less than 10% passing the No. 200 (75 µm) sieve. Materials classified as Type 2 shall be molded in a 4 in. (100 mm) diameter mold and compacted as per Tex-114-E in 2-in. (50-mm) lifts.

3.5 *Material Type 3* – These include all untreated subgrade soils that have a maximum particle size less than 3/8 in. (9.5 mm) and that meet the criteria of more than 10% passing the No. 200 (75 mm) sieve. Materials classified as Type 3 shall be molded in a 4 in. (100 mm) diameter mold and compacted as per Tex-114-E in 2-in. (50-mm) lifts.

3.6 *Permanent Deformation* – Permanent deformation is determined by repeated load compression tests on specimens of the unbound materials. Permanent deformation is the unrecovered deformation during the testing.

3.7 *Resilient Modulus* – The resilient modulus is determined by repeated load compression tests on test specimens of the unbound materials. Resilient modulus (Mr) is the ratio of the peak axial repeated deviator stress to the peak recoverable axial strain of the specimen.

3.8 *Loading Waveform* – Test specimens are loaded using a haversine load pulse with 0.1 to 0.2 second loading and 0.8 to 0.9 second rest period.

3.9 *Maximum Applied Axial Load* (P_{max}) – The load applied to the sample consisting of the contact load ($P_{contact}$) and cyclic load (P_{cyclic}, confining pressure is not included):

$$P_{max} = P_{contact} + P_{cyclic} \tag{A.1}$$

3.10 Contact Load ($P_{contact}$) – Vertical load placed on the specimen to maintain a positive contact between the loading ram and the specimen top cap. The contact load includes

the weight of the top cap and the static load applied by the ram of the loading system.

3.11 Cyclic Axial Load (P_{cyclic}) – Repetitive load applied to a test specimen:

3.12 *Maximum Applied Axial Stress* (σ_{max}) – The axial stress applied to the sample consisting of the contact stress and the cyclic stress (the confining stress is not included):

$$\sigma_{max} = P_{max}/A \tag{A.2}$$

where A is the cross sectional area of the sample.

3.13 *Cyclic Axial Stress* (σ_{cyclic}) – Cyclic applied axial stress:

$$\sigma_{cyclic} = P_{cyclic}/A \tag{A.3}$$

3.14 *Contact Stress* ($\sigma_{contact}$) – Axial stress applied to a test specimen to maintain a positive contact between the specimen cap and the specimen:

$$\sigma_{contact} = P_{contact}/A \tag{A.4}$$

The contact stress shall be maintained so as to apply a constant anisotropic confining stress ratio:

$$(\sigma_{contact} + \sigma_3)/\sigma 3 = 1.2 \tag{A.5}$$

where σ_3 is the applied confining pressure in the triaxial chamber (i.e., the minor principal stress).

3.15 e_r is the resilient (recoverable) axial deformation due to σ_{cyclic}.

3.17 ε_r is the resilient (recoverable) axial strain due to σ_{cyclic}:

$$\varepsilon_r = e_r/L \tag{A.6}$$

where L is the distance between axial deformation measurement points

3.18 e_p is the permanent (unrecoverable) axial deformation due to σ_{cyclic}.

3.19 ε_p is the permanent (unrecoverable) axial strain due to σ_{cyclic}:

$$\varepsilon_p = e_p / L \tag{A.7}$$

3.20 *Resilient Modulus* (M_r) is defined as:

$$M_r = \sigma_{cyclic} / \varepsilon_r \tag{A.8}$$

3.21 Load duration is the time interval the specimen is subjected to a cyclic stress pulse.

3.22 Cycle duration is the time interval between the successive applications of a cyclic stress.

4. SUMMARY OF METHOD

4.1 A repeated axial stress of fixed magnitude, load duration, and cycle duration is applied to a cylindrical test specimen. The test is performed in a triaxial cell, and the specimen is subjected to a repeated (cyclic) stress and a constant confining stress provided by means of cell air pressure. Both total resilient (recoverable) and permanent axial deformation responses of the specimen are recorded and used to calculate the permanent deformation properties and the resilient modulus.

5. SIGNIFICANCE AND USE

5.1 The resilient modulus test results provide a basic constitutive relationship between stiffness and stress state of pavement materials for use in the structural analysis of layered pavement systems.

5.2 The permanent deformation properties of pavement materials can be determined from the first 10,000 cycles of the repeated load test. The information is critical for pavement rutting performance prediction.

6. PERMANENT DEFORMATION AND RESILIENT MODULUS TEST APPARATUS

6.1 *Triaxial Pressure Chamber* – The pressure chamber contains the test specimen and the confining fluid during the test. A typical triaxial chamber suitable for use in resilient modulus testing is shown in Figure 1. The axial deformation is measured internally, directly on the specimen, using non-contact sensors[2] (shown in Figure 2).

Note: For soft (modulus less than 10 ksi (70 MPa) specimens the top to bottom platen measurements with LVDTs or external LVDTs to measure piston movement can be used to measure axial deformation of these weak soils[2].

6.1.1. Air shall be used in the triaxial chamber as the confining fluid for all testing.

6.1.2. The chamber shall be made of suitable transparent material (e.g., polycarbonate).

Figure A.1 – Sample in Triaxial Cell.

Figure A.2 – Sample with Instruments.

[2] Noncontact sensors are recommended instead of the LVDTs based on extensive study at UT-Austin and UTEP. Please see Research Report 1177-4F "Development of a Reliable Resilient Modulus Test for Subgrade and Non-Granular Subbase Materials for Use in Routine Pavement Design," http://library.ctr.utexas.edu/pdf1/1177-4f.pdf, and Research Report 1336-1 "Testing Methodology for Resilient Modulus of Base Materials." http://ctis.utep.edu/publications/Reports/RR0-1336-TestingMehtodolgyforResilientModulusofBaseMaterials.pdf. Those studies showed that the axial displacements are over-predicted (i.e., resilient modulus under-predicted) with the LVDTs. This problem becomes more severe as the specimen becomes stiffer.

6.2 *Loading Device* – The loading device shall be a top-loading, closed-loop electro-hydraulic testing machine with a function generator that is capable of applying repeated cycles of a haversine-shaped load pulse. Each pulse shall have a 0.1 sec duration followed by a rest period of 0.9 sec duration for base/subbase materials and 0.2 sec duration followed by a rest period of 0.8 sec duration for subgrade materials.

6.2.1 The electro-hydraulic system-generated haversine waveform and the response waveform shall be displayed to allow the operator to adjust the gains to ensure they coincide during conditioning and testing.

6.3 Load and Specimen Response Measuring Equipment

6.3.1 The axial load measuring device should be an electronic load cell, which shall be located inside the triaxial cell. The load cell should have the capacities presented in Table 1.

Table A.1 – Load Cell Capacity

Sample Diameter, in. (mm)	Load Capacity, lb (kN)	Required Accuracy, lb (N)
4.0 (100)	2000 (9)	±4 (±18)
6.0 (150)	5000 (22)	±5 (±22)

6.3.2 The chamber pressures shall be monitored with conventional pressure gauges, manometers, or pressure transducers accurate to 0.1 psi (0.7 kPa).

6.3.3 Axial deformation is to be measured with displacement transducers. On-specimen deformations shall be measured over approximately the middle half to middle third of the specimen[3]. Axial deformations shall be measured at a minimum of two locations 180 degrees apart (in a plan view). Table 2 summarizes the specifications for displacement transducers.

6.3.4. Data Acquisition: An analog-to-digital (A/D) data acquisition system is required. Suitable signal excitation, conditioning, and recording equipment are required for simultaneous recording of axial load and deformations. The system should meet or exceed the following additional requirements: (1) 25 μs A/D conversion time; (2) 12-bit resolution; (3) single- or multiple-channel throughput (gain = 1) of 30 kHz; (4) software selectable gains; (5) measurement accuracy of full scale (gain = 1) of ±0.02%; and (6) non-linearity of ±0.5%. The signal shall be clean and free of noise. Filtering the output signal during or after data acquisition is discouraged.

[3] Please see Pezo et al. (1998) entitled "Evaluation of Strain Variation within a Triaxial Specimen due to End Effects," TRR 1614, http://trb.metapress.com/content/8723721161084m5l/?referencesMode=Show. The middle half (for 4 in. diameter specimens) and middle third (for 6 in. diameter specimens) are recommended. This sensor spacing is recommended based on specimen preparation considerations. It is not appropriate to compact specimens to less than 2 in. lift for base materials given the top size aggregates allowed for bases. In order to center the top and bottom sensors along the specimen's height, a 4 in. sensor spacing is recommended for a 6 in. diameter specimen since the recommended height is 12 in.

If a filter is used, it should have a frequency higher than 10 to 20 Hz. A supplemental study should be made to ensure correct peak readings are obtained from filtered data compared to unfiltered data. A minimum of 200 data points from each displacement transducer shall be recorded per load cycle.

Table A.2 – Specifications for Measurements of Displacements

Sensor Type	Material	Specimen Diameter, in. (mm)	Min. Range, mils (mm)	Approximate Resilient Specimen Displacement, mils (μm)
LVDT	Aggregate Base	6.0 (150)	±0.25 ()	1 (25)
		4.0 (100)	±0.10 ()	0.6 (17)
	Subgrade Soil (sand/ cohesive)	4.0 (100)	±0.25 ()	1.4 (35)
Non-Contact Sensors	Aggregate Base	6.0 (150)	±0.08 (2)	1 (25)
		4.0 (100)	±0.04 (1)	0.6 (17)
	Subgrade Soil (sand/ cohesive)	4.0 (100)	±0.08 (2)	1.4 (35)

6.4 *Specimen Preparation Equipment* – A variety of equipment is required to prepare compacted specimens that are representative of field conditions. Use of different materials and different methods of compaction in the field requires the use of varying compaction energies in the laboratory.

6.5 *Miscellaneous Apparatus* – This includes calipers, micrometer gauge, steel rule (calibrated to 0.02 in., 0.5 mm), rubber membranes 0.02 to 0.03 in. (0.25 to 0.8 mm) thickness, rubber O-rings, vacuum source with bubble chamber and regulator, membrane expander, porous stones (subgrade), 0.25 in. (6.4 mm) thick porous stones or bronze discs (base/subbase), scales, moisture content cans, and data sheets.

6.6 *Periodic System Calibration* – The entire system (transducers, signal conditioning, and recording devices) shall be calibrated every two weeks or after every 50 tests. Daily and other periodic checks of the system may also be performed as necessary. No permanent deformation and resilient modulus testing will be conducted unless the entire system meets the established calibration requirements.

7. PREPARATION OF TEST SPECIMENS

7.1 The following guidelines, based on the sieve analysis test results, shall be used to

determine the test specimen size[4]:

7.1.1 Use 6 in. (150 mm) diameter and 12 in. (300 mm) high specimens for all Type 1 material.

7.1.2 Use 4 in. (100 mm) diameter and 8 in. (200 mm) high specimens for all Type 2 and Type 3 materials.

7.2 *Laboratory Compacted Specimens* – Reconstituted test specimens of all types shall be prepared to the specified or in situ dry unit weight (γ_d) and moisture content (ω). Laboratory compacted specimens shall be prepared for all unbound granular base and subbase material and for all subgrade soils. For materials sampled from a quarry or job site before compaction, new or fresh material shall be used for each specimen.

7.2.1 *Moisture Content* – For in situ materials, the moisture content of the laboratory compacted specimen shall be the in situ moisture content for that layer obtained in the field using Tex-103-E. If data are not available on in situ moisture content, refer to Section 7.2.3.

7.2.1.1 The moisture content of the laboratory compacted specimen should not vary from the nominal value by more than 5% of the optimum moisture content or ±0.3% for all materials.

7.2.2 *Compacted Density* – The unit weight of a compacted specimen shall be the in-place dry unit weight obtained in the field for that layer using Tex-115-E or other suitable methods. If these data are not available on in situ density, refer to Section 7.2.3.

7.2.2.1 The dry unit weight of a laboratory compacted specimen should not vary more than ±1% from the target dry unit weight for that layer.

7.2.3 If either the in situ moisture content or the in-place dry unit weight is not available, use the optimum moisture content and 100% of the maximum dry unit weight by using Tex-113-E for the base/subbase and 95 to 100% of Tex-114-E for the subgrade.

7.2.3.1 The moisture content of the laboratory compacted specimen should not vary from the required value by more than ±0.5% for all materials. The dry unit weight of a laboratory compacted specimen should not vary more than ±1% from the target dry unit weight for that layer.

7.2.4 *Sample Reconstitution* – Reconstitute the specimen for all materials. The target moisture content and unit weight to be used in determining needed material qualities are given in Section 7.2. After this step is completed, specimen compaction can begin.

7.3 Compaction Methods and Equipment for Reconstituting Specimens

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[4] Please see Pezo et al. (1998) entitled "Evaluation of Strain Variation within a Triaxial Specimen due to End Effects," TRR 1614, http://trb.metapress.com/content/8723721161084m5l/?referencesMode=Show. A 2-to-1 height-to-diameter is universally considered as appropriate for these tests.

7.3.1 Specimens of Type 1 materials shall be compacted by Tex-113-E in 2-in. (50-mm) lifts[5].

7.3.2 Specimens of Type 2 or Type 3 materials shall be compacted by Tex-114-E in 2-in. (50 mm) lifts.

7.4 Preparation of Specimen

7.4.1 Specimens of Type 1, 2 or 3 should be grouted with Jadestone (ISO Type 5 from Whip Mix) or similar (Figure 3)[6]. Mix the Jade stone with water to a toothpaste-consistency, and applied to the lower platen. Center the specimen on the platen. Use a cross-check level on top of the specimen to ensure that the specimen is level. Wipe away any excess Jadestone from the platen and let cure for 15 minutes. Mix a second Jadestone paste with a more liquid-like consistency, and place on top of the specimen. Place the platen on top of the mixture and again check with a cross-check level on top of the platen to ensure that it is level. Center the platen with the specimen. Remove excess Jadestone.

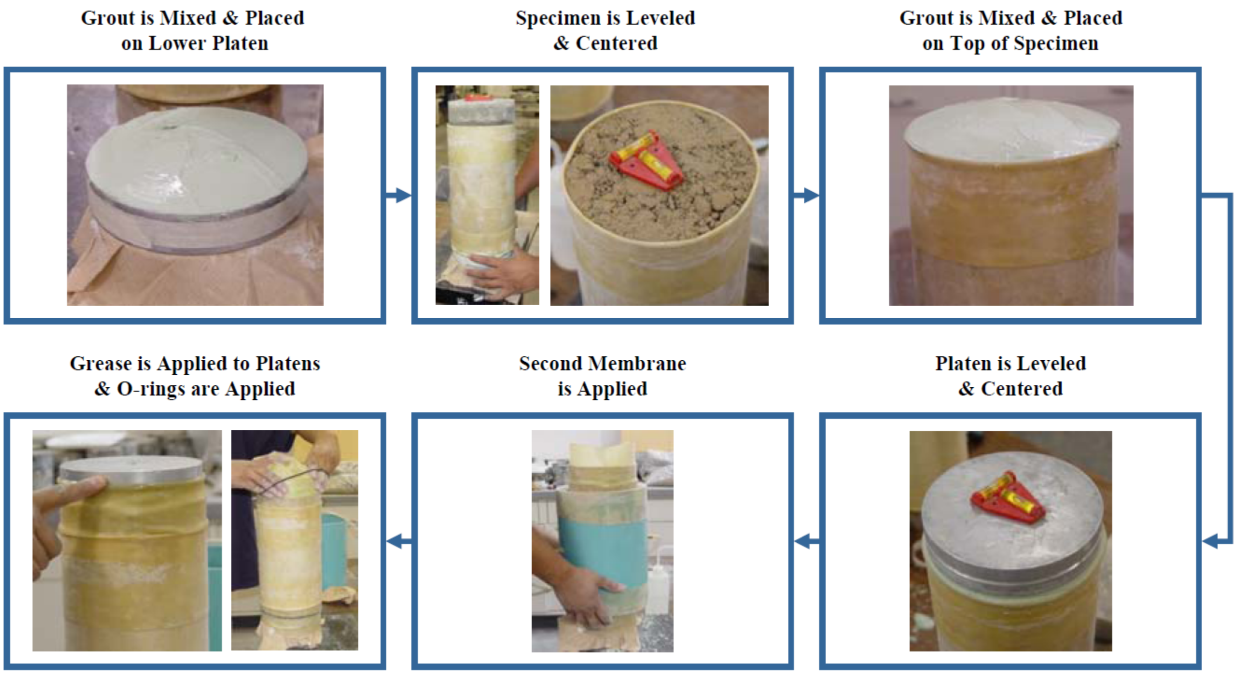

Figure A.3 – Specimen Grouting Process

7.4.2 Apply a membrane to the specimen using a membrane expander.

7.4.3 Apply vacuum grease to the top and bottom platens in the pre-machined grooves.

7.4.4 Roll the membrane over the bottom and top platens place an O-ring over the

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[5] It is not appropriate to compact specimens to less than 2 in. lift for base materials given the top size aggregates allowed for bases.

[6] For negative consequences of not utilizing grout please see Research Report 1177-4F "Development of a Reliable Resilient Modulus Test for Subgrade and Non-Granular Subbase Materials for Use in Routine Pavement Design." Grouting the specimen to the top and bottom platen minimizes the possibility of stress concentrations in the specimen during the test.

membrane and into the grooves, roll the membrane over onto the specimen.

8. TEST PROCEDURE

8.1 *Apparatus and Sample Preparation*

8.1.1 Assembly of the triaxial cell: If not already in place, place the specimen with end platens into position on the pedestal of the triaxial cell. Proper positioning of the specimen is extremely critical in applying a concentric load to the specimen. Couple the loading device to the specimen using a smooth steel ball. To center the specimen, slowly rotate the ball as the clearance between the load piston ball decreases and a small amount of load is applied to the specimen. Be sure the ball is concentric with the piston that applies the load (watch the gap around the ball). Shift the specimen laterally to achieve a concentric loading.

8.1.2 Check and adjust the axial displacement measurement system, load cell, and data acquisition system, and make sure they are working properly.

8.1.3 If not already connected, connect the confining air pressure supply line to the triaxial chamber.

8.1.4 Open all valves on drainage lines leading to the inside of the specimen. This is necessary to develop confining pressure on the specimen.

8.2 Permanent Deformation Test

8.2.1 Prepare a new specimen as per Section 7 and set it up as per Section 8.1.1.

8.2.2 *Preconditioning*: Apply 100 repetitions of preconditioning at a maximum axial stress and a corresponding cyclic stress as shown in Table 3 using a haversine-shaped load pulse followed by a rest period also shown in Table 3. A contact stress equal to 20% of the confining pressure shall be applied to the specimen so that the load piston stays in contact with the top platen at all times.

Table A.3 – Preconditioning and Permanent Deformation Test Load Sequence

Material Type	**Sequence**	**Confining Pressure**		**Cyclic Stress**		**Maximum Stress**		**Load Pulse Duration**	**Rest Period**
		kPa	**psi**	**kPa**	**psi**	**kPa**	**psi**	**sec**	**sec**
1	**Preconditioning**	105	15	21	3	41.4	6	0.1	0.9
	Permanent Deformation	70	10	140	20	154	22		
2	**Preconditioning**	28	4	7	1	12.5	1.8	0.2	0.8
	Permanent Deformation	28	4	56	8	61	8.8		
3	**Preconditioning**	28	4	7	1	12.5	1.8	0.2	0.8
	Permanent Deformation	28	4	49	7	54	7.8		

8.2.3 Apply 10,000 cycles of haversine loading (P_{cyclic}) equivalent to a maximum axial stress and a corresponding cyclic stress using a haversine-shaped, load pulse followed by a rest period as shown in Table 3. Stop the test if the vertical

permanent strain reaches 5% before 10,000 cycles are completed.

8.2.4 During the load applications, record the load applied and the axial deformation measured from the two sets of displacement transducers through the data acquisition system. Signal-to-noise ratio should be at least 10. All data should be collected in real time and collected/processed so as to minimize phase errors due to sequential channel sampling. In order to save storage space during data acquisition for 10,000 cycles, collect data for the cycles shown in Table 4.

8.2.5 At the completion of this test, reduce the confining pressure to zero, and remove the sample from the triaxial chamber.

8.2.6 Remove the membrane from the specimen, and use the entire specimen to determine moisture content in accordance with Tex-103-E.

8.3 Calculation of Permanent Deformation Parameters

8.3.1 Calculate the average axial deformation for each specimen by averaging the readings from the two sets of displacement transducers. Convert the average deformation values to total axial strain by dividing by the gauge length, L. Typical total axial strain versus time is shown in Figure 4.

Table A.4 – Suggested Minimum Data Collection for Triaxial Load Permanent Deformation Test for all Materials

Data Collection During Cycles	Data Collection During Cycles	Data Collection During Cycles	Data Collection During Cycles
1--15	450	1300	4000
20	500	1400	4500
30	550	1500	5000
40	600	1600	5500
60	650	1700	6000
80	700	1800	6500
100	750	1900	7000
130	800	2000	7500
160	850	2200	8000
200	900	2400	8500
250	950	2600	9000
300	1000	2800	9500
350	1100	3000	10000
400	1200	3500	

8.3.2 Compute the cumulative axial permanent strain (ε_p) from the 10000th cycle. If the vertical permanent strain reaches 5% before 10,000 cycles are completed, report ε_p as 5% along with the number of cycles to reach 5% strain.

8.3.3 Compute the resilient strain (ε_r) at 200th load repetition.

8.3.4 Plot the cumulative axial permanent strain versus the number of loading cycles in a log space (shown in Figure 5). Determine the permanent deformation parameters, intercept (a) and slope (b), from the linear portion of the permanent strain curve (log-log scale), which is also demonstrated in Figure 5.

8.3.5 Compute the rutting parameters α, μ from

$$\propto = 1 - b \qquad\qquad \mu = \frac{ab}{\varepsilon_r}$$

8.4 Reporting of Permanent Deformation Test Results

8.4.1 Report all specimen basic information including:

- specimen identification
- dates of preparation and testing,
- specimen diameter and length,
- moisture content and dry unit weight

8.4.2 Report permanent deformation test results including:

- confining pressure and axial stresses used
- resilient and permanent strains (ε_r and ε_p)
- number of load repetitions applied
- axial permanent deformation parameters: α, μ (or a, and b).

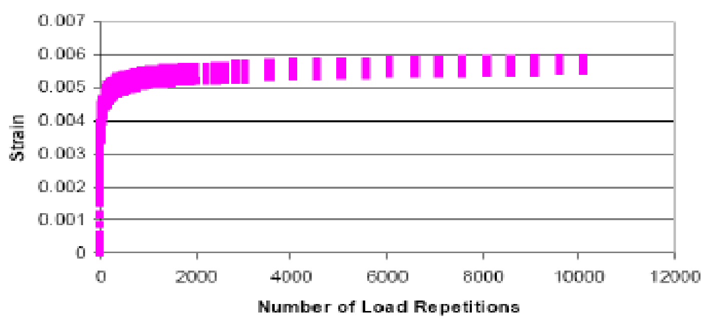


Figure A.5 – Permanent Strain vs. Number of Load Repetitions

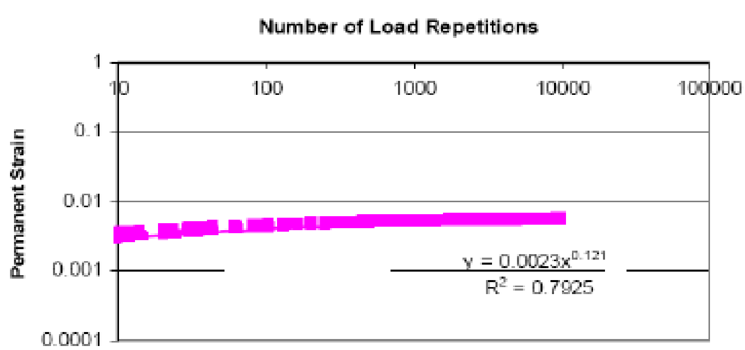


Figure A.4 – Triaxial Repeated Load Test Results: Strain vs. Number of Load Repetitions

8.5 *Resilient Modulus Test*

8.5.1 *Prepare* a new specimen as per Section 7 and set it up as per Section 8.1.1.

8.5.2 Apply 100 preconditioning repetitions of the corresponding cyclic axial stress using a haversine-shaped load pulse followed by a rest period described in Tables 5 through 7 based on the soil type.

8.5.2.1 Apply 100[7] repetitions of the corresponding cyclic axial stress using a haversine-shaped load pulse followed by a rest period described in Table 3. Record the average recovered deformations from each displacement transducer separately for the last five cycles.

8.5.3 At the completion of this test, reduce the confining pressure to zero, and remove the sample from the triaxial chamber.

8.5.4 Remove the membrane from the specimen, and use the entire specimen to determine moisture content in accordance with Tex-103-E.

8.6 *Calculation of Resilient Modulus Parameters*

8.6.1 The resilient modulus is calculated from each of the last five cycles of each load sequence and then averaged. The data reduction processes preferred to be fully automated to minimize the chance for human error.

8.6.2 Using nonlinear regression techniques fit the following resilient modulus model to the data obtained from the applied procedure. The equation for the nonlinear models is as follows:

$$— \quad — \qquad (k_1, k_2 \geq 0, k_3 \leq 0)$$

where:

MR = resilient modulus,
Θ = bulk stress, $\theta = \sigma_1 + \sigma_2 + \sigma_3$
τ_{oct} = octahedral shear stress,

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

σ_1 = major principal stress = $\sigma_{max} + \sigma_c$
$\sigma_2 = \sigma_3$ = minor principal stresses = σ_c
k_1, k_2, k_3 = regression constants,

[7] Since MR test is an stage test, to minimize the degradation of the specimen between different loading sequences, especially during higher axial stress at lower confining pressures, 25 cycles instead of 100 cycle was recommended in Research Report 1177-4F “Development of a Reliable Resilient Modulus Test for Subgrade and Non-Granular Subbase Materials for Use in Routine Pavement Design,” http://library.ctr.utexas.edu/pdf1/1177-4f.pdf. Research Report 1336-1 "Testing Methodology for Resilient Modulus of Base Materials." http://ctis.utep.edu/publications/Reports/RR0-1336-TestingMehtodolgyforResilientModulusofBaseMaterials.pdf evaluated and concurred with that recommendation. A number of comparative studies since then at UTEP have shown that 25 cycles can be used instead of 100 to optimize the testing time without scarifying accuracy.

p_a = atmospheric pressure (14.7 psi).

An Excel© Macro has been developed to directly read the output file from the resilient modulus test and automatically determine parameters k_1, k_2, and k_3.

8.7 Reporting of Resilient Modulus Test Results

8.7.1 Report all specimen basic information including:

- specimen identification
- dates of preparation and testing,
- specimen diameter and length,
- moisture content and dry unit weight

8.7.2 Report the average peak stress (σ_o) and strain (ε_o) for each confining pressure–cyclic stress combination tested.

8.7.3 For each confining pressure–cyclic stress combination tested, report the resilient modulus for each replicate test specimen.

8.7.4 Report nonlinear resilient modulus model and the model parameters: k_1, k_2, and k_3.

Table A.5 – Resilient Modulus Test for Type 1 Material

Sequence	Confining Pressure		Contact Stress		Cyclic Stress		Maximum Stress		Nrep.
	KPa	psi	KPa	psi	KPa	psi	KPa	psi	
Preconditioning	103.5	15.0	20.7	3.0	20.7	3.0	41.4	6.0	100
1	20.7	3.0	4.1	0.6	10.4	1.5	14.5	2.1	100
2	41.4	6.0	8.3	1.2	20.7	3.0	29.0	4.2	100
3	69.0	10.0	13.8	2.0	34.5	5.0	48.3	7.0	100
4	103.5	15.0	20.7	3.0	51.8	7.5	72.5	10.5	100
5	138.0	20.0	27.6	4.0	69.0	10.0	96.6	14.0	100
6	20.7	3.0	4.1	0.6	20.7	3.0	24.8	3.6	100
7	41.4	6.0	8.3	1.2	41.4	6.0	49.7	7.2	100
8	69.0	10.0	13.8	2.0	69.0	10.0	82.8	12.0	100
9	103.5	15.0	20.7	3.0	103.5	15.0	124.2	18.0	100
10	138.0	20.0	27.6	4.0	138.0	20.0	165.6	24.0	100
11	20.7	3.0	4.1	0.6	41.4	6.0	45.5	6.6	100
12	41.4	6.0	8.3	1.2	82.8	12.0	91.1	13.2	100
13	69.0	10.0	13.8	2.0	138.0	20.0	151.8	22.0	100
14	103.5	15.0	20.7	3.0	207.0	30.0	227.7	33.0	100
15	138.0	20.0	27.6	4.0	276.0	40.0	303.6	44.0	100
16	20.7	3.0	4.1	0.6	62.1	9.0	66.2	9.6	100
17	41.4	6.0	8.3	1.2	124.2	18.0	132.5	19.2	100
18	69.0	10.0	13.8	2.0	207.0	30.0	220.8	32.0	100
19	103.5	15.0	20.7	3.0	310.5	45.0	331.2	48.0	100
20	138.0	20.0	27.6	4.0	414.0	60.0	441.6	64.0	100
21	20.7	3.0	4.1	0.6	103.5	15.0	107.6	15.6	100
22	41.4	6.0	8.3	1.2	207.0	30.0	215.3	31.2	100
23	69.0	10.0	13.8	2.0	345.0	50.0	358.8	52.0	100
24	20.7	3.0	4.1	0.6	144.9	21.0	149.0	21.6	100
25	41.4	6.0	8.3	1.2	289.8	42.0	298.1	43.2	100

Table A.6 – Resilient Modulus Test Sequences for Type 2 Material

Sequence	Confining Pressure		Contact Stress		Cyclic Stress		Maximum Stress		Nrep.
	KPa	psi	KPa	psi	KPa	psi	KPa	psi	
Preconditioning	27.6	4.0	5.5	0.8	6.9	1.0	12.4	1.8	100
1	13.8	2.0	2.8	0.4	6.9	1.0	9.7	1.4	100
2	27.0	4.0	5.5	0.8	55.2	8.0	60.7	8.8	100
3	41.4	6.0	8.3	1.2	20.7	3.0	29.0	4.2	100
4	55.2	8.0	11.0	1.6	27.6	4.0	38.6	5.6	100
5	82.2	12.0	16.6	2.4	41.4	6.0	58.0	8.4	100
6	13.8	2.0	2.8	0.4	13.8	2.0	16.6	2.4	100
7	27.6	4.0	5.5	0.8	27.6	4.0	33.1	4.8	100
8	41.4	6.0	8.3	1.2	41.4	6.0	49.7	7.2	100
9	55.2	8.0	11.0	1.6	55.2	8.0	66.2	9.6	100
10	82.8	12.0	16.6	2.4	82.8	12.0	99.4	14.4	100
11	13.8	2.0	2.8	0.4	27.6	4.0	30.4	4.4	100
12	27.6	4.0	5.5	0.8	55.2	8.0	60.7	8.8	100
13	41.4	6.0	8.3	1.2	82.8	12.0	91.1	13.2	100
14	55.2	8.0	11.0	1.6	110.4	16.0	121.4	17.6	100
15	82.8	12.0	16.6	2.4	165.6	24.0	182.2	26.4	100
16	13.8	2.0	2.8	0.4	41.4	6.0	44.2	6.4	100
17	27.6	4.0	5.5	0.8	82.8	12.0	88.3	12.8	100
18	41.4	6.0	8.3	1.2	124.2	18.0	132.5	19.2	100
19	55.2	8.0	11.0	1.6	165.6	24.0	176.6	25.6	100
20	82.8	12.0	16.6	2.4	248.4	36.0	265.0	38.4	100

Table A.7 – Resilient Modulus Test for Type 3 Material

Sequence	Confining Pressure		Contact Stress		Cyclic Stress		Maximum Stress		Nrep.
	KPa	psi	KPa	psi	KPa	psi	KPa	psi	
Preconditioning	27.6	4.0	5.5	0.8	6.9	1.0	12.4	1.8	100
1	55.2	8.0	11.0	1.6	27.6	4.0	38.6	5.6	100
2	41.4	6.0	8.3	1.2	27.6	4.0	35.9	5.2	100
3	27.6	4.0	5.5	0.8	27.6	4.0	33.1	4.8	100
4	13.8	2.0	2.8	0.4	27.6	4.0	30.4	4.4	100
5	55.2	8.0	11.0	1.6	48.3	7.0	59.3	8.6	100
6	41.4	6.0	8.3	1.2	48.3	7.0	56.6	8.2	100
7	27.6	4.0	5.5	0.8	48.3	7.0	53.8	7.8	100
8	13.8	2.0	2.8	0.4	48.3	7.0	51.1	7.4	100
9	55.2	8.0	11.0	1.6	69.0	10.0	80.0	11.6	100
10	41.4	6.0	8.3	1.2	69.0	10.0	77.3	11.2	100
11	27.6	4.0	5.5	0.8	69.0	10.0	74.5	10.8	100
12	13.8	2.0	2.8	0.4	69.0	10.0	71.8	10.4	100
13	55.2	8.0	11.0	1.6	96.0	14.0	107.6	15.6	100
14	41.4	6.0	8.3	1.2	96.0	14.0	104.9	15.2	100
15	27.6	4.0	5.5	0.8	96.0	14.0	102.1	14.8	100
16	13.8	2.0	2.8	0.4	96.0	14.0	99.4	14.4	100

Appendix B - Resilient Modulus Results and Permanent Deformation Results

Description: Bryan 5.1%

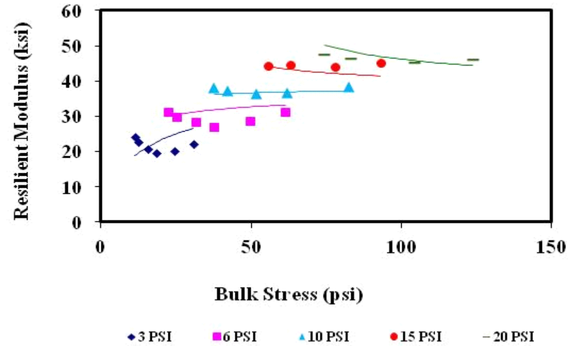
Field Conditions:
MC: 5.10%

Before Testing:

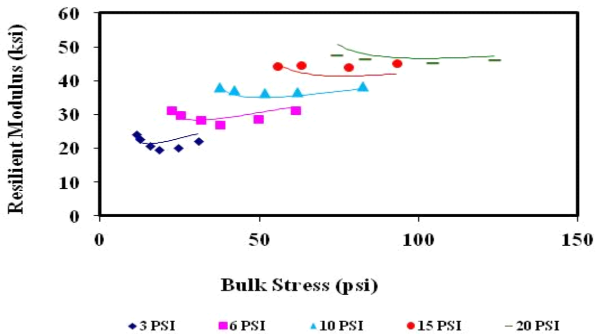
OMC:	5.4%
Diameter:	6.1 in.
Height:	12.0 in.
Gage Length:	12.0 in.
Volume:	351.5 $in.^3$
Wet Density:	139.8 pcf
Dry Density:	133.0 pcf
Dry Mass:	27.1 lb.

	MEPDG Model	Uzan and Witczak (1988) Model
k_1 =	1570	889
k_2 =	0.62	0.70
k_3 =	-0.60	-0.29
R^2 =	0.918	0.967

Cycle No.	Axial Strain (%)	Bulk Stress (psi)	Oct Stress (psi)	Resilient Modulus (ksi)	MEPDG Model Predicted Modulus (ksi)	Uzan and Witczak (1988) Model Predicted Modulus (ksi)
1	0.01	11.31	1.09	24	19	23
2	0.01	12.34	1.58	23	19	22
3	0.03	15.35	3.00	21	21	21
4	0.04	18.41	4.44	20	23	22
5	0.07	24.48	7.30	20	25	23
6	0.09	30.57	10.17	22	27	24
7	0.01	22.33	0.00	31	30	31
8	0.02	25.10	3.35	30	28	29
9	0.04	31.31	6.27	28	30	28
10	0.07	37.30	9.10	27	31	29
11	0.10	49.36	14.78	29	32	30
12	0.13	61.31	20.42	31	33	32
13	0.02	37.59	3.58	38	36	38
14	0.03	42.06	5.69	37	36	36
15	0.05	51.72	10.24	37	37	35
16	0.08	62.02	15.09	37	37	36
17	0.13	82.23	24.62	39	37	38
18	0.02	55.45	4.93	44	44	45
19	0.03	63.02	8.50	45	43	42
20	0.07	77.70	15.42	44	42	41
21	0.10	92.84	22.55	45	41	42
22	0.02	74.40	6.79	48	50	51
23	0.04	83.25	10.96	46	48	48
24	0.09	104.22	20.85	45	46	47
25	0.13	123.67	30.02	46	44	47



a) MEPDG MODEL



b) Uzan and Witczak (1988) Model

Figure B.1 – Bryan -1.5% OMC #1 LVDT Results

Description: Bryan 5.1%

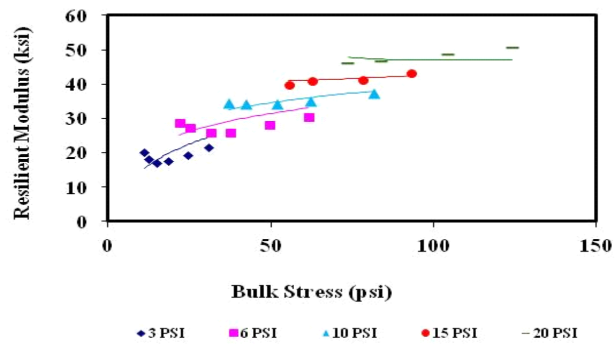
Field Conditions:
MC: 5.10%

Before Testing:

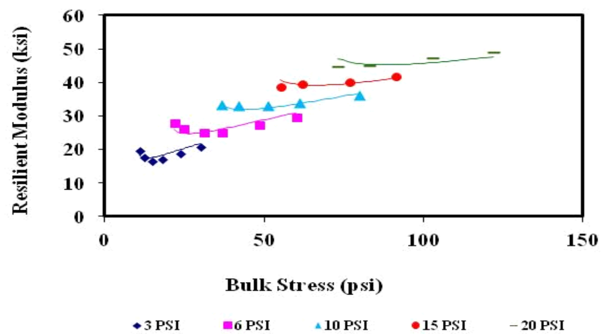
OMC:	5.4%	
Diameter:	6.1	in.
Height:	12.0	in.
Gage Length:	12.0	in.
Volume:	351.7	$in.^3$
Wet Density:	139.0	pcf
Dry Density:	132.3	pcf
Dry Mass:	26.9	lb.

	MEPDG Model	Uzan and Witczak (1988) Model
k_1 =	1312	889
k_2 =	0.67	0.70
k_3 =	-0.49	-0.29
R^2 =	0.951	0.967

Cycle No.	Axial Strain (%)	Bulk Stress (psi)	Oct Stress (psi)	Resilient Modulus (ksi)	MEPDG Model Predicted Modulus (ksi)	Uzan and Witczak (1988) Model Predicted Modulus (ksi)
1	0.01	11.02	0.95	20	15	18
2	0.02	12.47	1.64	18	16	17
3	0.03	14.88	2.77	17	18	18
4	0.05	18.24	4.36	18	20	18
5	0.07	24.20	7.16	20	22	20
6	0.10	30.69	10.22	22	24	22
7	0.01	21.87	0.00	29	25	26
8	0.02	25.09	3.34	27	25	25
9	0.05	31.35	6.29	26	27	25
10	0.07	37.42	9.16	26	29	26
11	0.11	49.33	14.77	28	31	28
12	0.14	61.39	20.45	31	33	31
13	0.02	37.13	3.36	35	33	33
14	0.03	42.49	5.89	34	33	32
15	0.06	51.99	10.36	34	35	32
16	0.09	62.28	15.22	35	36	34
17	0.13	81.76	24.40	37	38	37
18	0.02	55.47	4.93	40	41	41
19	0.04	62.60	8.30	41	41	39
20	0.07	77.97	15.54	41	42	40
21	0.10	92.86	22.56	43	42	41
22	0.02	73.69	6.46	46	48	47
23	0.04	83.80	11.22	47	47	45
24	0.08	104.46	20.96	49	47	46
25	0.12	124.15	30.24	51	47	48



a) MEPDG MODEL



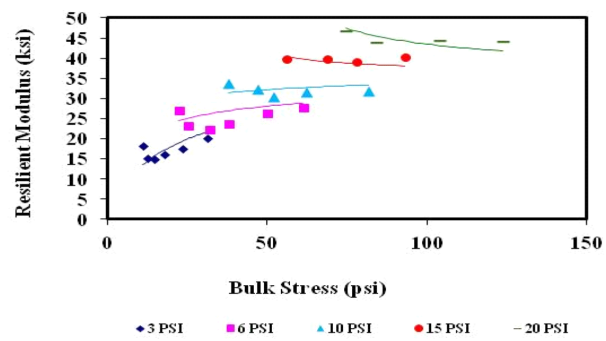
b) Uzan and Witczak (1988) Model

Figure B.2 – Bryan -1.5% OMC #2 LVDT Results

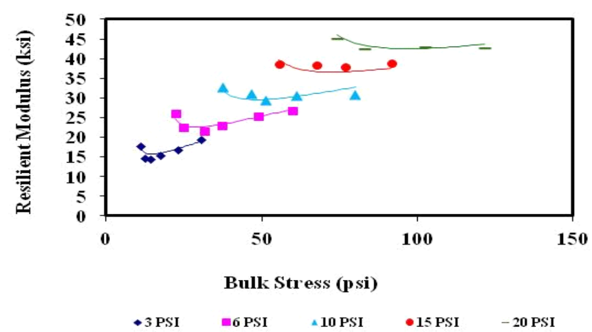
Description:	**Bryan 6.2%**			
		Field Conditions:		
Before Testing:		**MC:**	**5.10%**	
OMC:	**6.8%**			
Diameter:	**6.1 in.**			
Height:	**12.0 in.**			
Gage Length:	**12.0 in.**			
Volume:	**350.3 in.^{3}**			
Wet Density:	**143.6 pcf**			
Dry Density:	**135.2 pcf**			
Dry Mass:	**27.4 lb.**			

	MEPDG Model	Uzan and Witczak (1988) Model
k_1 =	1208	615
k_2 =	0.77	0.85
k_3 =	-0.71	-0.32
R^2 =	0.961	0.988

					MEPDG Model	Uzan and Witczak (1988) Model
Cycle No.	**Axial Strain (%)**	**Bulk Stress (psi)**	**Oct Stress (psi)**	**Resilient Modulus (ksi)**	**Predicted Modulus (ksi)**	**Predicted Modulus (ksi)**
1	0.01	10.94	0.91	18	19	17
2	0.02	12.30	1.56	15	19	16
3	0.03	14.42	2.55	15	21	16
4	0.05	17.63	4.07	16	23	16
5	0.08	23.29	6.73	18	25	17
6	0.11	31.05	10.40	20	27	19
7	0.01	22.21	0.00	27	30	25
8	0.02	25.02	3.31	23	28	23
9	0.06	31.82	6.51	22	30	23
10	0.08	37.73	9.30	24	31	23
11	0.12	49.85	15.02	26	32	25
12	0.15	61.08	20.31	28	33	27
13	0.02	37.71	3.63	34	36	32
14	0.04	47.04	8.03	32	36	30
15	0.07	52.06	10.40	30	37	30
16	0.10	62.19	15.18	32	37	30
17	0.16	81.75	24.39	32	37	33
18	0.02	55.89	5.13	40	44	40
19	0.05	68.42	11.04	40	43	37
20	0.08	77.73	15.43	39	42	37
21	0.11	93.01	22.63	40	41	38
22	0.02	74.63	6.90	47	50	46
23	0.05	84.00	11.31	44	48	43
24	0.09	103.93	20.71	44	46	43
25	0.14	123.73	30.04	44	44	44



a) MEPDG MODEL



b) Uzan and Witczak (1988) Model

Figure B.3 – Bryan OMC #1 LVDT Results

Description: Bryan 7.0%

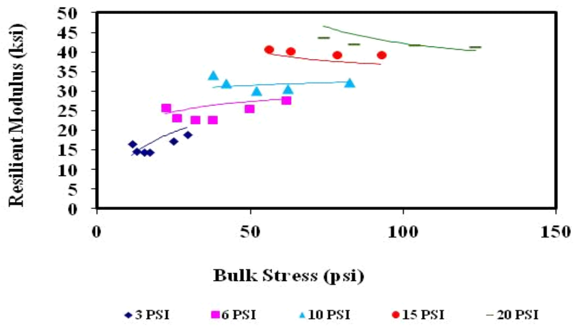
Field Conditions:
MC: 5.10%

Before Testing:

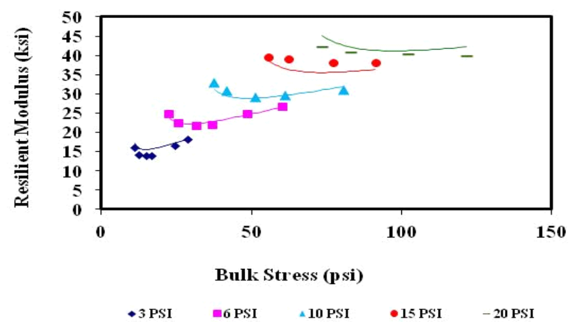
OMC:	6.8%
Diameter:	6.1 in.
Height:	12.0 in.
Gage Length:	12.0 in.
Volume:	350.5 in.^{3}
Wet Density:	144.6 pcf
Dry Density:	135.2 pcf
Dry Mass:	27.4 lb.

	MEPDG Model	Uzan and Witczak (1988) Model
k_1 =	1197	610
k_2 =	0.77	0.84
k_3 =	-0.73	-0.32
R^2 =	0.961	0.978

Cycle No.	Axial Strain (%)	Bulk Stress (psi)	Oct Stress (psi)	Resilient Modulus (ksi)	MEPDG Model Predicted Modulus (ksi)	Uzan and Witczak (1988) Model Predicted Modulus (ksi)
1	0.01	11.12	1.00	17	14	17
2	0.02	12.51	1.66	15	14	16
3	0.04	14.99	2.83	15	16	16
4	0.05	16.97	3.76	14	17	16
5	0.09	24.82	7.46	17	20	17
6	0.10	29.25	9.55	19	21	18
7	0.01	22.21	0.00	26	24	24
8	0.03	25.59	3.58	23	23	23
9	0.05	31.81	6.51	23	24	22
10	0.08	37.36	9.12	23	25	23
11	0.12	49.44	14.82	26	27	25
12	0.15	61.39	20.45	28	28	26
13	0.02	37.81	3.68	34	31	31
14	0.03	42.15	5.73	32	31	29
15	0.07	51.94	10.34	30	32	29
16	0.10	62.21	15.18	31	32	30
17	0.16	82.38	24.69	32	32	32
18	0.02	55.91	5.14	41	40	39
19	0.04	62.77	8.38	40	39	36
20	0.08	78.02	15.57	39	38	36
21	0.11	92.63	22.45	39	37	36
22	0.02	73.98	6.59	44	47	45
23	0.05	83.98	11.30	42	44	42
24	0.10	103.72	20.61	42	42	41
25	0.14	123.58	29.97	41	40	42



a) MEPDG MODEL



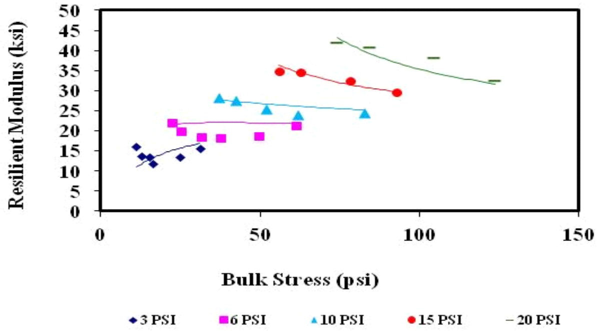
b) Uzan and Witczak (1988) Model

Figure B.4 – Bryan OMC #2 LVDT Results

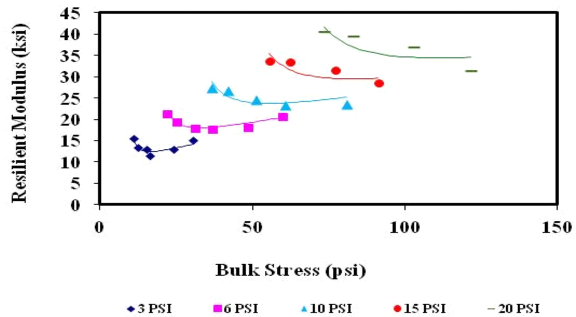
Description:	**Bryan 7.9%**		
		Field Conditions:	
Before Testing:		**MC:**	**7.90%**
OMC:	**8.4%**		
Diameter:	**6.1 in.**		
Height:	**12.0 in.**		
Gage Length:	**12.0 in.**		
Volume:	**351.5 in.^{3}**		
Wet Density:	**145.5 pcf**		
Dry Density:	**134.9 pcf**		
Dry Mass:	**27.4 lb.**		

	MEPDG Model	Uzan and Witczak (1988) Model
k_1 =	1022	398
k_2 =	0.89	0.99
k_3 =	-1.04	-0.45
R^2 =	0.951	0.975

Cycle No.	Axial Strain (%)	Bulk Stress (psi)	Oct Stress (psi)	Resilient Modulus (ksi)	MEPDG Model Predicted Modulus (ksi)	Uzan and Witczak (1988) Model Predicted Modulus (ksi)
1	0.01	11.00	0.94	16	11	15
2	0.02	12.49	1.64	14	12	13
3	0.04	15.27	2.96	14	13	13
4	0.05	16.29	3.44	12	13	12
5	0.11	24.64	7.37	14	16	13
6	0.14	31.03	10.38	16	17	14
7	0.01	22.04	0.00	22	22	22
8	0.03	25.16	3.38	20	20	19
9	0.07	31.52	6.37	19	20	18
10	0.10	37.31	9.10	18	21	18
11	0.16	49.48	14.84	19	22	19
12	0.20	61.10	20.32	22	22	20
13	0.02	36.93	3.27	28	28	29
14	0.04	42.54	5.91	28	27	25
15	0.08	52.09	10.41	25	27	24
16	0.13	61.97	15.07	24	26	24
17	0.21	82.72	24.85	24	25	25
18	0.02	55.70	5.04	35	36	36
19	0.04	62.71	8.35	35	34	32
20	0.09	78.22	15.66	33	31	30
21	0.15	92.72	22.50	30	30	30
22	0.03	74.04	6.62	42	43	42
23	0.05	83.99	11.31	41	39	37
24	0.11	104.39	20.92	38	35	35
25	0.18	123.62	29.99	32	32	35



a) MEPDG MODEL



b) Uzan and Witczak (1988) Model

Figure B.5 – Bryan +1.5 OMC #1 LVDT Results

Description: Bryan 8.3%

Field Conditions:

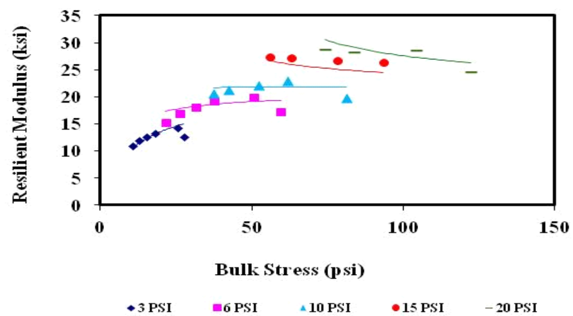
MC: 7.90%

Before Testing:

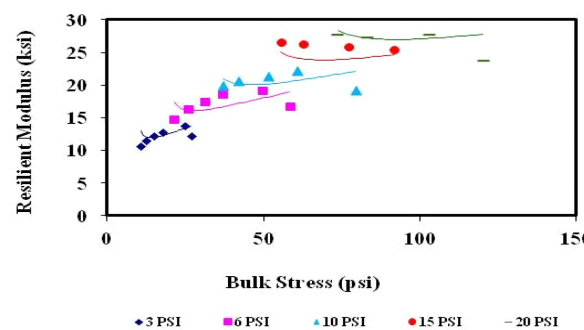
OMC:	8.4%
Diameter:	6.1 in.
Height:	12.0 in.
Gage Length:	12.0 in.
Volume:	351.0 in.^{3}
Wet Density:	145.1 pcf
Dry Density:	133.9 pcf
Dry Mass:	27.2 lb.

	MEPDG Model	Uzan and Witczak (1988) Model
k_1 =	922	550
k_2 =	0.65	0.66
k_3 =	-0.66	-0.23
R^2 =	0.954	0.910

Cycle No.	Axial Strain (%)	Bulk Stress (psi)	Oct Stress (psi)	Resilient Modulus (ksi)	MEPDG Model Predicted Modulus (ksi)	Uzan and Witczak (1988) Model Predicted Modulus (ksi)
1	0.01	10.69	0.80	11	11	13
2	0.02	12.57	1.68	12	11	12
3	0.04	15.04	2.85	13	12	12
4	0.06	17.85	4.17	13	13	12
5	0.11	25.38	7.72	14	15	13
6	0.14	27.48	8.71	13	15	14
7	0.01	21.36	0.00	15	17	17
8	0.04	26.01	3.78	17	17	16
9	0.07	31.54	6.38	18	18	16
10	0.09	37.37	9.13	19	18	17
11	0.16	50.61	15.37	20	19	18
12	0.23	59.56	19.59	17	19	19
13	0.03	37.31	3.45	21	22	21
14	0.05	42.46	5.87	21	22	20
15	0.09	52.42	10.57	22	22	20
16	0.13	61.94	15.06	23	22	21
17	0.25	81.21	24.14	20	22	22
18	0.03	55.69	5.04	27	27	25
19	0.06	63.07	8.52	27	26	24
20	0.11	78.07	15.59	27	25	24
21	0.17	93.25	22.75	26	24	25
22	0.04	74.12	6.66	29	31	28
23	0.07	83.78	11.21	28	29	27
24	0.14	104.34	20.90	29	27	27
25	0.24	122.36	29.40	25	26	28



a) MEPDG MODEL



b) Uzan and Witczak (1988) Model

Figure B.6 – Bryan +1.5 OMC #2 LVDT Results

Description: Bryan 5.1% 0

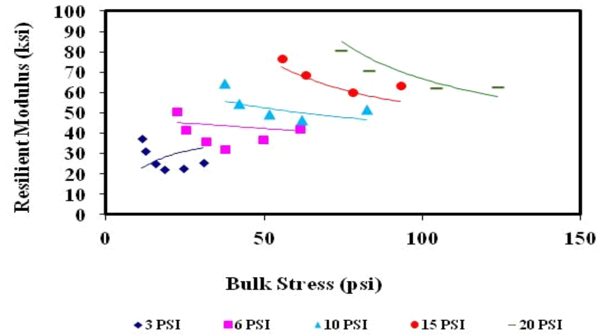
Field Conditions:
MC: 5.10%

Before Testing:

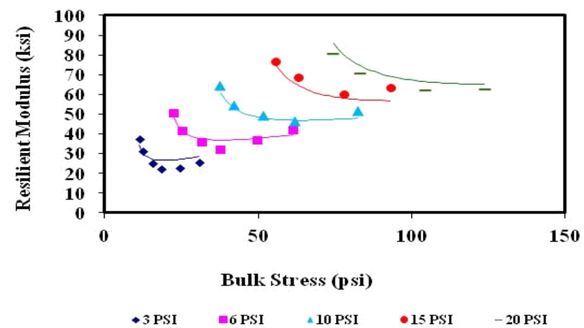
OMC:	5.4%	
Diameter:	6.1	in.
Height:	12.0	in.
Gage Length:	12.0	in.
Volume:	351.5	$in.^3$
Wet Density:	139.8	pcf
Dry Density:	133.0	pcf
Dry Mass:	27.1	lb.

	MEPDG Model	Uzan and Witczak (1988) Model
k_1 =	2113	763
k_2 =	0.89	1.00
k_3 =	-1.14	-0.53
R^2 =	0.894	0.966

Cycle No.	Axial Strain (%)	Bulk Stress (psi)	Oct Stress (psi)	Resilient Modulus (ksi)	MEPDG Model Predicted Modulus (ksi)	Uzan and Witczak (1988) Model Predicted Modulus (ksi)
1	0.00	11.31	1.09	37	23	34
2	0.01	12.34	1.58	31	24	31
3	0.02	15.35	3.00	25	26	27
4	0.04	18.41	4.44	22	28	26
5	0.06	24.48	7.30	23	31	27
6	0.08	30.57	10.17	26	33	28
7	0.01	22.33	2.04	51	45	48
8	0.01	25.10	3.35	42	40	42
9	0.03	31.31	6.27	36	41	38
10	0.06	37.30	9.10	32	41	37
11	0.08	49.36	14.78	37	41	38
12	0.10	61.31	20.42	42	41	39
13	0.01	37.59	3.58	65	56	61
14	0.02	42.06	5.69	55	54	53
15	0.04	51.72	10.24	49	52	48
16	0.06	62.02	15.09	47	50	47
17	0.10	82.23	24.62	52	47	48
18	0.01	55.45	4.93	77	73	76
19	0.02	63.02	8.50	69	67	65
20	0.05	77.70	15.42	60	60	58
21	0.07	92.84	22.55	64	55	57
22	0.01	74.40	6.79	81	85	86
23	0.03	83.25	10.96	71	77	75
24	0.06	104.22	20.85	62	65	66
25	0.10	123.67	30.02	63	58	65



a) MEPDG MODEL



b) Uzan and Witczak (1988) Model

Figure B.7 – Bryan -1.5 OMC #1 PROX Results

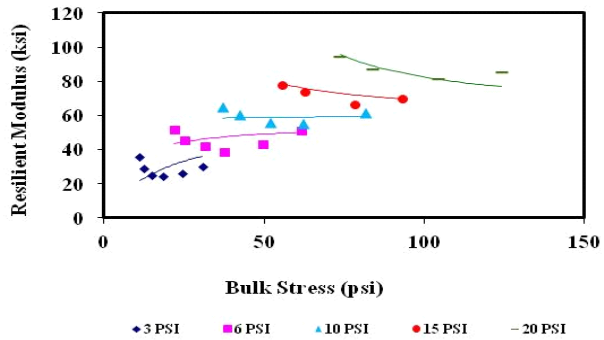
Description:	Bryan 5.1% 0	
Before Testing:		
OMC:	5.4%	
Diameter:	6.1	in.
Height:	12.0	in.
Gage Length:	4.0	in.
Volume:	351.7	$in.^3$
Wet Density:	139.0	pcf
Dry Density:	132.3	pcf
Dry Mass:	26.9	lb.

Field Conditions:

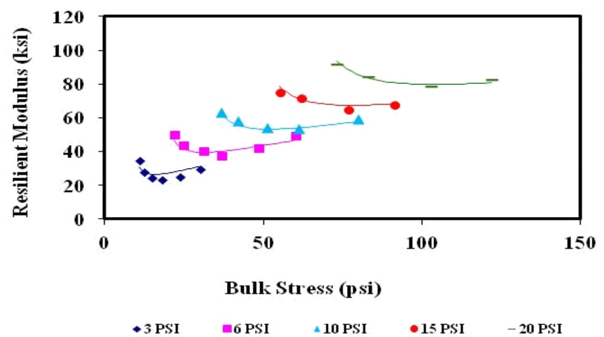
MC: 5.10%

	MEPDG Model	Uzan and Witczak (1988) Model
k_1 =	2032	871
k_2 =	0.93	1.01
k_3 =	-0.94	-0.43
R^2 =	0.944	0.990

Cycle No.	Axial Strain (%)	Bulk Stress (psi)	Oct Stress (psi)	Resilient Modulus (ksi)	MEPDG Model Predicted Modulus (ksi)	Uzan and Witczak (1988) Model Predicted Modulus (ksi)
1	0.00	11.02	0.95	36	22	31
2	0.01	12.47	1.64	29	23	28
3	0.02	14.88	2.77	25	26	26
4	0.03	18.24	4.36	24	29	27
5	0.06	24.20	7.16	26	33	29
6	0.07	30.69	10.22	31	36	31
7	0.00	21.87	0.00	52	43	47
8	0.01	25.09	3.34	45	41	42
9	0.03	31.35	6.29	42	43	40
10	0.05	37.42	9.16	39	45	40
11	0.07	49.33	14.77	44	48	43
12	0.08	61.39	20.45	51	50	47
13	0.01	37.13	3.36	65	58	62
14	0.02	42.49	5.89	60	59	55
15	0.04	51.99	10.36	56	59	53
16	0.05	62.28	15.22	56	59	54
17	0.08	81.76	24.40	62	59	58
18	0.01	55.47	4.93	78	79	79
19	0.02	62.60	8.30	74	76	71
20	0.04	77.97	15.54	67	72	67
21	0.06	92.86	22.56	70	70	68
22	0.01	73.69	6.46	95	96	93
23	0.02	83.80	11.22	87	89	84
24	0.05	104.46	20.96	82	81	80
25	0.07	124.15	30.24	85	77	81



a) MEPDG MODEL



b) Uzan and Witczak (1988) Model

Figure B.8 – Bryan -1.5 OMC #2 PROX Results

Description: Bryan 6.2%

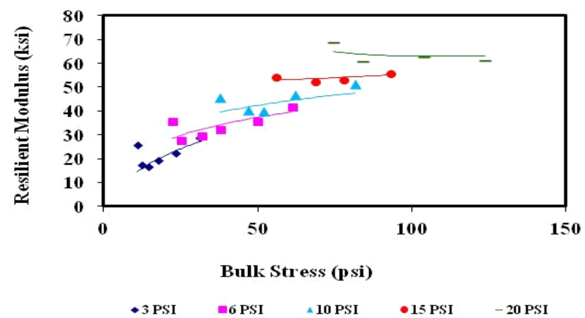
Field Conditions:
MC: 6.20%

Before Testing:

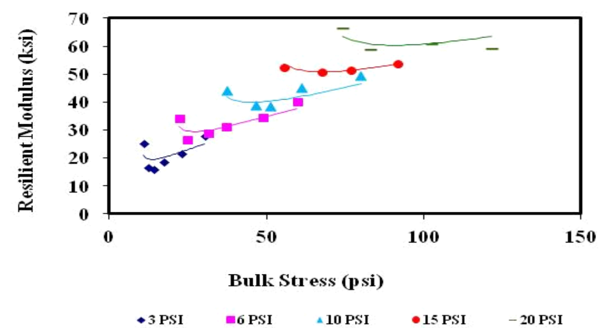
OMC:	6.8%
Diameter:	6.1 in.
Height:	12.0 in.
Gage Length:	4.0 in.
Volume:	350.3 $in.^3$
Wet Density:	143.6 pcf
Dry Density:	135.2 pcf
Dry Mass:	27.4 lb.

	MEPDG Model	Uzan and Witczak (1988) Model
k_1 =	1348	792
k_2 =	0.89	0.90
k_3 =	-0.66	-0.30
R^2 =	0.987	0.977

Cycle No.	Axial Strain (%)	Bulk Stress (psi)	Oct Stress (psi)	Resilient Modulus (ksi)	MEPDG Model Predicted Modulus (ksi)	Uzan and Witczak (1988) Model Predicted Modulus (ksi)
1	0.01	10.94	0.91	26	15	21
2	0.01	12.30	1.56	17	16	20
3	0.03	14.42	2.55	17	18	19
4	0.04	17.63	4.07	19	20	20
5	0.06	23.29	6.73	23	23	22
6	0.07	31.05	10.40	29	27	25
7	0.01	22.21	0.00	36	29	31
8	0.02	25.02	3.31	28	28	30
9	0.04	31.82	6.51	30	31	30
10	0.06	37.73	9.30	32	33	31
11	0.09	49.85	15.02	36	37	34
12	0.10	61.08	20.31	42	40	38
13	0.01	37.71	3.63	46	39	42
14	0.04	47.04	8.03	40	42	40
15	0.05	52.06	10.40	40	43	40
16	0.06	62.19	15.18	47	45	42
17	0.10	81.75	24.39	51	48	46
18	0.02	55.89	5.13	54	53	54
19	0.04	68.42	11.04	53	54	51
20	0.06	77.73	15.43	53	54	51
21	0.08	93.01	22.63	56	55	54
22	0.02	74.63	6.90	69	65	64
23	0.03	84.00	11.31	61	64	61
24	0.06	103.93	20.71	63	63	61
25	0.10	123.73	30.04	61	63	64



a) MEPDG MODEL

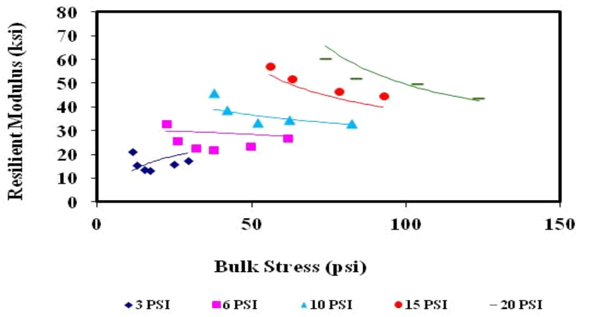


b) Uzan and Witczak (1988) Model

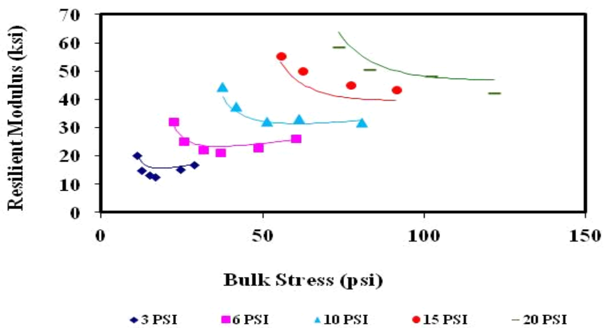
Figure B.9 – Bryan OMC #1 PROX Results

Description:	**Bryan 7.0%**					
			Field Conditions:			
Before Testing:			**MC:**			**7.00%**
OMC:	**6.8%**					
					MEPDG Model	**Uzan and Witczak (1988) Model**
Diameter:	**6.1 in.**					
Height:	**12.0 in.**					
Gage Length:	**4.0 in.**			k_1 =	**1298**	**697**
Volume:	**350.5 in.^{3}**			k_2 =	**1.07**	**1.05**
Wet Density:	**144.6 pcf**			k_3 =	**-1.33**	**-0.57**
Dry Density:	**135.2 pcf**			R^2 =	**0.932**	**0.950**
Dry Mass:	**27.4 lb.**					

Cycle No.	Axial Strain (%)	Bulk Stress (psi)	Oct Stress (psi)	Resilient Modulus (ksi)	MEPDG Model Predicted Modulus (ksi)	Uzan and Witczak (1988) Model Predicted Modulus (ksi)
1	0.01	11.12	1.00	21	13	21
2	0.02	12.51	1.66	16	14	18
3	0.04	14.99	2.83	14	15	16
4	0.05	16.97	3.76	13	16	16
5	0.09	24.82	7.46	16	19	16
6	0.11	29.25	9.55	18	20	17
7	0.01	22.21	0.00	33	30	32
8	0.02	25.59	3.58	26	26	26
9	0.05	31.81	6.51	23	27	24
10	0.08	37.36	9.12	22	27	23
11	0.13	49.44	14.82	24	28	24
12	0.16	61.39	20.45	27	28	26
13	0.01	37.81	3.68	46	39	41
14	0.03	42.15	5.73	39	38	36
15	0.06	51.94	10.34	33	36	32
16	0.09	62.21	15.18	34	35	31
17	0.15	82.38	24.69	33	33	33
18	0.01	55.91	5.14	57	53	53
19	0.03	62.77	8.38	52	50	45
20	0.06	78.02	15.57	47	44	40
21	0.10	92.63	22.45	45	40	40
22	0.02	73.98	6.59	60	66	64
23	0.04	83.98	11.30	52	58	54
24	0.08	103.72	20.61	50	48	48
25	0.14	123.58	29.97	44	43	47



a) MEPDG MODEL



b) Uzan and Witczak (1988) Model

Figure B.10 – Bryan OMC #1 PROX Results

Description:	Austin 6.5%

Field Conditions:

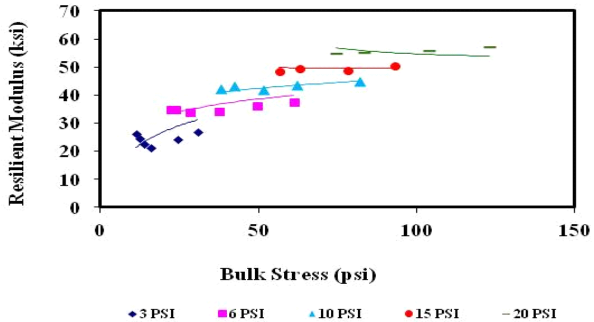
MC:	6.80%

Before Testing:

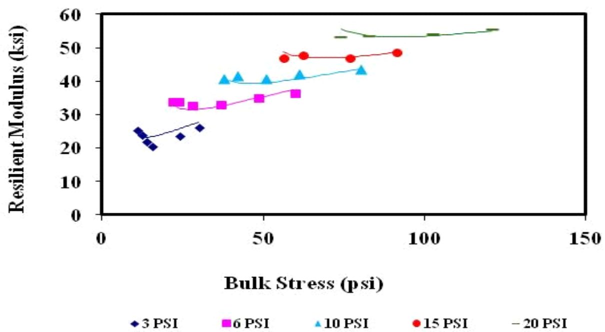
OMC:	7.2%	
Diameter:	6.1	in.
Height:	12.0	in.
Gage Length:	12.0	in.
Volume:	350.5	$in.^3$
Wet Density:	139.5	pcf
Dry Density:	130.6	pcf
Dry Mass:	26.5	lb.

	MEPDG Model	Uzan and Witczak (1988) Model
k_1 =	1766	1067
k_2 =	0.60	0.67
k_3 =	-0.49	-0.23
R^2 =	0.954	0.985

Cycle No.	Axial Strain (%)	Bulk Stress (psi)	Oct Stress (psi)	Resilient Modulus (ksi)	MEPDG Model Predicted Modulus (ksi)	Uzan and Witczak (1988) Model Predicted Modulus (ksi)
1	0.01	11.10	0.99	26	21	24
2	0.01	12.26	1.54	25	22	23
3	0.02	13.85	2.28	23	23	23
4	0.03	15.71	3.16	21	25	23
5	0.06	24.37	7.25	24	29	26
6	0.08	30.78	10.27	27	31	28
7	0.01	22.16	0.00	35	33	33
8	0.01	23.76	2.72	35	32	32
9	0.03	28.30	4.86	34	33	31
10	0.05	37.34	9.12	34	36	33
11	0.08	49.49	14.85	36	38	35
12	0.11	61.18	20.36	38	40	37
13	0.01	37.98	3.76	42	41	41
14	0.02	42.38	5.84	43	42	40
15	0.05	51.63	10.19	42	43	40
16	0.07	62.36	15.25	44	44	41
17	0.11	81.87	24.45	45	45	44
18	0.02	56.54	5.44	49	50	49
19	0.03	62.90	8.44	50	50	47
20	0.06	77.97	15.54	49	50	47
21	0.09	92.87	22.57	51	50	49
22	0.02	74.50	6.84	55	57	56
23	0.04	83.45	11.05	55	56	54
24	0.07	103.91	20.70	56	54	54
25	0.10	123.10	29.75	57	54	55



a) MEPDG MODEL



b) Uzan and Witczak (1988) Model

Figure B.11 – Austin -1.5% OMC #1 LVDT Results

Description: Austin 6.9%

Field Conditions:

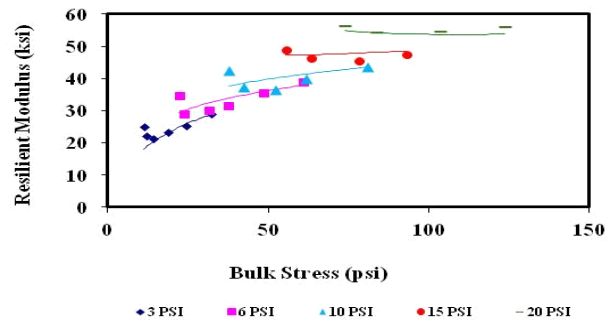
MC: 6.90%

Before Testing:

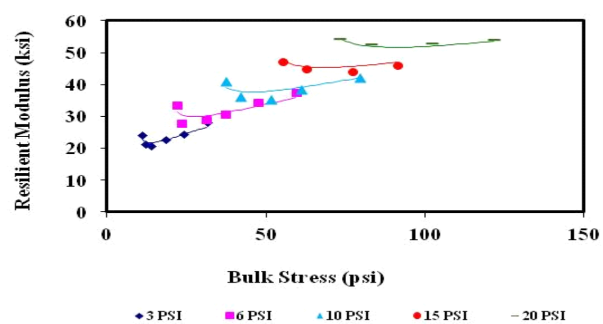
OMC:	7.2%
Diameter:	6.1 in.
Height:	12.0 in.
Gage Length:	12.0 in.
Volume:	350.4 in.^{3}
Wet Density:	139.6 pcf
Dry Density:	130.6 pcf
Dry Mass:	26.5 lb.

	MEPDG Model	Uzan and Witczak (1988) Model
k_1 =	1529	992
k_2 =	0.67	0.69
k_3 =	-0.49	-0.24
R^2 =	0.981	0.985

Cycle No.	Axial Strain (%)	Bulk Stress (psi)	Oct Stress (psi)	Resilient Modulus (ksi)	MEPDG Model Predicted Modulus (ksi)	Uzan and Witczak (1988) Model Predicted Modulus (ksi)
1	0.01	11.09	0.99	25	18	23
2	0.01	12.02	1.42	22	19	22
3	0.02	14.02	2.37	22	20	22
4	0.04	18.73	4.59	23	23	23
5	0.06	24.48	7.30	25	26	24
6	0.08	32.08	10.88	29	29	27
7	0.01	22.14	0.00	35	30	31
8	0.01	23.50	2.59	29	28	31
9	0.04	31.47	6.35	30	31	30
10	0.06	37.56	9.22	32	33	31
11	0.08	48.45	14.36	36	36	33
12	0.11	60.72	20.14	39	38	36
13	0.01	37.75	3.65	42	38	39
14	0.03	42.55	5.92	37	39	38
15	0.06	52.22	10.47	37	40	38
16	0.08	62.03	15.10	40	41	39
17	0.11	81.13	24.10	44	44	42
18	0.02	55.41	4.91	49	47	48
19	0.03	63.28	8.62	47	47	46
20	0.07	78.07	15.59	46	48	46
21	0.09	92.86	22.56	48	49	47
22	0.02	73.74	6.48	56	55	54
23	0.04	83.89	11.26	55	54	52
24	0.07	103.62	20.56	55	54	52
25	0.11	123.81	30.08	56	54	54



a) MEPDG MODEL

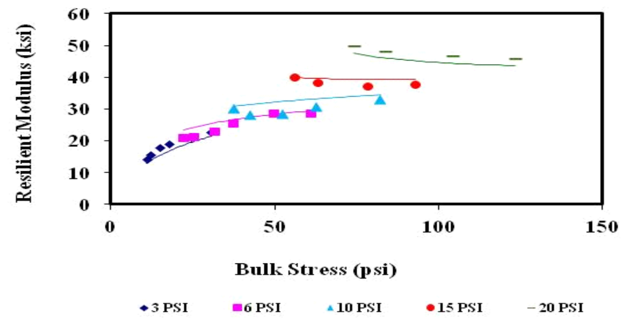


b) Uzan and Witczak (1988) Model

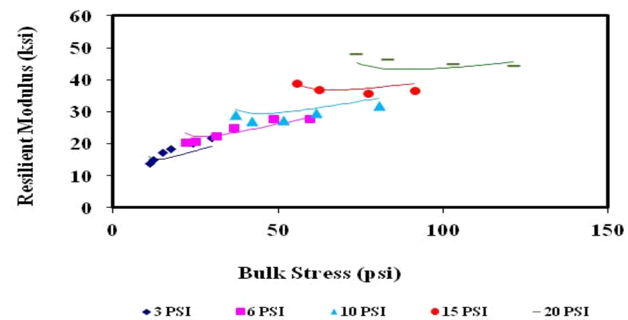
Figure B.12 – Austin -1.5% OMC #2 LVDT Results

Description:	**Austin 8.4%**					
			Field Conditions:			
Before Testing:			**MC:**		**8.40%**	
OMC:	**8.7%**					
Diameter:	**6.1 in.**				**MEPDG Model**	**Uzan and Witczak (1988) Model**
Height:	**11.8 in.**					
Gage Length:	**11.8 in.**			k_1 =	**1159**	**653**
Volume:	**343.7 $in.^3$**			k_2 =	**0.79**	**0.82**
Wet Density:	**143.8 pcf**			k_3 =	**-0.66**	**-0.27**
Dry Density:	**132.7 pcf**			R^2 =	**0.966**	**0.960**
Dry Mass:	**26.4 lb.**					

Cycle No.	Axial Strain (%)	Bulk Stress (psi)	Oct Stress (psi)	Resilient Modulus (ksi)	MEPDG Model Predicted Modulus (ksi)	Uzan and Witczak (1988) Model Predicted Modulus (ksi)
1	0.01	10.94	0.91	14	13	16
2	0.01	11.88	1.36	16	14	15
3	0.03	14.92	2.79	18	15	15
4	0.04	17.68	4.09	19	17	16
5	0.07	24.37	7.25	21	19	17
6	0.09	30.46	10.11	23	21	19
7	0.01	21.97	0.00	21	23	23
8	0.03	24.94	3.27	21	23	22
9	0.05	31.43	6.33	23	24	22
10	0.07	36.93	8.92	26	26	23
11	0.11	49.56	14.88	29	28	26
12	0.14	60.80	20.17	29	29	28
13	0.02	37.28	3.43	30	31	31
14	0.04	42.31	5.80	28	31	30
15	0.07	52.19	10.46	28	32	30
16	0.10	62.43	15.29	31	33	31
17	0.15	82.16	24.59	33	34	34
18	0.02	55.70	5.04	40	40	39
19	0.04	62.93	8.45	38	40	37
20	0.08	77.99	15.55	37	39	37
21	0.12	92.75	22.51	38	39	39
22	0.02	74.15	6.67	50	47	45
23	0.04	83.76	11.20	48	46	43
24	0.09	104.26	20.86	47	44	44
25	0.13	123.39	29.88	46	44	46



a) MEPDG MODEL

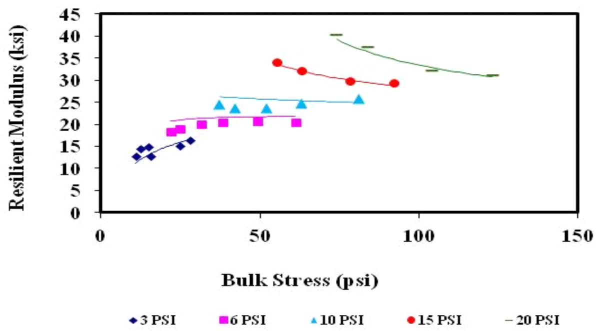


b) Uzan and Witczak (1988) Model

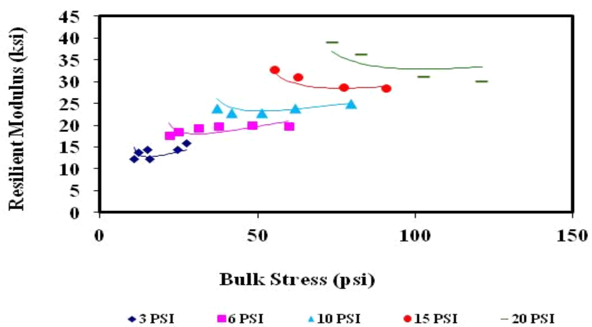
Figure B.13 – Austin OMC #1 LVDT Results

Description:	Austin 8.5%					
		Field Conditions:				
Before Testing:		MC:			8.50%	
OMC:	8.7%					
					MEPDG Model	Uzan and Witczak (1988) Model
Diameter:	6.1 in.					
Height:	12.0 in.					
Gage Length:	12.0 in.			k_1 =	1025	477
Volume:	349.2 $in.^3$			k_2 =	0.80	0.85
Wet Density:	144.1 pcf			k_3 =	-0.88	-0.35
Dry Density:	132.8 pcf			R^2 =	0.978	0.957
Dry Mass:	26.8 lb.					

					MEPDG Model	Uzan and Witczak (1988) Model
Cycle No.	Axial Strain (%)	Bulk Stress (psi)	Oct Stress (psi)	Resilient Modulus (ksi)	Predicted Modulus (ksi)	Predicted Modulus (ksi)
1	0.01	10.73	0.82	13	11	15
2	0.02	12.20	1.51	14	12	13
3	0.03	14.86	2.76	15	13	13
4	0.05	15.54	3.08	13	13	13
5	0.10	24.76	7.43	15	16	14
6	0.11	27.88	8.90	17	17	14
7	0.01	21.87	0.00	18	21	21
8	0.03	24.74	3.17	19	19	19
9	0.06	31.36	6.30	20	20	18
10	0.09	38.19	9.52	21	21	18
11	0.14	49.07	14.65	21	21	19
12	0.20	61.00	20.27	21	22	21
13	0.02	37.24	3.41	25	26	26
14	0.04	41.99	5.65	24	26	24
15	0.08	51.94	10.34	24	26	23
16	0.12	63.06	15.59	25	25	24
17	0.19	81.11	24.09	26	25	25
18	0.02	55.29	4.85	34	34	32
19	0.05	62.99	8.48	32	32	30
20	0.10	78.06	15.58	30	30	28
21	0.15	92.05	22.18	30	29	29
22	0.03	74.03	6.61	40	39	37
23	0.05	83.65	11.15	38	36	34
24	0.12	104.12	20.80	32	33	33
25	0.19	123.14	29.76	31	31	33



a) MEPDG MODEL



b) Uzan and Witczak (1988) Model

Figure B.14 – Austin OMC #2 LVDT Results

Description: Austin 6.8%

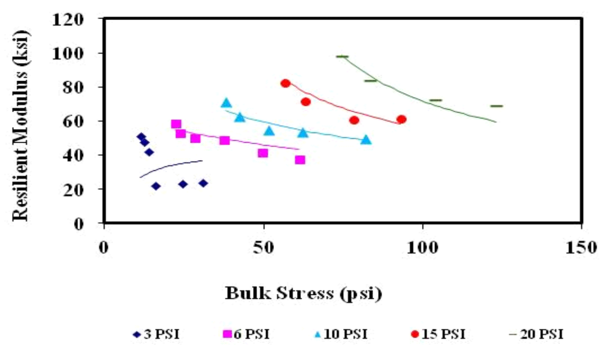
Field Conditions:
MC: 6.80%

Before Testing:

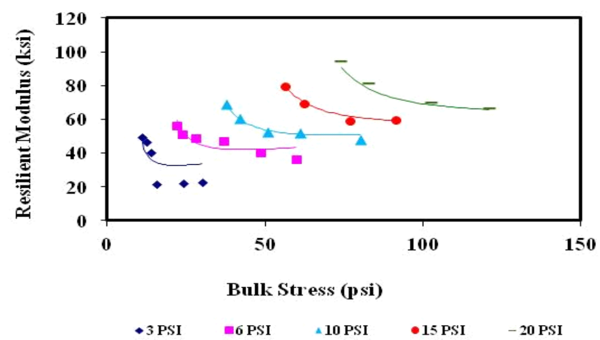
OMC:	7.2%
Diameter:	6.1 in.
Height:	12.0 in.
Gage Length:	4.0 in.
Volume:	350.5 in.^{3}
Wet Density:	139.5 pcf
Dry Density:	130.6 pcf
Dry Mass:	26.5 lb.

	MEPDG Model	Uzan and Witczak (1988) Model
k_1 =	2571	1080
k_2 =	0.90	1.07
k_3 =	-1.32	-0.52
R^2 =	0.889	0.920

Cycle No.	Axial Strain (%)	Bulk Stress (psi)	Oct Stress (psi)	Resilient Modulus (ksi)	MEPDG Model Predicted Modulus (ksi)	Uzan and Witczak (1988) Model Predicted Modulus (ksi)
1	0.00	11.10	0.99	51	27	46
2	0.01	12.26	1.54	48	28	40
3	0.01	13.85	2.28	42	30	36
4	0.03	15.71	3.16	23	31	34
5	0.06	24.37	7.25	23	35	33
6	0.09	30.78	10.27	24	37	34
7	0.01	22.16	0.00	59	55	59
8	0.01	23.76	2.72	53	47	53
9	0.02	28.30	4.86	50	47	46
10	0.04	37.34	9.12	49	46	42
11	0.07	49.49	14.85	42	45	42
12	0.11	61.18	20.36	38	43	43
13	0.01	37.98	3.76	71	66	68
14	0.02	42.38	5.84	63	63	60
15	0.04	51.63	10.19	55	59	53
16	0.06	62.36	15.25	54	54	51
17	0.10	81.87	24.45	50	49	51
18	0.01	56.54	5.44	83	84	80
19	0.02	62.90	8.44	72	77	70
20	0.05	77.97	15.54	61	66	62
21	0.07	92.87	22.57	62	58	59
22	0.01	74.50	6.84	98	99	91
23	0.02	83.45	11.05	84	86	78
24	0.06	103.91	20.70	73	69	69
25	0.09	123.10	29.75	69	60	66



a) MEPDG MODEL



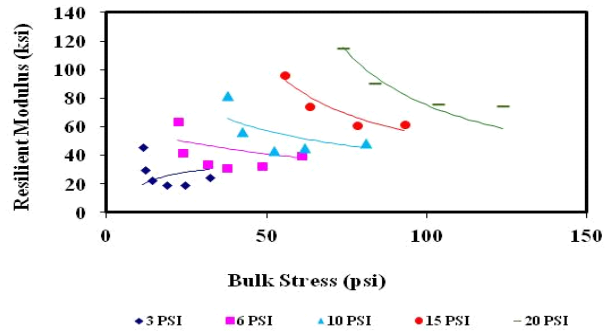
b) Uzan and Witczak (1988) Model

Figure B.15 – Austin -1.5% OMC #1 PROX Results

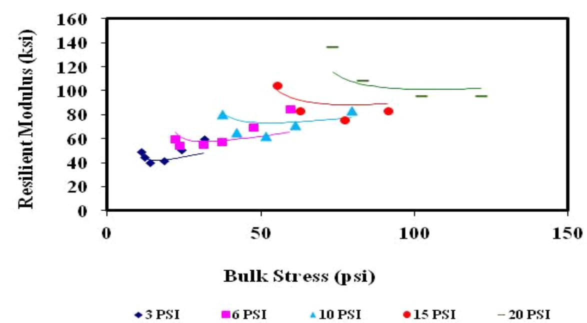
Description:	Austin 6.9%		
		Field Conditions:	
Before Testing:		**MC:**	6.90%
OMC:	7.2%		
Diameter:	6.1 in.		
Height:	12.0 in.		
Gage Length:	4.0 in.		
Volume:	350.4 $in.^3$		
Wet Density:	139.6 pcf		
Dry Density:	130.6 pcf		
Dry Mass:	26.5 lb.		

	MEPDG Model	Uzan and Witczak (1988) Model
k_1 =	2074	1562
k_2 =	1.23	0.82
k_3 =	-1.75	-0.35
R^2 =	0.883	0.856

					MEPDG Model	Uzan and Witczak (1988) Model
Cycle No.	**Axial Strain (%)**	**Bulk Stress (psi)**	**Oct Stress (psi)**	**Resilient Modulus (ksi)**	**Predicted Modulus (ksi)**	**Predicted Modulus (ksi)**
1	0.00	11.09	0.99	46	19	48
2	0.01	12.02	1.42	30	20	45
3	0.02	14.02	2.37	23	22	42
4	0.05	18.73	4.59	19	25	42
5	0.08	24.48	7.30	19	28	44
6	0.09	32.08	10.88	25	30	48
7	0.00	22.14	0.00	64	50	66
8	0.01	23.50	2.59	42	41	62
9	0.04	31.47	6.35	34	41	58
10	0.06	37.56	9.22	31	41	58
11	0.09	48.45	14.36	33	40	61
12	0.10	60.72	20.14	40	38	65
13	0.01	37.75	3.65	82	66	82
14	0.02	42.55	5.92	57	62	76
15	0.05	52.22	10.47	44	56	73
16	0.07	62.03	15.10	45	52	74
17	0.10	81.13	24.10	49	45	78
18	0.01	55.41	4.91	96	94	101
19	0.02	63.28	8.62	75	81	92
20	0.05	78.07	15.59	61	66	88
21	0.07	92.86	22.56	62	57	89
22	0.01	73.74	6.48	115	116	116
23	0.02	83.89	11.26	91	95	105
24	0.05	103.62	20.56	76	72	101
25	0.08	123.81	30.08	74	59	102



a) MEPDG MODEL



b) Uzan and Witczak (1988) Model

Figure B.16 – Austin -1.5% OMC #2 PROX Results

Description: Austin 8.4%

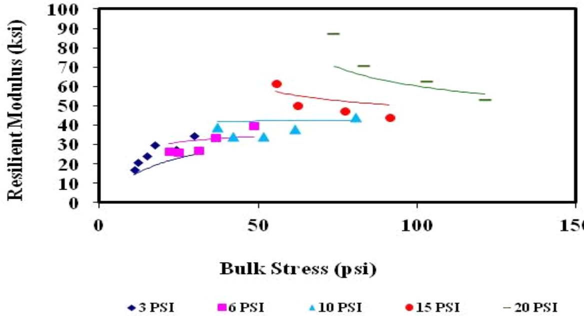
Field Conditions:
MC: 8.40%

Before Testing:

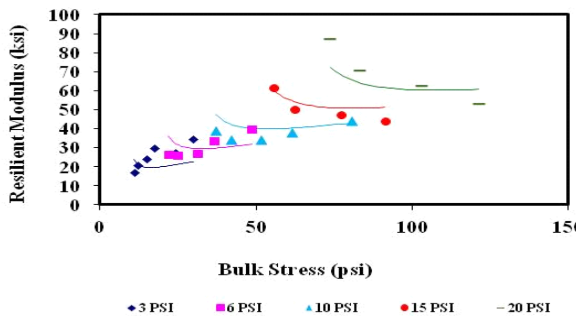
OMC:	8.7%	
Diameter:	6.1	in.
Height:	11.8	in.
Gage Length:	4.0	in.
Volume:	343.7	$in.^3$
Wet Density:	143.8	pcf
Dry Density:	132.7	pcf
Dry Mass:	26.4	lb.

	MEPDG Model	Uzan and Witczak (1988) Model
k_1 =	1400	601
k_2 =	0.99	1.10
k_3 =	-1.00	-0.50
R^2 =	0.856	0.817

Cycle No.	Axial Strain (%)	Bulk Stress (psi)	Oct Stress (psi)	Resilient Modulus (ksi)	MEPDG Model Predicted Modulus (ksi)	Uzan and Witczak (1988) Model Predicted Modulus (ksi)
1	0.01	10.88	0.88	17	14	24
2	0.01	11.79	1.31	21	15	22
3	0.02	14.72	2.70	24	17	20
4	0.03	17.39	3.96	30	19	20
5	0.05	23.87	7.01	28	23	21
6	0.06	29.76	9.79	35	25	23
7	0.01	21.84	0.00	27	30	36
8	0.02	24.71	3.16	26	28	32
9	0.04	30.99	6.13	27	30	29
10	0.05	36.31	8.63	34	32	30
11	0.07	48.54	14.39	40	34	32
12						
13	0.01	37.04	3.32	39	42	48
14	0.03	41.91	5.61	34	42	42
15	0.06	51.47	10.12	34	42	40
16	0.08	61.38	14.79	38	42	40
17	0.11	80.46	23.79	44	42	43
18	0.01	55.35	4.88	62	57	61
19	0.03	62.34	8.18	50	55	54
20	0.06	76.91	15.04	48	52	51
21	0.10	91.20	21.78	44	51	51
22	0.01	73.69	6.45	88	71	72
23	0.03	82.98	10.83	71	66	64
24	0.06	102.82	20.19	63	59	60
25	0.11	121.33	28.91	53	56	61



a) MEPDG MODEL



b) Uzan and Witczak (1988) Model

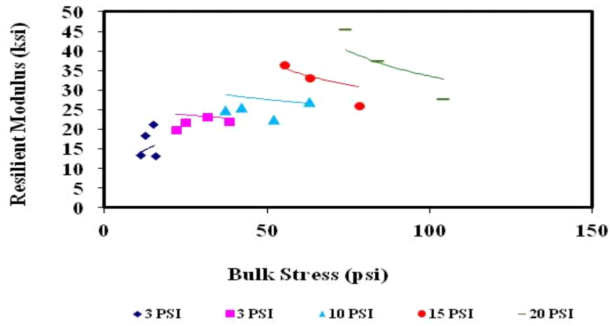
Figure B.17 – Austin OMC #1 PROX Results

Description: Austin 8.5%

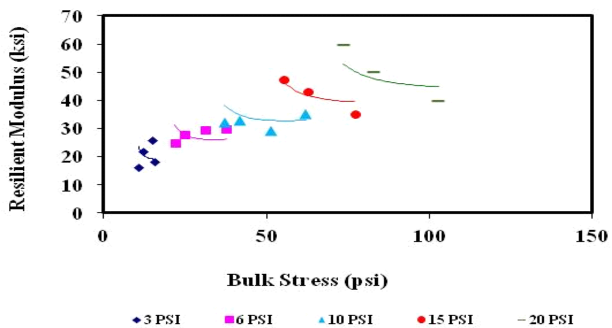
Field Conditions:

Before Testing:		**MC:**		8.50%
OMC:	8.7%			
			MEPDG Model	Uzan and Witczak (1988) Model
Diameter:	6.1 in.			
Height:	12.0 in.			
Gage Length:	4.0 in.	k_1 =	1232	679
Volume:	349.2 $in.^3$	k_2 =	0.70	0.84
Wet Density:	144.1 pcf	k_3 =	-0.87	-0.39
Dry Density:	132.8 pcf	R^2 =	0.771	0.855
Dry Mass:	26.8 lb.			

					MEPDG Model	Uzan and Witczak (1988) Model
Cycle No.	**Axial Strain (%)**	**Bulk Stress (psi)**	**Oct Stress (psi)**	**Resilient Modulus (ksi)**	**Predicted Modulus (ksi)**	**Predicted Modulus (ksi)**
1	0.01	10.73	0.82	14	14	24
2	0.01	12.20	1.51	19	15	21
3	0.02	14.86	2.76	21	16	19
4	0.04	15.54	3.08	13	16	19
5						
6						
7	0.01	21.87	0.00	20	24	31
8	0.02	24.74	3.17	22	22	28
9	0.05	31.36	6.30	23	23	26
10	0.09	38.19	9.52	22	23	26
11						
12						
13	0.02	37.24	3.41	25	29	38
14	0.04	41.99	5.65	26	28	35
15	0.09	51.94	10.34	23	27	33
16	0.11	63.06	15.59	27	27	33
17						
18	0.02	55.29	4.85	37	36	47
19	0.05	62.99	8.48	33	34	42
20	0.11	78.06	15.58	26	31	39
21						
22	0.02	74.03	6.61	46	40	53
23	0.05	83.65	11.15	37	37	48
24	0.14	104.12	20.80	28	33	45
25						



a) MEPDG MODEL

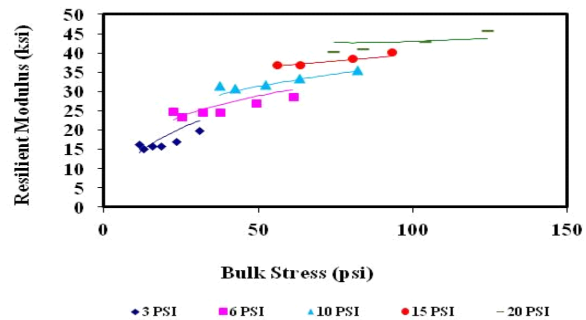


b) Uzan and Witczak (1988) Model

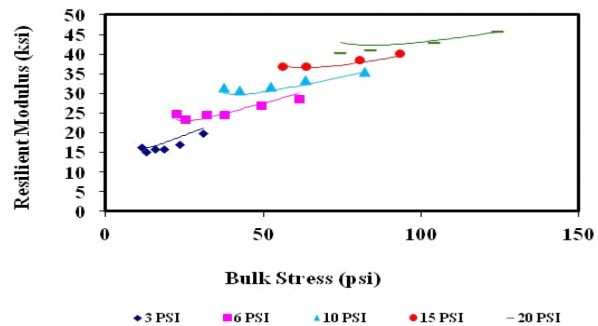
Figure B.18 – Austin OMC #2 PROX Results

Description:	Paris 4.6%					
			Field Conditions:			
Before Testing:			MC:			4.60%
OMC:	5.0%					
					MEPDG Model	Uzan and Witczak (1988) Model
Diameter:	6.1 in.					
Height:	12.0 in.					
Gage Length:	12.0 in.			k_1 =	1172	790
Volume:	349.5 in.^{3}			k_2 =	0.66	0.71
Wet Density:	139.4 pcf			k_3 =	-0.42	-0.20
Dry Density:	133.3 pcf			R^2 =	0.970	0.986
Dry Mass:	27.0 lb.					

Cycle No.	Axial Strain (%)	Bulk Stress (psi)	Oct Stress (psi)	Resilient Modulus (ksi)	MEPDG Model Predicted Modulus (ksi)	Uzan and Witczak (1988) Model Predicted Modulus (ksi)
1	0.01	11.37	1.12	17	14	16
2	0.02	12.61	1.70	15	15	16
3	0.04	15.63	3.12	16	17	17
4	0.05	18.35	4.41	16	18	17
5	0.08	23.15	6.67	17	20	19
6	0.11	30.81	10.28	20	22	21
7	0.01	22.38	0.00	25	23	23
8	0.03	25.21	3.40	24	23	23
9	0.05	31.82	6.52	25	25	24
10	0.07	37.29	9.09	25	26	25
11	0.11	49.02	14.62	27	28	27
12	0.15	61.10	20.32	29	31	30
13	0.02	37.27	3.43	32	29	30
14	0.03	42.36	5.82	31	30	30
15	0.06	52.24	10.48	32	32	31
16	0.09	63.14	15.62	34	33	32
17	0.14	81.95	24.49	36	35	35
18	0.02	55.86	5.12	37	37	37
19	0.04	63.14	8.55	37	37	37
20	0.08	80.36	16.67	39	38	38
21	0.11	92.87	22.57	40	39	39
22	0.03	74.42	6.80	40	43	43
23	0.05	83.92	11.27	41	43	42
24	0.09	103.84	20.66	43	43	43
25	0.13	124.25	30.29	46	44	46



a) MEPDG MODEL



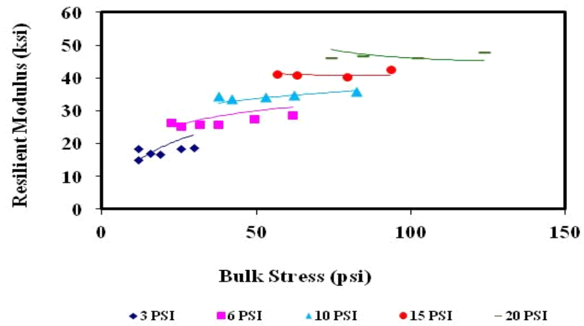
b) Uzan and Witczak (1988) Model

Figure B.19 – Paris -1.5% OMC #1 LVDT Results

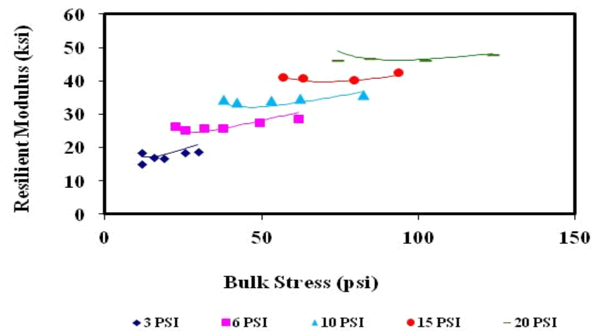
Description:	Paris 4.8%			
		Field Conditions:		
Before Testing:		MC:		4.80%
OMC:	5.0%			
Diameter:	6.1 in.			
Height:	11.9 in.			
Gage Length:	11.9 in.			
Volume:	348.7 in.^{3}			
Wet Density:	139.3 pcf			
Dry Density:	132.9 pcf			
Dry Mass:	26.8 lb.			

	MEPDG Model	Uzan and Witczak (1988) Model
k_1 =	1251	712
k_2 =	0.75	0.81
k_3 =	-0.62	-0.29
R^2 =	0.968	0.986

Cycle No.	Axial Strain (%)	Bulk Stress (psi)	Oct Stress (psi)	Resilient Modulus (ksi)	MEPDG Model Predicted Modulus (ksi)	Uzan and Witczak (1988) Model Predicted Modulus (ksi)
1	0.01	11.50	1.18	19	15	18
2	0.01	11.44	1.15	15	15	18
3	0.04	15.65	3.13	17	17	17
4	0.05	18.74	4.59	17	19	18
5	0.08	25.39	7.73	18	21	20
6	0.11	29.50	9.67	19	23	21
7	0.01	22.31	0.00	27	25	26
8	0.02	25.39	3.48	25	24	25
9	0.05	31.32	6.28	26	26	25
10	0.07	37.54	9.21	26	27	26
11	0.11	49.18	14.70	28	29	28
12	0.15	61.60	20.55	29	31	31
13	0.02	37.76	3.66	35	32	34
14	0.03	42.10	5.71	34	33	32
15	0.06	53.13	10.90	34	34	32
16	0.09	62.36	15.25	35	35	34
17	0.14	82.29	24.65	36	36	37
18	0.02	56.41	5.38	41	41	42
19	0.04	62.89	8.44	41	41	40
20	0.08	79.07	16.06	41	41	40
21	0.11	93.20	22.72	43	41	42
22	0.02	74.24	6.71	46	49	49
23	0.04	84.36	11.48	47	47	47
24	0.08	102.09	19.84	46	46	46
25	0.13	123.72	30.04	48	45	48



a) MEPDG MODEL



b) Uzan and Witczak (1988) Model

Figure B.20 – Paris -1.5% OMC #2 LVDT Results

Description: Paris 6%

Field Conditions:

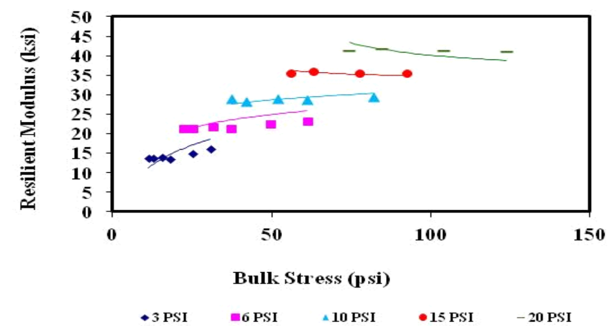
MC: 6.00%

Before Testing:

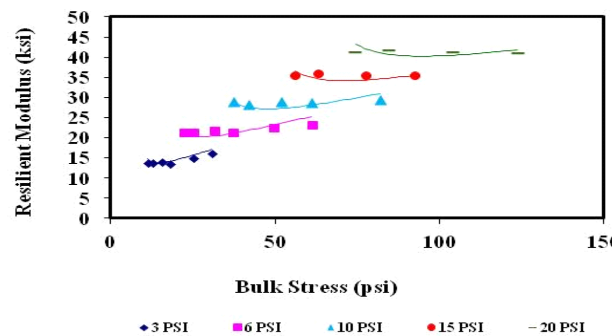
OMC:	**6.5%**	
Diameter:	**6.1**	**in.**
Height:	**11.9**	**in.**
Gage Length:	**11.9**	**in.**
Volume:	**348.4**	**in.^{3}**
Wet Density:	**142.4**	**pcf**
Dry Density:	**134.3**	**pcf**
Dry Mass:	**27.1**	**lb.**

	MEPDG Model	Uzan and Witczak (1988) Model
k_1 =	1011	712
k_2 =	0.83	0.81
k_3 =	-0.73	-0.29
R^2 =	0.975	0.986

Cycle No.	Axial Strain (%)	Bulk Stress (psi)	Oct Stress (psi)	Resilient Modulus (ksi)	MEPDG Model Predicted Modulus (ksi)	Uzan and Witczak (1988) Model Predicted Modulus (ksi)
1	0.01	11.18	1.03	14	11	15
2	0.02	12.62	1.71	14	12	14
3	0.04	15.53	3.08	14	14	14
4	0.06	18.13	4.31	14	15	14
5	0.10	24.91	7.50	15	17	16
6	0.13	30.70	10.23	16	19	17
7	0.01	22.19	0.00	21	21	22
8	0.03	25.06	3.33	21	20	21
9	0.05	31.35	6.30	22	22	20
10	0.08	37.17	9.04	21	23	21
11	0.13	49.42	14.81	23	25	23
12	0.18	61.17	20.35	23	26	25
13	0.02	37.34	3.46	29	28	29
14	0.04	41.93	5.62	28	28	28
15	0.07	52.10	10.42	29	29	27
16	0.10	61.21	14.71	29	29	28
17	0.17	82.11	24.56	30	30	31
18	0.02	55.95	5.16	36	36	37
19	0.04	62.90	8.44	36	36	35
20	0.08	77.32	15.24	36	35	34
21	0.13	92.25	22.28	36	35	35
22	0.03	74.36	6.77	41	43	43
23	0.05	84.46	11.53	42	42	41
24	0.10	104.06	20.77	41	40	40
25	0.15	123.81	30.08	41	39	42



a) MEPDG MODEL



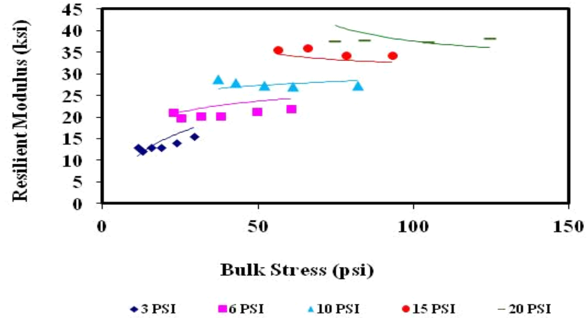
b) Uzan and Witczak (1988) Model

Figure B.21 – Paris OMC #1 LVDT Results

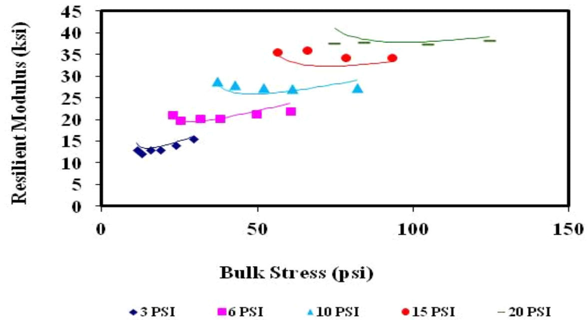
Description:	Paris 6.1%		
Before Testing:		**Field Conditions:**	
		MC:	6.10%
OMC:	6.5%		
Diameter:	6.1 in.		
Height:	12.0 in.		
Gage Length:	12.0 in.		
Volume:	349.5 in.^{3}		
Wet Density:	143.6 pcf		
Dry Density:	135.4 pcf		
Dry Mass:	27.4 lb.		

	MEPDG Model	Uzan and Witczak (1988) Model
k_1 =	988	509
k_2 =	0.82	0.89
k_3 =	-0.75	-0.34
R^2 =	0.966	0.975

Cycle No.	Axial Strain (%)	Bulk Stress (psi)	Oct Stress (psi)	Resilient Modulus (ksi)	MEPDG Model Predicted Modulus (ksi)	Uzan and Witczak (1988) Model Predicted Modulus (ksi)
1	0.01	11.14	1.01	13	11	15
2	0.02	12.50	1.65	12	12	14
3	0.04	15.46	3.04	13	13	13
4	0.07	18.51	4.48	13	14	14
5	0.10	23.52	6.85	14	16	15
6	0.13	29.32	9.58	16	18	16
7	0.02	22.65	0.00	21	21	21
8	0.03	25.14	3.37	20	19	20
9	0.06	31.33	6.28	20	21	20
10	0.09	37.62	9.25	20	22	20
11	0.14	49.31	14.76	21	23	22
12	0.19	60.47	20.02	22	24	24
13	0.02	37.18	3.38	29	27	28
14	0.04	42.86	6.06	28	27	26
15	0.07	51.91	10.33	27	27	26
16	0.11	61.08	14.65	27	28	27
17	0.18	81.98	24.50	27	28	29
18	0.02	56.20	5.28	36	35	35
19	0.05	65.61	9.72	36	34	33
20	0.09	78.02	15.57	34	33	32
21	0.13	93.07	22.66	34	33	33
22	0.03	74.73	6.94	38	41	41
23	0.05	84.16	11.39	38	39	39
24	0.11	104.52	20.99	37	37	38
25	0.16	124.47	30.39	38	36	39



a) MEPDG MODEL



b) Uzan and Witczak (1988) Model

Figure B.22 – Paris OMC #2 LVDT Results

Description: Paris 7.7%

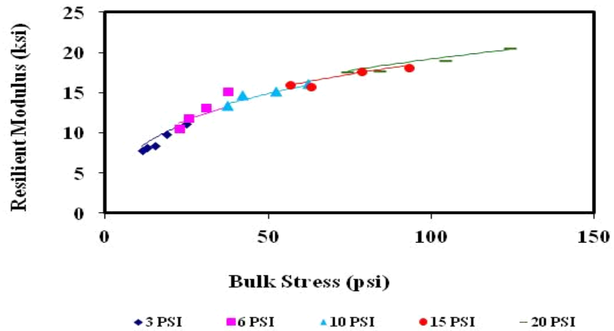
Field Conditions:
MC: 7.70%

Before Testing:

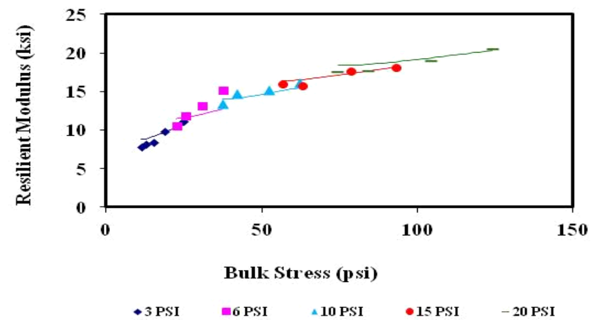
OMC:	8.0%
Diameter:	6.1 in.
Height:	11.9 in.
Gage Length:	11.9 in.
Volume:	347.8 $in.^3$
Wet Density:	144.6 pcf
Dry Density:	134.2 pcf
Dry Mass:	27.0 lb.

	MEPDG Model	Uzan and Witczak (1988) Model
k_1 =	640	522
k_2 =	0.42	0.49
k_3 =	-0.10	-0.10
R^2 =	0.971	0.949

Cycle No.	Axial Strain (%)	Bulk Stress (psi)	Oct Stress (psi)	Resilient Modulus (ksi)	MEPDG Model Predicted Modulus (ksi)	Uzan and Witczak (1988) Model Predicted Modulus (ksi)
1	0.02	11.16	1.02	8	8	9
2	0.04	12.57	1.68	8	9	9
3	0.07	15.24	2.94	8	9	9
4	0.09	18.52	4.49	10	10	10
5	0.14	24.74	7.42	11	11	11
6						
7	0.03	22.44	0.00	11	11	11
8	0.05	25.27	3.43	12	12	12
9	0.09	30.69	5.98	13	12	12
10	0.12	37.36	9.13	15	13	13
11						
12						
13	0.04	37.32	3.45	13	14	14
14	0.07	42.19	5.75	15	14	14
15	0.13	52.30	10.51	15	15	15
16	0.19	62.05	15.11	16	16	16
17						
18	0.06	56.53	5.44	16	16	16
19	0.10	62.84	8.41	16	16	17
20	0.17	78.47	15.78	18	18	17
21	0.25	93.12	22.68	18	18	18
22	0.06	74.37	6.77	18	18	18
23	0.12	84.16	11.39	18	18	19
24	0.21	104.38	20.92	19	19	19
25	0.29	124.18	30.25	21	20	20



a) MEPDG MODEL



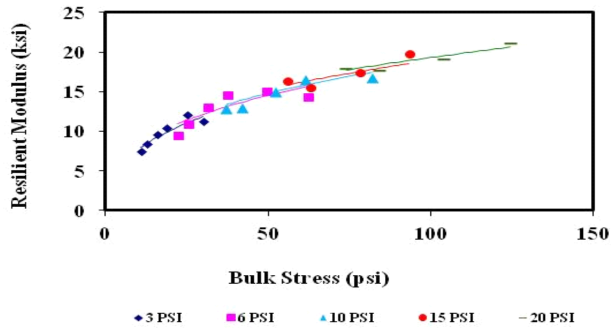
b) Uzan and Witczak (1988) Model

Figure B.23 – Paris +1.5% OMC #1 LVDT Results

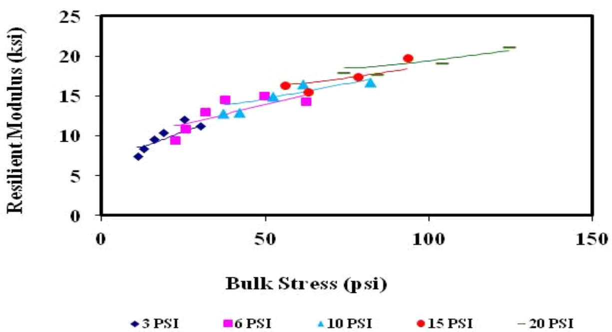
Description:	Paris 7.9%				
Field Conditions:					
Before Testing:		MC:	7.90%		
OMC:	8.0%				
Diameter:	6.1 in.				
Height:	12.0 in.				
Gage Length:	12.0 in.				
Volume:	350.6 $in.^3$				
Wet Density:	143.9 pcf				
Dry Density:	133.4 pcf				
Dry Mass:	27.1 lb.				

	MEPDG Model	Uzan and Witczak (1988) Model
k_1 =	622	511
k_2 =	0.43	0.51
k_3 =	-0.10	-0.10
R^2 =	0.955	0.929

Cycle No.	Axial Strain (%)	Bulk Stress (psi)	Oct Stress (psi)	Resilient Modulus (ksi)	MEPDG Model Predicted Modulus (ksi)	Uzan and Witczak (1988) Model Predicted Modulus (ksi)
1	0.01	10.78	0.84	8	8	9
2	0.03	12.58	1.69	8	8	9
3	0.06	15.85	3.23	10	9	9
4	0.09	18.75	4.60	11	10	10
5	0.13	25.03	7.56	12	11	11
6	0.18	29.99	9.89	11	12	11
7	0.03	22.25	0.00	10	11	11
8	0.05	25.27	3.43	11	11	11
9	0.09	31.52	6.37	13	12	12
10	0.12	37.33	9.11	15	13	13
11	0.20	49.55	14.87	15	14	14
12	0.30	62.24	20.85	14	16	15
13	0.04	37.19	3.39	13	13	14
14	0.08	42.12	5.71	13	14	14
15	0.14	52.14	10.44	15	15	15
16	0.18	61.43	14.82	17	16	16
17	0.30	82.10	24.56	17	17	17
18	0.05	55.76	5.07	16	16	16
19	0.10	62.94	8.46	16	16	17
20	0.17	78.27	15.68	18	18	17
21	0.23	93.24	22.74	20	19	18
22	0.06	74.05	6.62	18	18	18
23	0.12	84.26	11.43	18	18	19
24	0.21	104.00	20.74	19	20	20
25	0.29	124.39	30.35	21	21	21



a) MEPDG MODEL

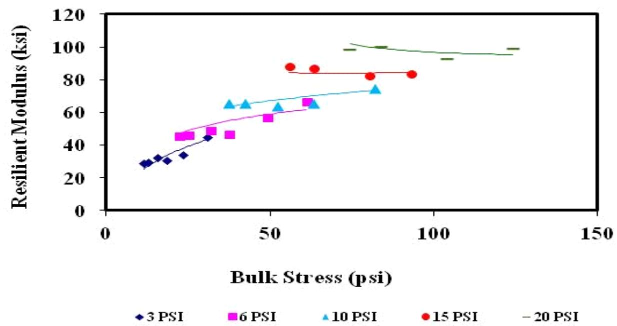


b) Uzan and Witczak (1988) Model

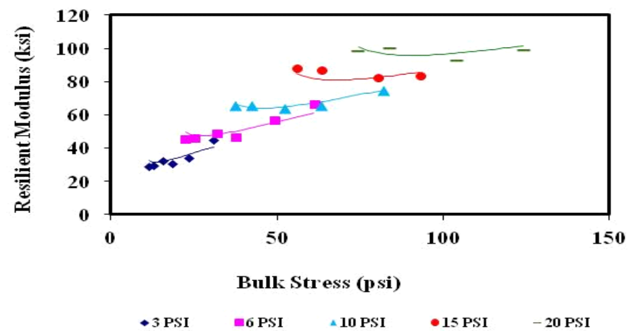
Figure B.24 – Paris +1.5% OMC #2 LVDT Results

Description:	Paris 4.6%					
			Field Conditions:			
Before Testing:			MC:			4.60%
OMC:	5.0%				MEPDG Model	Uzan and Witczak (1988) Model
Diameter:	6.1 in.					
Height:	12.0 in.					
Gage Length:	4.0 in.			k_1 =	2256	1293
Volume:	349.5 in.^{3}			k_2 =	0.85	0.89
Wet Density:	139.4 pcf			k_3 =	-0.68	-0.30
Dry Density:	133.3 pcf			R^2 =	0.983	0.983
Dry Mass:	27.0 lb.					

					MEPDG Model	Uzan and Witczak (1988) Model
Cycle No.	Axial Strain (%)	Bulk Stress (psi)	Oct Stress (psi)	Resilient Modulus (ksi)	Predicted Modulus (ksi)	Predicted Modulus (ksi)
1	0.01	11.37	1.12	29	25	33
2	0.01	12.61	1.70	30	27	32
3	0.02	15.63	3.12	32	31	32
4	0.03	18.35	4.41	31	33	33
5	0.04	23.15	6.67	35	38	36
6	0.05	30.81	10.28	45	43	41
7	0.01	22.38	0.00	45	47	50
8	0.01	25.21	3.40	46	46	48
9	0.03	31.82	6.52	49	50	48
10	0.04	37.29	9.09	47	53	50
11	0.05	49.02	14.62	57	58	55
12	0.06	61.10	20.32	67	62	61
13	0.01	37.27	3.43	65	63	67
14	0.02	42.36	5.82	66	65	64
15	0.03	52.24	10.48	64	68	65
16	0.05	63.14	15.62	65	70	68
17	0.07	81.95	24.49	75	73	75
18	0.01	55.86	5.12	88	84	85
19	0.02	63.14	8.55	87	84	81
20	0.04	80.36	16.67	83	84	83
21	0.05	92.87	22.57	84	85	86
22	0.01	74.42	6.80	99	102	101
23	0.02	83.92	11.27	101	99	96
24	0.04	103.84	20.66	93	96	97
25	0.06	124.25	30.29	99	95	102



a) MEPDG MODEL

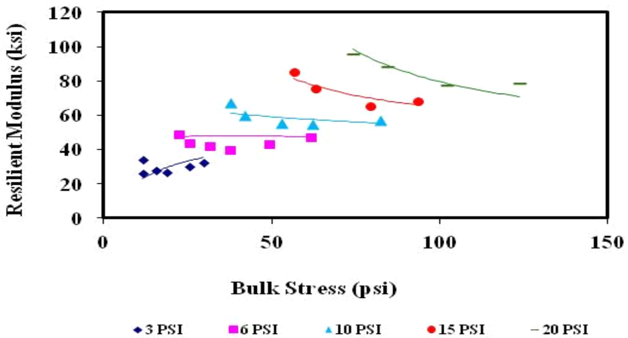


b) Uzan and Witczak (1988) Model

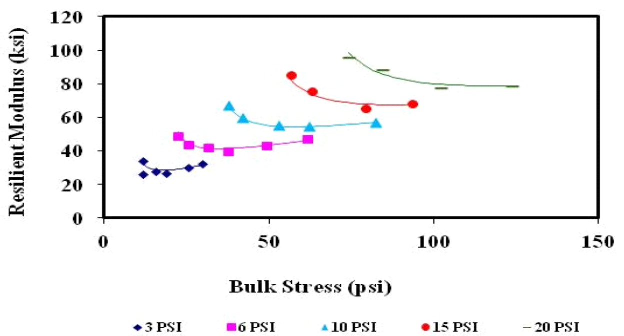
Figure B.25 – Paris -1.5% OMC #1 PROX Results

Description:	Paris 4.8%				
		Field Conditions:			
Before Testing:		MC:		4.80%	
OMC:	5.0%				
				MEPDG Model	Uzan and Witczak (1988) Model
Diameter:	6.1 in.				
Height:	11.9 in.				
Gage Length:	4.0 in.		k_1 =	2157	1293
Volume:	348.7 $in.^3$		k_2 =	0.96	0.89
Wet Density:	139.3 pcf		k_3 =	-1.11	-0.30
Dry Density:	132.9 pcf		R^2 =	0.966	0.983
Dry Mass:	26.8 lb.				

Cycle No.	Axial Strain (%)	Bulk Stress (psi)	Oct Stress (psi)	Resilient Modulus (ksi)	MEPDG Model Predicted Modulus (ksi)	Uzan and Witczak (1988) Model Predicted Modulus (ksi)
1	0.01	11.50	1.18	34	23	34
2	0.01	11.44	1.15	26	23	34
3	0.02	15.65	3.13	28	27	29
4	0.03	18.74	4.59	27	30	28
5	0.05	25.39	7.73	30	33	30
6	0.06	29.50	9.67	32	35	31
7	0.01	22.31	0.00	49	47	51
8	0.01	25.39	3.48	44	42	45
9	0.03	31.32	6.28	42	44	41
10	0.05	37.54	9.21	40	45	41
11	0.07	49.18	14.70	44	47	43
12	0.09	61.60	20.55	47	47	46
13	0.01	37.76	3.66	68	61	66
14	0.02	42.10	5.71	60	60	59
15	0.04	53.13	10.90	56	59	55
16	0.06	62.36	15.25	55	57	54
17	0.09	82.29	24.65	57	55	57
18	0.01	56.41	5.38	85	81	83
19	0.02	62.89	8.44	76	77	74
20	0.05	79.07	16.06	66	70	68
21	0.07	93.20	22.72	68	66	68
22	0.01	74.24	6.71	96	99	99
23	0.02	84.36	11.48	88	89	86
24	0.05	102.09	19.84	77	79	80
25	0.08	123.72	30.04	79	71	79



a) MEPDG MODEL

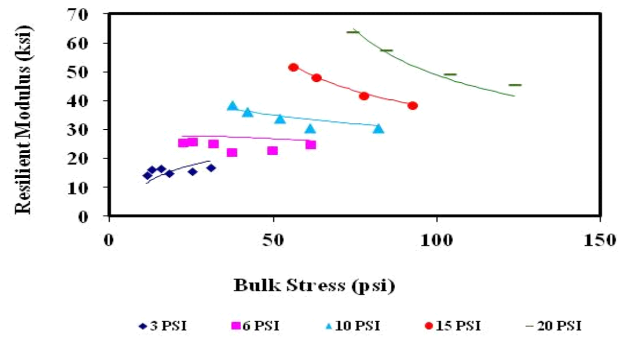


b) Uzan and Witczak (1988) Model

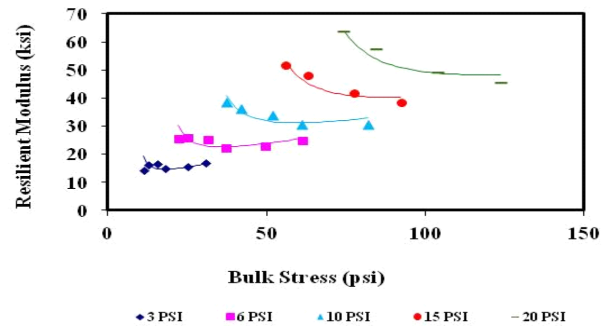
Figure B.26 – Paris -1.5% OMC #2 PROX Results

Description:	**Paris 6%**					
			Field Conditions:			
Before Testing:			**MC:**			**6.00%**
OMC:	**6.5%**					
Diameter:	**6.1 in.**				**MEPDG Model**	**Uzan and Witczak (1988) Model**
Height:	**11.9 in.**					
Gage Length:	**4.0 in.**			k_1 =	1170	361
Volume:	**348.4 in.^{3}**			k_2 =	1.15	1.24
Wet Density:	**142.4 pcf**			k_3 =	-1.40	-0.61
Dry Density:	**134.3 pcf**			R^2 =	0.979	0.981
Dry Mass:	**27.1 lb.**					

Cycle No.	Axial Strain (%)	Bulk Stress (psi)	Oct Stress (psi)	Resilient Modulus (ksi)	MEPDG Model Predicted Modulus (ksi)	Uzan and Witczak (1988) Model Predicted Modulus (ksi)
1	0.01	11.18	1.03	15	11	19
2	0.02	12.62	1.71	17	12	16
3	0.03	15.53	3.08	17	14	15
4	0.06	18.13	4.31	15	15	15
5	0.10	24.91	7.50	16	18	15
6	0.12	30.70	10.23	17	19	17
7	0.01	22.19	0.00	26	28	30
8	0.02	25.06	3.33	26	24	26
9	0.05	31.35	6.30	25	25	23
10	0.08	37.17	9.04	22	25	23
11	0.13	49.42	14.81	23	26	24
12	0.17	61.17	20.35	25	26	26
13	0.01	37.34	3.46	38	37	41
14	0.03	41.93	5.62	36	36	35
15	0.06	52.10	10.42	34	35	32
16	0.10	61.21	14.71	31	33	31
17	0.16	82.11	24.56	31	31	33
18	0.02	55.95	5.16	52	52	53
19	0.03	62.90	8.44	48	48	45
20	0.07	77.32	15.24	42	43	41
21	0.12	92.25	22.28	39	39	40
22	0.02	74.36	6.77	64	65	64
23	0.04	84.46	11.53	58	57	54
24	0.08	104.06	20.77	49	47	49
25	0.13	123.81	30.08	45	42	48



a) MEPDG MODEL

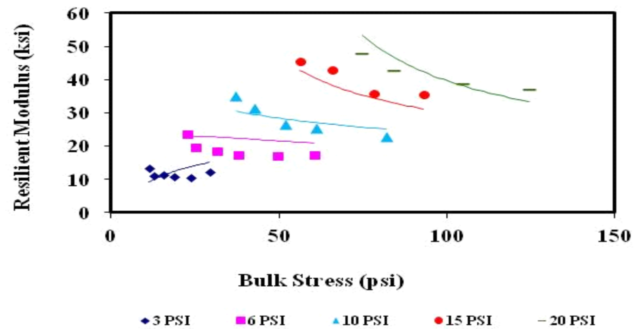


b) Uzan and Witczak (1988) Model

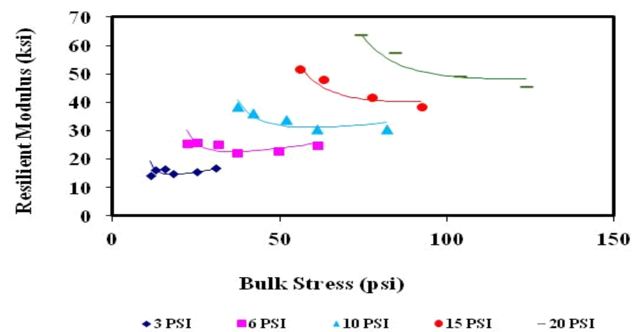
Figure B.27 – Paris OMC #1 PROX Results

Description:	**Paris 6.1%**				
			Field Conditions:		
Before Testing:			**MC:**		**6.10%**
OMC:	**6.5%**				
Diameter:	**6.1**	**in.**		**MEPDG Model**	**Uzan and Witczak (1988) Model**
Height:	**12.0**	**in.**			
Gage Length:	**4.0**	**in.**	k_1 =	**942**	**361**
Volume:	**349.5**	**in.^{3}**	k_2 =	**1.17**	**1.24**
Wet Density:	**143.6**	**pcf**	k_3 =	**-1.45**	**-0.61**
Dry Density:	**135.4**	**pcf**	R^2 =	**0.934**	**0.981**
Dry Mass:	**27.4**	**lb.**			

Cycle No.	Axial Strain (%)	Bulk Stress (psi)	Oct Stress (psi)	Resilient Modulus (ksi)	MEPDG Model Predicted Modulus (ksi)	Uzan and Witczak (1988) Model Predicted Modulus (ksi)
1	0.01	11.14	1.01	13	9	16
2	0.03	12.50	1.65	11	10	13
3	0.05	15.46	3.04	12	11	11
4	0.08	18.51	4.48	11	12	11
5	0.13	23.52	6.85	11	14	12
6	0.16	29.32	9.58	12	15	12
7	0.01	22.65	0.00	24	23	23
8	0.03	25.14	3.37	20	19	20
9	0.06	31.33	6.28	19	20	18
10	0.11	37.62	9.25	17	21	17
11	0.17	49.31	14.76	17	21	18
12	0.24	60.47	20.02	17	21	19
13	0.02	37.18	3.38	35	30	33
14	0.03	42.86	6.06	31	29	27
15	0.08	51.91	10.33	27	28	25
16	0.12	61.08	14.65	25	27	24
17	0.22	81.98	24.50	23	25	25
18	0.02	56.20	5.28	46	43	42
19	0.04	65.61	9.72	43	38	35
20	0.08	78.02	15.57	36	34	32
21	0.13	93.07	22.66	36	31	31
22	0.02	74.73	6.94	48	53	51
23	0.05	84.16	11.39	43	47	43
24	0.11	104.52	20.99	39	38	38
25	0.16	124.47	30.39	37	33	37



a) MEPDG MODEL



b) Uzan and Witczak (1988) Model

Figure B.28 – Paris OMC #2 PROX Results

Description: IH 35

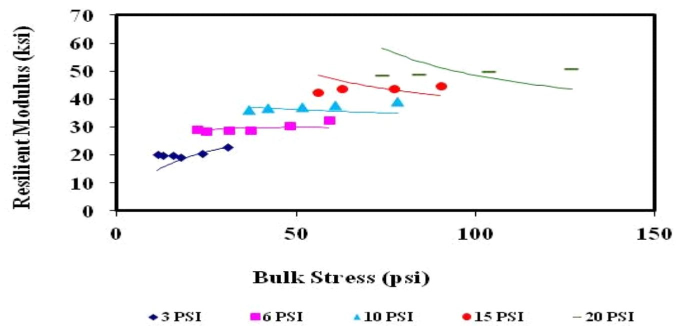
Field Conditions:

MC: 6.30%

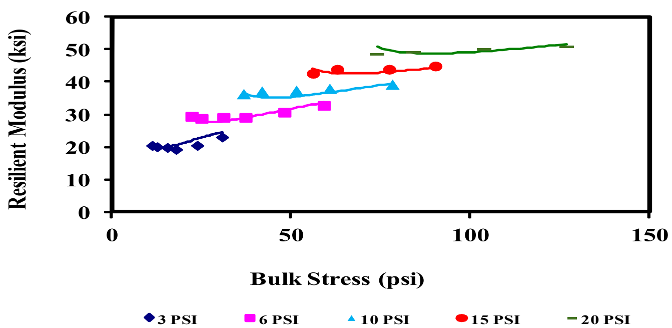
Before Testing:

OMC:	6.5%			
Diameter:	6.1 in.		MEPDG Model	Uzan and Witczak (1988) Model
Height:	11.8 in.			
Gage Length:	11.8 in.	k_1 =	1350	916
Volume:	344.9 in.^{3}	k_2 =	0.90	0.70
Wet Density:	144.8 pcf	k_3 =	-1.00	-0.23
Dry Density:	136.2 pcf	R^2 =	0.918	0.989
Dry Mass:	27.2 lb.			

Cycle No.	Axial Strain (%)	Bulk Stress (psi)	Oct Stress (psi)	Resilient Modulus (ksi)	MEPDG Model Predicted Modulus (ksi)	Uzan and Witczak (1988) Model Predicted Modulus (ksi)
1	0.01	11.12	1.00	20	14	21
2	0.01	12.48	1.64	20	15	20
3	0.03	15.35	2.99	20	17	20
4	0.04	17.77	4.13	19	18	21
5	0.07	23.69	6.92	21	21	22
6	0.09	30.63	10.20	23	23	25
7	0.01	22.10	0.00	29	29	29
8	0.02	24.85	3.23	29	26	28
9	0.04	30.98	6.12	29	27	28
10	0.06	37.15	9.03	29	28	29
11	0.09	48.01	14.15	31	29	31
12	0.12	58.96	19.31	33	30	34
13	0.01	36.80	3.21	36	37	37
14	0.03	41.91	5.62	37	37	35
15	0.05	51.51	10.14	37	36	36
16	0.08	60.79	14.52	38	36	37
17	0.12	78.29	22.76	39	35	40
18	0.02	55.95	5.16	43	49	44
19	0.03	62.71	8.35	44	46	43
20	0.07	77.19	15.18	44	43	43
21	0.09	90.09	21.26	45	41	44
22	0.02	73.98	6.59	49	58	51
23	0.04	84.15	11.38	49	53	49
24	0.08	103.76	20.63	50	48	49
25	0.12	126.80	31.49	51	44	52



a) MEPDG MODEL

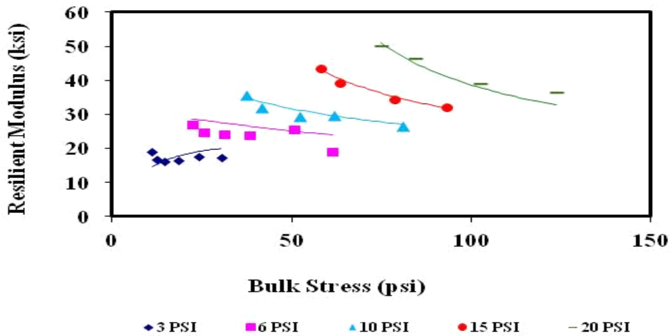


b) Uzan and Witczak (1988) Model

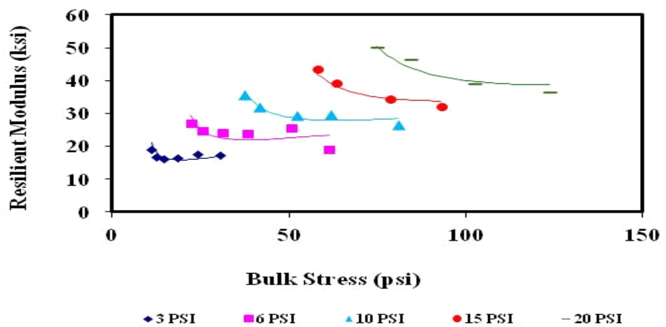
Figure B.29 – IH 35 OMC #1 LVDT Results

Description:	IH 35 #1					
			Field Conditions:			
Before Testing:			MC:			6.50%
OMC:	6.5%					
Diameter:	6.0 in.				MEPDG Model	Uzan and Witczak (1988) Model
Height:	11.6 in.					
Gage Length:	11.6 in.			k_1 =	1367	456
Volume:	328.0 $in.^3$			k_2 =	0.86	1.00
Wet Density:	146.2 pcf			k_3 =	-1.21	-0.53
Dry Density:	137.2 pcf			R^2 =	0.959	0.967
Dry Mass:	26.0 lb.					

Cycle No.	Axial Strain (%)	Bulk Stress (psi)	Oct Stress (psi)	Resilient Modulus (ksi)	MEPDG Model Predicted Modulus (ksi)	Uzan and Witczak (1988) Model Predicted Modulus (ksi)
1	0.01	11.06	0.97	19	15	21
2	0.02	12.43	1.62	17	15	18
3	0.03	14.32	2.51	16	16	17
4	0.05	18.25	4.36	16	18	16
5	0.08	23.81	6.98	18	19	16
6	0.12	30.28	10.03	18	20	17
7	0.01	22.18	0.00	27	29	29
8	0.02	25.38	3.48	25	25	25
9	0.05	31.06	6.16	24	25	22
10	0.08	38.11	9.48	24	25	22
11	0.12	50.62	15.38	26	25	23
12	0.22	61.28	20.40	19	24	23
13	0.01	37.28	3.43	36	35	37
14	0.03	41.86	5.59	32	34	32
15	0.07	52.16	10.45	29	31	29
16	0.10	61.73	14.96	30	30	28
17	0.19	81.04	24.06	27	27	28
18	0.02	58.05	6.15	44	43	42
19	0.04	63.22	8.59	39	41	38
20	0.09	78.56	15.82	34	35	34
21	0.14	93.10	22.67	32	32	34
22	0.02	74.86	7.01	50	51	51
23	0.04	84.34	11.47	46	45	44
24	0.10	102.43	20.00	39	38	40
25	0.16	123.84	30.09	37	33	39



a) MEPDG MODEL



b) Uzan and Witczak (1988) Model

Figure B.30 – IH 35 OMC #2 LVDT Results

Description: IH 35 #1

Field Conditions:

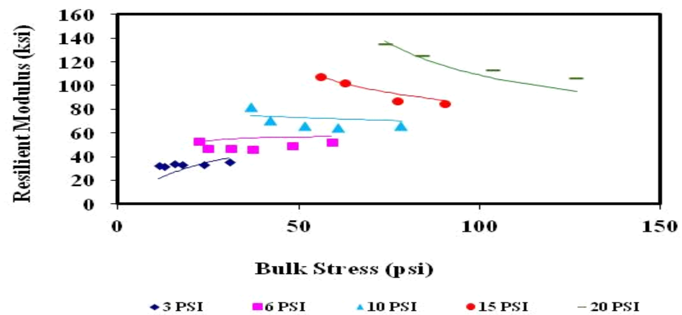
MC: 6.50%

Before Testing:

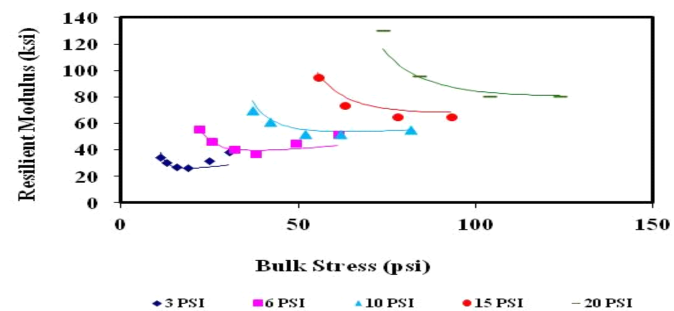
OMC:	**6.5%**
Diameter:	**6.0 in.**
Height:	**11.9 in.**
Gage Length:	**4.0 in.**
Volume:	**335.8 in.^{3}**
Wet Density:	**146.2 pcf**
Dry Density:	**137.2 pcf**
Dry Mass:	**26.7 lb.**

	MEPDG Model	Uzan and Witczak (1988) Model
k_1 =	2190	606
k_2 =	1.20	1.26
k_3 =	-1.31	-0.66
R^2 =	0.969	0.960

Cycle No.	Axial Strain (%)	Bulk Stress (psi)	Oct Stress (psi)	Resilient Modulus (ksi)	MEPDG Model Predicted Modulus (ksi)	Uzan and Witczak (1988) Model Predicted Modulus (ksi)
1	0.00	11.12	1.00	33	21	38
2	0.01	12.48	1.64	32	23	31
3	0.02	15.35	2.99	34	27	27
4	0.02	17.77	4.13	33	29	26
5	0.04	23.69	6.92	33	34	27
6	0.06	30.63	10.20	36	39	29
7	0.01	22.10	0.00	53	52	58
8	0.01	24.85	3.23	47	47	46
9	0.02	30.98	6.12	47	50	41
10	0.04	37.15	9.03	47	52	40
11	0.06	48.01	14.15	50	55	41
12	0.08	58.96	19.31	53	57	43
13	0.01	36.80	3.21	82	75	77
14	0.01	41.91	5.62	71	74	63
15	0.03	51.51	10.14	66	73	55
16	0.04	60.79	14.52	65	72	54
17	0.07	78.29	22.76	66	70	55
18	0.01	55.95	5.16	108	108	98
19	0.01	62.71	8.35	103	102	80
20	0.03	77.19	15.18	88	93	70
21	0.05	90.09	21.26	85	88	68
22	0.01	73.98	6.59	135	138	116
23	0.02	84.15	11.38	125	123	95
24	0.04	103.76	20.63	113	106	83
25	0.06	126.80	31.49	106	95	81



a) MEPDG MODEL

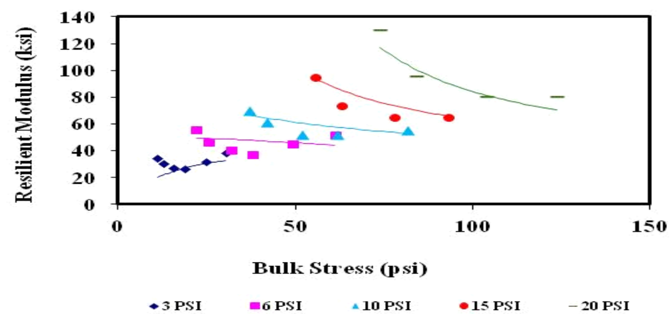


b) Uzan and Witczak (1988) Model

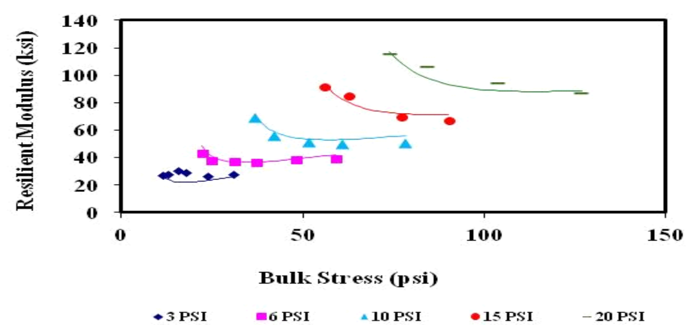
Figure B.31 – IH 35 OMC #1 PROX Results

Description:	IH 35 #2					
			Field Conditions:			
Before Testing:			MC:		6.30%	
OMC:	6.5%					
					MEPDG Model	Uzan and Witczak (1988) Model
Diameter:	6.0 in.					
Height:	11.9 in.					
Gage Length:	4.0 in.			k_1 =	2080	497
Volume:	335.8 $in.^3$			k_2 =	1.18	1.39
Wet Density:	145.1 pcf			k_3 =	-1.50	-0.66
Dry Density:	136.2 pcf			R^2 =	0.940	0.975
Dry Mass:	26.5 lb.					

Cycle No.	Axial Strain (%)	Bulk Stress (psi)	Oct Stress (psi)	Resilient Modulus (ksi)	MEPDG Model Predicted Modulus (ksi)	Uzan and Witczak (1988) Model Predicted Modulus (ksi)
1	0.00	11.03	0.96	35	20	29
2	0.01	12.57	1.68	31	22	25
3	0.02	15.59	3.10	27	25	22
4	0.03	18.64	4.54	27	27	22
5	0.05	24.63	7.37	32	30	23
6	0.05	30.42	10.10	39	33	26
7	0.01	22.03	0.00	56	49	49
8	0.01	25.52	3.55	46	42	41
9	0.03	31.64	6.43	40	44	37
10	0.05	37.63	9.25	37	44	37
11	0.07	49.12	14.67	45	45	39
12	0.08	61.10	20.32	52	44	42
13	0.01	36.93	3.27	70	67	71
14	0.02	42.12	5.71	62	64	59
15	0.04	52.00	10.37	52	61	53
16	0.06	61.88	15.03	52	58	53
17	0.09	81.85	24.44	55	53	56
18	0.01	55.36	4.88	95	94	93
19	0.02	62.97	8.47	74	85	80
20	0.05	77.93	15.52	65	74	72
21	0.07	92.85	22.56	65	66	71
22	0.01	73.89	6.55	130	117	117
23	0.02	84.08	11.35	96	101	98
24	0.05	104.03	20.76	81	81	89
25	0.07	123.67	30.01	80	70	89



a) MEPDG MODEL

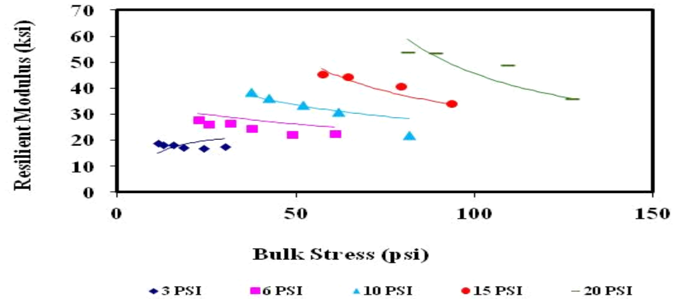


b) Uzan and Witczak (1988) Model

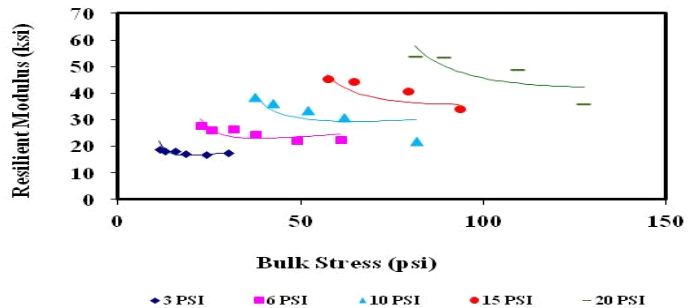
Figure B.32 – IH 35 OMC #2 PROX Results

Description:	**SH 21 #1**					
			Field Conditions:			
Before Testing:			**MC:**			**7.30%**
OMC:	**7.5%**					
Diameter:	**6.1 in.**				**MEPDG Model**	**Uzan and Witczak (1988) Model**
Height:	**11.7 in.**					
Gage Length:	**11.7 in.**			k_1 =	**1407**	**477**
Volume:	**341.3 in.^{3}**			k_2 =	**0.89**	**0.99**
Wet Density:	**147.8 pcf**			k_3 =	**-1.26**	**-0.52**
Dry Density:	**137.8 pcf**			R^2 =	**0.939**	**0.924**
Dry Mass:	**27.2 lb.**					

Cycle No.	Axial Strain (%)	Bulk Stress (psi)	Oct Stress (psi)	Resilient Modulus (ksi)	MEPDG Model Predicted Modulus (ksi)	Uzan and Witczak (1988) Model Predicted Modulus (ksi)
1	0.01	11.33	1.00	19	15	22
2	0.01	12.58	1.56	18	16	19
3	0.03	15.38	2.86	18	17	17
4	0.05	18.34	4.24	17	18	17
5	0.08	24.09	6.93	17	20	17
6	0.11	29.94	9.69	18	21	18
7	0.01	22.56	0.00	28	30	30
8	0.02	25.30	3.23	26	26	26
9	0.04	31.30	6.04	27	26	24
10	0.07	37.60	8.97	25	26	23
11	0.13	48.76	14.19	22	26	24
12	0.18	60.86	19.89	23	25	25
13	0.01	37.58	3.26	39	37	39
14	0.03	42.53	5.53	36	36	34
15	0.06	52.04	10.00	34	33	30
16	0.09	61.99	14.59	31	31	29
17	0.22	81.59	23.81	22	28	30
18	0.02	57.11	5.08	46	48	47
19	0.03	64.25	8.25	45	44	41
20	0.07	79.09	15.25	41	38	37
21	0.13	93.33	21.93	34	34	36
22	0.02	81.32	6.71	54	59	58
23	0.04	89.23	10.89	53	51	49
24	0.08	109.30	20.25	49	41	44
25	0.16	127.49	28.83	36	36	42



a) MEPDG MODEL

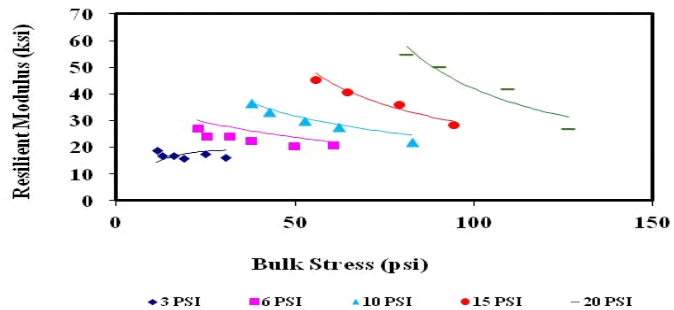


b) Uzan and Witczak (1988) Model

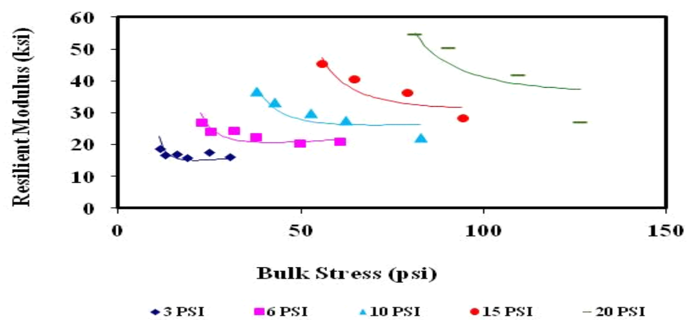
Figure B.33 – SH 21 OMC #1 LVDT Results

Description:	SH 21 #2					
			Field Conditions:			
Before Testing:			MC:		7.70%	
OMC:	7.5%					
					MEPDG Model	Uzan and Witczak (1988) Model
Diameter:	6.1 in.					
Height:	11.7 in.					
Gage Length:	11.7 in.			k_1 =	1382	404
Volume:	341.9 in.^{3}			k_2 =	0.92	1.02
Wet Density:	148.1 pcf			k_3 =	-1.44	-0.57
Dry Density:	137.5 pcf			R^2 =	0.958	0.913
Dry Mass:	27.2 lb.					

Cycle No.	Axial Strain (%)	Bulk Stress (psi)	Oct Stress (psi)	Resilient Modulus (ksi)	MEPDG Model Predicted Modulus (ksi)	Uzan and Witczak (1988) Model Predicted Modulus (ksi)
1	0.01	11.12	0.85	19	15	23
2	0.02	12.70	1.53	17	15	18
3	0.03	15.73	2.96	17	17	16
4	0.05	18.71	4.36	16	17	15
5	0.08	24.76	7.19	18	18	15
6	0.13	30.46	9.87	16	19	16
7	0.01	22.61	0.00	27	30	30
8	0.02	25.22	2.97	24	26	26
9	0.05	31.46	5.91	24	25	22
10	0.08	37.50	8.73	23	25	21
11	0.14	49.33	14.26	21	23	21
12	0.19	60.35	19.46	21	22	22
13	0.01	37.91	3.13	37	37	38
14	0.03	42.73	5.32	33	35	32
15	0.06	52.66	9.97	30	31	27
16	0.10	62.26	14.47	28	28	26
17	0.22	82.78	24.09	22	25	26
18	0.01	55.58	4.19	46	48	47
19	0.04	64.47	8.18	41	42	38
20	0.08	78.93	14.96	36	35	33
21	0.15	93.99	22.03	29	30	32
22	0.02	81.11	6.36	55	58	55
23	0.04	90.28	11.16	50	48	45
24	0.09	109.27	20.11	42	37	39
25	0.21	126.38	28.12	27	31	37



a) MEPDG MODEL



b) Uzan and Witczak (1988) Model

Figure B.34 – SH 21 OMC #2 LVDT Results

Description: SH 21 #1

Before Testing:

OMC:	7.5%
Diameter:	6.1 in.
Height:	11.7 in.
Gage Length:	4.0 in.
Volume:	341.3 in.^{3}
Wet Density:	147.8 pcf
Dry Density:	137.8 pcf
Dry Mass:	27.2 lb.

Field Conditions:

MC: 7.30%

	MEPDG Model	Uzan and Witczak (1988) Model
k_1 =	2003	394
k_2 =	1.15	1.32
k_3 =	-1.88	-0.77
R^2 =	0.853	0.786

Cycle No.	Axial Strain (%)	Bulk Stress (psi)	Oct Stress (psi)	Resilient Modulus (ksi)	MEPDG Model Predicted Modulus (ksi)	Uzan and Witczak (1988) Model Predicted Modulus (ksi)
1	0.01	11.13	1.00	25	19	31
2	0.01	12.31	1.56	27	20	26
3	0.02	15.07	2.86	30	22	21
4	0.03	18.00	4.24	33	23	20
5						
6						
7	0.01	22.22	0.00	35	47	46
8	0.02	24.85	3.23	35	37	37
9	0.03	30.82	6.04	40	36	30
10	0.05	37.02	8.97	36	35	29
11						
12						
13	0.01	36.91	3.26	56	58	62
14	0.02	41.73	5.53	47	53	49
15	0.04	51.22	10.00	44	46	40
16	0.07	60.96	14.59	41	41	38
17						
18	0.01	55.78	5.08	72	78	76
19	0.02	62.50	8.25	65	67	61
20	0.05	77.34	15.25	57	52	50
21	0.11	91.53	21.93	40	43	48
22	0.01	74.24	6.71	92	93	90
23	0.02	83.11	10.89	87	76	72
24	0.05	102.96	20.25	72	54	59
25						

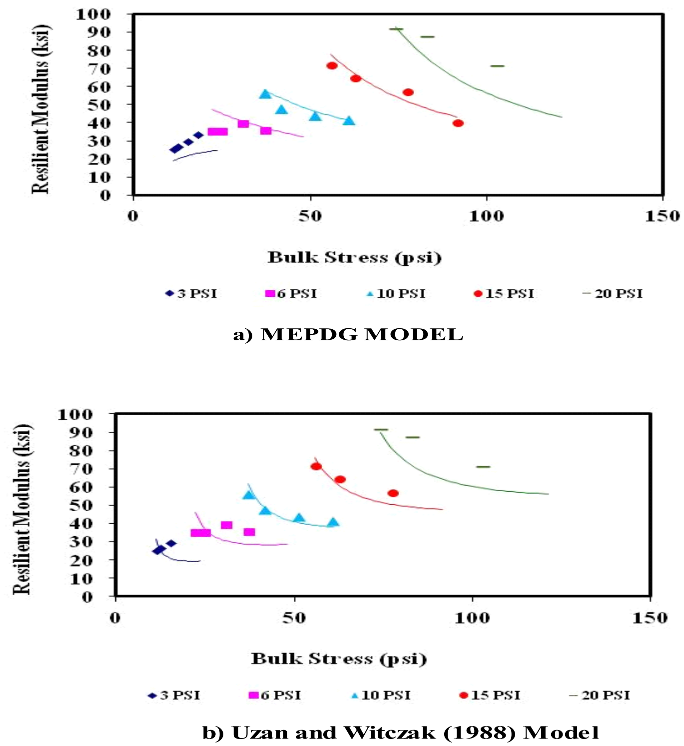
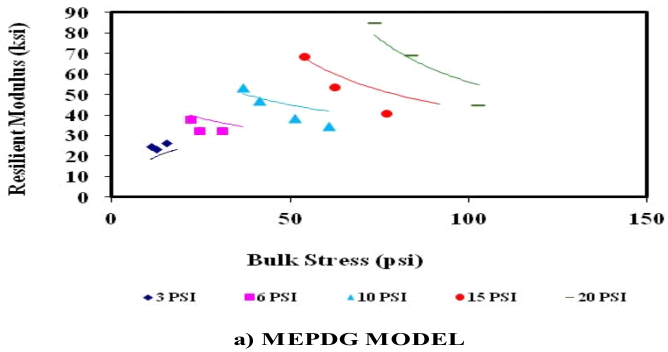


Figure B.35 – SH 21 OMC #1 PROX Results

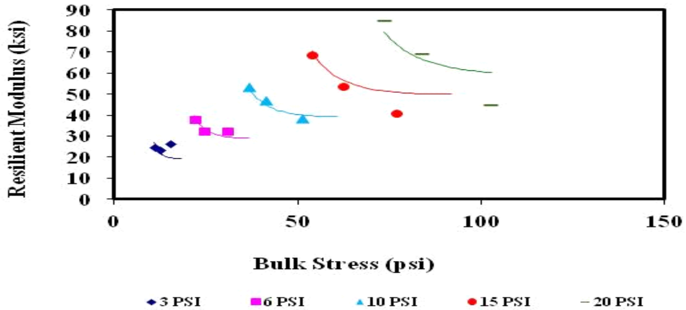
Description:	SH 21 #2		
		Field Conditions:	
Before Testing:		MC:	7.70%
OMC:	7.5%		
Diameter:	6.1 in.		
Height:	11.7 in.		
Gage Length:	4.0 in.		
Volume:	341.9 $in.^3$		
Wet Density:	148.1 pcf		
Dry Density:	137.5 pcf		
Dry Mass:	27.2 lb.		

	MEPDG Model	Uzan and Witczak (1988) Model
k_1 =	1836	505
k_2 =	0.98	1.17
k_3 =	-1.38	-0.58
R^2 =	0.779	0.831

Cycle No.	Axial Strain (%)	Bulk Stress (psi)	Oct Stress (psi)	Resilient Modulus (ksi)	MEPDG Model Predicted Modulus (ksi)	Uzan and Witczak (1988) Model Predicted Modulus (ksi)
1	0.00	10.79	0.85	25	18	5
2	0.01	12.24	1.53	24	20	6
3	0.02	15.28	2.96	26	22	7
4	0.04	18.24	4.36	20	23	8
5						
6						
7	0.01	21.90	0.00	38	40	11
8	0.02	24.30	2.97	33	34	12
9	0.03	30.53	5.91	33	35	14
10	0.07	36.52	8.73	25	34	16
11						
12						
13	0.01	36.64	3.13	53	50	19
14	0.02	41.28	5.32	47	48	21
15	0.05	51.16	9.97	38	45	24
16	0.08	60.70	14.47	35	42	26
17						
18	0.01	53.88	4.19	69	68	29
19	0.03	62.36	8.18	54	60	31
20	0.07	76.74	14.96	41	51	34
21	0.06	91.72	22.03	75	45	37
22	0.01	73.50	6.36	85	79	40
23	0.03	83.68	11.16	69	68	41
24	0.09	102.67	20.11	45	55	44
25						



a) MEPDG MODEL

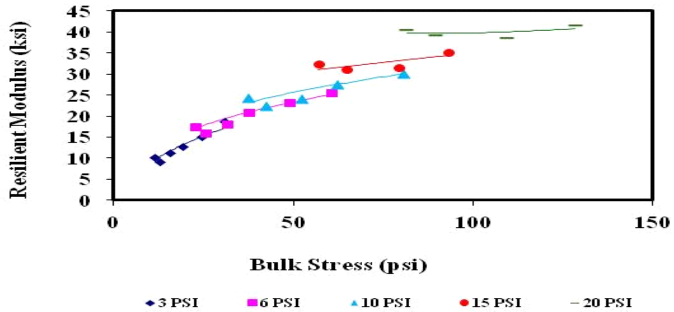


b) Uzan and Witczak (1988) Model

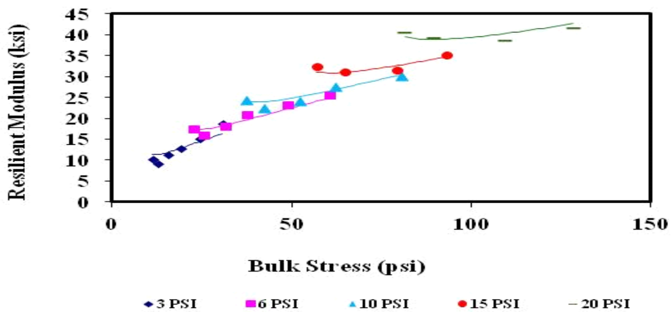
Figure B.36 – SH 21 OMC #2 PROX Results

Description:	Loop 480 #1			
		Field Conditions:		
Before Testing:		MC:		6.50%
OMC:	6.8%			
			MEPDG Model	Uzan and Witczak (1988) Model
Diameter:	6.1 in.			
Height:	11.6 in.			
Gage Length:	11.6 in.	k_1 =	827	566
Volume:	339.6 in.^{3}	k_2 =	0.79	0.82
Wet Density:	146.9 pcf	k_3 =	-0.46	-0.20
Dry Density:	137.9 pcf	R^2 =	0.989	0.987
Dry Mass:	27.1 lb.			

Cycle No.	Axial Strain (%)	Bulk Stress (psi)	Oct Stress (psi)	Resilient Modulus (ksi)	MEPDG Model Predicted Modulus (ksi)	Uzan and Witczak (1988) Model Predicted Modulus (ksi)
1	0.01	11.17	0.94	10	10	7
2	0.03	12.64	1.58	9	10	7
3	0.05	15.55	2.94	11	12	8
4	0.07	18.90	4.52	13	13	10
5	0.10	24.38	7.10	15	15	12
6	0.11	30.60	10.04	19	17	14
7	0.02	22.51	0.00	18	17	11
8	0.04	25.54	3.29	16	17	13
9	0.07	31.46	6.11	18	19	14
10	0.08	37.36	8.85	21	20	16
11	0.12	48.79	14.24	23	23	19
12	0.16	60.54	19.80	26	25	22
13	0.02	37.61	3.23	24	23	17
14	0.04	42.50	5.37	22	24	19
15	0.08	52.39	10.09	24	26	21
16	0.11	62.13	14.68	28	28	24
17	0.16	80.56	23.38	30	30	28
18	0.02	56.80	4.86	32	31	24
19	0.05	64.78	8.37	31	32	26
20	0.09	79.28	15.17	32	33	29
21	0.12	92.95	21.58	35	34	31
22	0.02	81.50	6.45	41	40	31
23	0.05	89.57	10.81	39	39	33
24	0.10	109.20	20.03	39	40	36
25	0.14	128.39	29.01	42	41	39



a) MEPDG MODEL

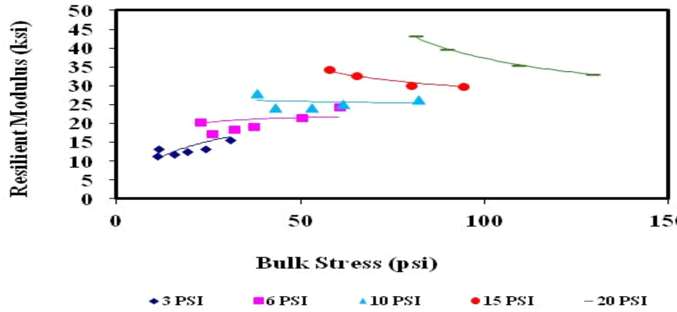


b) Uzan and Witczak (1988) Model

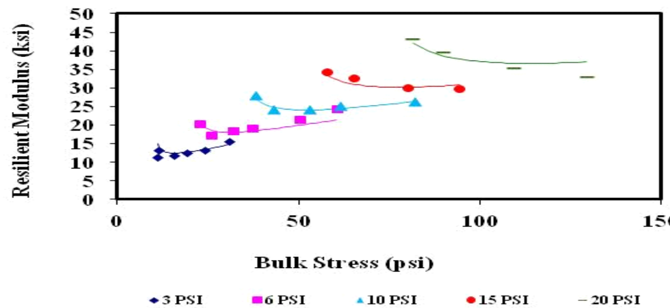
Figure B.37 – Loop 480 OMC #1 LVDT Results

Description:	Loop 480 #2					
			Field Conditions:			
Before Testing:			MC:			6.60%
OMC:	6.8%					
Diameter:	6.1 in.				MEPDG Model	Uzan and Witczak (1988) Model
Height:	11.6 in.					
Gage Length:	11.6 in.			k_1 =	951	441
Volume:	339.3 in.^{3}			k_2 =	0.84	0.92
Wet Density:	147.1 pcf			k_3 =	-0.88	-0.37
Dry Density:	138.0 pcf			R^2 =	0.977	0.972
Dry Mass:	27.1 lb.					

Cycle No.	Axial Strain (%)	Bulk Stress (psi)	Oct Stress (psi)	Resilient Modulus (ksi)	MEPDG Model Predicted Modulus (ksi)	Uzan and Witczak (1988) Model Predicted Modulus (ksi)
1	0.01	11.10	0.87	13	11	5
2	0.01	11.00	0.74	11	10	5
3	0.05	15.63	2.92	12	13	6
4	0.07	18.87	4.47	13	14	7
5	0.11	24.08	6.93	13	15	9
6	0.13	30.73	10.04	16	16	11
7	0.01	22.49	0.00	20	20	9
8	0.03	25.83	3.24	17	19	10
9	0.06	31.76	6.02	19	20	12
10	0.09	37.24	8.63	19	20	13
11	0.14	50.10	14.68	22	21	15
12	0.17	60.42	19.52	24	22	17
13	0.02	38.12	3.27	28	26	14
14	0.04	43.12	5.44	24	26	15
15	0.08	53.08	10.05	24	26	17
16	0.11	61.65	14.15	25	26	19
17	0.18	82.16	23.72	26	25	22
18	0.02	57.46	5.01	34	34	20
19	0.04	64.99	8.14	33	33	22
20	0.10	79.97	15.10	30	31	24
21	0.15	94.22	21.84	30	30	25
22	0.02	81.47	6.46	43	43	27
23	0.05	89.97	10.77	40	39	28
24	0.11	109.34	19.78	35	36	30
25	0.18	129.39	29.22	33	33	32



a) MEPDG MODEL

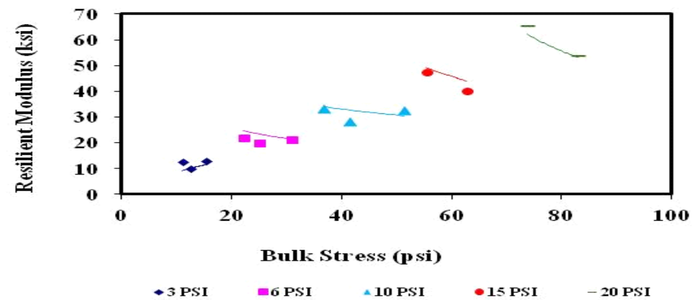


b) Uzan and Witczak (1988) Model

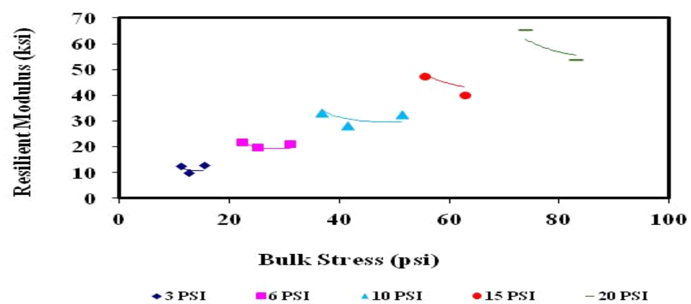
Figure B.38 – Loop 480 OMC #2 LVDT Results

Description:	Loop 480					
			Field Conditions:			
Before Testing:			MC:		6.50%	
OMC:	6.8%					
					MEPDG Model	Uzan and Witczak (1988) Model
Diameter:	6.1 in.					
Height:	11.6 in.					
Gage Length:	4.0 in.			k_1 =	1000	295
Volume:	339.6 in.^{3}			k_2 =	1.26	1.38
Wet Density:	146.9 pcf			k_3 =	-1.63	-0.53
Dry Density:	137.9 pcf			R^2 =	0.981	0.986
Dry Mass:	27.1 lb.					

Cycle No.	Axial Strain (%)	Bulk Stress (psi)	Oct Stress (psi)	Resilient Modulus (ksi)	MEPDG Model Predicted Modulus (ksi)	Uzan and Witczak (1988) Model Predicted Modulus (ksi)
1	0.01	10.99	0.94	13	9	12
2	0.03	12.35	1.58	10	10	11
3	0.04	15.25	2.94	13	11	11
4						
5						
6						
7	0.01	22.14	0.00	22	25	22
8	0.03	24.98	3.29	20	21	20
9	0.06	30.95	6.11	21	21	19
10						
11						
12						
13	0.02	36.85	3.23	33	34	34
14	0.03	41.39	5.37	28	33	31
15	0.06	51.40	10.09	33	30	30
16						
17						
18	0.02	55.30	4.86	48	49	48
19	0.04	62.75	8.37	40	44	43
20						
21						
22	0.02	73.69	6.45	66	62	62
23	0.04	82.94	10.81	54	53	56
24						
25						



a) MEPDG MODEL



b) Uzan and Witczak (1988) Model

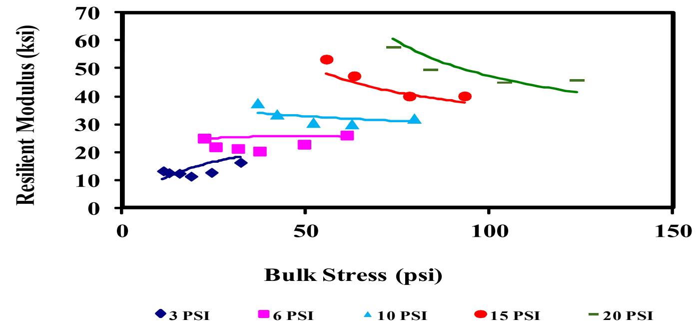
Figure B.39 – Loop 480 OMC #1 PROX Results

Before Testing: MC: 6.60%

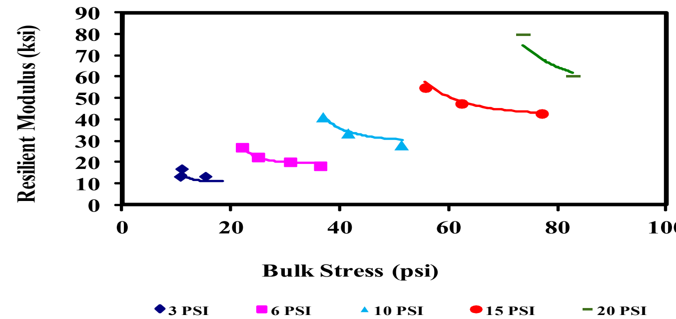
OMC:	6.8%	
Diameter:	6.1	in.
Height:	11.6	in.
Gage Length:	4.0	in.
Volume:	339.3	$in.^3$
Wet Density:	147.1	pcf
Dry Density:	138.0	pcf
Dry Mass:	27.1	lb.

	MEPDG Model	Uzan and Witczak (1988) Model
k_1 =	1049	220
k_2 =	1.14	1.58
k_3 =	-1.29	-0.73
R^2 =	0.963	0.964

Cycle No.	Axial Strain (%)	Bulk Stress (psi)	Oct Stress (psi)	Resilient Modulus (ksi)	MEPDG Model Predicted Modulus (ksi)	Uzan and Witczak (1988) Model Predicted Modulus (ksi)
1	0.01	11.05	0.97	13	10	16
2	0.02	12.58	1.69	13	11	17
3	0.05	15.40	3.02	12	13	11
4	0.08	18.59	4.52	11	14	11
5	0.11	24.15	7.14	13	16	
6	0.14	32.09	10.88	16	18	
7	0.01	22.13	0.00	25	25	28
8	0.03	25.24	3.42	22	22	22
9	0.06	31.35	6.29	21	23	20
10	0.09	37.22	9.06	20	24	20
11	0.13	49.36	14.78	23	25	
12	0.16	60.98	20.26	26	25	
13	0.01	36.88	3.24	38	34	41
14	0.03	42.16	5.73	33	33	34
15	0.07	52.05	10.39	31	33	31
16	0.10	62.55	15.34	30	32	
17	0.15	79.53	23.35	32	31	
18	0.01	55.41	4.91	53	48	58
19	0.03	62.98	8.47	47	45	48
20	0.08	78.00	15.56	40	41	43
21	0.11	93.04	22.64	40	38	
22	0.02	73.86	6.53	57	60	75
23	0.04	83.95	11.29	49	54	62
24	0.09	104.12	20.80	45	46	
25	0.13	123.76	30.06	46	41	



a) MEPDG MODEL



b) Uzan and Witczak (1988) Model

Figure B.40 – Loop 480 OMC #2 PROX Results

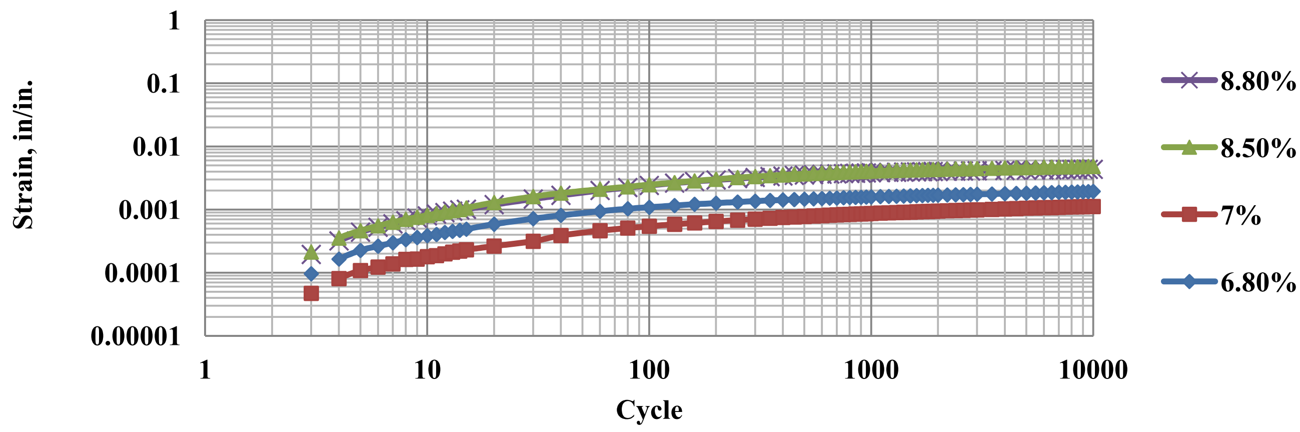


Figure B.41 – Austin Permanent Deformation Results LVDT Results

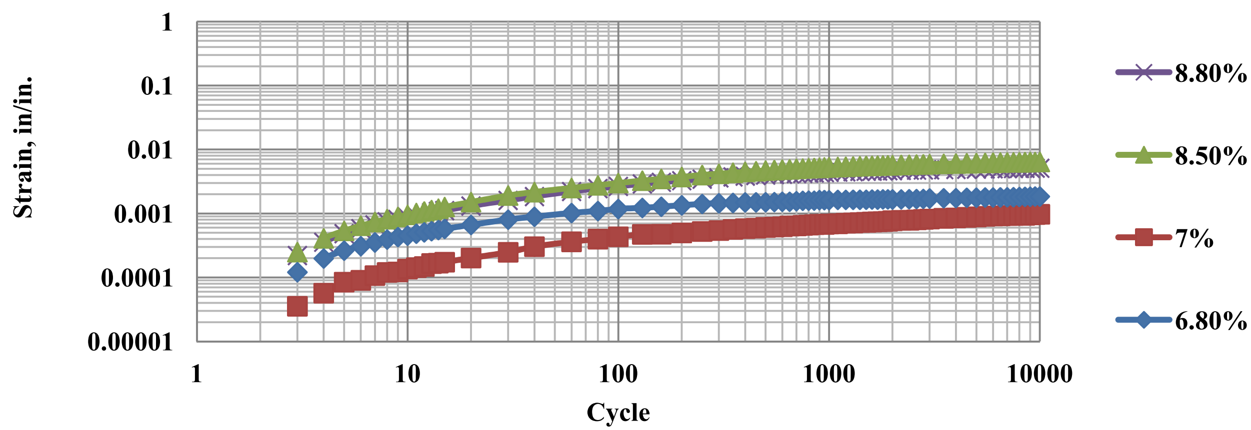


Figure B.42 – Austin Permanent Deformation Results PROX Results

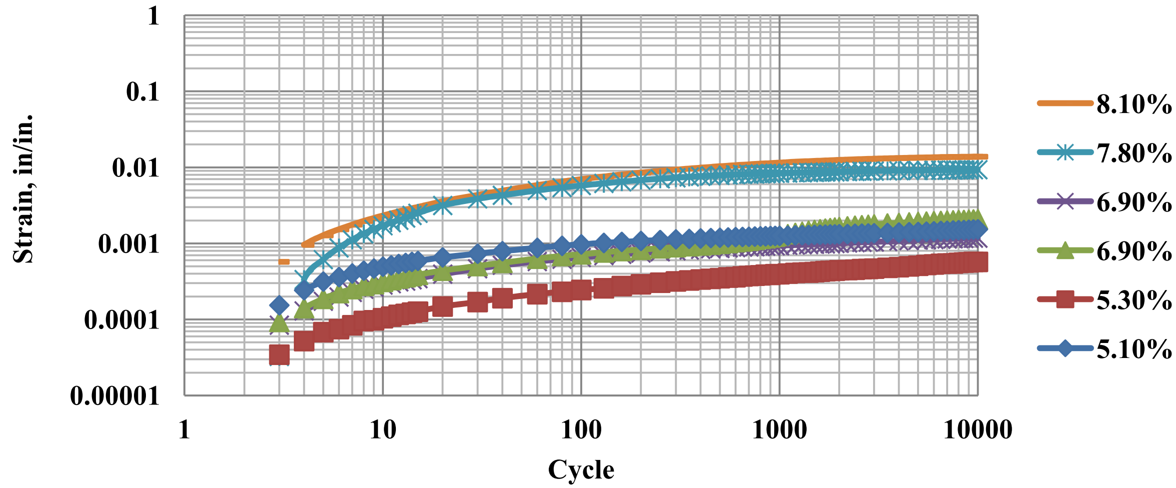


Figure B.43 – Bryan Permanent Deformation Results LVDT Results

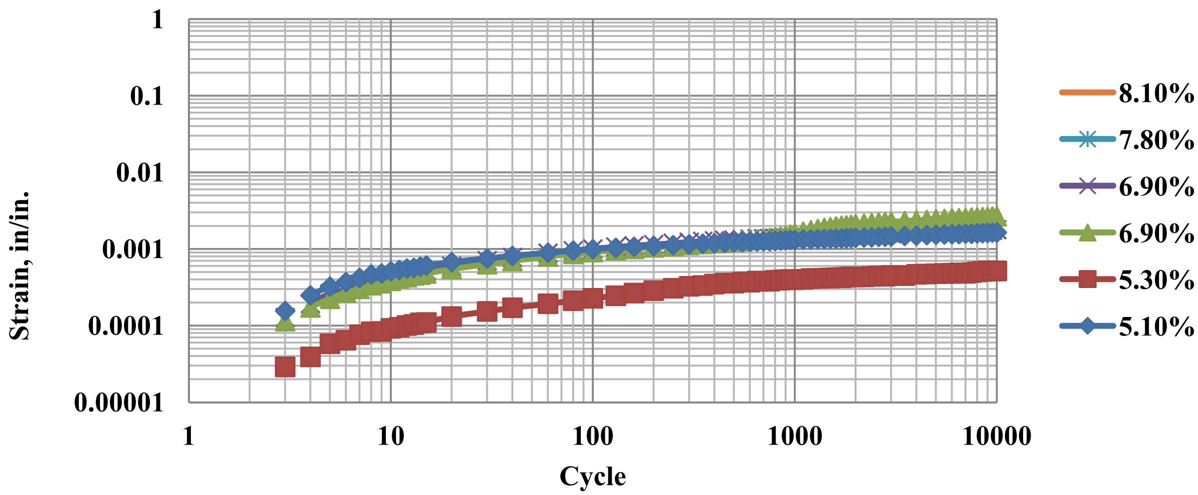


Figure B.44 – Bryan Permanent Deformation Results PROX Results

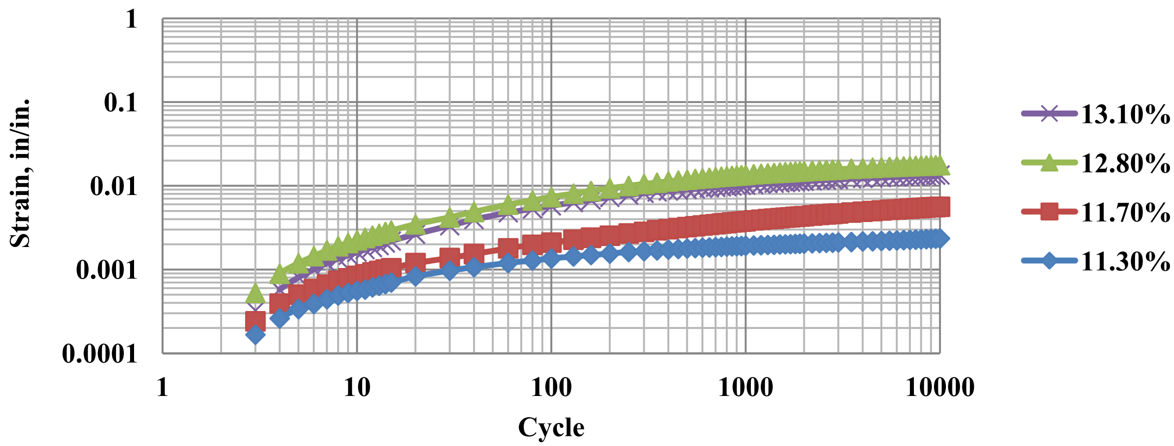


Figure B.45 – Pharr Permanent Deformation Results LVDT Results

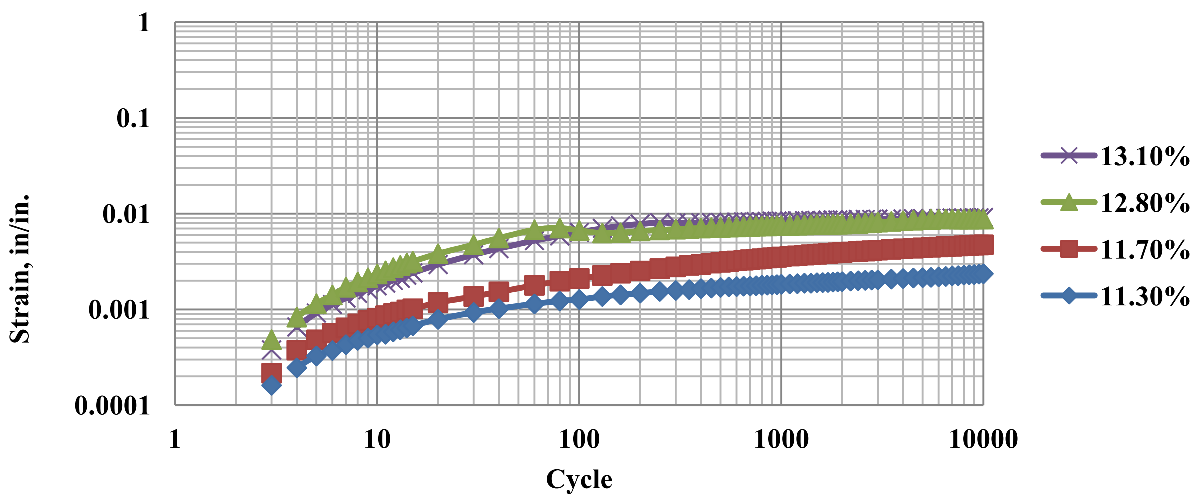


Figure B.46 – Pharr Permanent Deformation Results PROX Results

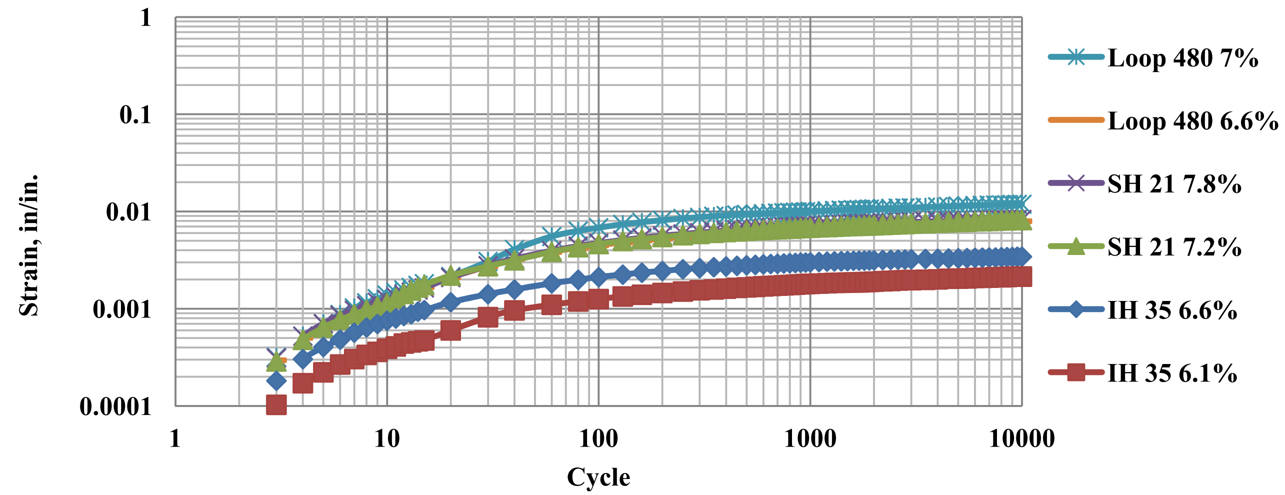


Figure B.47 – Supplementary Materials Permanent Deformation Results LVDT Results

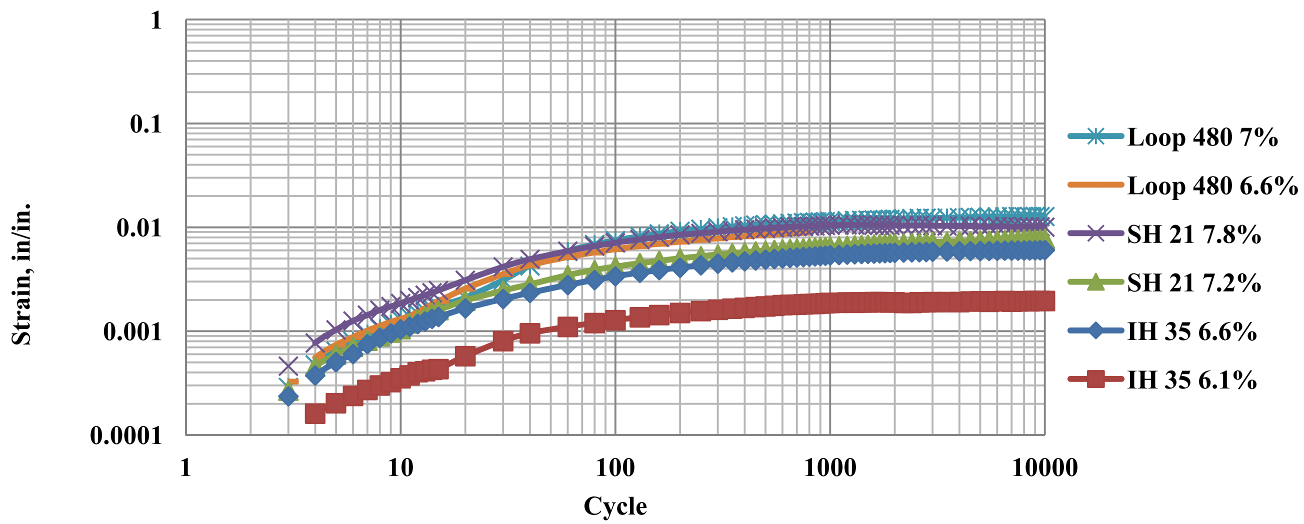


Figure B.48 – Supplementary Materials Permanent Deformation Results PROX Results

APPENDIX C – β COEFFICIENTS FOR DIFFERENT INDEX PARAMETERS FOR ESTIMATING MR AND PD

Table C.1 – β Coefficients for Different Index Parameters for Estimating MR k Parameters (Wet Sieve Analysis)

Parameter k_1			Parameter k_2			Parameter k_3		
Rank	**Index Property**	**β Coefficient**	**Rank**	**Index Property**	**β Coefficient**	**Rank**	**Index Property**	**β Coefficient**
1	Percent Passing 7/8" Sieve	-0.988	1	Maximum or Optimum Dry Density	0.786	1	Maximum or Optimum Dry Density	-0.957
2	Percent Passing #40 Sieve	-0.575	2	Percent of Coarse Sand	-0.286	2	Percent Passing 3/8" Sieve	0.391
3	Percent of Clay	0.406	3	Plastic Index	-0.188	3	Percent of Silt	-0.280
4	Percent of Coarse Sand	-0.236	4	Dry Density Ratio	-0.048	4	Ratio of MC and MOIST	-0.202
5	Liquid Limit	0.008	5	Percent Passing #4 Sieve	-0.045	5	Dry Density Ratio	-0.178
6	Maximum or Optimum Dry Density	-0.007	6	Percent Passing #200	-0.037	6	Liquid Limit	0.043
7	Optimum Moisture Content	0.006	7	Percent Passing #40 Sieve	-0.037	7	Percent Passing #200	0.035
8	Ratio of MC and MOIST	-0.006	8	Percent Passing 3/8" Sieve	-0.029	8	Percent of Coarse Sand	-0.033
9	Specimen Moisture Content	0.006	9	Ratio of MC and MOIST	0.028	9	Percent Passing #40 Sieve	0.031
10	Dry Density of the Sample	-0.006	10	Plastic Limit	-0.027	10	Plastic Index	0.021
11	Dry Density Ratio	0.005	11	Liquid Limit	-0.020	11	Percent of Sand	-0.020
12	Percent of Sand	-0.004	12	Percent of Silt	-0.016	12	Percent Passing 7/8" Sieve	-0.020
13	Percent Fine Sand	-0.004	13	Dry Density of the Sample	-0.008	13	Percent Passing #4 Sieve	0.016
14	Percent Passing #200	0.003	14	Percent Passing 7/8" Sieve	-0.006	14	Plastic Limit	0.015
15	Percent Passing 3/8" Sieve	-0.003	15	Optimum Moisture Content	-0.005	15	Percent of Clay	-0.014
16	Plastic Index	0.002	16	Specimen Moisture Content	-0.003	16	Percent Fine Sand	-0.008
17	Plastic Limit	0.000	17	Percent of Clay	0.002	17	Optimum Moisture Content	0.001
18	Percent Passing #4 Sieve	0.000	18	Percent of Sand	0.002	18	Specimen Moisture Content	0.001
19	Percent of Silt	0.000	19	Percent Fine Sand	0.002	19	Dry Density of the Sample	0.000

Table C.2 – β Coefficients for Different Index Parameters for Estimating MR k Parameters using ITEM 247 Parameters (Dry Sieve Analysis)

Parameter k_1			Parameter k_2			Parameter k_3		
Rank	**Index Property**	**β Coefficient**	**Rank**	**Index Property**	**β Coefficient**	**Rank**	**Index Property**	**β Coefficient**
1	Percent Passing 3/8" Sieve	-0.901	1	Maximum or Optimum Dry Density	0.619	1	Maximum or Optimum Dry Density	-0.860
2	Plastic Limit	0.209	2	Percent of Coarse Sand	-0.349	2	Percent Passing 7/8" Sieve	0.333
3	Specimen Moisture Content	-0.201	3	Percent Passing #40 Sieve	0.145	3	Plastic Index	0.316
4	Liquid Limit	-0.031	4	Plastic Limit	-0.089	4	Ratio of MC and MOIST	-0.220
5	Coefficient of Curvature	0.024	5	Uniformity Coefficient	0.042	5	Dry Density Ratio	-0.158
6	Dry Density Ratio	-0.024	6	Liquid Limit	0.035	6	Percent of Coarse Sand	0.024
7	Dry Density of the Sample	-0.022	7	Plastic Index	-0.035	7	Plastic Limit	-0.023
8	Maximum or Optimum Dry Density	-0.018	8	Coefficient of Curvature	0.023	8	Percent Passing #40 Sieve	-0.021
9	Percent Passing 7/8" Sieve	0.017	9	Dry Density Ratio	-0.015	9	Liquid Limit	0.014
10	Uniformity Coefficient	-0.016	10	Ratio of MC and MOIST	0.013	10	Optimum Moisture Content	0.011
11	Plastic Index	0.012	11	Optimum Moisture Content	0.012	11	Specimen Moisture Content	0.010
12	Ratio of MC and MOIST	-0.008	12	Specimen Moisture Content	0.011	12	Uniformity Coefficient	-0.009
13	Percent of Coarse Sand	-0.007	13	Percent Passing 7/8" Sieve	-0.011	13	Percent Passing 3/8" Sieve	0.002
14	Percent Passing #4 Sieve	-0.006	14	Percent Passing 3/8" Sieve	-0.005	14	Coefficient of Curvature	0.001
15	Optimum Moisture Content	0.000	15	Dry Density of the Sample	-0.002	15	Percent Passing #4 Sieve	-0.001
16	Percent Passing #40 Sieve	0.000	16	Percent Passing #4 Sieve	-0.002	16	Dry Density of the Sample	0.000

Table C.3 – β Coefficients for Different Index Parameters for Estimating PD (Wet Sieve Analysis)

Parameter Resilient Strain εr			Parameter μ			Parameter α		
Rank	**Index Property**	**β Coefficient**	**Rank**	**Index Property**	**β Coefficient**	**Rank**	**Index Property**	**β Coefficient**
1	Specimen Moisture Content	3.347	1	Percent Passing #200	-1.374	1	Percent of Silt	0.844
2	Maximum or Optimum Dry Density	2.704	2	Percent of Silt	1.168	2	Plastic Index	0.735
3	Percent Passing #40 Sieve	0.494	3	Liquid Limit	0.444	3	Percent Passing 3/8" Sieve	-0.608
4	Dry Density Ratio	-0.260	4	Dry Density of the Sample	-0.337	4	Ratio of MC and MOIST	0.398
5	Plastic Index	-0.123	5	Dry Density Ratio	-0.115	5	Dry Density Ratio	0.291
6	Percent of Silt	0.116	6	Percent Passing #4 Sieve	-0.070	6	Percent of Sand	-0.178
7	Percent Fine Sand	0.092	7	Percent of Sand	-0.069	7	Liquid Limit	0.138
8	Percent of Sand	0.085	8	Plastic Limit	-0.068	8	Optimum Moisture Content	-0.042
9	Percent Passing 3/8" Sieve	-0.070	9	Percent of Coarse Sand	-0.057	9	Specimen Moisture Content	-0.040
10	Percent Passing #200	-0.069	10	Percent Fine Sand	-0.049	10	Percent of Coarse Sand	-0.040
11	Percent of Clay	-0.067	11	Percent Passing #40 Sieve	-0.048	11	Dry Density of the Sample	0.039
12	Ratio of MC and MOIST	-0.060	12	Ratio of MC and MOIST	-0.046	12	Maximum or Optimum Dry Density	0.038
13	Liquid Limit	-0.053	13	Percent of Clay	-0.046	13	Percent of Clay	-0.038
14	Plastic Limit	-0.048	14	Maximum or Optimum Dry Density	-0.041	14	Percent Passing 7/8" Sieve	-0.034
15	Percent Passing 7/8" Sieve	-0.043	15	Percent Passing 3/8" Sieve	-0.040	15	Percent Passing #40 Sieve	0.030
16	Percent Passing #4 Sieve	-0.040	16	Specimen Moisture Content	0.030	16	Percent Passing #200	0.018
17	Percent of Coarse Sand	-0.028	17	Optimum Moisture Content	-0.028	17	Percent Fine Sand	0.014
18	Optimum Moisture Content	0.005	18	Percent Passing 7/8" Sieve	-0.026	18	Percent Passing #4 Sieve	0.009
19	Dry Density of the Sample	0.000	19	Plastic Index	0.018	19	Plastic Limit	0.000

Table C.4 – Coefficients for Different Index Parameters for Estimating PD Using Item 247 Parameters (Dry Sieve Analysis)

Parameter Resilient Strain εr			Parameter μ			Parameter α		
Rank	Index Property	β Coefficient	Rank	Index Property	β Coefficient	Rank	Index Property	β Coefficient
1	Specimen Moisture Content	2.224	1	Optimum Moisture Content	-1.374	1	Maximum or Optimum Dry Density	-2.543
2	Maximum or Optimum Dry Density	1.240	2	Percent of Coarse Sand	1.168	2	Dry Density of the Sample	2.056
3	Coefficient of Curvature	-0.918	3	Uniformity Coefficient	0.444	3	Percent of Coarse Sand	-0.647
4	Percent Passing 3/8" Sieve	-0.656	4	Dry Density of the Sample	-0.337	4	Liquid Limit	0.603
5	Uniformity Coefficient	0.546	5	Dry Density Ratio	-0.115	5	Ratio of MC and MOIST	0.429
6	Dry Density Ratio	-0.079	6	Plastic Limit	-0.070	6	Plastic Index	-0.100
7	Ratio of MC and MOIST	0.033	7	Percent Passing #40 Sieve	-0.068	7	Percent Passing #40 Sieve	0.050
8	Plastic Limit	0.014	8	Percent Passing #4 Sieve	-0.048	8	Percent Passing #4 Sieve	0.037
9	Dry Density of the Sample	-0.013	9	Ratio of MC and MOIST	-0.046	9	Coefficient of Curvature	-0.036
10	Plastic Index	0.010	10	Percent Passing 3/8" Sieve	-0.041	10	Plastic Limit	0.032
11	Optimum Moisture Content	-0.003	11	Percent Passing 7/8" Sieve	-0.040	11	Percent Passing 3/8" Sieve	0.031
12	Percent Passing #40 Sieve	0.002	12	Coefficient of Curvature	0.030	12	Percent Passing 7/8" Sieve	0.025
13	Percent of Coarse Sand	-0.002	13	Plastic Index	-0.028	13	Optimum Moisture Content	-0.010
14	Liquid Limit	0.001	14	Maximum or Optimum Dry Density	0.018	14	Specimen Moisture Content	-0.009
15	Percent Passing 7/8" Sieve	0.001	15	Specimen Moisture Content	-0.007	15	Uniformity Coefficient	0.002
16	Percent Passing #4 Sieve	0.000	16	Liquid Limit	-0.006	16	Dry Density Ratio	-0.001

Table C.5 – β Coefficients for Different Index Parameters for Estimating PD at -1.5%OMC (Wet Sieve Analysis)

Parameter Resilient Strain εr			Parameter μ			Parameter α		
Rank	**Index Property**	**β Coefficient**	**Rank**	**Index Property**	**β Coefficient**	**Rank**	**Index Property**	**β Coefficient**
1	Percent Passing 7/8" Sieve	0.722	1	Percent Passing #200	-0.439	1	Plastic Limit	0.528
2	Percent Passing 3/8" Sieve	-0.345	2	Ratio of MC and MOIST	0.131	2	Ratio of MC and MOIST	-0.292
3	Percent of Sand	0.048	3	Dry Density Ratio	0.077	3	Specimen Moisture Content	-0.255
4	Percent Fine Sand	0.047	4	Dry Density of the Sample	0.038	4	Optimum Moisture Content	-0.235
5	Percent Passing #200	-0.035	5	Percent of Clay	-0.032	5	Maximum or Optimum Dry Density	0.232
6	Percent of Silt	0.035	6	Plastic Limit	-0.028	6	Percent Passing 7/8" Sieve	-0.207
7	Percent of Clay	0.032	7	Percent Passing #4 Sieve	-0.025	7	Dry Density Ratio	-0.205
8	Percent of Coarse Sand	0.030	8	Specimen Moisture Content	0.025	8	Dry Density of the Sample	0.200
9	Liquid Limit	-0.026	9	Percent Passing #40 Sieve	-0.023	9	Liquid Limit	-0.158
10	Plastic Limit	0.017	10	Percent Fine Sand	-0.021	10	Percent of Silt	-0.130
11	Plastic Index	-0.016	11	Percent Passing 3/8" Sieve	-0.021	11	Percent Fine Sand	0.123
12	Dry Density of the Sample	-0.016	12	Percent of Sand	-0.020	12	Percent of Sand	0.117
13	Maximum or Optimum Dry Density	-0.012	13	Maximum or Optimum Dry Density	0.014	13	Percent Passing #200	-0.104
14	Specimen Moisture Content	0.012	14	Percent of Silt	-0.013	14	Percent of Clay	-0.045
15	Ratio of MC and MOIST	0.009	15	Plastic Index	-0.012	15	Percent Passing 3/8" Sieve	-0.024
16	Percent Passing #4 Sieve	0.009	16	Optimum Moisture Content	-0.008	16	Percent Passing #4 Sieve	-0.014
17	Dry Density Ratio	-0.005	17	Liquid Limit	-0.006	17	Percent of Coarse Sand	0.006
18	Percent Passing #40 Sieve	0.004	18	Percent Passing 7/8" Sieve	0.003	18	Plastic Index	-0.002
19	Optimum Moisture Content	0.004	19	Percent of Coarse Sand	0.003	19	Percent Passing #40 Sieve	-0.002

Table C.6 – β Coefficients for Different Index Parameters for Estimating PD at -1.5%OMC Using Item 247 Parameters (Dry Sieve Analysis)

Parameter Resilient Strain εr			Parameter μ			Parameter α		
Rank	Index Property	β Coefficient	Rank	Index Property	β Coefficient	Rank	Index Property	β Coefficient
1	Percent Passing #40 Sieve	-0.891	1	Liquid Limit	-0.425	1	Plastic Limit	0.528
2	Percent Passing 7/8" Sieve	-0.472	2	Ratio of MC and MOIST	0.227	2	Ratio of MC and MOIST	-0.292
3	Plastic Limit	-0.071	3	Specimen Moisture Content	0.133	3	Specimen Moisture Content	-0.255
4	Ratio of MC and MOIST	-0.064	4	Uniformity Coefficient	-0.108	4	Optimum Moisture Content	-0.235
5	Percent Passing #4 Sieve	-0.054	5	Optimum Moisture Content	0.099	5	Maximum or Optimum Dry Density	0.232
6	Maximum or Optimum Dry Density	0.053	6	Dry Density Ratio	0.098	6	Percent of Coarse Sand	-0.220
7	Percent Passing 3/8" Sieve	-0.050	7	Maximum or Optimum Dry Density	-0.098	7	Percent Passing #40 Sieve	0.207
8	Dry Density Ratio	-0.049	8	Dry Density of the Sample	-0.081	8	Dry Density Ratio	-0.205
9	Optimum Moisture Content	-0.046	9	Percent Passing #40 Sieve	-0.072	9	Dry Density of the Sample	0.200
10	Specimen Moisture Content	-0.044	10	Plastic Index	-0.058	10	Percent Passing 3/8" Sieve	-0.160
11	Dry Density of the Sample	0.043	11	Percent Passing 7/8" Sieve	-0.052	11	Liquid Limit	-0.158
12	Liquid Limit	-0.041	12	Percent of Coarse Sand	0.044	12	Coefficient of Curvature	-0.157
13	Percent of Coarse Sand	-0.039	13	Plastic Limit	-0.013	13	Percent Passing #4 Sieve	-0.113
14	Plastic Index	-0.037	14	Percent Passing #4 Sieve	-0.012	14	Uniformity Coefficient	0.102
15	Uniformity Coefficient	0.034	15	Coefficient of Curvature	0.008	15	Percent Passing 7/8" Sieve	-0.071
16	Coefficient of Curvature	0.020	16	Percent Passing 3/8" Sieve	0.006	16	Plastic Index	-0.002

CURRICULUM VITA

Eric Navarro was born in June 25, 1986 in Parral ,Chihuahua, Mexico. He is the second son of Gonzalo Navarro and Luz Amanda Villalobos. He graduated from the Instituto Parralense in spring 2003 and entered to the University of Texas at El Paso (UTEP) in fall 2004. He received his bachelor's degree in Civil Engineering from the University of Texas at El Paso in 2010. While pursuing his bachelor degree he joined the Center for Transportation Infrastructure Systems (CTIS) at UTEP as an undergraduate research assistant. After completion of his undergraduate studies, he became Graduate Research Assistant. He continued his master degree while working in CTIS working in a project named: "Development of Models to Estimate Modulus and Permanent Deformation of Texas Bases" funded by the Texas Department of Transportation.

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