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CORRELATION OF RESILIENT MODULUS OF FINE-GRAINED SOILS
WITH COMMON SOIL PARAMETERS FOR USE IN DESIGN OF
FLEXIBLE PAVEMENTS

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Abstract

This thesis describes research conducted at the University of Hawaii at Manoa to evaluate the resilient modulus properties of tropical Hawaiian fine-grained soils for use in flexible pavement design. The objectives of this study were to: a) measure the resilient modulus of four fine-grained soils found on the island of O`ahu, and b) develop predictive equations for resilient modulus based on easily measured soil index properties. Each soil was tested at 100% and 95% relative compaction based on the Standard Proctor compaction test. At each relative compaction, the soils were compacted at three different water contents: at optimum, 2% above- and 2% below optimum.

Correlations were developed based on two resilient modulus stress-state models published by Uzan (1985) and Ni et al. (2002). Regression parameters obtained from the Uzan and Ni et al. models are correlated to soil index properties and physical-state conditions. A total of four regression models are proposed which correlate the resilient modulus to soil stress-state, physical-state, and soil index properties.

Tropical soils may undergo irreversible changes upon drying, resulting in permanent alterations in soil properties. As a result, the resilient modulus of an MH soil was measured at three different stages of drying as follows: (1) at the in situ state; (2) after drying the soil to half the natural water content; and (3) after oven drying. In general, the resilient modulus was found to be more sensitive to changes in confining and deviatoric stresses upon increasing the degree of drying.

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Chapter 1: Introduction

1.1 Background and Problem Statement

The resilient modulus represents a rational measure of the elastic response of roadbed soils subjected to dynamic traffic loading. It has been selected by the American Association of State Highway and Transportation Officials (AASHTO, 1993) as the definitive material property to characterize roadbed soils for mechanistic pavement design. The use of resilient modulus in a mechanistic design procedure provides several benefits over prior design procedures that implement the use of the soil support value, and bearing ratio in a non-mechanistic design approach (AASHTO, 2002). They include:

- Create more efficient and cost-effective designs
- Improve design reliability
- Reduce life cycle costs
- Increase support for cost allocation
- Predict specific failure modes (so they can be minimized)
- Extrapolate from limited field and laboratory data
- Better evaluate the impact of new load levels and conditions
- Make better use of available materials
- Minimize premature failures
- Better characterize seasonal/drainage effects
- Improve rehabilitation design
- Bring daily, seasonal, and yearly changes in materials, climate, and traffic into design process

The resilient modulus test requires expensive equipment and high start-up costs. As a result, it is not an economical test for most laboratories to implement as part of their daily testing schedule. Many states have taken the AASHTO recommendations to establish correlations to approximate resilient modulus as a function of frequently performed laboratory index tests. Although several empirical correlations exist which relate resilient modulus to soil index tests, they were not developed based on tests performed on tropical soils from this region.

1.2 Objectives

The principal objectives of this study were to: a) investigate the resilient properties of Hawaiian fine-grained tropical soils and b) develop a regression model to predict the resilient modulus of fine-grained soils based on easily measured index and other physical properties. More specifically, possible predictor variables investigated included:

- Soil index properties – Atterberg Limits, gradation, and sand equivalent
- Specimen Characteristics – Dry density, relative compaction, moisture content, degree of saturation, and the initial slope of the stress-strain curve from an unconfined compression test

Some tropical soils have a tendency to undergo irreversible changes, especially those that are rich in halloysites. Halloysite consists of alternating kaolinite unit cells and one layer of water molecules resulting in a much weaker bond between the kaolinite units (Mitchell and Sitar, 1982). As weathering

proceeds, the kaolinite content decreases and the halloysite content increases. The halloysite particles are characterized by a tubular morphology. As a result of heating or air-drying, the water layer in the halloysite is removed irreversibly, i.e., the material will not rehydrate to its former amorphous state. The addition of water to the dehydrated sample will result in different properties than the same undried soil of equal moisture content.

An additional objective of this research was to investigate the variation of the resilient modulus for a soil with high in situ moisture content at several stages of drying. Upon drying to each stage, the soil is subjected to the same matrix of tests and differences in the properties are recorded.

1.3 Scope

A literature review is summarized in Chapter 2, which includes a definition of the resilient modulus and a summary of the resilient modulus test procedure as set forth in LTPP Protocol P-46 (1996). Factors that influence the resilient properties of fine-grained soils are then reviewed. A summary of published regression models for predicting resilient modulus of fine-grained soils is also summarized.

Chapter 3 provides a summary of the procedures and results of the index and soil property tests performed in this study. Chapter 4 provides details of the resilient modulus test equipment. Procedures for sample preparation, testing, and data reduction are also discussed. Chapter 5 describes the statistical analyses involved in the development of the regressions equations to predict the resilient

modulus for fine-grained Hawaiian tropical soils. Chapter 6 summarizes the findings of this study and suggests possible areas for further research.

Chapter 2: Review of Previous Work

2.1 Definition of Resilient Modulus

In the United States, one of the methods available for design of flexible pavements is provided in the AASHTO Guide for Design of Pavement Structures (AASHTO, 1993). The AASHTO design guide requires pavement design based on mechanical properties of the asphalt, base course, and soil subgrade layers. A key mechanical property used in flexible pavement design is the resilient modulus (M_r). Under individual cycles of traffic loading, pavement layers essentially behave in an elastic manner. However, minute plastic deformations in the subgrade soil can accumulate over a period of repeated cycles. After a number of loading cycles, the soil's modulus attains a nearly constant value, as the soil behavior becomes approximately elastic. The near constant resilient modulus (M_r), was first observed by Hveem (1955). It is defined as the secant slope of the deviator stress-axial strain curve as depicted in Figure 1.

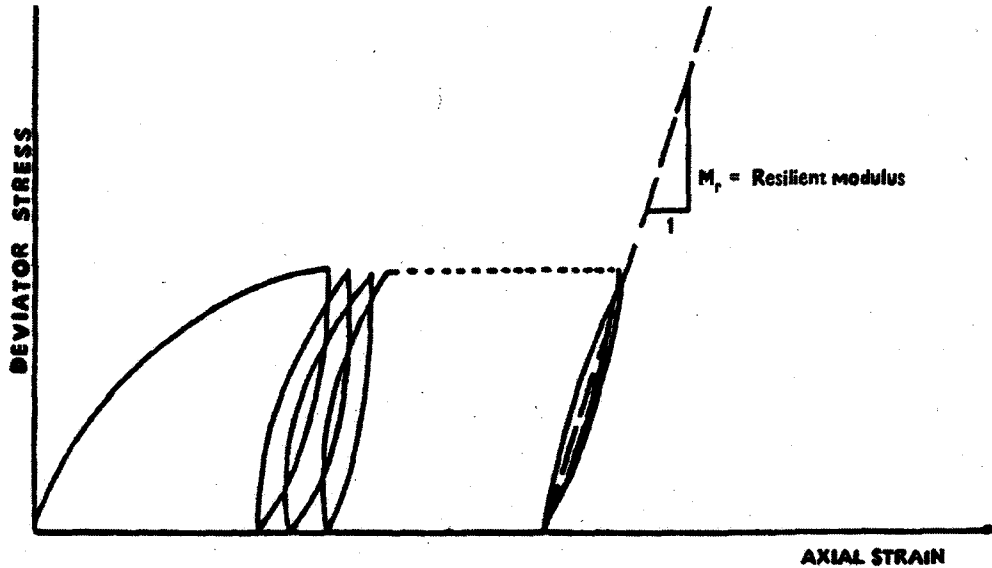


Figure 1: Definition of resilient modulus (after Farrar and Turner, 1991)

$$M_r = \frac{\sigma_d}{\epsilon_d} \quad (1)$$

where M_r = resilient modulus (FL^{-2}), $\sigma_d = \sigma_1 - \sigma_3$, the cyclic deviator stress (FL^{-2}), σ_1 = applied axial or major principal stress (FL^{-2}), σ_3 = applied radial or minor principal stress (FL^{-2}), ϵ_d = resilient or recoverable axial strain (L/L).

Tests to determine the resilient modulus are commonly performed in accordance with the Long Term Pavement Performance (LTPP) Protocol P46 (1996), which has been adopted in AASHTO T307 (2002). The test is performed in a triaxial cell where a haversine shaped cyclic deviator load is applied on a soil specimen subjected to a constant cell pressure. The haversine shaped load pulse has a 0.1 second duration followed by a 0.9-second steady contact load. The contact load is specified to be 10 percent of the maximum axial load applied to the

sample during the respective loading stage. Prior to the test, the protocol requires application of 500 to 1000 cycles of a deviator stress of 27.6 kPa (4.0 psi) under a 41.4 kPa (6 psi) confining pressure to condition the sample. The purposes of conditioning are to: (1) better simulate the events occurring between compaction and traffic loading and (2) reduce the effects of improper contact between the top cap and the specimen. The LTPP Protocol P46 testing sequence for subgrade soils is summarized in Table 1.

Table 1: Testing Sequence for Subgrade Soils (LTPP Protocol P46, 1996)

| Sequence No. | Confining Pressure, σ_3 | | Max. Axial Stress σ_{max} | | Cyclic Stress σ_{cyclic} | | Contact Stress $0.1\sigma_{max}$ | | No. of Load Applications |
|--------------|--------------------------------|-----|----------------------------------|-----|---------------------------------|-----|----------------------------------|-----|--------------------------|
| | kPa | psi | kPa | psi | kPa | psi | kPa | psi | |
| 0 | 41.1 | 6 | 27.6 | 4 | 24.8 | 3.6 | 2.8 | 0.4 | 500-1000 |
| 1 | 41.1 | 6 | 13.8 | 2 | 12.4 | 4.8 | 1.4 | 0.2 | 100 |
| 2 | 41.1 | 6 | 27.6 | 4 | 24.8 | 3.6 | 2.8 | 0.4 | 100 |
| 3 | 41.1 | 6 | 41.4 | 6 | 37.3 | 5.4 | 4.1 | 0.6 | 100 |
| 4 | 41.1 | 6 | 55.2 | 8 | 49.7 | 7.2 | 5.5 | 0.8 | 100 |
| 5 | 41.1 | 6 | 68.9 | 10 | 62 | 9 | 6.9 | 1 | 100 |
| 6 | 27.6 | 4 | 13.8 | 2 | 12.4 | 1.8 | 1.4 | 0.2 | 100 |
| 7 | 27.6 | 4 | 27.6 | 4 | 24.8 | 3.6 | 2.8 | 0.4 | 100 |
| 8 | 27.6 | 4 | 41.4 | 6 | 37.3 | 5.4 | 4.1 | 0.6 | 100 |
| 9 | 27.6 | 4 | 55.2 | 8 | 49.7 | 7.2 | 5.5 | 0.8 | 100 |
| 10 | 27.6 | 4 | 68.9 | 10 | 62 | 9 | 6.9 | 1 | 100 |
| 11 | 13.8 | 2 | 13.8 | 2 | 12.4 | 1.8 | 1.4 | 0.2 | 100 |
| 12 | 13.8 | 2 | 27.6 | 4 | 24.8 | 3.6 | 2.8 | 0.4 | 100 |
| 13 | 13.8 | 2 | 41.4 | 6 | 37.3 | 5.4 | 4.1 | 0.6 | 100 |
| 14 | 13.8 | 2 | 55.2 | 8 | 49.7 | 7.2 | 5.5 | 0.8 | 100 |
| 15 | 13.8 | 2 | 68.9 | 10 | 62 | 9 | 6.9 | 1 | 100 |

Protocol P46 requires a total of about 2500 load cycles at various confining and deviatoric stresses during the conditioning and shearing stages of each test. Adding the significant cost and time required for equipment set-up, verification and calibration makes this test uneconomical for routine pavement design. Therefore, various researchers have proposed alternative methods of estimating the resilient modulus. These methods are summarized in Section 2.3.

2.2 Factors Influencing Resilient Modulus of Fine-Grained Soils

Factors that influence the magnitude of resilient modulus of fine-grained soils can be grouped into three major categories: (1) loading condition or stress state, (2) soil type and structure, and (3) soil physical state (Li and Selig, 1994).

2.2.1 Loading Condition or Stress State

Loading condition or stress state includes the effects of deviator stress, confining pressure, and number of load cycles. Fine-grained soils typically display a decrease in moduli with increasing deviator stress. Confining stress has a less significant effect than deviator stress for fine-grained soils. However, soils typically display a higher resilient modulus at higher confining stresses. Elliott et al (1988) indicated that at higher confining pressures in fine-grained soils, variations in resilient modulus due to changes in confining stress are reduced. Pavement subgrades are usually subjected to low confining pressures. Therefore, neglecting the effects of confining pressure as proposed in many models may compromise the accuracy of the resilient modulus estimate. Confining stress has been shown to have a reasonably small effect on high plasticity soils (Pezo and Hudson, 1994). However, it becomes increasingly important when the plasticity decreases; i.e., as the soil becomes more granular.

Constitutive models for predicting the resilient modulus of granular and cohesive soils have been summarized in the literature (Barksdale et al., 1997, Li

and Selig, 1994, Maher et al., 2000, and Ni et al., 2002). The constitutive models can be divided into four categories:

(1) models that include the effects of confining stress only (Dunlap, 1963);

$$M_r = K_1 \sigma_3^{K_2} \quad (2)$$

where σ_3 is the confining stress and K_1 and K_2 are regression constants.

(2) models that include the effects of bulk stress only (Seed et al., 1967);

$$M_r = K_1 \theta^{K_2} \quad (3)$$

where θ is the bulk stress = $(\sigma_1 + \sigma_2 + \sigma_3)$.

(3) models that include the effects of deviator stress only;

- Bilinear model (Thompson and Robnett, 1976) – see Figure 2. A bilinear model is typically characterized by a “breakpoint” resilient modulus, where a significant change in slope occurs.

$$M_r = K_1 + K_2 \sigma_d \quad \text{for } \sigma_d < \sigma_{d\text{breakpoint}} \quad (4)$$

$$M_r = K_3 + K_4 \sigma_d \quad \text{for } \sigma_d > \sigma_{d\text{breakpoint}} \quad (5)$$

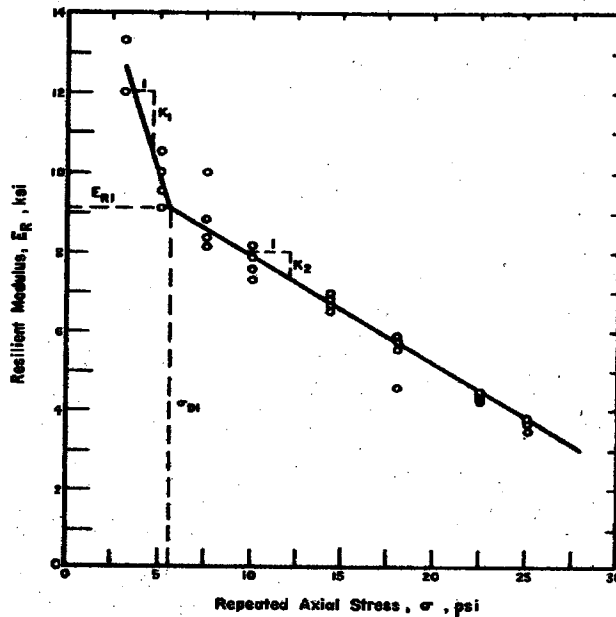


Figure 2: Bilinear Variation of Resilient Modulus with Deviator Stress (Thompson and Robnett, 1979)

- Hyperbolic model (Drumm et al., 1990)

$$M_r = \frac{K_1 + K_2 \sigma_d}{\sigma_d} \quad (6)$$

- Power model (Moossazadeh and Witczak, 1981; Pezo et al., 1991; Brown et al., 1975; and Brown, 1979)

$$M_r = K_1 \sigma_d^{K_2} \quad (7)$$

- Semi-log model (Fredlund et al., 1977; and Raymond et al., 1979)

$$M_r = 10^{(K_1 - K_2 \sigma_d)} \quad (8)$$

(4) models that include the effects of confinement and shear.

Overall, these models are more comprehensive than the ones in the previous categories and are summarized in Table 2 along with their shortcomings.

Table 2: Resilient Modulus Models that Include Effects of Confinement and Shear

| Model | Equation | Shortcomings |
|-------------------------|---------------------------------------------------------------------------------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Shackel (1973) | $M_r = K_1 \frac{\sigma_{oct}^{K_2}}{\tau_{oct}^{K_3}}$ | 1. In an isotropic stress state, M_r tends to infinity. 2. M_r is undefined when $\sigma_1 = \sigma_2 = \sigma_3 = 0$. |
| Brown et al. (1987) | $M_r = K_1 \sigma_d \left(\frac{\sigma_{oct}}{\sigma_d} \right)^{K_2}$ | 1. In an isotropic stress state, M_r is undefined. 2. M_r is undefined when $\sigma_1 = \sigma_2 = \sigma_3 = 0$. |
| Uzan (1985) | $M_r = K_1 p_a \left[\frac{\theta}{p_a} \right]^{K_2} \left[\frac{\sigma_d}{p_a} \right]^{K_3}$ | 1. In an isotropic stress state, $M_r = 0$ when $K_3 > 0$ and M_r tends to infinity when $K_3 < 0$. 2. $M_r = 0$ when $\sigma_1 = \sigma_2 = \sigma_3 = 0$. |
| Witczak and Uzan (1988) | $M_r = K_1 p_a \left[\frac{\theta}{p_a} \right]^{K_2} \left[\frac{\tau_{oct}}{p_a} \right]^{K_3}$ | Same as above |
| Pezo (1993) | $M_r = K_1 p_a \left[\frac{\sigma_3}{p_a} \right]^{K_2} \left[\frac{\sigma_d}{p_a} \right]^{K_3}$ | Same as above |
| Ni et al. (2002) | $M_r = K_1 \left(1 + \frac{\sigma_3}{p_a} \right)^{K_2} \left(1 + \frac{\sigma_d}{p_a} \right)^{K_3}$ | None |

Definitions

1. M_r = resilient modulus
2. σ_{oct} = octahedral normal stress = $(\sigma_1 + \sigma_2 + \sigma_3)/3$
3. τ_{oct} = octahedral shear stress = $[(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2]^{1/2}/3$
4. θ = bulk stress = $(\sigma_1 + \sigma_2 + \sigma_3)$
5. σ_d = deviator stress = $\sigma_1 - \sigma_3$
6. $\sigma_1, \sigma_2, \sigma_3$ = major, intermediate and minor principal stresses
7. p_a = atmospheric pressure
8. K_1, K_2, K_3 = regression constants

The Shackel (1973) and Witczak and Uzan (1988) models are identical. The models summarized in Table 2 are the most comprehensive models available for practitioners. The two models that are considered in this study are the models of Uzan (1985) and Ni et al. (2002). Other more advanced models are geared

towards research applications (e.g., Boyce, 1976; Brown and Pappin, 1981; Crockford et al., 1990). However, as the focus of this thesis is to develop correlations geared for design, the advanced models are not considered herein.

The number of loading cycles also affects the resilient modulus, but for values of deviator stress below the soil shear strength, the resilient modulus will tend to a constant value with increasing number of load cycles.

2.2.2 Soil Type or Structure

Soil structure is affected by compaction method, compaction effort, and molding water content. Soil structure affects the resilient modulus of compacted fine-grained soils. Seed et al. (1962) showed that clayey soils subjected to kneading compaction wet of optimum tend to have a more dispersed structure, whereas dry-of-optimum soils under the same compaction method tend to be more flocculated. In general, clays with a flocculated structure tend to display higher resilient modulus than similar clays with a dispersed structure (Farrar and Turner, 1991). Elliot et al. (1988) has also noted the higher resilient modulus of statically compacted samples versus simulated samples subjected to a kneading compaction. LTPP protocol P46 and AASHTO T-307 require static compaction for fine-grained soils.

2.2.3 Soil Physical State

Soil physical state can be represented by moisture content and dry unit weight. These two factors define the coordinates on a compaction curve for a given compaction effort. Based on a compilation of resilient modulus test results from the literature, Li and Selig (1994) showed that for a given dry unit weight the resilient modulus decreases with increasing water content.

The influence of dry density on the resilient modulus is shown in Figure 3. At low moisture contents, higher values of resilient modulus are attained with increasing dry density whereas at high moisture contents, the resilient modulus decreases with increasing dry density.

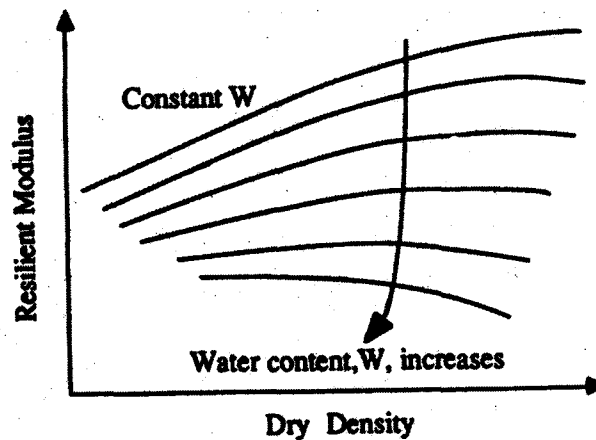


Figure 3: Resilient Modulus Relationship to Soil Physical State (Li and Selig, 1994)

Soil thixotropy has also been shown to affect resilient modulus of laboratory compacted specimens (Pezo and Hudson, 1994). Kneading compacted samples that are allowed to age prior to testing have shown some gain in resilient modulus.

However, the effect of soil thixotropy is most evident in high plasticity soils (Pezo and Hudson, 1994).

2.3 Statistical Models for Estimating Resilient Modulus

Statistical models provide relationships between resilient modulus and common soil parameters. Many models are available in the literature and they include those developed by:

- Jones and Witczak (1972)
- Thompson and Robnett (1979)
- Carmichael and Stuart (1985)
- Elliott, et al. (1988)
- Thompson and LaGrow (1988)
- Drumm, et al. (1990)
- Farrar and Turner (1991)
- Hudson, et al. (1994)
- Li and Selig (1994)
- Pezo and Hudson (1994)
- Berg et al. (1996)
- Other models

A summary of the variables used in the models discussed in Sections 2.3.1 through 2.3.11 is provided below:

w = Water content (%)

w_{opt} = Optimum water content based on AASHTO T99 Standard Proctor compaction tests (%)

S = Degree saturation (%)
 σ_d = Deviatoric stress (F/L^2)
 σ_c = Confining stress (F/L^2)
 S_{200} = Percent passing the #200 sieve
 % CLAY = Percent Clay (%)
 % SILT = Percent Silt (%)
 CLASS = Numerical value based on AASHTO classification (i.e. an A-7-6 soil would be issued a value of 7.6)
 CL = 1 for CL soil; 0 otherwise
 MH = 1 for MH; 0 otherwise
 a' and b' = see discussion in Section 2.3.6
 $\Delta\gamma_d$ = Deviation from maximum dry density based on AASHTO T99 (F/L^3)
 Δw = Deviation from optimum water content (w_{opt}) based on Standard Proctor compaction test (%)
 F1 through F6 = Refer to Table 4
 $f(S)$ = Normalized degree of saturation
 $f(\sigma)$ = Normalized octahedral stress

2.3.1 Jones and Witczak (1972)

Jones and Witczak (1972) developed a model based on the analysis of 97 undisturbed field samples of Southern-California clay. All the samples tested are classified as A7-6 in accordance with the AASHTO soil classification system. The soil samples were tested under a maximum cyclic deviator stress of 6 psi and a confining pressure of 2 psi. The model relating resilient modulus with the degree of saturation and water content is as follows:

$$\text{Log } M_r \text{ (ksi)} = -0.111 w + 0.0217 S + 1.179 \quad (9)$$

The coefficient of determination (R^2) in this study was 0.44.

2.3.2 Thompson and Robnett (1979)

Thompson and Robnett (1979) studied the resilient characteristics of several Illinois fine-grained subgrade soils. Samples were prepared using a kneading compactor. Linear regression equations were developed to relate the resilient modulus, in ksi, at a deviatoric stress of 6 psi to several key soil characteristics. The equation with one of the highest coefficients of determination ($R^2 = 0.796$) is as follows:

$$M_r(\text{ksi}) = 6.37 + 0.034\% \text{CLAY} + 0.450 \text{PI} - 0.0038\% \text{SILT} - 0.244 \text{CLASS} \quad (10)$$

where

M_r = resilient modulus measured at $\sigma_d = 6$ psi for soils with a relative compaction of 95% in accordance with AASHTO T99 density

%CLAY = clay content (%)

PI = plasticity index (%)

%SILT = silt content (%)

CLASS = AASHTO classification, e.g. an A7-6 soils would be entered as 7.6

This model has limited use as it calculates the resilient modulus estimate at only one stress-state.

2.3.3 Carmichael and Stuart (1985)

Based on a literature search, Carmichael and Stuart (1985) collected results of resilient modulus tests performed on over 250 different soils from several states. The test results were placed in a computer database for regression studies. The resulting model for estimating resilient modulus, in ksi, of cohesive soils is as follows:

$$M_r = 37.431 - 0.4566PI - 0.6179w - 0.1424S200 + 0.1791\sigma_3 - 0.3248\sigma_d + 36.422CL + 17.097MH \quad (11)$$

where

CH = 1 for CH soil, 0 otherwise (for MH, ML, or CL soil)

MH = 1 for MH soil, 0 otherwise

S200 = Percent passing the #200 sieve (%)

The coefficient of determination (R^2) was 0.759.

It should be noted that Carmichael and Stuart did not perform the tests used to develop this correlation. Much of the data used were results of tests performed prior to development of AASHTO T274-82, when no standard procedure existed.

2.3.4 Elliot *et al.* (1988)

Twelve Arkansas subgrade soils were tested in this study. One soil was coarse-grained (AASHTO classification of A-2-4), while the other 11 soils were fine-grained. Atterberg limits, grain size distribution, organic content, R-value, and

AASHTO T99 tests were performed on the soils to examine possible correlations with soil resilient modulus. Resilient modulus testing was performed in accordance with AASHTO T274-82. The study resulted in two resilient modulus models at two different deviator stresses of 4 and 8 psi as follows:

$\sigma_d = 4$ psi:

$$M_r \text{ (ksi)} = 11.21 + 0.17 \% \text{CLAY} + 0.20 \text{ PI} - 0.73 w_{\text{opt}} \quad (12)$$

$\sigma_d = 8$ psi:

$$M_r \text{ (ksi)} = 9.81 + 0.13 \% \text{CLAY} + 0.16 \text{ PI} - 0.60 w_{\text{opt}} \quad (13)$$

The coefficients of determination for Equations 12 and 13 were 0.80 and 0.77, respectively.

2.3.5 Thompson and LaGrow (1988)

Thompson and LaGrow analyzed the data from prior resilient modulus testing performed on several Illinois fine-grained soils. The study was conducted to analyze resilient modulus moisture adjustment factors for different fine-grained soils. The moisture adjustment factor represents the decrease in resilient modulus (ksi) per each 1 percent increase in moisture above optimum. The moisture adjustment factors developed by Thompson and LaGrow are as follows:

Table 3: Moisture Adjustment Factors (Thompson and LaGrow, 1988)

| USDA Textural Class | Moisture Sensitivity (ksi/%) |
|-------------------------------------|---------------------------------|
| clay / silty clay / silty clay loam | 0.7 |
| silt loam | 1.5 |
| Loam | 2.1 |

2.3.6 Drumm et al. (1990)

Drumm et al. (1990) tested eleven different fine-grained soils sampled throughout the state of Tennessee. Resilient modulus tests were performed in accordance with AASHTO T274-82. Two prediction models were developed based on the results of resilient modulus and unconfined compression tests (AASHTO T208, ASTM D2166). One model, which estimates the breakpoint resilient modulus at a deviator stress of 6 psi (41 kPa), is as follows:

$$M_{ri}(\text{ksi}) = 45.8 + \frac{0.00052}{a} + 0.188q_u + 0.45PI - 0.216\gamma_d - 0.25S - 0.15S200 \quad (14)$$

where

M_{ri} = breakpoint resilient modulus

a = initial tangent modulus (psi) of a stress-strain curve from unconfined compression tests (see Figure 4.)

q_u = unconfined compressive strength (psi)

γ_d = dry unit weight (pcf)

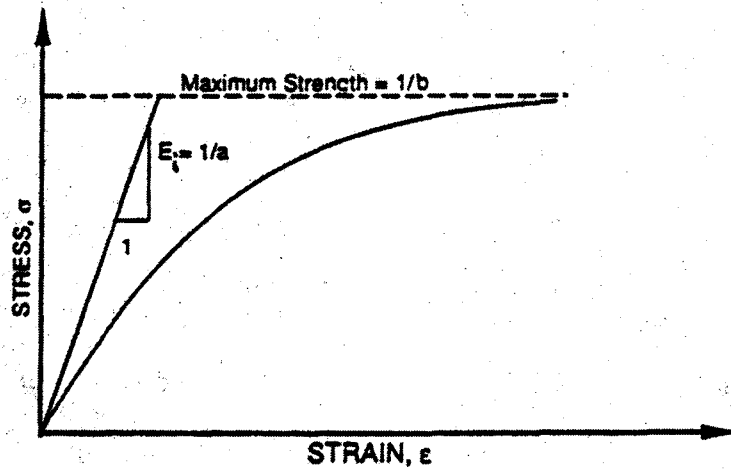


Figure 4: Stress-Strain Curve From an Unconfined Compression Test and Definition of the Initial Tangent Modulus (1/a), (Drumm et al., 1990)

The coefficient of determination (R^2) of this model was 0.83.

The second model relates the soil resilient modulus to the deviator stress using a hyperbolic equation as follows:

$$M_r(\text{ksi}) = \frac{a' + b'\sigma_d}{\sigma_d} \quad (15)$$

where

$$a' = 318.2 + 0.377q_u + 0.73\% \text{CLAY} + 2.26\text{PI} - 0.915\gamma_d - 2.19\text{S} - 0.304\text{S200} \quad (16)$$

$$b' = 2.10 + \frac{0.00039}{a} + 0.104(q_u) + 0.09(\text{LL}) + -0.10(\text{S200}) \quad (17)$$

where

LL = liquid limit (%)

%CLAY = percent finer than 0.002 mm

The coefficient of determination of the model for estimating resilient modulus at various deviator stresses is 0.80. This model is noted to have discrepancies when estimating resilient modulus at low deviatoric stresses. However, the model accurately predicts resilient modulus values over the range of deviator stress required in pavement design.

2.3.7 Farrar and Turner (1991)

Farrar and Turner (1991) developed a correlation between resilient modulus and several easily measured soil properties for thirteen typical Wyoming fine-grained subgrade soils. AASHTO classifications of the soil samples ranged from A4 to A7-6. Each soil was sampled from the field and compacted at three different moisture contents and dry densities in accordance with AASHTO T99. Soil samples were compacted using an electro-hydraulic kneading compactor. The prepared specimens were then sealed and stored in a moisture room for a 24-hour period minimum to allow uniform moisture distribution as well as dissipation of transient pore pressures. The resilient modulus tests were performed in accordance with AASHTO T274. The resilient modulus model developed by Farrar and Turner is as follows:

$$M_r = 30280 - 359S - 325\sigma_d + 237\sigma_c + 86PI + 107S200 \quad (18)$$

The coefficient of determination (R^2) was 0.663.

2.3.8 Hudson et al. (1994)

Seventy-five resilient modulus tests were performed on eight Tennessee subgrade soils in accordance with SHRP Protocol P46 (1989). The soils tested ranged from A4 through A7-6 based on the AASHTO classification system. The specimens were prepared under a range of moisture contents and dry densities using a kneading pneumatic compactor. Specimens were capped with a hydrocal gypsum cement to fill imperfections in specimen ends and provide a smooth surface for loading. Hudson et al. (1994) proposed the following model for the estimation of resilient modulus:

$$\begin{aligned} \text{Log}M_r(\text{psi}) = & 46.93 + 0.0188\sigma_d + 0.0333\Delta\gamma_d - 0.1143\text{LI} + 0.4680\text{S} + 0.0085\text{CLASS}^2 \\ & - 0.0033\Delta\gamma_d^2 - 0.0012\sigma_c^2 + 0.0001\text{PL}^2 - 0.0278\text{LI}^2 - 0.0017\text{S}^2 - 38.44\text{LogS} \\ & - 0.2222\text{Log}\sigma_d \end{aligned} \tag{19}$$

where

- $\Delta\gamma_d$ = deviation from the Standard Proctor maximum dry density (\pm pcf)
= $\gamma_d - \gamma_{d\text{max}}$
- LI = liquidity index (%)
- Δw = deviation from the optimum water content, w_{opt} , based on the Standard Proctor compaction tests (\pm %)

The coefficient of determination (R^2) was 0.70.

2.3.9 Li and Selig (1994)

Li and Selig (1994) proposed a method for predicting the resilient modulus of fine-grained soils that considers the influence of soil physical and stress states. To consider the effect of physical state, Li and Selig proposed two equations relating resilient modulus to moisture content. These equations are based on a literature review of numerous cyclic triaxial tests performed on various soils from all over the continental United States. One equation, for resilient modulus estimation along paths of constant dry density, is as follows:

$$R_{m1} = 0.98 - 0.28\Delta w + 0.29\Delta w^2 \quad (20)$$

where

$R_{m1} = M_r / M_{r\text{opt}}$ for the case of constant dry density and $M_{r\text{opt}}$ is the resilient modulus at the optimum water content. Equation 20 is derived based on Fig. 5 and has a coefficient of determination of 0.76.

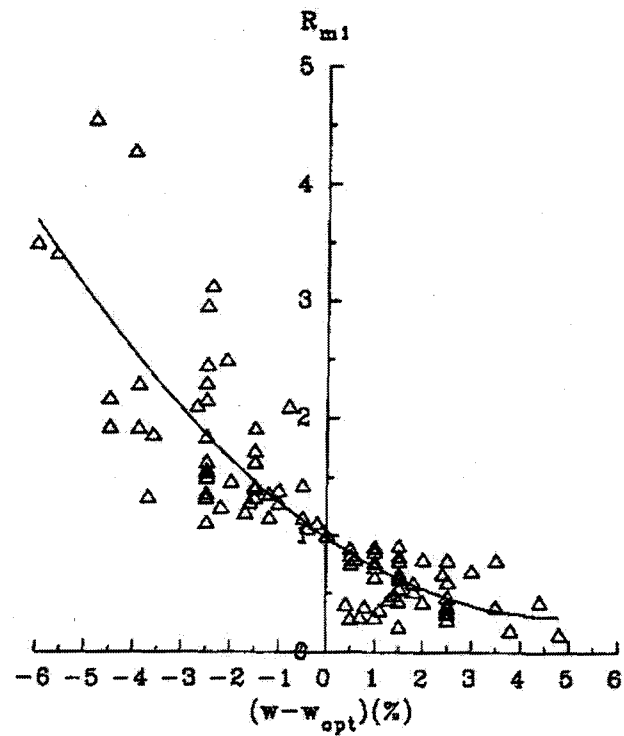


Figure 5: Resilient Modulus and Moisture Content Relationship with Constant Dry Density (Li and Selig, 1994)

The other equation is for paths of constant compactive effort as follows:

$$R_{m2} = 0.96 - 0.18\Delta w + 0.067\Delta w^2 \quad (21)$$

where

$$R_{m2} = M_r / M_{ropt} \text{ for the case of constant compactive effort}$$

Equation 21 is derived from the results shown in Figure 6 and has a coefficient of determination of 0.83.

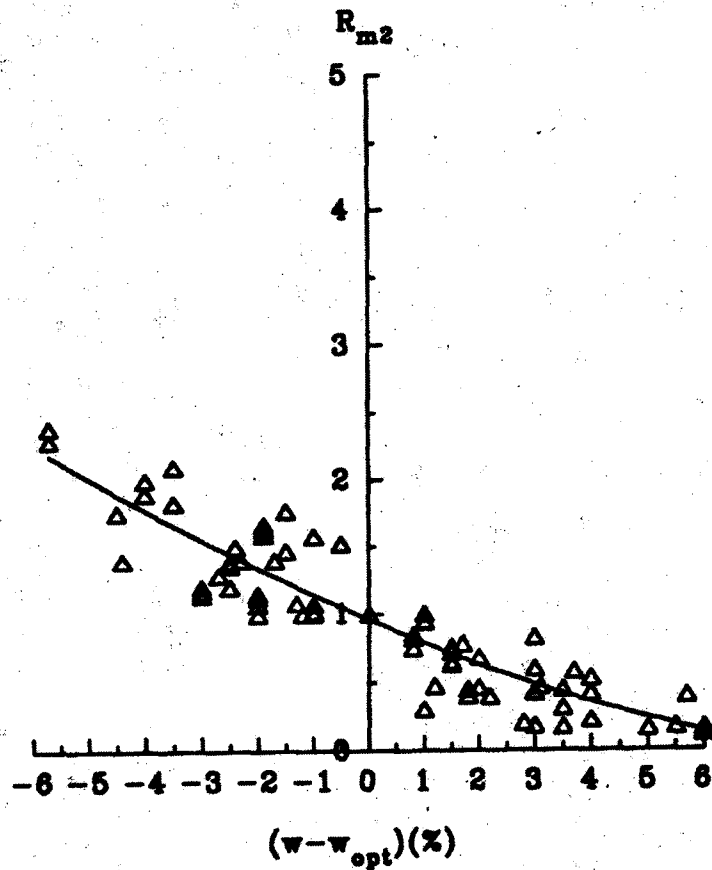


Figure 6: Relation Between M_r and w at Constant Compactive Effort (Li and Selig, 1994)

Li and Selig's procedure requires estimation of the resilient modulus at one physical state *a priori*. Typically, the resilient modulus at maximum dry density and optimum moisture content can be estimated via laboratory testing or using one of the other methods described in this chapter. Their procedure for estimation of resilient modulus at any physical state is as follows:

1. Estimate $M_{r, \text{opt}}$ either directly by testing or using available models from previous tests on other soils.

2. If the resilient modulus is needed at another physical state (another compactive effort or moisture content and dry density) other than that for Step 1, then Equations 20 and/or 21 should be used as follows:
 - a. If the resilient modulus is required at constant dry density but at a different compactive effort, use Equation 20. The resilient modulus, $M_r = R_{m1}M_{r\text{opt}}$. If the resilient modulus is required at constant compactive effort but at a different moisture content and dry density, then use Equation 21. In this case, the resilient modulus, $M_r = R_{m2}M_{r\text{opt}}$.
 - b. If the resilient modulus is required at a different compactive effort and a different dry density and moisture content, then several steps are required. The following three cases may be encountered:
 - i. If M_r at Point Q in Figure 7 is required and M_r is known at Point O from step a, then Path OQ = Path OA + Path AQ. Using the value of M_r at Point A, estimate M_r at Point Q using Equation 21.

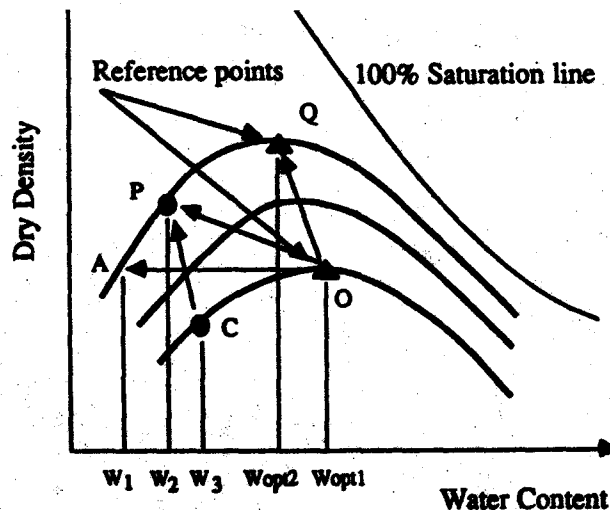


Figure 7: Paths for Determining Resilient Modulus at Any Physical State (Li and Selig, 1994)

- ii. If M_r at Point P is required and M_r is known at Point O from Step a, then Path OP = Path OA + Path AQ + Path QP. M_r at Point Q can be estimated using Step i. Using the value of M_r at Point Q, estimate M_r at Point P using Equation 20.
- iii. In a general case where M_r at Point C is known and M_r at Point P is required, then Path CP = Path CO + Path OA + Path AQ + Path QP. First, using the M_r at Point C, estimate M_r at Point O using Equation 21. Then estimate M_r at Point P using Step ii.

2.3.10 Pezo and Hudson (1994)

Soil samples with a wide range of characteristics were selected throughout the state of Texas for this study. Resilient modulus tests were performed in accordance with SHRP Protocol P46 (1989) procedure. A resilient modulus prediction model was established based on six factors that gave the highest degree of correlation for these soils. The model is as follows:

$$M_r = F_0 * F_1 * F_2 * F_3 * F_4 * F_5 * F_6 \quad (22)$$

where

$F_0 = 9.80$ ksi (English units) or 67.60 MPa (SI units)

$F_1 =$ correction factor for moisture content

$F_2 =$ correction factor for percent of dry density with respect to the maximum density

$F_3 =$ correction factor for soil plasticity

$F_4 =$ correction factor for age of compacted specimen

F_5 = correction factor for confining pressure

F_6 = correction factor for deviator stress

The coefficient of determination for this model was 0.803. Values for the correction factors are shown in Table 4. Other factors such as AASHTO classification, dry density, seating pressures, and percent fines were also analyzed for resilient modulus correlation. However, within the scope of the study no correlations for these factors were evident.

Table 4: Correction Factors (Pezo and Hudson, 1994)

| Moisture Content (%) | F_1 |
|----------------------|-------|
| 10 | 4.0 |
| 15 | 2.0 |
| 20 | 1.0 |
| 25 | 0.5 |

| γ_d / γ_{dmax} (%) | F_2 |
|--------------------------------|-------|
| 100 | 1.00 |
| 95 | 0.90 |
| 90 | 0.80 |
| 85 | 0.70 |

| Plasticity Index (%) | F_3 |
|----------------------|-------|
| 10 | 1.00 |
| 20 | 1.50 |
| 30 | 2.00 |
| ≥ 40 | 2.50 |

| Sample Age (days) | F_4 |
|-------------------|-------|
| 2 | 1.00 |
| 10 | 1.10 |
| 20 | 1.15 |
| ≥ 30 | 1.20 |

| σ_c (kPa / psi) | F_5 |
|------------------------|-------|
| 13.8 / 2 | 1.00 |
| 27.6 / 4 | 1.05 |
| 41.4 / 6 | 1.10 |
| | |
| | |

| σ_d (kPa / psi) | F_6 |
|------------------------|-------|
| 13.8 / 2 | 1.00 |
| 27.6 / 4 | 0.98 |
| 41.4 / 6 | 0.96 |
| 55.2 / 8 | 0.94 |
| 69.0 / 10 | 0.92 |

The properties of the soils tested fall within the following ranges: (1) moisture content from 10 to 35%; (2) relative compaction from 80 to 100% based on AASHTO T99; (3) plasticity index from 4 to 52%; (4) compacted specimen age from 2 to 188 days; (5) confining stress from 13.8 to 41.4 kPa (2 to 6 psi); and (6) deviator stress from 11 to 102.8 kPa (1.6 to 14.9 psi).

2.3.11 Berg et al. (1996)

Berg et al. (1996) conducted a study on one fine-grained and several coarse-grained Minnesota soils. The fine-grained soil was a sandy lean clay (CL). The soil was prepared at several different moisture contents but at a single dry density of about 110 pcf. The final form of the resilient modulus model is as follows:

$$M_r (\text{psi}) = 1.518 \times 10^{30} [f(S)]^{-13.85} [f(\sigma)]^{-0.272} \quad (23)$$

where

$f(S)$ = Saturation normalized by a unit saturation of 1.0%

$f(\sigma)$ = Octahedral shear stress, τ_{oct} , normalized by a unit stress of 1.0 psi

$$\tau_{\text{oct}} = (\sqrt{2}/3) \sigma_d \quad (24)$$

The coefficient of determination (R^2) was 0.95.

2.3.12 Other Models

Correlations of M_r with strength parameters, such as CBR and Hveem resistance or R-value exist. However, CBR and R-value correlations do not

acknowledge the stress state dependence of the resilient modulus and are therefore limited in applicability. The Asphalt Institute (1982) published the following relationship between resilient modulus and R-value:

$$M_r = A + B \times R \quad (25)$$

where

A = constant which varies from 772 to 1,155

B = constant which varies from 369 to 555

R = R-value (AASHTO T190)

For fine-grained soils with an R-value less than or equal to 20, AASHTO (1993) recommends A = 1000 and B = 555.

Tri Buu (1980) reported the following relationship for fine-grained Idaho soils with R-values greater than 20.

$$M_r (\text{ksi}) = 1.6 + 0.038R \quad (26)$$

This correlation was developed for resilient modulus under the following conditions, $\sigma_d = 6$ psi and $\sigma_3 = 2$ psi.

Heukelom and Klomp (1962) proposed the following relationship between the CBR value and the resilient modulus:

$$M_r (\text{psi}) = 1500\text{CBR} \quad (27)$$

However, the lower and upper bound values of the constant proportionality were 750 and 3000, respectively. According to AASHTO (1993), Equation 27 gives reasonable estimates of resilient modulus for fine-grained soils with a CBR value of 10 or less.

Powell et al. (1984) related resilient modulus to CBR based on tests on U.K. soils. In the U.K., the CBR test is usually performed on samples prepared at the same dry density and moisture content as the soils in the field without soaking. Their proposed relationship is:

$$M_r (\text{psi}) = 2555 \times \text{CBR}^{0.64} \quad (28)$$

2.3.13 Summary of Models

Several models proposed by researchers around the United States have been summarized in Section 2.3. Application of these models to design in practice should be approached with practical engineering judgment. The following are questions engineers should ask prior to applying a resilient modulus model for use in design:

- Is the correlation based on soils similar to the ones in the field?
- What is the range of dry density and water content that the model is based on?
- How many samples and tests are the models based on?
- Is the measured resilient modulus used for developing the model based on standardized test procedures?

The previously published models described in Section 2.3 were judged to be inapplicable to tropical soils because they were derived based on non-tropical soils, in some cases, the coefficient of determination was too low or the model was derived based on non-standard procedures for measuring the resilient modulus. A summary of these models is included in Table 5.

Table 5: Summary of Equations Predicting the Resilient Modulus of Fine-Grained Soils

| State | Researcher | Resilient Modulus | R ² |
|---------|------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|----------------|
| CA | Jones and Witczak | $\text{Log } M_r \text{ (ksi)} = -0.111 w + 0.0217 S + 1.179$ | 0.44 |
| CO | Farrar and Turner | $M_r \text{ (psi)} = 30280 - 359 S - 325 d + 237 c + 86 \text{ PI} + 107 \text{ S200}$ | 0.663 |
| IL | Thompson and Robnett | $M_r \text{ (ksi)} = 6.37 + 0.034 \% \text{CLAY} + 0.450 \text{ PI} - 0.0038 \% \text{SILT} - 0.244 \text{ CLASS}$ | 0.796 |
| General | Carmichael and Stewart | $M_r \text{ (ksi)} = 37.431 - 0.4566 \text{ PI} - 0.6179 w - 0.1424 \text{ S200} + 0.1791 3 - 0.3248 d + 36.422 \text{ CL} + 17.097 \text{ MH}$ | 0.759 |
| AK | Elliot, et al. | $M_r \text{ (ksi)} = 11.21 + 0.17 \% \text{CLAY} + 0.20 \text{ PI} - 0.73 w_{\text{opt}}$; when $d = 4 \text{ psi}$ | 0.8 |
| | | $M_r \text{ (ksi)} = 9.81 + 0.13 \% \text{CLAY} + 0.16 \text{ PI} - 0.60 w_{\text{opt}}$; when $d = 8 \text{ psi}$: | 0.77 |
| WY | Farrar and Turner | $M_r \text{ (psi)} = 30280 - 359 S - 325 d + 236 c + 86 \text{ PI} + 107 \text{ S200}$ | 0.663 |
| TN | Drumm, et al. | $M_r \text{ (ksi)} = (a' + b' \sigma_d) / (\sigma_d)$ | 0.8 |
| TN | Hudson et al. | $\text{Log } M_r \text{ (psi)} = 46.93 + 0.0188 d + 0.0333 \Delta w d - 0.1143 \text{ LI} + 0.4680 S + 0.0085 \text{ CLASS}^2 - 0.0033 \Delta w^2 - 0.0012 c^2 + 0.0001 \text{ PL}^2 - 0.0278 \text{ LI}^2 - 0.0017 S^2 - 38.44 \log S - 0.2222 \log d$ | 0.7 |
| General | Li and Selig | $R_{m1} = 0.98 - 0.28 \Delta w + 0.029 \Delta w^2$ | 0.76 |
| | | $R_{m2} = 0.96 - 0.18 \Delta w + 0.067 \Delta w^2$ | 0.83 |
| TX | Pezo and Hudson | $M_r = F_0 * F_1 * F_2 * F_3 * F_4 * F_5 * F_6$ | 0.803 |
| MN | Berg, et al. | $M_r = 1.518 * 10^{30} f(S)^{-13.85} f(\sigma)^{-0.272}$ | 0.95 |

Chapter 3: Soil Index Property Testing

3.1 Sampling Locations

Sample locations were selected to obtain soils with widely varying Atterberg Limits. However, due to the difficult process of permitting, and right of way issues final selection of soils for resilient testing was somewhat hampered. As a result, soils from the following four locations on the island of O'ahu, Hawai'i, were sampled for resilient testing (Figure 8):

- Waipio - February 1, 2001
- Kapolei - May 24, 2001
- Mililani Mauka - September 25, 2001
- Wahiawa - February 7, 2002

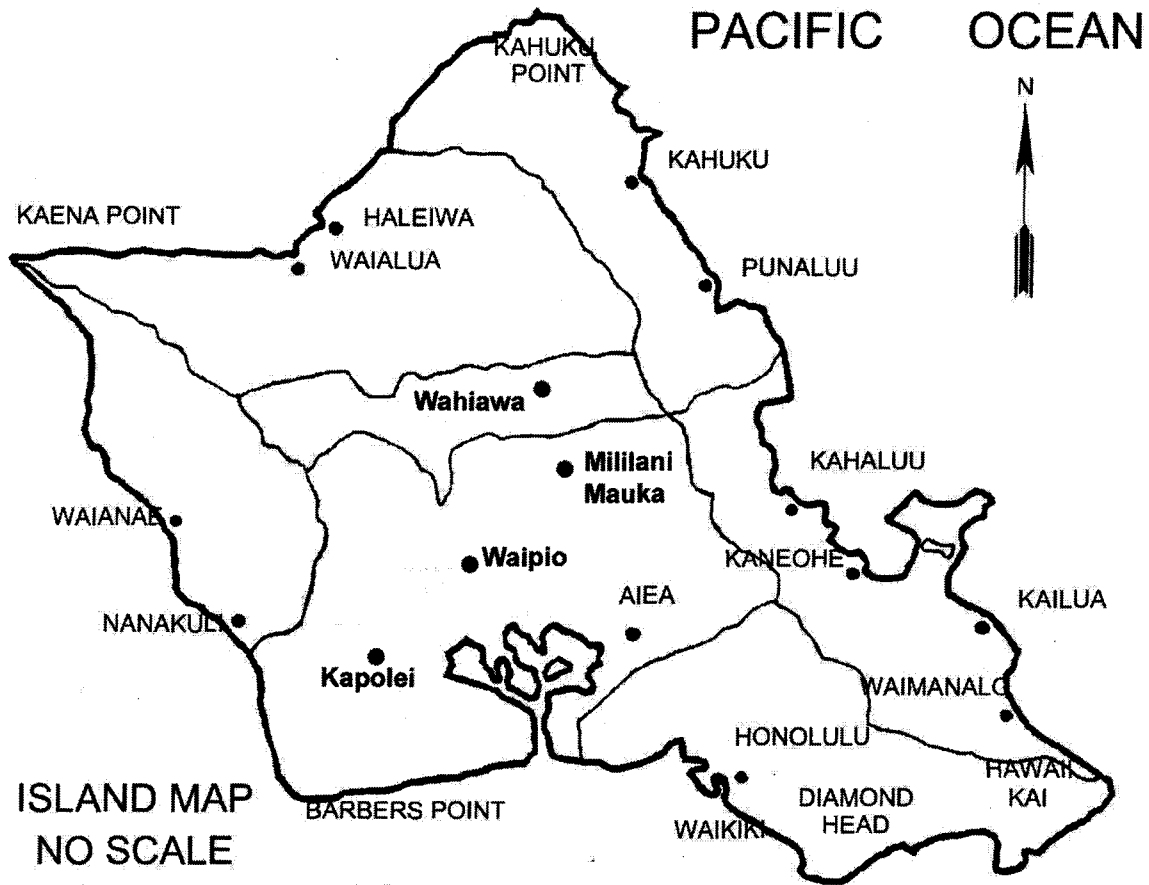


Figure 8: Soil Sampling and Testing Locations

A trench was dug at each location to expose the undesiccated soil for in situ testing. To preserve the in-situ moisture content, the soil samples were placed in durable plastic bags, which were then heat-sealed, placed in a 5-gallon plastic bucket, and capped off with a lid containing an O-ring seal. The buckets were stored in a 100%-humidity, curing room located in the structures lab in Holmes Hall at the Department of Civil and Environmental Engineering, University of Hawai'i. Additionally, moisture contents were recorded on the day of sampling to monitor any changes in moisture content during the storage time between sampling and

testing. These steps are necessary to avoid possible irreversible changes in properties that could occur upon drying.

The Wahiawa soil had very high in situ water contents (51 to 57%). This soil was tested at various stages of drying to study the effects of irreversible changes on the various soil properties. The Wahiawa soil was subjected to the following three stages of drying:

1. No drying or testing at the in situ water content.
2. Drying to approximately half the in situ water content.
3. Owendrying.

The other soils had lower in situ moisture contents and were tested without drying except in some cases where a few tests were performed on owendried samples to see if they undergo irreversible changes upon drying.

3.2 Index Tests and Results

Laboratory tests were performed to determine the following:

- Atterberg limits
- Grain size distribution
- Specific gravity
- Sand equivalent
- Compaction curves

3.2.1 Atterberg Limits

Liquid and plastic limits were determined in accordance with ASTM Standard D4318-98 and are summarized in Table 6.

Table 6: Atterberg Limits Test Results

| | | Atterberg Limits | | | | | | Average | Ovendried |
|---------------------------|------------------|------------------|----|----|-----|----|----|-----------|-----------|
| | | | | | | | | | |
| Kapolei | Liquid Limit | 42 | 40 | 42 | 41 | 41 | -- | 41 | 37 |
| | Plastic Limit | 26 | 28 | 26 | 28 | 28 | -- | 27 | 25 |
| | Plasticity Index | 16 | 12 | 15 | 14 | 13 | -- | 14 | 12 |
| Waipio | Liquid Limit | 45 | 43 | 48 | 46 | -- | -- | 46 | 43 |
| | Plastic Limit | 25 | 27 | 38 | 29 | -- | -- | 30 | 31 |
| | Plasticity Index | 20 | 17 | 10 | 17 | -- | -- | 16 | 12 |
| Mililani Mauka | Liquid Limit | 97 | 88 | 96 | 100 | -- | -- | 95 | 58 |
| | Plastic Limit | 47 | 44 | 39 | 47 | -- | -- | 44 | 38 |
| | Plasticity Index | 50 | 44 | 57 | 53 | -- | -- | 51 | 20 |
| Wahiawa <i>in situ</i> | Liquid Limit | 94 | 97 | 97 | 109 | 97 | -- | 99 | -- |
| | Plastic Limit | 44 | 48 | 49 | 49 | 45 | -- | 47 | -- |
| | Plasticity Index | 50 | 49 | 47 | 60 | 52 | -- | 51 | -- |
| Wahiawa Intermediate | Liquid Limit | 90 | 85 | 88 | -- | -- | -- | 87 | -- |
| | Plastic Limit | 41 | 42 | 44 | -- | -- | -- | 42 | -- |
| | Plasticity Index | 49 | 43 | 44 | -- | -- | -- | 45 | -- |
| Wahiawa Ovendry | Liquid Limit | 71 | 60 | 69 | 55 | 65 | 63 | 64 | -- |
| | Plastic Limit | 48 | 44 | 44 | 42 | 43 | 45 | 44 | -- |
| | Plasticity Index | 24 | 17 | 25 | 12 | 22 | 17 | 19 | -- |

The test results are also summarized in a plasticity chart shown in Figure 9. Based on the Unified Soil Classification System (USCS), soils from Waipio and Kapolei are classified as low plasticity silt, or ML. Soils from Mililani Mauka and Wahiawa are classified as high plasticity silt, or MH.

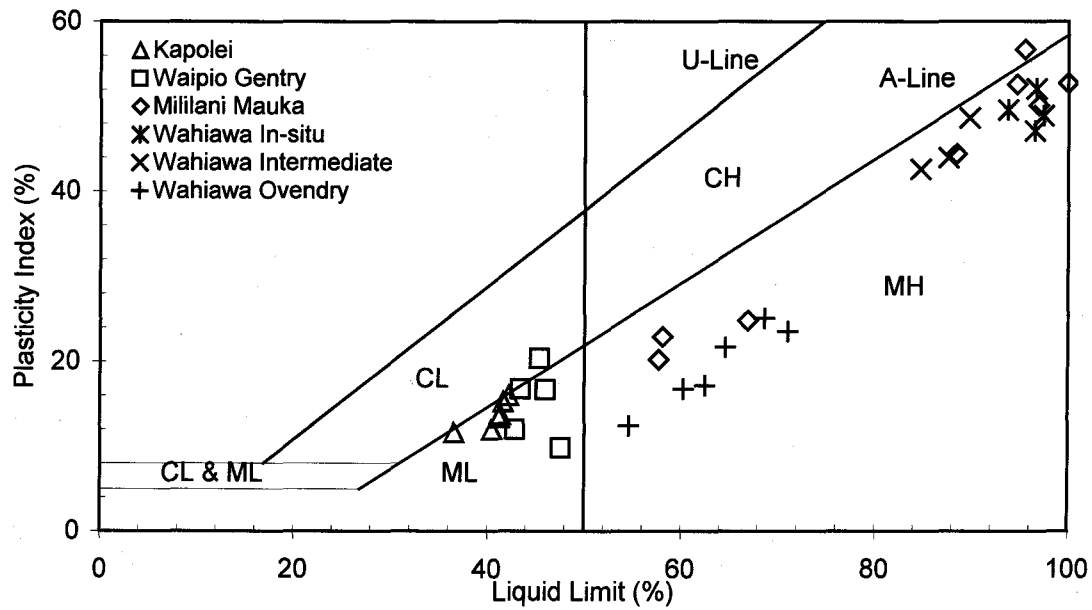


Figure 9: Atterberg Limits and Plasticity Chart

3.2.2 Compaction

Standard Proctor tests were performed in accordance with Procedure C of ASTM Standard D698-91. The soil was compacted in three lifts (56 blows per lift) in a 6-inch-diameter mold using a 5.5-lb-hammer. In general, the ML soils have a higher maximum dry unit weight and lower optimum water content than the MH soils. The compaction curves for all soils in this study are plotted in Figure 10.

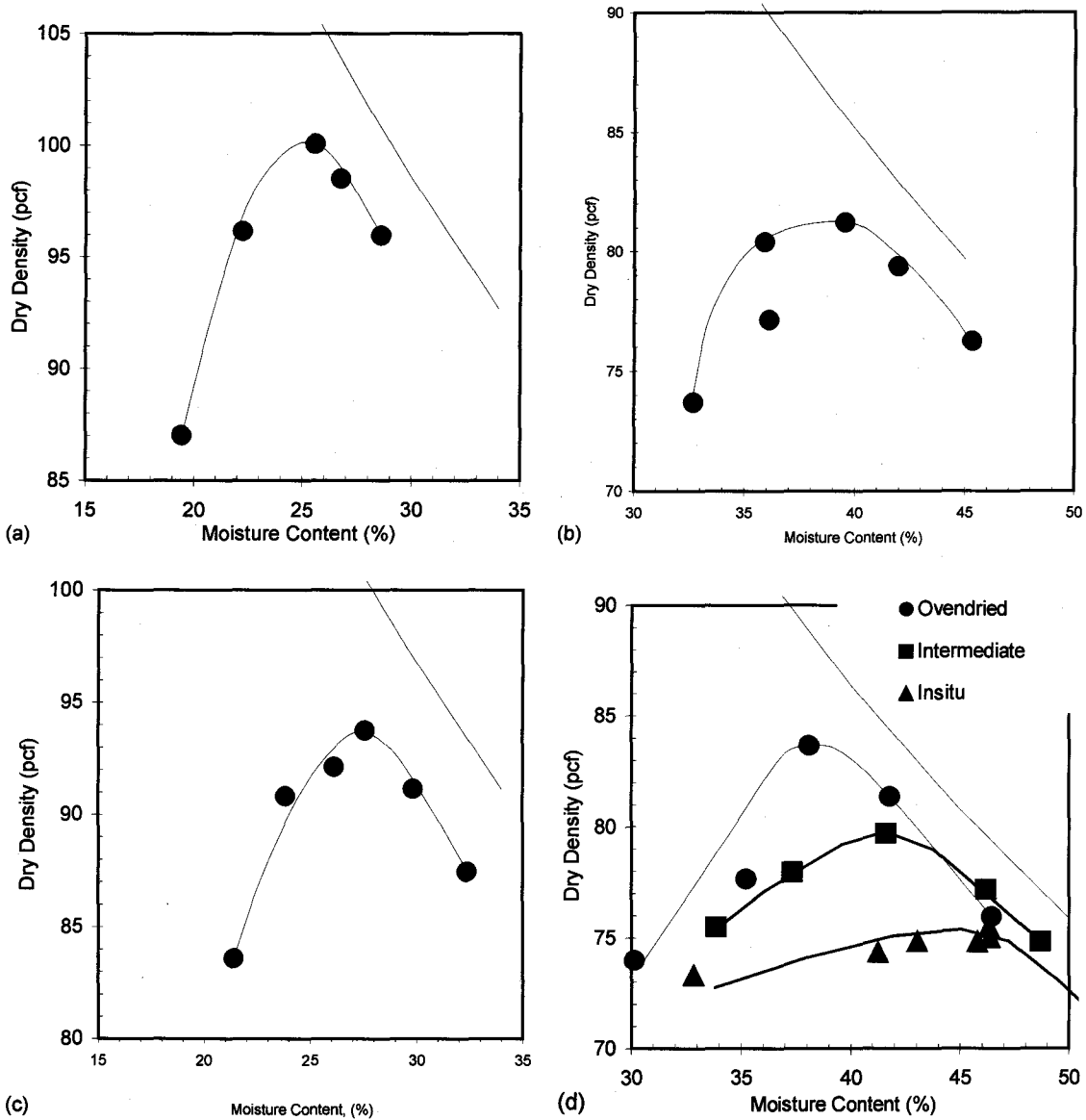


Figure 10: Standard Proctor Compaction Curves for (a) Kapolei, (b) Mililani Mauka, (c) Waipio, and (d) Wahiawa

In cases where the target molding moisture contents were lower than in situ values, individual batches of soil were dried down to the target moisture content. This wet-to-dry compaction was necessary to minimize irreversible changes that might occur had the soils been dried and then rewetted.

3.2.3 Grain Size Distribution

Grain size distributions were obtained by performing hydrometer testing and wet sieve analyses in accordance with ASTM Standard D422-63. Three variations of the wet sieve/hydrometer tests were used on the Kapolei soil to assess the sensitivity of each method:

Method 1.

1. Soil from the same bucket were divided into two 100g portions.
2. The total dry weight was then estimated.
3. One portion of (1) is wet sieved and the material retained on the sieves was oven-dried to determine the dry weights. The portion passing the No. 200 sieve is not saved.
4. The second portion of the soil from (1) was wet sieved through the No. 200 sieve and the fines and water were collected.
5. The collected soil/water mix from (4) was then dried to a moisture content that is near, but not less than the in situ value.
6. After determining the moisture content, a portion of the moist, fines from (5), equivalent to a dry weight of approximately 50g was subjected to hydrometer testing. The actual dry weight of soil used in the hydrometer test was determined at the conclusion of the hydrometer test.
7. The results from (3) and (6) were then combined to yield the complete grain size distribution.

Method 2.

This method is the same as method 1 except for steps 1 and 5. In step 1, only one portion of the sample was used for wet sieving. In step 5, all the fines passing the No. 200 sieve were collected for hydrometer testing.

Method 3.

This method is the same as method 2 except that the soil retained on the No.60, 100 and 200 sieves was mixed with 100ml of standard sodium hexametaphosphate solution for several hours and stirred in a mechanical blender. The deflocculated material was wet sieved through the stack of the three finest sieves again. The material retained on the sieves was oven-dried to determine the dry weights while the fraction passing through the No. 200 sieve was collected and dried to a moisture content near the in situ value. After determining the moisture content, a portion of the moist fines equivalent to a dry weight of 50g was subjected to hydrometer testing.

The results from all three methods are plotted in Figure 11. Methods 2 and 3 are the most tedious to perform because a significant amount of water has to be dried off prior to the hydrometer test. When the gradation from the methods were compared, they all yielded similar results, although method 3 yielded a slightly finer grain size distribution because of the use of the deflocculant prior to wet sieving through the three smallest sieves. Because the differences are relatively insignificant, and for the sake of convenience, the grain size distributions of the soil from the other three locations were obtained using the simpler method 1.

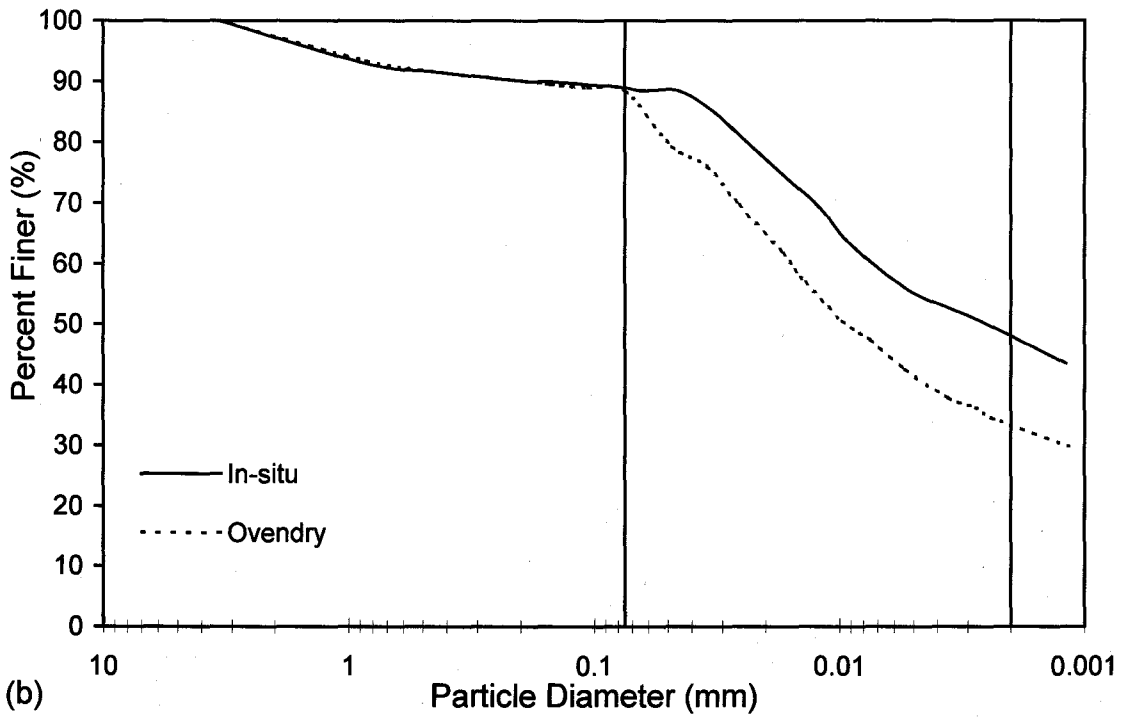
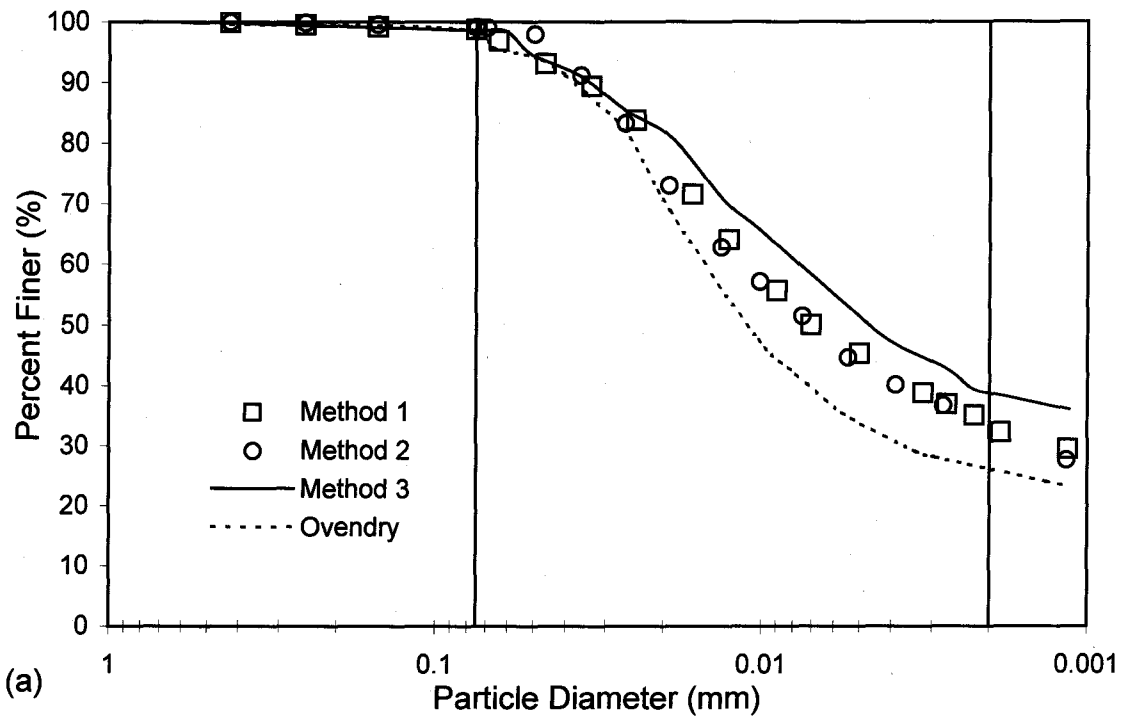


Figure 11: Grain Size Distribution for Soils from (a) Kapolei, (b) Waipio, (c) Mililani Mauka, and (d) Wahiawa

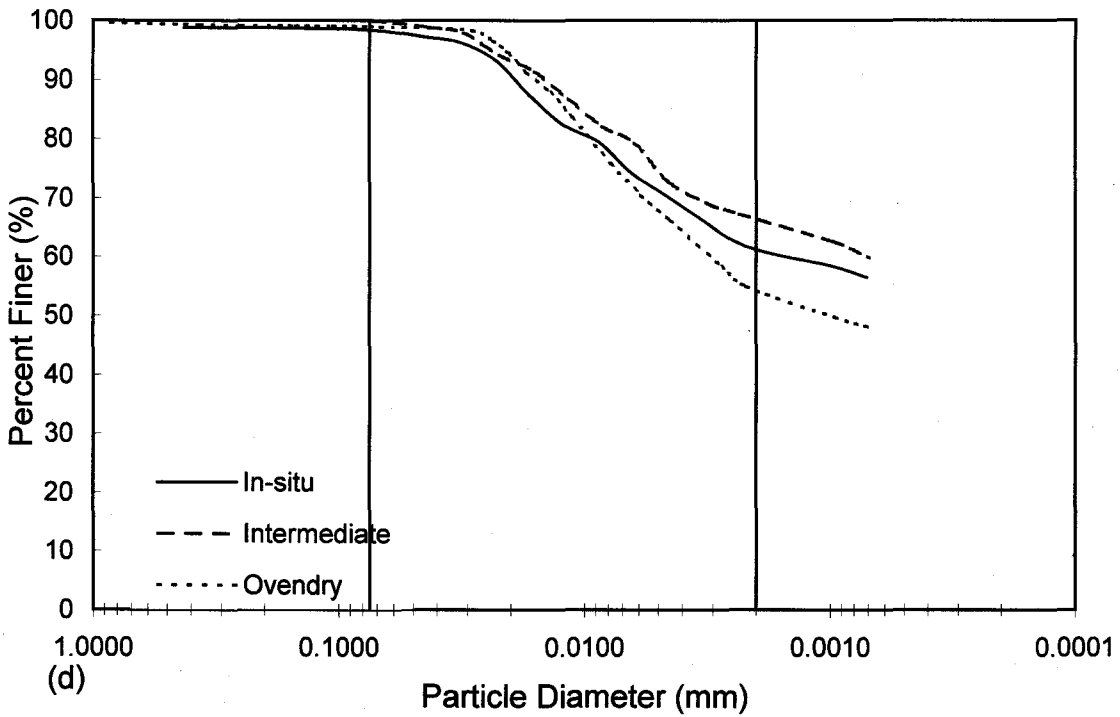
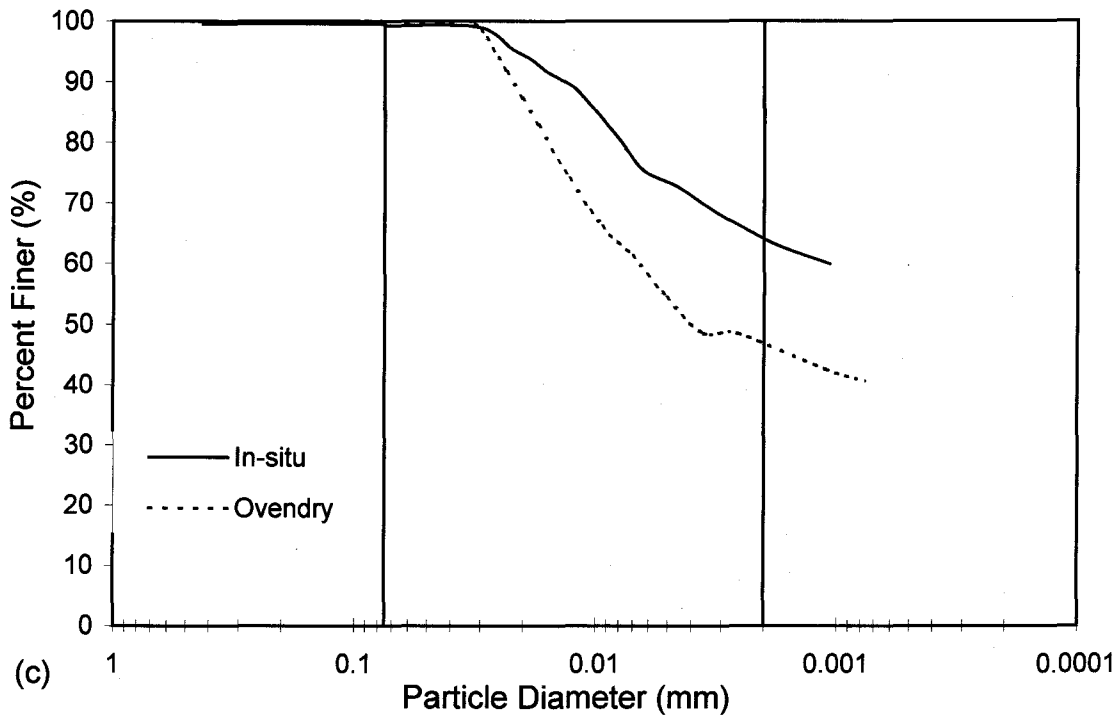


Figure 11: Grain Size Distribution for Soils from (a) Kapolei, (b) Waipio, (c) Mililani Mauka, and (d) Wahiawa

3.2.4 Sand Equivalent

The sand equivalent tests were performed in accordance with AASHTO T176-97, the results of which are summarized in Table 7.

Table 7: Sand Equivalent Test Results

| | Sand Equivalent | | |
|------------------------|-----------------|-----------|---------|
| | In situ | Std. Dev. | Ovendry |
| Kapolei | 8 | 1 | 12 |
| Waipio | 12 | 4 | 12 |
| Mililani Mauka | 11 | 3 | 10 |
| Wahiawa <i>in situ</i> | 15 | 2 | -- |
| Wahiawa Intermediate | 24 | 0 | -- |
| Wahiawa Owendry | 20 | 1 | -- |

3.2.5 Specific Gravity

The specific gravity of the soils in this study was measured in accordance with ASTM Standard D854-98, the results of which are summarized in Table 8.

Table 8: Specific Gravity Test Results

| | Specific Gravity | | |
|------------------------|------------------|-----------|---------|
| | In situ | Std. Dev. | Owendry |
| Kapolei | 3.00 | 0.08 | 3.06 |
| Waipio | 2.90 | 0.07 | 2.90 |
| Mililani Mauka | 2.98 | 0.04 | 3.00 |
| Wahiawa <i>in situ</i> | 3.08 | 0.12 | -- |
| Wahiawa Owendry | 3.11 | 0.13 | -- |

Chapter 4: Resilient Modulus Equipment and Test Procedure

4.1 Equipment

The resilient modulus testing equipment used consists of a closed-loop electrohydraulic loading control system capable of applying repeated cycles of a haversine-shaped load pulse, nominally 0.1 seconds in duration; followed by a rest period of 0.9 seconds. Figure 12 shows a general overview of the major system components.

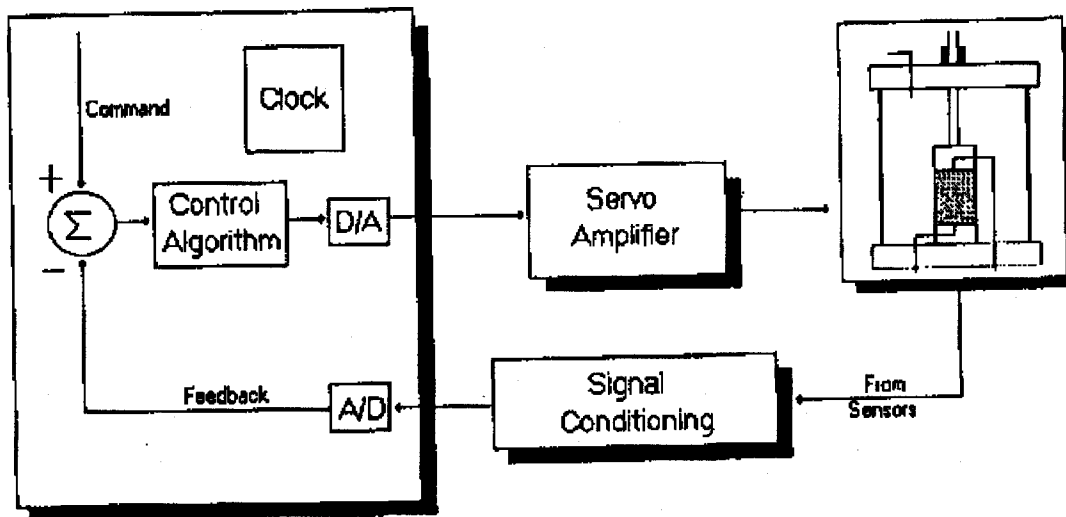


Figure 12: Resilient Modulus Testing System Overview (GCTS).

The major components of the resilient modulus testing system include:

- Signal Conditioner
- Computer
 - Analog to Digital Board (A/D)

- Digital to Analog Board (D/A)
- Servo Amplifier
- Triaxial Loading Apparatus
 - Load Cell
 - Confining and Pore Pressure Sensors
 - Linear Variable Differential Transducers (LVDT)

A Daytronic SPS6000 signal conditioner converts the voltage input from the sensors and transducers to an analog output signal, which is then sent to a Keithley DAS-1600 A/D board in the computer. The A/D board converts the analog input to a digital output for computerized test control and data processing. A digital servo controller and software, developed by Geotechnical Consulting and Testing Systems (GCTS), is used for computerized testing control and data processing.

Digital computerized control signals are converted to an analog output by a Keithley DDA-06 D/A board. The analog signal is then sent to an SBEL Series 7: amplifier, servo valve and motor control unit. The SBEL amplifier uses computer-controlled signals to control loading.

The triaxial loading apparatus consists of several components used to measure soil loading, deformation, and pore and confining pressures. The triaxial cell is a HX-100 model supplied by SBEL. Soil loading is measured via an Omegadyne model LCUW-1K 1000 lb load cell. Pore and confining pressures are measured with separate Sensotec pressure transducers; model THE/0708-11TJG with a 150-psi rated capacity. Loading piston movement is monitored by an externally-mounted LVDT, manufactured by Shaevitz Sensors; model HR-1000 with a range

of ± 1 inch. Measurement of soil deformation is monitored by two internally-mounted LVDTs manufactured by Sentech Inc.; model 375-100 XA, with a range of ± 0.1 -inch. These internal LVDTs are attached to the side of the specimen by a pair of clamps, which are held in contact with the specimen via miniature rubber bands. Soil displacements in the resilient modulus test typically ranged between 0.0001 to 0.01 inches. The alignment of the LVDT and clamps was critical for obtaining accurate measurements at such small displacements.

The Sentech LVDTs contained a special feature to attain highly repeatable test results. They were manufactured with a larger gap clearance between the coil housing and the actuator core. This increased gap allows for slight misalignments in the LVDTs without affecting the accuracy and repeatability of the test results. The Sentech LVDTs were calibrated over a range of ± 0.025 inches to increase LVDT sensitivity in measurement of displacements on the order of 0.0001 inch.

4.2 Calibration

Due to the dynamic nature of the resilient modulus test and its dependence on electronic data, a laboratory startup quality control procedure is needed to ensure accurate and reliable test results. Procedures for verification of properly functioning system electronics for resilient modulus testing equipment have been developed by Alavi et al. (1997). The procedure is designed to verify the accuracy of all the resilient modulus test system components. As part of the startup and quality control procedure, each component of the system is verified individually. The entire system is then verified to ensure all components are working properly

together. As a result of the electronic verification process, the original SBEL signal conditioner purchased for resilient modulus testing was found to be inadequate and was subsequently replaced with the Daytronics SPS6000.

The laboratory startup and quality control procedure consists of three phases: (i) electronic system performance verification; (ii) calibration check and overall system performance verification; and (iii) proficiency of the tester. The first two phases are detailed below.

4.2.1 Electronic System Performance Verification

The electronic system performance verification procedures test the signal conditioning, data acquisition, and control system response to electronic signals. A function generator was used to produce a sinusoidal signal to simulate the dynamic signals encountered during actual testing. The signal was then fed through the signal conditioner and data acquisition system. The frequency of the signal was varied between 2 and 50 Hz, and the characteristic of the output signal was then compared with that of the input. The electronic system performance verification include checks on the:

- Output waveform shape
- Input-to-output delays
- Electronic signal attenuation with increasing frequency

Normalized input and output waveforms were compared to check for proper output waveform shape. No electronic spikes or excess noise were observed in the recorded output.

Input-to-output delays can be caused by inadequate filters in the signal conditioner or by an inadequate data acquisition system. Ideally, these delays should be less than allowable values specified by Alavi et al. (1997). The adequacy of the signal conditioner and data acquisition can be verified by comparing the input sinusoidal signal from the function generator with the output signal (after it is sent through the signal conditioner) on the data acquisition system. To check the performance of the data acquisition system alone for delays, the sinusoidal wave from the function generator is sent directly to the A/D board in the computer where the output signal from the signal conditioner would normally go. With the signal conditioner bypassed, the delays due to the data acquisition system were measured to be 0. Therefore, input-to-output delays are due primarily to the signal conditioner processing and these were monitored over a range of frequencies. A key parameter that was monitored is the input-to-output delay at a 50 Hz input signal.

Signal attenuation was also monitored with the same calibration setup as used with the input-to-output delay verification. The electronic system verification procedure recommends monitoring deviations (signal attenuation) in output amplitude as the input signal ranges from 2 Hz to 10 Hz. The results of the input-to-output delay, and signal attenuation calibration are summarized in Table 9.

Table 9: Electronic System Verification Signal Attenuation

| System Channel | Signal Attenuation (%) | Input-to-Output Delay (msec) |
|----------------|------------------------|------------------------------|
| Load Cell | 4.8 | 5 |
| Main LVDT | 1.6 | 5 |
| LVDT 1 | 6.6 | 5 |
| LVDT 2 | 6.9 | 5 |

4.2.2 Overall System Performance Verification

An overall system performance verification includes calibration of each of the system components to ensure accurate load, pressure, and deformation readings; as well as a dynamic load versus deformation response check. In the dynamic load versus deformation response check, the overall system response to a sinusoidal loading pattern of a synthetic rubber specimen was investigated. The synthetic rubber specimen (manufactured by Industrial Rubber Products Co.) is the same size as the compacted soil specimens. Sinusoidal dynamic loading with peak-to-peak amplitude of approximately 25 lbs, and frequencies of 1 Hz, 5 Hz, and 10 Hz is applied to the synthetic specimen. The time lag between the load and deformation channels can be quantified via a measurement of the phase angle delay according to the procedures described by Alavi et. al (1997). The phase angle delay was minimized by changing the electronic filter settings on the signal conditioner. The ideal frequency cutoff was found to be 40 Hz and 80 Hz for the strain gage and LVDT boards, respectively. Results of the dynamic response check are summarized in Table 10.

Table 10: Time Delay and Phase Shift with Respect to the Load Cell Response Obtained During Dynamic Load Response Verification

| Load Frequency (Hz) | External LVDT | | Internal LVDT 1 | | Internal LVDT 2 | |
|---------------------|------------------|-----------------|------------------|-----------------|------------------|-----------------|
| | Time Delay (sec) | Phase Shift (°) | Time Delay (sec) | Phase Shift (°) | Time Delay (sec) | Phase Shift (°) |
| 1 | 0.0059 | 2.1 | 0.013 | 4.8 | 0.0071 | 2.7 |
| 5 | 0.0016 | 2.92 | 0.0029 | 5.2 | 0.0018 | 3.22 |
| 10 | 0.0096 | 3.47 | 0.0016 | 5.8 | 0.0009 | 3.38 |

4.3 Sample Preparation

4.3.1 Matrix of Target Dry Densities and Water Contents

This work involved conducting resilient modulus tests on compacted cohesive soil specimens. The results of these tests would be useful for design of road pavements on embankments or compacted soils. A matrix of target densities and water contents were selected to define the scope of the resilient modulus test program. Target densities and water contents were selected over a range of values that are deemed practical for design. The Hawaii Department of Transportation (HDOT) specifications Section 203 Excavation and Embankment requires a minimum compactive effort based on results of sieve analysis and sand equivalent tests. For subgrade soils with greater than 35% fines that have a sand equivalent of less than 15, HDOT requires that soils be compacted to AASHTO T-99 Standard Proctor compactive effort. All natural soils selected in this study have more than 35% fines and have sand equivalents of less than 15. Therefore, the

maximum dry densities ($\gamma_{d \max}$) and optimum water contents (w_{opt}) are based on Standard Proctor compaction curves.

Samples were prepared at 100% and 95% relative compaction. At each relative compaction, samples were compacted at three different water contents: w_{opt} , $w_{opt} + 2\%$, and $w_{opt} - 2\%$. Each soil is therefore tested at six different physical states. A list of target dry densities and water contents based on Standard Proctor curves is shown in Table 11.

Table 11: Target Densities and Water Contents

| Location | 100% R.C. (γ_d , pcf) | 95% R.C. (γ_d , pcf) | $w_{opt} - 2\%$ | w_{opt} | $w_{opt} + 2\%$ | Moisture Content of Soil in Bucket | In situ Moisture Content |
|------------------------|----------------------------------|---------------------------------|-----------------|-----------|-----------------|------------------------------------|--------------------------|
| Kapolei | 100.2 | 95.2 | 23.2 | 25.2 | 27.2 | 23 | 19-23 |
| Mililani Mauka | 81.3 | 77.2 | 37.2 | 39.2 | 41.2 | 33 | 28-33 |
| Waipio | 93.7 | 89.0 | 25.4 | 27.4 | 29.4 | 24 | 24-29 |
| Wahiawa <i>in situ</i> | 75.4 | 71.6 | 42.8 | 44.8 | 46.8 | 55 | 51-57 |
| Wahiawa Intermediate | 79.8 | 75.8 | 39.6 | 41.6 | 43.6 | 26 | - |
| Wahiawa Owendried | 83.7 | 79.5 | 36.4 | 38.4 | 40.4 | 0 | - |

4.3.2 Moisture Adjustment

The Wahiawa soil was the only soil that required drying to obtain the desired moisture contents. The Wahiawa soil was tested wet to dry. All the other soils had moisture contents less than those desired for compaction and were tested dry to

wet. For the dry to wet soils, the following process of specimen moisture adjustment was used to obtain the desired moisture content:

1. Several moisture content determinations are obtained for the desired soil sampled from a 5-gallon bucket.
2. Based on the moisture content from 1, the weight of moist soil required for a specimen of known dry density and volume is calculated.
3. The weight of moist soil from 2 is increased by fifteen percent to allow for moisture contents to be determined during the actual compaction. The required amount of soil is then sampled.
4. The required amount of water is added to the soil from 3 to obtain the desired moisture content.
5. The soil from 4 is thoroughly mixed and placed in a heat-sealed bag, which is then placed in a 5-gallon bucket containing an o-ring seal, and stored for a minimum of 48-hours to allow the moisture to equilibrate prior to compaction.

For the Wahiawa soil, which was tested wet to dry, the following process was used to dry the soil to the desired moisture contents:

1. Several moisture content determinations are obtained for a 5-gallon bucket of soil.
2. The entire bucket of soil is placed in a drying pan approximately 4 ft x 4 ft x 6 inches deep.
3. The soil is then allowed to gradually air-dry until the desired moisture content for compaction is reached. The soil is mixed every hour to ensure even drying. This process may take several hours to a few days.
4. Upon reaching the desired moisture content, the entire batch of soil is placed in a heat sealed bag, the bag of soil is placed in a 5-gallon bucket with an o-ring seal for moisture equilibration.

To prepare the Wahiawa intermediate soil, the soil from Wahiawa was dried down to a moisture content of 26% using steps 1 through 4 of the drying procedure described above. Once the soil is dried to the desired moisture content, it is treated as a separate soil. The dry to wet procedure outlined in steps 1 through 5 are followed for readjusting moisture contents to above 26%.

To prepare the Wahiawa oven-dry specimens the soil is placed in an oven and allowed to dry completely. Once the soil is completely desiccated, it is removed from the oven, placed in a heat-sealed bag, and stored in 5-gallon buckets. The soil is tested from dry to wet and is prepared using steps 1 through 5 as described above.

4.3.3 Specimen Compaction

A five-layer static compaction method is used to prepare samples for resilient modulus testing. Static compaction is performed according to procedures detailed in Attachment C of LTPP Protocol P46 (1996). The resulting compacted specimen measures 2.8 inches in diameter, and 5.6 inches in height. 0.012-inch-thick rubber membranes, supplied by Humboldt Manufacturing Co., were used during resilient modulus testing.

Moisture content determinations are made when each of the 5 layers are compacted. At the conclusion of the resilient modulus test, the entire sample is oven dried for further verification of moisture content.

4.4 Sources of Experimental Error

The resilient modulus test procedure is detailed in Protocol P46 (1996) and in AASHTO T 307, and is not repeated herein. Upon conclusion of resilient modulus testing, an analysis of the test data revealed a bias in the measured deformations in that the LVDT 1 displacements were consistently larger than the LVDT 2 readings. LVDTs 1 and 2 are mounted directly to the side of the compacted test specimen via lightweight brackets. Each LVDT is located on opposite sides of the test specimen. Care was taken to consistently place LVDTs 1 and 2 in the same orientation relative to the triaxial cell for all tests. After noting this bias, the LVDTs were swapped and subsequent tests indicated higher LVDT 2 readings than LVDT 1. Therefore, it was determined that the bias is due to application of an eccentric load caused by misalignment of the loading piston or the load cell below.

A simple procedure to account for the effects of combined axial load and bending was considered to minimize this bias. Equation 29 is a general beam-column formula for estimating the bending stress, σ , due to combined axial load and bending.

$$\sigma = \frac{P}{A} \pm \frac{Mc}{I} \quad (29)$$

where

P = axial or deviator load

A = cross-sectional area of the specimen

M = moment due to the eccentric load = $P e$

c = distance from the centroid to the extreme fiber or the radius

I = moment of inertia of the specimen

e = load eccentricity

Assuming 1-D loading, Hooke's law states that $\sigma = E\varepsilon$, where E is the Young's modulus and ε is the strain. By substituting $E\varepsilon$ for σ in Equation 29, and replacing E by M_r , the resilient modulus can be expressed as follows:

$$M_r = \left(\frac{1}{\varepsilon_{\max}} \right) \left[\frac{P}{A} + \frac{Pec}{I} \right] \quad (30)$$

$$M_r = \left(\frac{1}{\varepsilon_{\min}} \right) \left[\frac{P}{A} - \frac{Pec}{I} \right] \quad (31)$$

where ε_{\max} and ε_{\min} are the strains corresponding to LVDT 1 and LVDT 2, respectively.

To minimize the bias, two values of resilient modulus were calculated for each test using Equations 30 and 31. The value of eccentricity that yielded the minimum sum of the squares of the differences in moduli for all tests was then determined. This value of eccentricity was found to be 0.057 inch. The corrected resilient modulus is then taken as the average of the two values estimated using Equations 30 and 31. A chart of the non-corrected resilient modulus versus the corrected values is shown in Figure 13. The maximum difference in the corrected and uncorrected resilient moduli is 16.6% while the average percent change due to eccentricity correction is 1.1% with a standard deviation of 1.54%

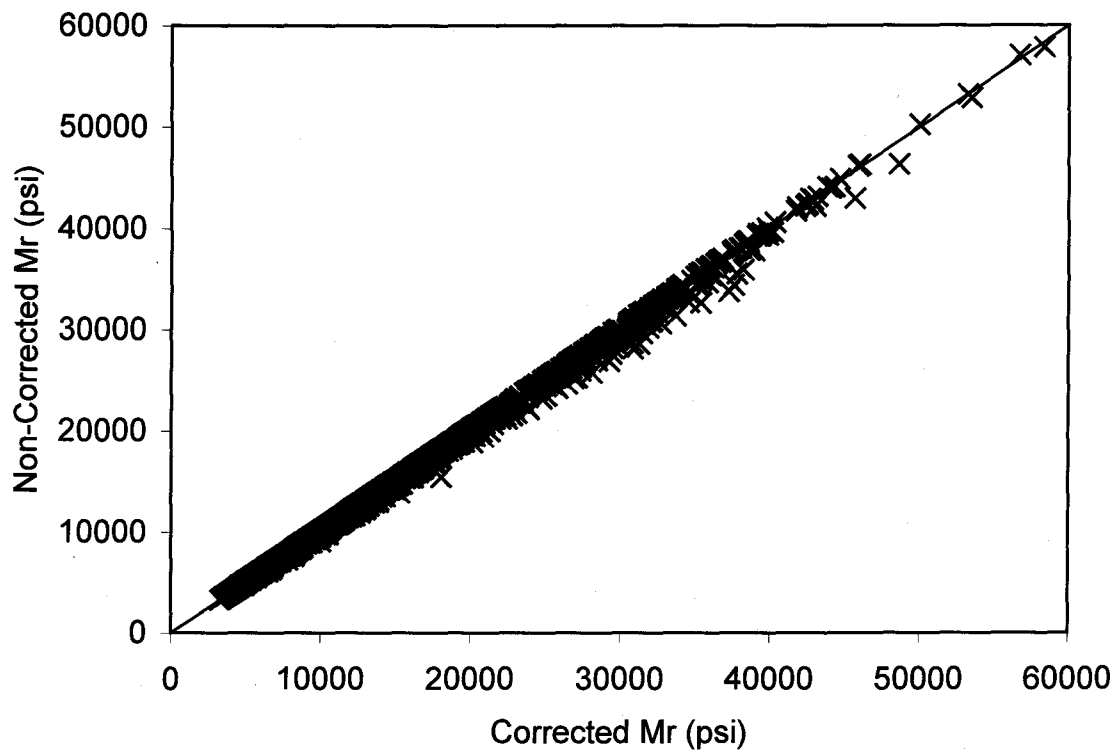


Figure 13: Resilient Modulus Corrected for Non-Concentric Loading

4.5 Test Data Reduction

The resilient modulus test load pulse is haversine shaped lasting 0.1 seconds followed by a 0.9 second minimal contact load. The total cycle time is therefore 1.0 second. Load and deformation readings were taken every 0.002 seconds during the 0.1 sec load pulse, and every 0.018 seconds during the contact loading period. The resilient modulus is calculated based on the last 5 loading cycles

Chapter 5: Test Results and Analysis

A total of 95 resilient modulus tests were performed including tests on the Wahiawa intermediate and oven-dry soils, a summary of the test results are contained in Appendix A. In the regression development process the Wahiawa oven-dry test results were removed from the data set because the samples were dried to temperature extremes that tropical soils typically do not experience, and therefore are judged to be inappropriate for inclusion in this work. Nevertheless, the oven-dry data did provide useful insight into the effects of drying on the resilient modulus and a discussion of this is provided in Section 5.3.

Linear regression models for correlating resilient modulus of Hawaiian tropical soils with common soil parameters are described in this section.

5.1 Definition of Regression Terms

Regression models describe a functional relationship between two or more variables in a mathematical formula. First-order regression models exist when the relationship between the dependent and independent variables are linear in nature. The general form linear regression equation is as follows:

$$Y_i = \beta_0 + \beta_1 X_{i,1} + \beta_2 X_{i,2} + \dots + \beta_{p-1} X_{i,p-1} + \varepsilon_i \quad (32)$$

where

Y_i = dependant variables

$\beta_0, \beta_1, \dots, \beta_{p-1}$ = regression parameters

$X_{i,1}, \dots, X_{i,p-1}$ = independent predictor variable

ε_i = independent error term

The error term, ε_i , is usually assumed to be normally distributed with a constant variance for all observations, X_i .

5.2 Regression Analysis

The regression analysis is described in detail first for the Uzan (1985) model. It is later applied to Ni et al.'s (2002) model in Section 5.2.2.

5.2.1 Uzan Model

As stated in Section 2.2.1, Uzan (1985) recommended a general equation to represent the constitutive relationship between resilient modulus and stress state. The Uzan equation may be transformed to a linear form by taking the logarithm of both sides as follows:

$$\text{Log}[M_r] = \text{Log}[K_1 p_a] + K_2 \text{Log}\left[\frac{\theta}{p_a}\right] + K_3 \text{Log}\left[\frac{\sigma_d}{p_a}\right] \quad (33)$$

where

$\text{Log}[M_r]$ = dependent variable, Y

$\text{Log}\left[\frac{\theta}{p_a}\right]$ = independent predictor variable, $X_{i,1}$

$\text{Log}\left[\frac{\sigma_d}{p_a}\right]$ = independent predictor variable, $X_{i,2}$

$\text{Log}[K_1 p_a]$ = regression parameter, β_0

K_2 = regression parameter, β_1

K_3 = regression parameter, β_2

Values of K_1 , K_2 , and K_3 , are evaluated for each test. A typical plot showing resilient modulus versus deviator stress for a test on the Waipio soil is shown in Figure 14, where the data points are shown as symbols and the regression curves using the Uzan model are depicted as solid lines.

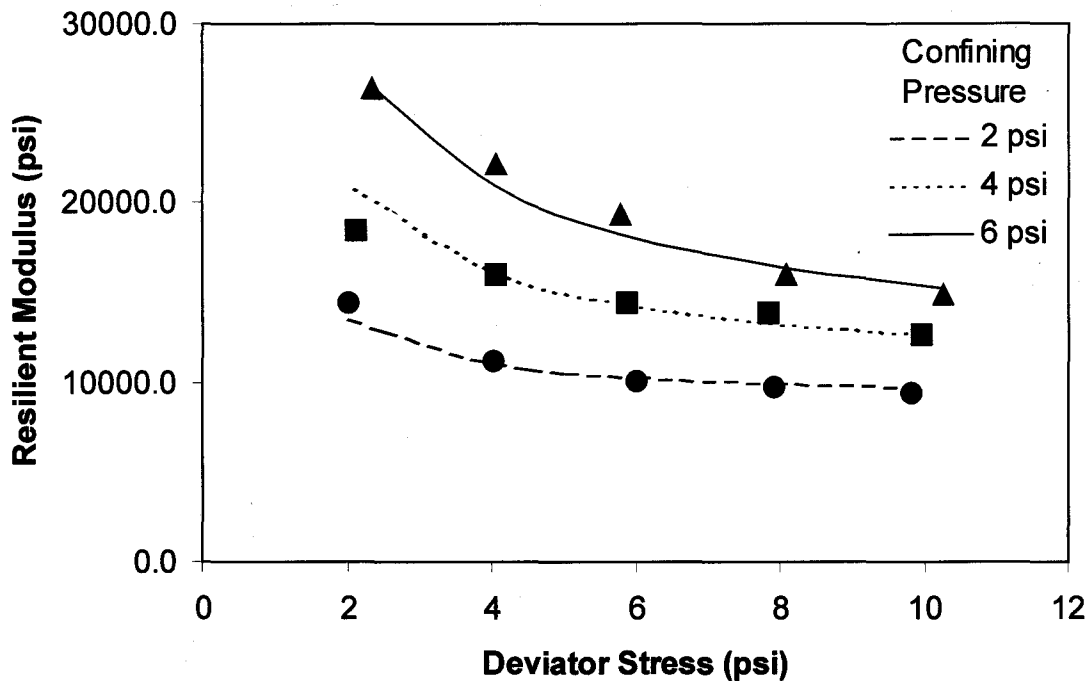


Figure 14: Resilient modulus as a function of deviator stress for a Waipio specimen compacted to 95% relative compaction at a molding water content of $w_{opt} + 2\%$

The range, mean, and standard deviation of the regression parameters K_i and the coefficient of determination, R^2 , for all the tests are listed in Table 12.

Table 12: Range, Mean and Standard Deviation of Measured K Values Based on Uzan Model

| | Max | Min | Mean | Std Dev |
|-------|-------|-------|-------|---------|
| K_1 | 2065 | 138 | 776 | 513 |
| K_2 | 1.17 | 0.00 | 0.32 | 0.27 |
| K_3 | -0.06 | -0.83 | -0.42 | 0.17 |
| R^2 | 0.99 | 0.65 | 0.91 | 0.07 |

5.2.1.1 Development of Prediction Models

Resilient modulus is heavily dependent on the stress state and this is automatically considered in the Uzan model. The Uzan model does not intrinsically consider the effects of soil properties and physical state. The next step in the development of the prediction model is to establish relationships between values of K_i , and soil index properties and physical state conditions.

A total of sixteen predictor variables were initially identified for correlation with K_i . These include the maximum dry unit weight ($\gamma_{d \max}$, pcf), optimum water content (w_{opt} , %), liquid limit (LL, %), plastic limit (PL, %), plasticity index (PI, %), liquidity index (LI), sand equivalent (SE, %), % silt, % clay, activity ($\frac{PI}{\%CLAY}$), dry unit weight (γ_d , pcf), relative compaction (RC, %), water content (w , %), $w - w_{opt}$ (%), and E_i/p_a , where E_i is the initial slope of an unconfined compression test that is performed at the conclusion of the resilient modulus test and p_a is atmospheric

pressure. Due to the large number of possible predictor variables, along with the three independent models to investigate; the sheer volume of candidate models to examine carefully is an overwhelming task. This list was trimmed to 9 variables. Variables that are already incorporated in other parameters were eliminated (e.g., PL is needed to define PI, LI and activity, γ_d and $\gamma_{d \max}$ are used in the definition of relative compaction, % clay is used to define activity, sand equivalent and % silt are correlated with % clay and hence activity, and w_{opt} is contained in $w - w_{opt}$).

A powerful tool to assist in narrowing down large pools of predictor variables is the bivariate correlation matrix (Farrar and Turner, 1991). The bivariate correlation matrix describes the linear association between two variables. Linear associations in the bivariate correlation matrix are quantified based on the Pearson's product-moment coefficient, r . A value of r near 1.0 represents two variables that are linearly related. A value of r near 0 represents two variables that display minimal linearity in their relation.

Table 13 contains the bivariate correlation matrix for the predictor variables evaluated for all soils tested in this study. Typically, a value of r in excess of 0.80 between two predictor variables is a strong indicator of multicollinearity, and is considered a problem for simultaneous use of these two variables (Berry, 1985). Multicollinearity is the linear relationship between variables. Regression between two or more predictor variables can still be performed if there is multicollinearity. However, it can inflate the standard errors of the estimated regression coefficients

(Neter at al., 1996). Therefore, the subset predictor variables of Table 14 were selected using a combination of two criteria:

1. Based on the r value, predictor variables that display strong multicollinearity were not combined (e.g., LL and PI have very high r values with activity and water content).
2. In Table 13, the r values between the dependent variables, Y_i , and the predictor variables are shown in the correlation matrix. The higher the r value, the higher the degree of linear association between predictor variables X_i and the dependent variables Y_i . Thus, predictor variables that had the highest r values with K_i were selected.

Table 13: Bivariate Correlation Matrix, Refined Predictor Variable Set for Uzan Ki Values

| | | X_1 | X_2 | X_3 | X_4 | X_5 | X_6 | X_7 | X_8 | X_9 | Y_1 | Y_2 | Y_3 |
|-------|---------------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|
| X_1 | LL (%) | 1 | | | | | | | | | | | |
| X_2 | PI (%) | 0.98 | 1 | | | | | | | | | | |
| X_3 | LI (%) | 0.51 | 0.57 | 1 | | | | | | | | | |
| X_4 | Activity | 0.94 | 0.97 | 0.53 | 1 | | | | | | | | |
| X_5 | R.C. (%) | -0.04 | -0.03 | -0.05 | -0.01 | 1 | | | | | | | |
| X_6 | w (%) | 0.92 | 0.86 | 0.54 | 0.78 | -0.04 | 1 | | | | | | |
| X_7 | S (%) | 0.34 | 0.31 | 0.51 | 0.26 | 0.61 | 0.5 | 1 | | | | | |
| X_8 | w_{opt} (%) | 0.03 | 0 | 0.59 | -0.04 | -0.03 | 0.28 | 0.65 | 1 | | | | |
| X_9 | E_i / P_a | -0.32 | -0.27 | -0.56 | -0.19 | 0.26 | -0.53 | -0.46 | -0.67 | 1 | | | |
| Y_1 | K_1 | -0.21 | -0.14 | -0.53 | -0.06 | 0.28 | -0.5 | -0.47 | -0.75 | 0.87 | 1 | | |
| Y_2 | K_2 | -0.53 | -0.58 | 0.02 | -0.65 | -0.11 | -0.29 | 0.18 | 0.56 | -0.41 | -0.5 | 1 | |
| Y_3 | K_3 | 0.08 | 0.18 | -0.22 | 0.3 | 0.19 | -0.24 | -0.4 | -0.73 | 0.66 | 0.81 | -0.72 | 1 |

Of the nine predictor variables, a subset of predictor variables was further selected for correlation with K_i . Derived using statistical tools, this subset of predictor variables are summarized in Table 14.

Table 14: Subset Predictor Variables Selected for Further Investigation

| | X_1 LL (%) | X_2 PI (%) | X_3 LI (%) | X_4 Activity | X_5 R.C. (%) | X_6 w (%) | X_7 S (%) | X_8 w-w _{opt} (%) | X_9 E_i/p_a |
|-------|-----------------|-----------------|-----------------|-------------------|-------------------|----------------|----------------|---------------------------------|--------------------|
| K_1 | | | × | | × | × | × | × | × |
| K_2 | | | | × | × | | × | × | × |
| K_3 | | | × | | × | | × | × | × |

5.2.1.2 Investigation of Subset Models

A stepwise process, described by Neter et al. (1996), is used to analyze the best combination of predictor variables for each K . Known as the R^2 criterion, the procedure is as follows:

1. Perform linear regression for each dependent variable, K , using all the initial subset predictor variables. If there are p predictor variables, plot the coefficient of determination (R^2) versus p .
2. Perform separate linear regressions for all possible combinations of $p-1$ predictor variables. Plot the coefficient of determination for $p-1$ predictor variables on the same plot described in Step 1.
3. Eliminate completely the predictor variable that resulted in the lowest R^2 from Step 2 and repeat Step 2 with $p - 2$ predictor variables.
4. Repeat Steps 2 and 3 until only one predictor variable is used.
5. From all the plots of R^2 versus number of predictor variables, identify the most logical combination, which is the one having the highest R^2 with the minimum number of predictor variables (point of sudden drop in R^2).

In Figure 15, the relationship between R^2 and the number of predictor variables is plotted for K_1 , K_2 and K_3 .

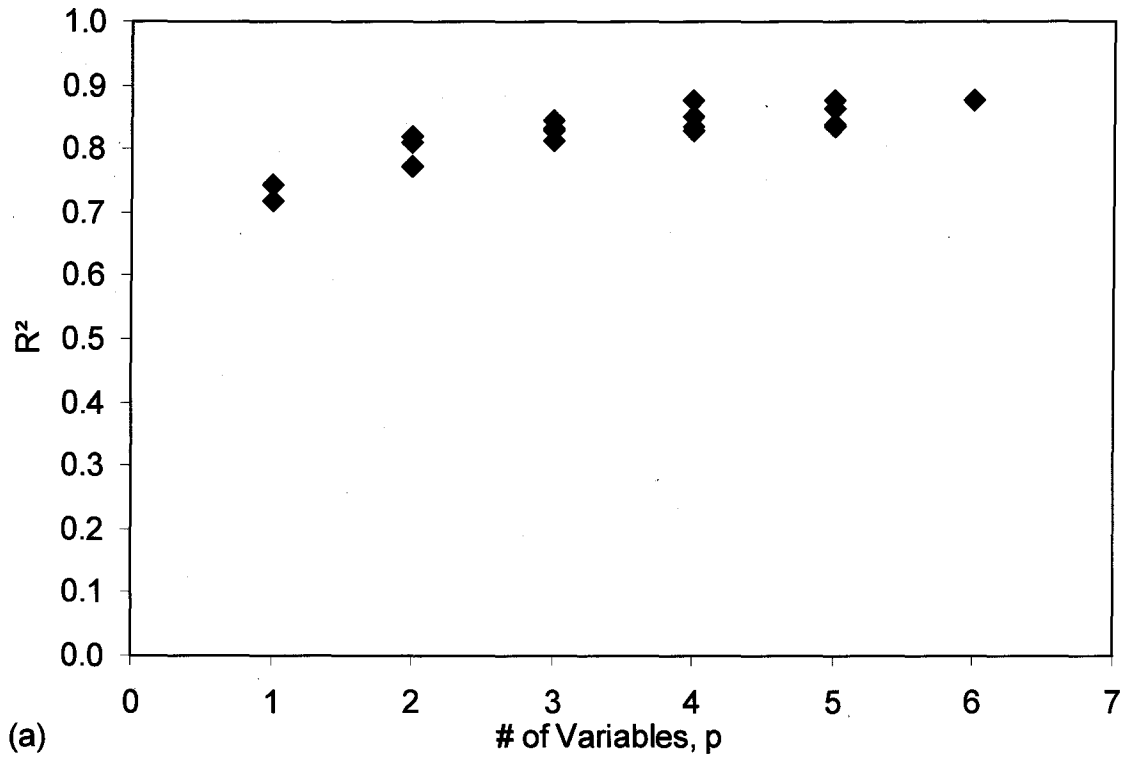


Figure 15: Coefficient of Multiple Determination Versus the Number of Predictor Variables for (a) K_1 , (b) K_2 , and (c) K_3

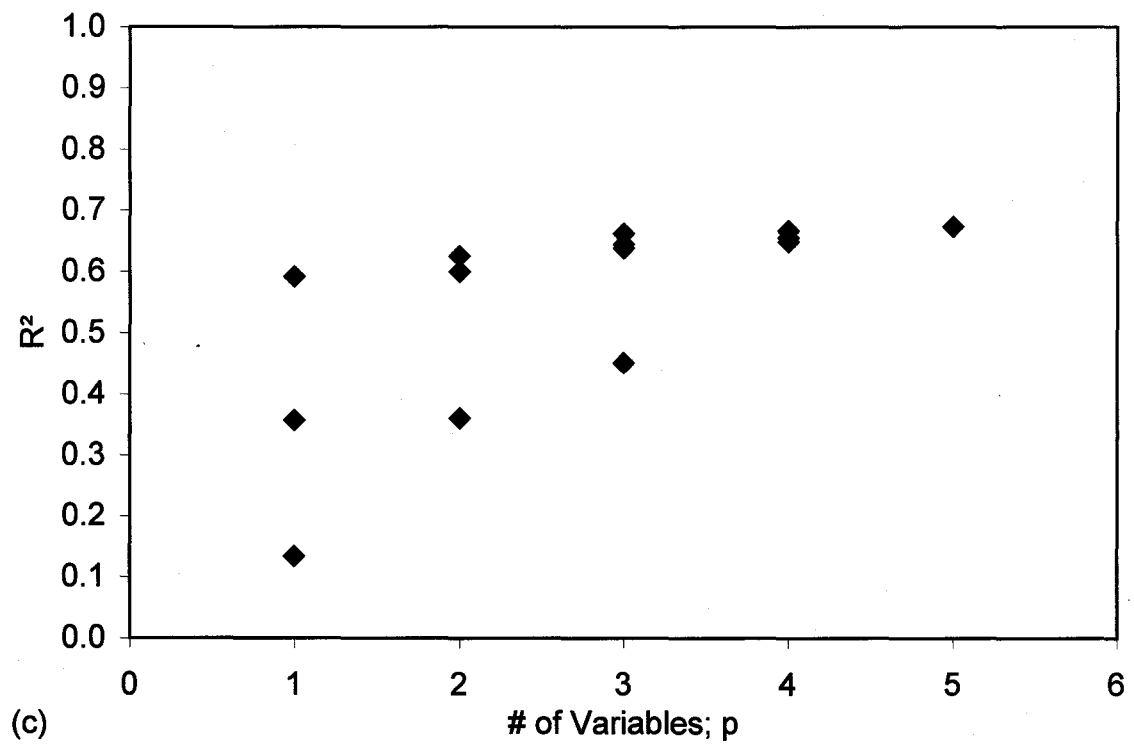
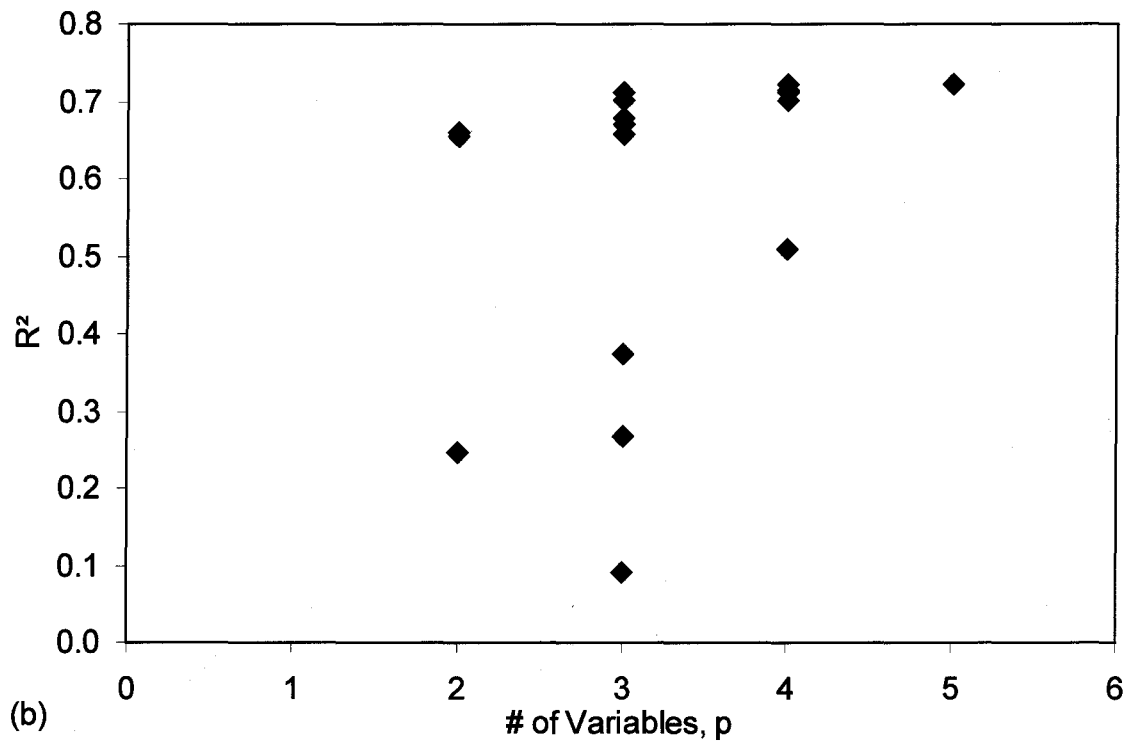


Figure 15: Coefficient of Multiple Determination Versus the Number of Predictor Variables for (a) K_1 , (b) K_2 , and (c) K_3

Table 15 lists the predictor variables and corresponding regression parameters, β_i , that provide the optimum R^2 at each value of ρ for K_1 , K_2 , and K_3 . The observed T-statistics, shown in parentheses for each regression parameter, is also listed in Table 15. The T-statistic is defined as the regression parameter, β_i divided by the standard error of estimate for the parameter β_i .

Table 15: Predictor Variables Yielding the Highest R² and their Regression Parameters with E_i/p_a Included

| | p | R ² | β ₀ | Regression Parameter, β _i | | | | | | E _i /P _a |
|----------------|---|----------------|----------------|--------------------------------------|------------------|-------------------|----------------|------------------|---------------------------|--------------------------------|
| | | | | LI (%) | Activity | R.C. (%) | w (%) | S (%) | (W-W _{opt}) (%) | |
| K ₁ | 6 | 0.878 | -1745 | -29.1 (4.87) | | -0.106 (0.004) | 4.83 (1.00) | 19.3 (1.20) | -89.2 (2.89) | 2.71 (4.91) |
| | 5 | 0.878 | -1750 | -29.1 (5.41) | | | 4.83 (1.14) | 19.2 (3.89) | -89.1 (4.07) | 2.71 (5.08) |
| | 4 | 0.876 | -1634 | -25.1 (6.14) | | | | 20.3 (4.18) | -101 (5.34) | 2.71 (4.76) |
| | 3 | 0.846 | 57.7 | -16.4 (4.22) | | | | | -68.9 (3.60) | 3.38 (6.01) |
| | 2 | 0.820 | -58.4 | -21.9 (5.69) | | | | | | 3.84 (6.85) |
| | 1 | 0.743 | -26.4 | | | | | | | 6.47 (14.9) |
| K ₂ | 5 | 0.723 | 2.76 | | -1.09 (13.7) | -0.0609 (5.20) | | 0.111 (5.37) | -0.0360 (1.91) | -0.00085 (2.84) |
| | 4 | 0.715 | 1.49 | | -0.921 (10.8) | -0.0457 (5.23) | | 0.0783 (6.61) | | -0.00073 (2.44) |
| | 3 | 0.713 | 1.06 | | -0.930 (11.0) | -0.0599 (8.85) | | 0.0982 (4.91) | | |
| | 2 | 0.592 | -0.409 | | | | | | -0.0679 (10.6) | |
| K ₃ | 5 | 0.674 | -0.390 | -0.0054 (2.00) | | -0.0150 (1.29) | | 0.0159 (2.35) | -0.0776 (6.75) | 0.0003 (1.19) |
| | 4 | 0.668 | -0.566 | -0.0065 (2.52) | | -0.0122 (1.07) | | 0.0151 (2.24) | -0.0793 (6.93) | |
| | 3 | 0.662 | -1.15 | -0.0042 (2.84) | | | | 0.0083 (3.71) | -0.0713 (8.18) | |
| | 2 | 0.626 | -0.882 | | | | | 0.0056 (2.64) | -0.0821 (10) | |
| | 1 | 0.592 | -0.404 | | | | | | -0.0679 (10.6) | |

The slope of an unconfined compression test is an easy parameter to measure for most geotechnical laboratories. For the benefit of agencies without the capability of preparing and extruding a statically compacted specimen for triaxial testing, a second model was

developed where the predictor variable, E_i/P_a , was removed altogether from the group of predictor variables. The same process, the R^2 criterion, was reapplied to the smaller subset of predictor variables, (Table 14) to generate the graphs shown in Figure 16.

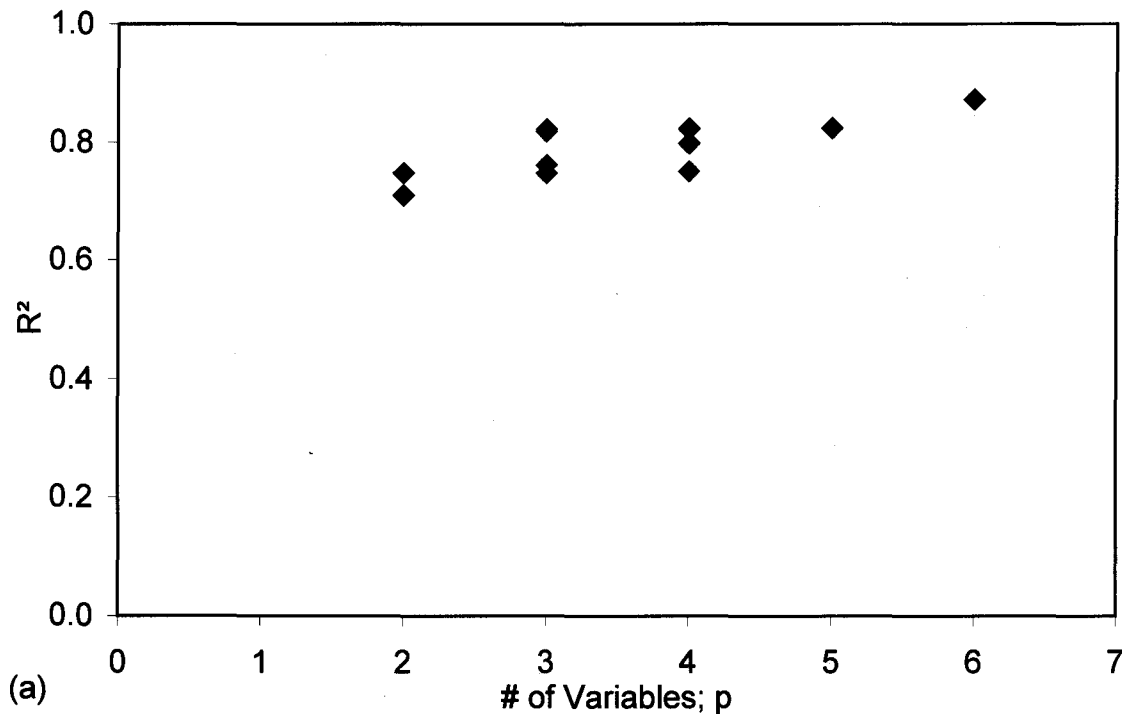


Figure 16: Coefficient of Multiple Determination Versus the Number of Predictor Variables for (a) K_1 , (b) K_2 , and (c) K_3 ; Subset Group with E_i/P_a Removed

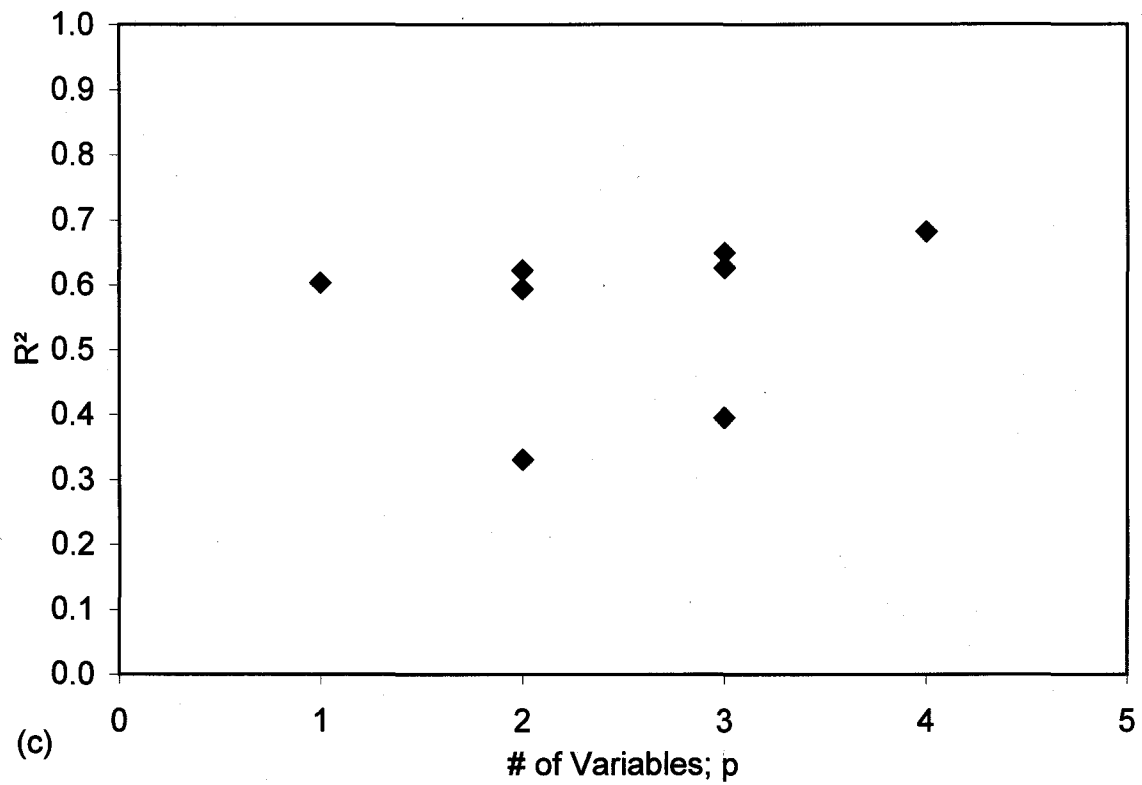
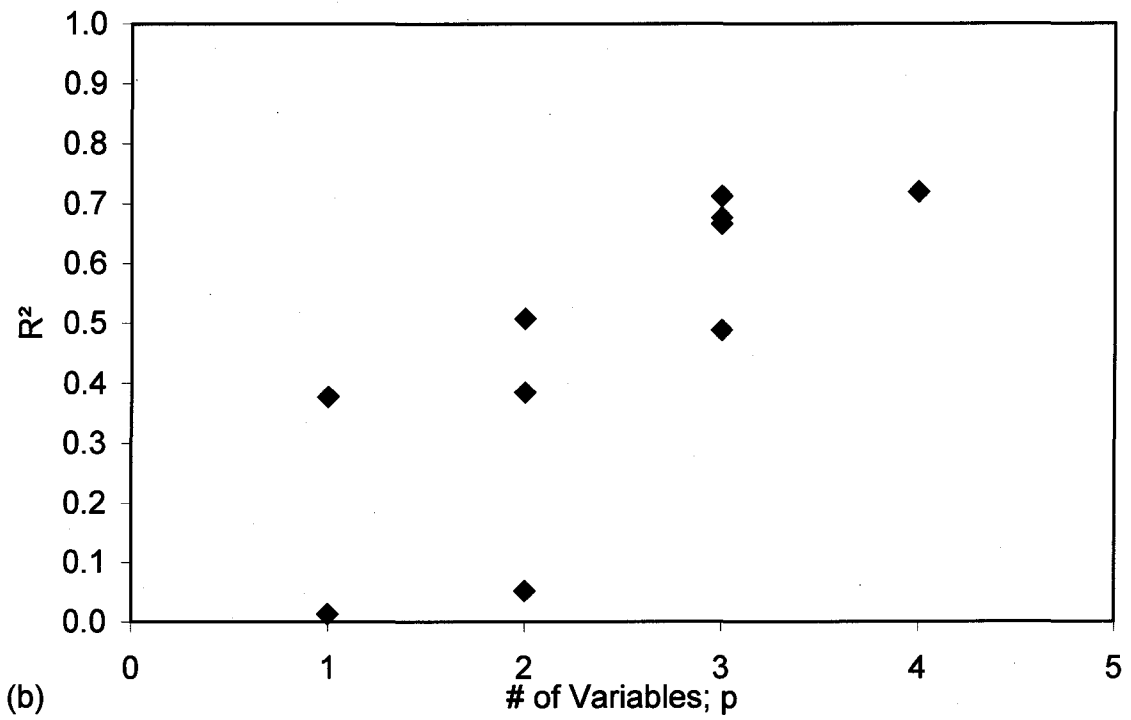


Figure 16: Coefficient of Multiple Determination Versus the Number of Predictor Variables for (a) K_1 , (b) K_2 , and (c) K_3 ; Subset Group with E_i/P_a Removed

Table 16 lists the combination of predictor variables and corresponding regression parameters, β_i , that provide the optimum R^2 for K_1 , K_2 , and K_3 with E_i/P_a removed from the subset of predictor variables. The observed T-statistics, shown in parentheses, for each regression parameter is also listed in Table 16.

Table 16: Predictor Variables Yielding the Highest R² and their Regression Parameters without E_i/p_a

| | p | R ² | β ₀ | Regression Parameter, β _i | | | | | |
|----------------|---|----------------|----------------|--------------------------------------|-----------------|-------------------|----------------|------------------|---------------------------|
| | | | | LI (%) | Activity | R.C. (%) | w (%) | S (%) | (w-w _{opt}) (%) |
| K ₁ | 5 | 0.824 | -3630 | -37.7 (5.59) | | 25.30 (0.80) | 3.85 (0.65) | 16.9 (0.88) | -125 (3.30) |
| | 4 | 0.823 | -3090 | -36.4 (5.70) | | 15.8 (0.57) | | 23.2 (1.40) | -142 (5.14) |
| | 3 | 0.822 | -2330 | -39.3 (10.5) | | | | 32.1 (5.68) | -151 (6.97) |
| | 2 | 0.748 | 484 | -29.9 (7.56) | | | | | -107 (4.46) |
| K ₂ | 4 | 0.720 | 5.57 | | -1.37 (7.83) | -0.0859 (3.94) | | 0.0466 (3.59) | -0.0325 (0.93) |
| | 3 | 0.712 | 4.40 | | -1.25 (13.3) | -0.0648 (7.39) | | 0.352 (9.36) | |
| | 2 | 0.509 | -0.460 | | -1.02 (8.86) | | | 0.0160 (4.54) | |
| K ₃ | 4 | 0.682 | 0.0647 | -0.0066 (2.45) | | 0.00227 (1.96) | | 0.0199 (2.89) | -0.0966 (8.05) |
| | 3 | 0.650 | -1.16 | -0.0039 (02.45) | | | | 0.0084 (3.50) | -0.0773 (8.37) |
| | 2 | 0.622 | -0.901 | | | | | 0.0058 (2.61) | -0.0866 (9.98) |
| | 1 | 0.603 | -0.411 | | | | | | -0.0724 (10.9) |

Two variations of the K coefficients for the Uzan (1985) model are proposed for predicting the resilient modulus. The first model, which incorporates E_i/P_a is as follows:

$$K_1 = -1634 - 25.11 \times LI + 20.3 \times S - 101 \times (w - w_{opt}) + 2.71 \times \frac{E_i}{p_a} \quad (34)$$

$$K_2 = 1.06 - 0.930 \times LI - 0.0599 \times RC + 0.0982 \times S \quad (35)$$

$$K_3 = -0.882 + 0.0056 \times S - 0.0821 \times (w - w_{opt}) \quad (36)$$

When combined with Equation 33, a linear regression of the predicted versus measured resilient modulus yields a coefficient of determination, R^2 of 0.797 (Figure 17).

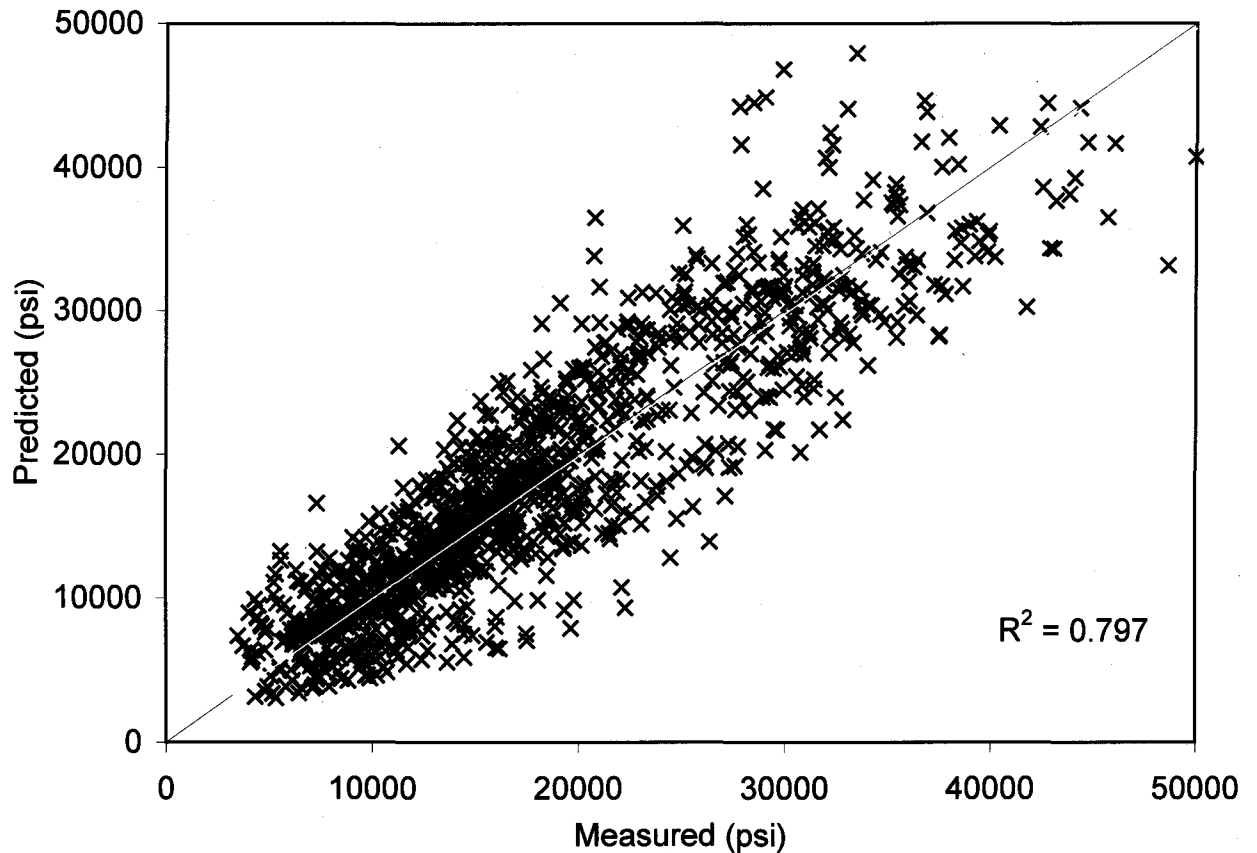


Figure 17: Predicted Versus Measured Resilient Modulus using the Uzan Model with E_i/P_a Included in the Data Set

The Uzan K parameters for the second case where E_i/P_a was removed from the matrix of predictor variables can be correlated with the following common soil parameters.

$$K_1 = -2327 - 39.3 \times LI + 32.1 \times S - 151 \times (w - w_{opt}) \quad (37)$$

$$K_2 = 4.40 - 1.25 \times \text{ACTIVITY} - 0.0648 \times \text{RC} + 0.0352 \times S \quad (38)$$

$$K_3 = -1.16 - 0.0039 \times \text{LI} + 0.0084 \times S - 0.0773(w - w_{\text{opt}}) \quad (39)$$

When combined with Equation 33, this second model has a coefficient of determination, R^2 , of 0.691. Figure 18 shows the predicted versus measured values of resilient modulus based on Equations 37, 38, 39, and the Uzan model in Equation 33.

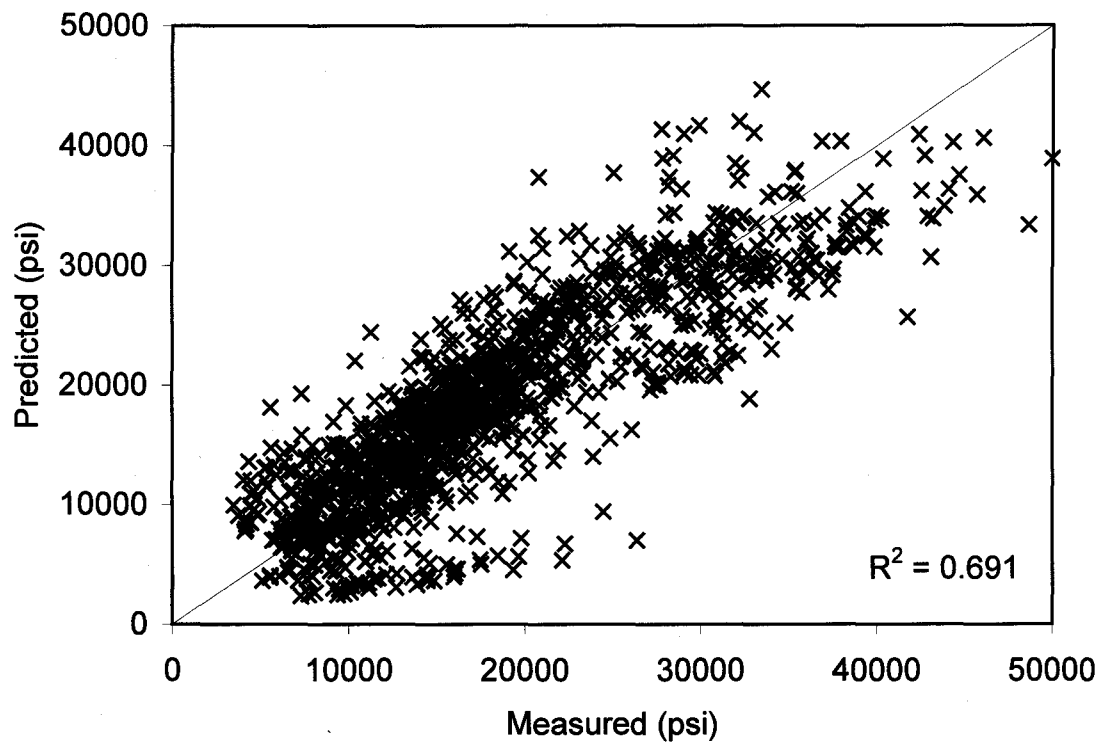


Figure 18: Predicted Versus Measured Resilient Modulus using the Uzan Model with K_i not a function of E_i/P_a .

Scatter plots showing the relationship between K_1 , K_2 , and K_3 and the various predictor variables in Equations 34 through 39 are included in Appendix B.

5.2.2 Ni et al.'s Model

Values of K_1 , K_2 , and K_3 , based on the Ni et al. model are evaluated for each test. The range, mean, and standard deviation of the regression parameters K_i and the coefficient of determination, R^2 , for all the tests are listed in Table 17.

Table 17: Range, Mean and Standard Deviation of Measured K_i Values Based on Ni et al. Model

| | Max | Min | Mean | Std Dev |
|-------|--------|-------|-------|---------|
| K_1 | 3255 | 211 | 1390 | 0.667 |
| K_2 | 4.35 | 0.065 | 1.17 | 0.951 |
| K_3 | -0.230 | -2.61 | -1.38 | 0.551 |
| R^2 | 0.992 | 0.682 | 0.949 | 0.062 |

The coefficients of determination ranged from 0.682 to 0.992 with an average of 0.95 for all tests including Wahiawa ovoidry. Compared to the Uzan model, the higher coefficient of determination and lower standard deviation indicates that the Ni et al. model is better suited for the prediction of resilient modulus over the tested range of stress state conditions for Hawaiian tropical soils. Overall, the fit of the Ni et al. model is better than the Uzan model for the soils in this study.

5.2.3 Development of Prediction Model

The analysis described in Section 5.2.1 for the Uzan (1985) model was repeated using Ni et al.'s (2002) model. Similarly, the Ni et al. equation may be transformed to a linear form by taking the logarithm of both sides as follows:

$$\text{Log}[M_r] = \text{Log}[K_1 p_a] + K_2 \text{Log}\left[1 + \frac{\sigma_3}{p_a}\right] + K_3 \text{Log}\left[1 + \frac{\sigma_d}{p_a}\right] \quad (40)$$

where

$\text{Log}[M_r]$ = dependant variable, Y

$\text{Log}\left[1 + \frac{\sigma_3}{p_a}\right]$ = independent predictor variable, $X_{i,1}$

$\text{Log}\left[1 + \frac{\sigma_d}{p_a}\right]$ = independent predictor variable, $X_{i,2}$

$\text{Log}[K_1 p_a]$ = regression parameter, β_0

K_2 = regression parameter, β_1

K_3 = regression parameter, β_2

A typical plot showing resilient modulus versus deviator stress for a test on the Waipio soil is shown in Figure 19, where the data points are shown as symbols and the regression curves using the Ni et al. model are depicted as solid lines.

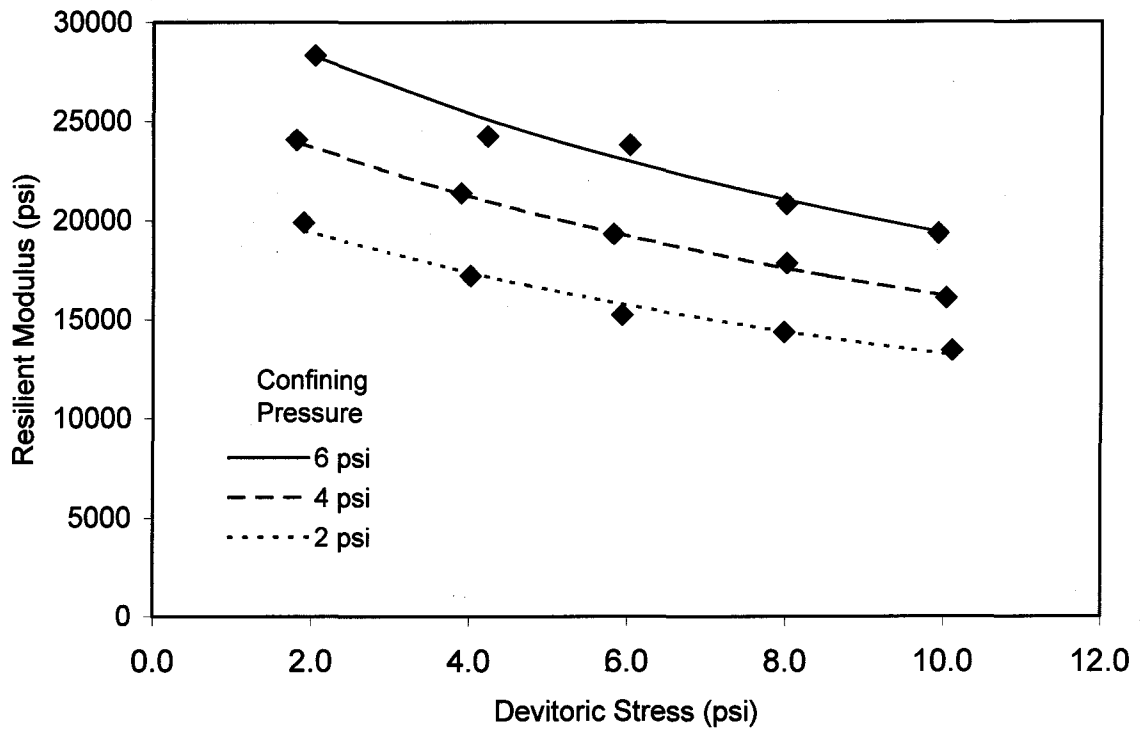


Figure 19: Resilient Modulus as a Function of Deviatoric Stress for a Waipio Specimen Compacted to 95% Relative Compaction at Optimum Water Content

5.2.3. Investigation of Subset Models

The same predictor variables were considered for regression analysis with the dependent variables K_1 , K_2 and K_3 . The R^2 criterion process was repeated with the Ni et al. method. Again, the process was performed with the matrix of predictor variables including E_i/p_a and without.

The R^2 criterion was used to determine the optimum combination of parameters and Figure 20 shows the R^2 versus p plots for K_1 , K_2 , and K_3 .

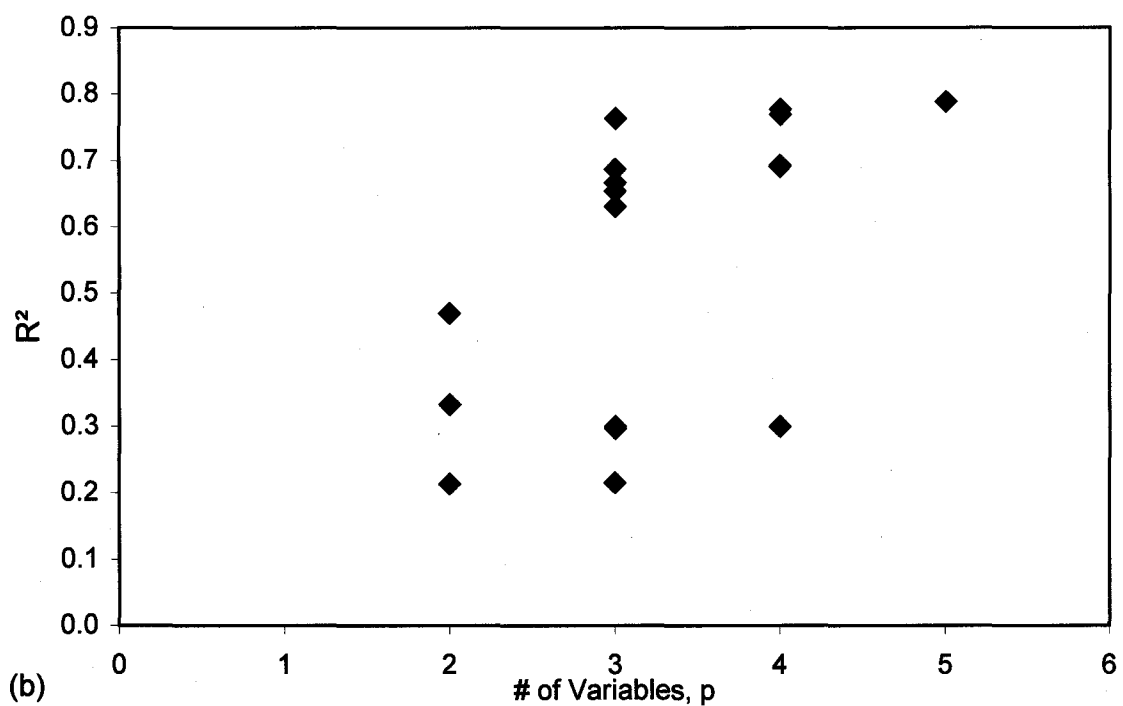
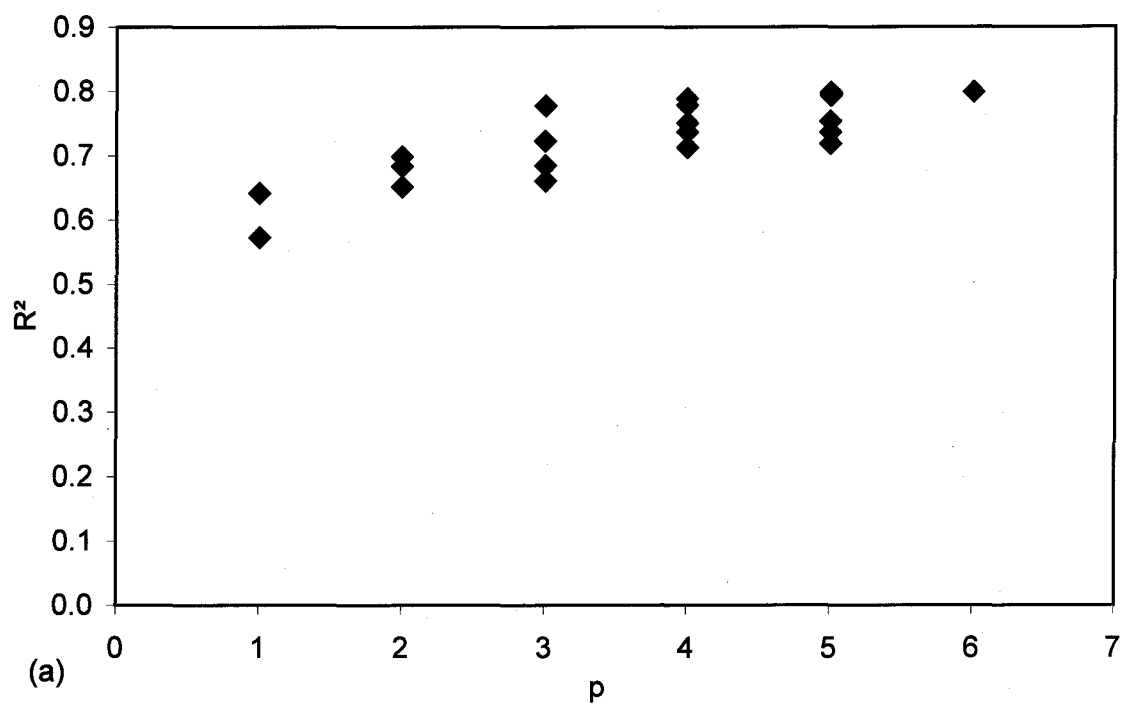


Figure 20: Coefficient of Determination Versus the Number of Predictor Variables for (a) K_1 , (b) K_2 , and (c) K_3 ; Based on the Ni et al. Method.

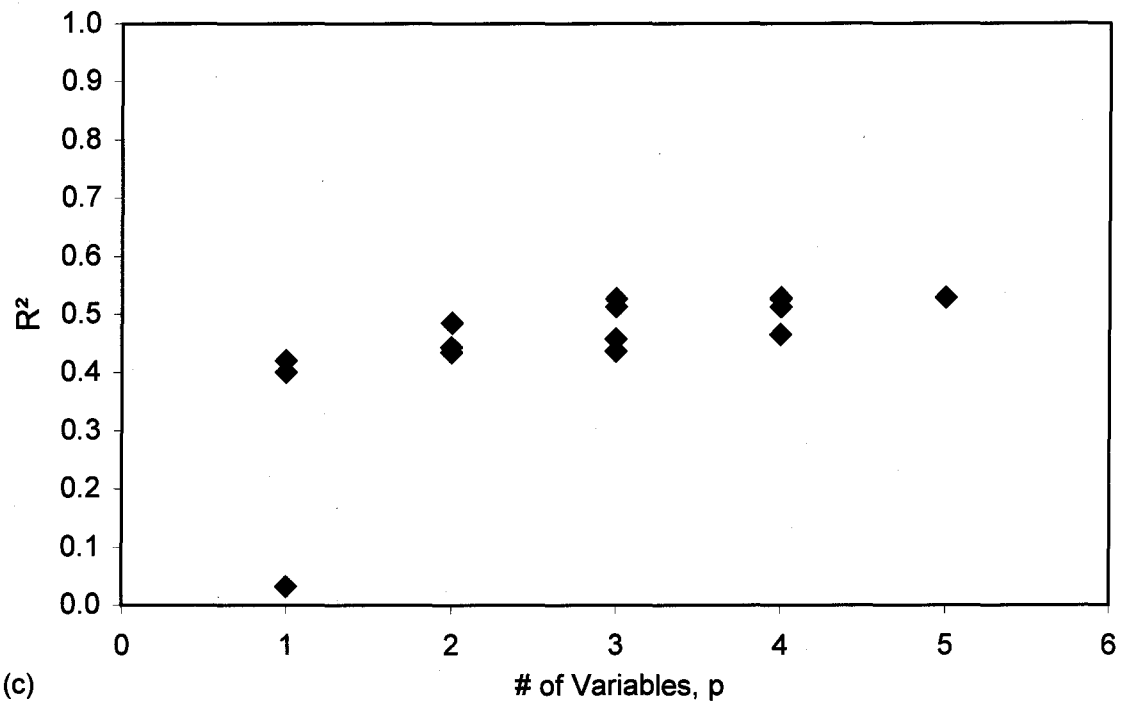


Figure 20: Coefficient of Determination Versus the Number of Predictor Variables for (a) K_1 , (b) K_2 , and (c) K_3 ; Based on the Ni et al. Method.

Table 18 lists the combination of predictor variables and corresponding regression parameters, β_i , that provide the optimum R^2 for each value of p for K_1 , K_2 , and K_3 corresponding to Figure 20. The observed T-statistics, shown in parentheses, is also listed in Table 20.

Table 18: Predictor Variables Yielding the Highest R² and their Regression Parameters Based on the Ni et al. Method

| | p | R ² | β ₀ | Regression Parameter, β _i | | | | | | |
|----------------|---|----------------|----------------|--------------------------------------|-----------------|-------------------|----------------|-------------------|---------------------------|--------------------------------|
| | | | | LI (%) | Activity | R.C. (%) | w (%) | S (%) | (W-W _{opt}) (%) | E _i /P _a |
| K ₁ | 6 | 0.795 | -3480 | -47.3 (4.76) | | 20.16 (0.49) | 31.4 (3.94) | 8.87 (0.33) | -45.7 (0.89) | 3.63 (3.95) |
| | 5 | 0.795 | -2460 | -49.1 (5.58) | | | 29.9 (4.21) | 20.3 (2.46) | -61.9 (1.70) | 3.73 (4.19) |
| | 4 | 0.787 | -2260 | -55.1 (6.59) | | | 35.8 (5.75) | 14.0 (1.88) | | 4.14 (4.79) |
| | 3 | 0.776 | -1040 | -47.0 (6.59) | | | 35.4 (5.60) | | | 4.47 (5.19) |
| | 2 | 0.696 | -748 | -73.2 (12.1) | | | 40.7 (5.62) | | | |
| K ₂ | 5 | 0.733 | 9.07 | | -3.45 (7.34) | -0.0965 (1.54) | | 0.0469 (1.28) | 0.0778 (0.90) | -0.00301 (2.42) |
| | 4 | 0.730 | 11.2 | | -3.79 (13.1) | -0.142 (3.82) | | 0.0762 (4.47) | | -0.00289 (2.34) |
| | 3 | 0.710 | 14.5 | | -3.85 (13.0) | -0.206 (7.93) | | 0.106 (9.29) | | |
| | 2 | 0.467 | -0.927 | | -3.04 (8.11) | | | 0.0445 (3.94) | | |
| K ₃ | 5 | 0.522 | -7.21 | -0.0092 (0.793) | | 0.0897 (1.80) | | -0.0350 (1.20) | -0.747 (1.51) | -0.00014 (0.127) |
| | 4 | 0.522 | -7.12 | -0.0087 (0.80) | | 0.884 (1.83) | | -0.0347 (1.21) | -0.0740 (1.52) | |
| | 3 | 0.517 | -8.45 | | | 0.120 (4.27) | | -0.0542 (3.59) | -0.0609 (1.33) | |
| | 2 | 0.506 | -9.54 | | | 0.146 (7.08) | | -0.0710 (8.54) | | |
| | 1 | 0.400 | -1.35 | | | | | -0.198 (7.71) | | |

When E_i/p_a was included, the final combination of predictor variables based on the R² criterion and engineering judgment for correlating with K₁, K₂ and K₃ are as follows:

$$K_1 = -1040 - 47.0 \times LI + 35.4 \times w + 4.47 \times \frac{E_i}{P_a} \quad (41)$$

$$K_2 = 14.5 - 3.85 \times \text{ACTIVITY} - 0.206 \times \text{RC} + 0.106 \times S \quad (42)$$

$$K_3 = -9.54 + 0.146 \times \text{R.C.} - 0.0710 \times S \quad (43)$$

Using these expressions and Ni et al.'s model, the resilient modulus was calculated and compared with the measured values. Overall, the coefficient of determination is 0.810, which is a slight improvement over the Uzan model ($R^2 = 0.727$). Figure 21 shows the predicted versus measured resilient modulus based on Equations 40 through 43.

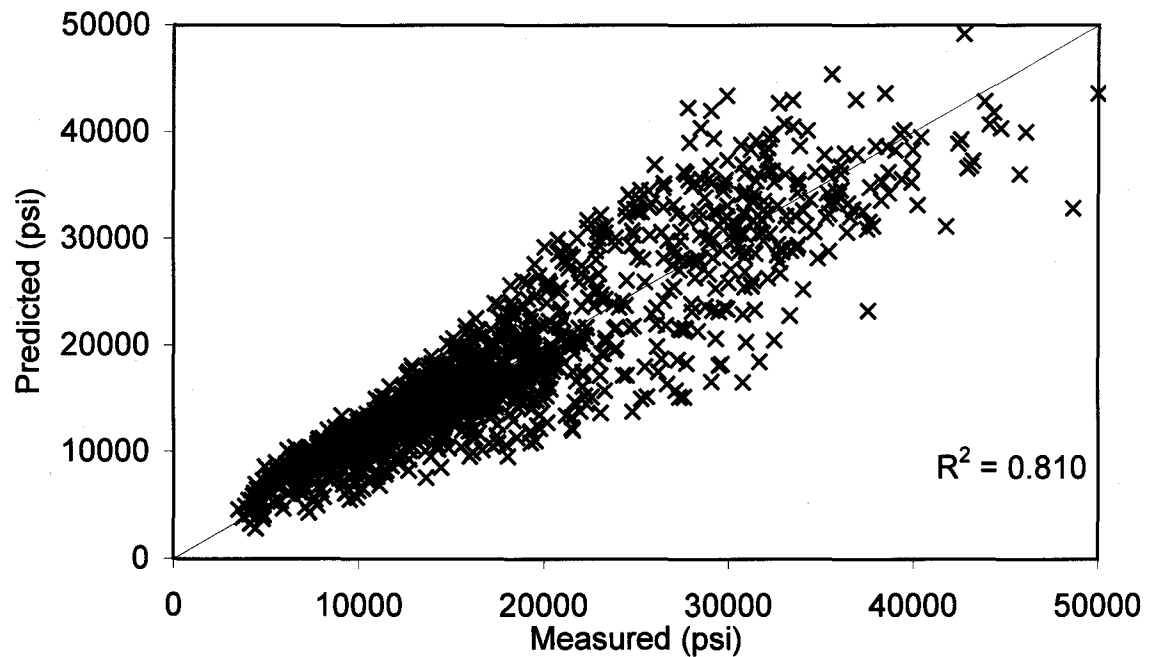


Figure 21: Predicted Versus Measured Resilient Modulus Based on Ni et al.'s (2002) Method with K_i as a Function of E_i/P_a

The R^2 criterion was applied once again using the Ni et al. model and the subset of predictor variables with E_i/P_a removed. Table 19 lists the combination of predictor variables

and corresponding regression parameters, β_i , that provide the optimum R^2 for K_1 , K_2 , and K_3 . The observed T-statistics values, shown in parentheses, are also listed in Table 19.

Table 19: Predictor Variables Yielding the Highest R^2 and their Regression Parameters Based on the Ni et al. Method; E_i/p_a Removed From the Predictor Variable Set.

| | p | R^2 | β_0 | Regression Parameter, β_i | | | | | |
|-------|-----|-------|-----------|---------------------------------|-----------------|------------------|----------------|-------------------|-------------------|
| | | | | LI (%) | Activity | R.C. (%) | w (%) | S (%) | $(W-W_{opt})$ (%) |
| K_1 | 5 | 0.761 | -6680 | -59.2 (5.85) | | 69.9 (1.47) | 32.9 (3.70) | -5.61 (1.17) | -64.6 (1.13) |
| | 4 | 0.760 | -6280 | -60.3 (7.13) | | 61.1 (4.28) | 32.1 (4.19) | | -73.1 (2.01) |
| | 3 | 0.748 | -6410 | -73.5 (13.5) | | 58.3 (4.02) | 40.4 (5.93) | | |
| | 2 | 0.695 | -727 | -73.7 (12.4) | | | 40.6 (5.65) | | |
| K_2 | 4 | 0.726 | 14.4 | | -3.95 (7.53) | -0.204 (3.39) | | 0.107 (0.288) | -0.0371 (0.38) |
| | 3 | 0.725 | 15.3 | | -4.11 (13.6) | -0.224 (7.45) | | 0.120 (9.93) | |
| | 2 | 0.500 | -1.53 | | -3.32 (8.68) | | | 0.0537 (4.58) | |
| K_3 | 4 | 0.487 | -6.23 | -0.00962 (0.90) | | 0.0715 (1.54) | | -0.0258 (0.93) | -0.0852 (1.85) |
| | 3 | 0.481 | -2.76 | -0.0229 (3.63) | | | | 0.0143 (1.50) | -0.129 (3.50) |
| | 2 | 0.455 | -1.51 | -0.0187 (3.28) | | | | | -0.109 (3.15) |
| | 1 | 0.401 | -1.32 | | | | | | -0.190 (7.23) |

When E_i/p_a was excluded, the R^2 criterion plots are shown in Figure 22.

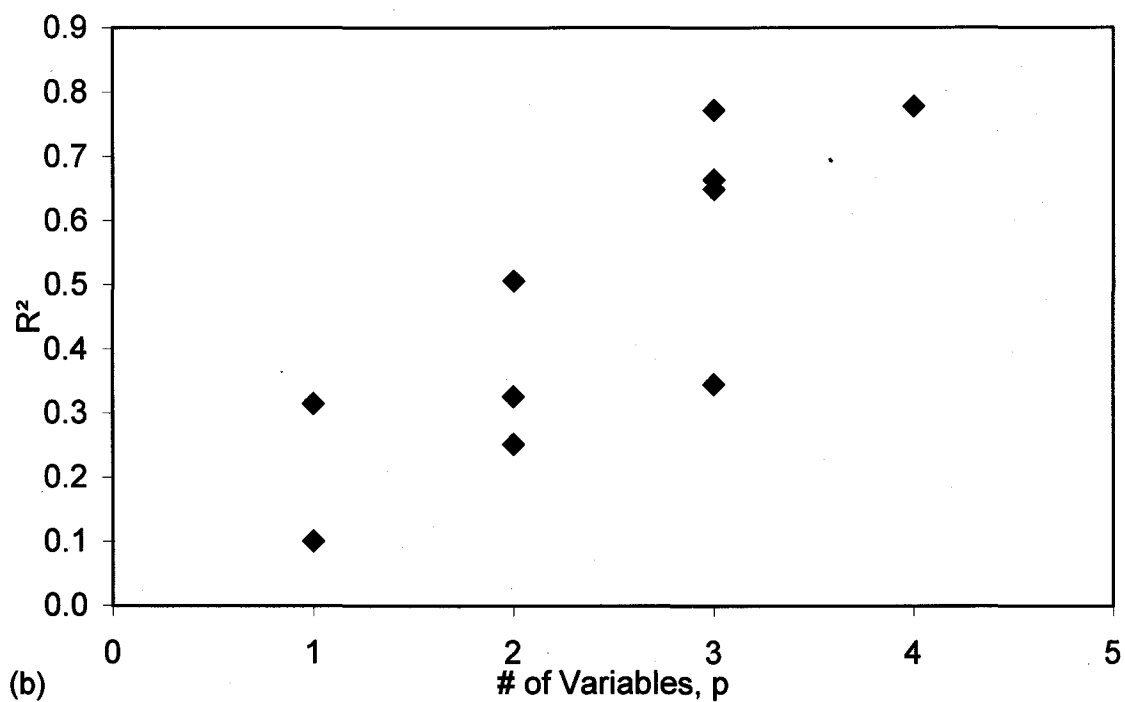
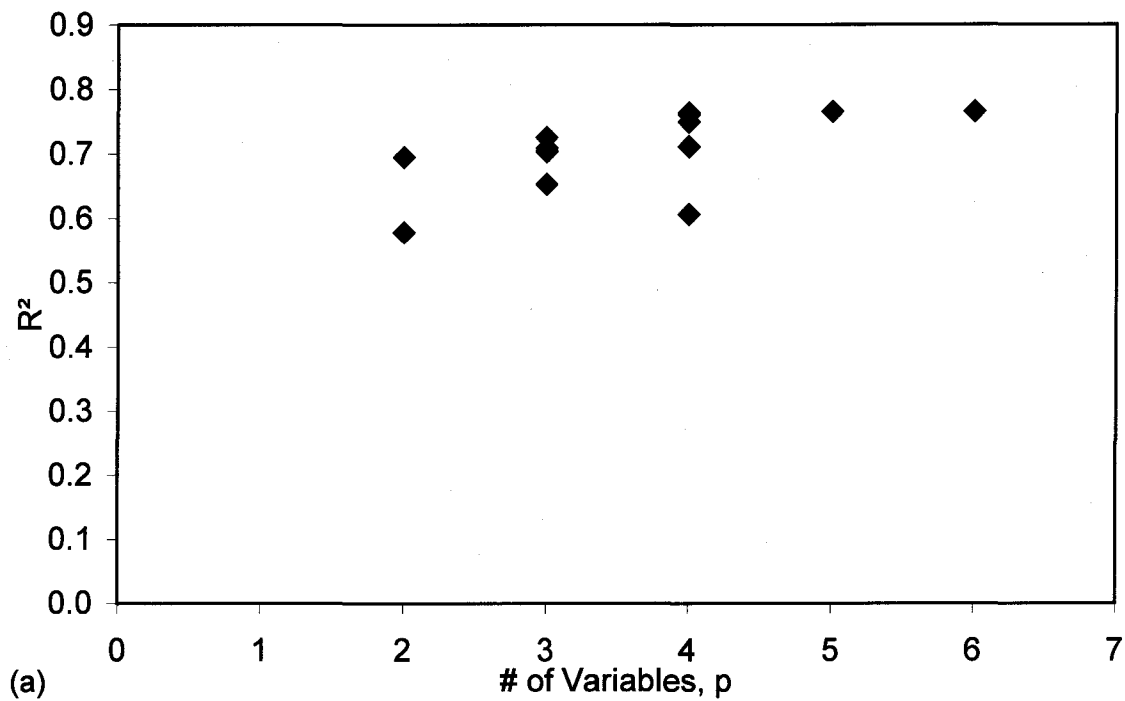


Figure 22: Coefficient of Determination Versus the Number of Predictor Variables for (a) K_1 , (b) K_2 , and (c) K_3 with E_i/p_a Removed From the Subset of Predictor Variables; Based on the Ni et al Method.

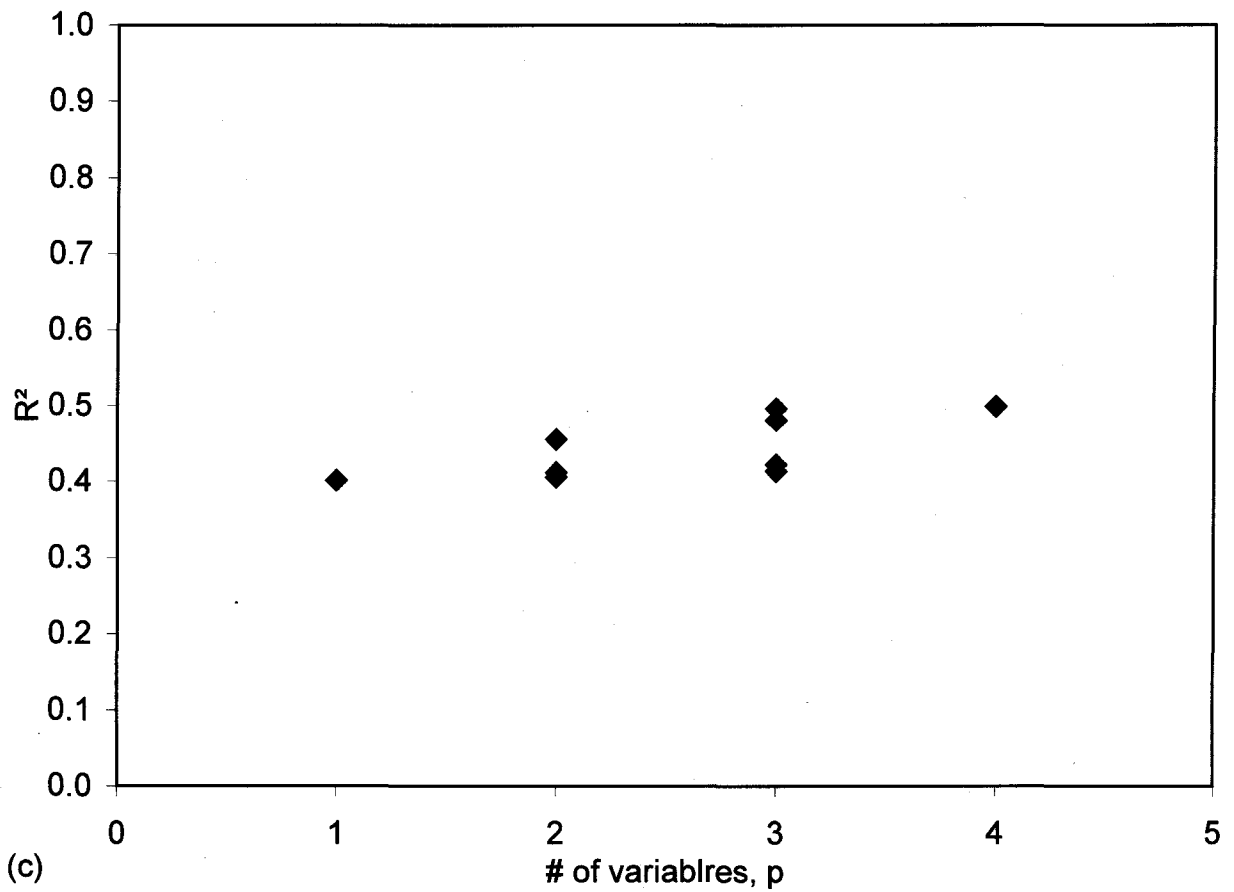


Figure 22: Coefficient of Determination Versus the Number of Predictor Variables for (a) K_1 , (b) K_2 , and (c) K_3 with E_i/p_a Removed From the Subset of Predictor Variables; Based on the Ni et al Method.

Again, the final combination of predictor variables based on the R^2 criterion and engineering judgment for correlating with K_1 , K_2 and K_3 are as follows:

$$K_1 = -6280 - 60.3 \times LI + 61.1 \times R.C + 32.1 \times w - 73.1 \times (w - w_{opt}) \quad (44)$$

$$K_2 = 15.3 - 4.11 \times ACTIVITY - 0.224 \times RC + 0.120 \times S \quad (45)$$

$$K_3 = -2.76 - 0.0229 \times LI + 0.0143 \times S - 0.129 \times (w - w_{opt}) \quad (46)$$

Using these expressions and Ni et al.'s model, the resilient modulus was calculated and compared with the measured values. Overall, the coefficient of determination is 0.778, which again is a slight improvement over the Uzan model ($R^2 = 0.691$). Predicted versus measured resilient modulus values, based on Ni et al.'s model and Equations 44 to 46, are shown in Figure 23.

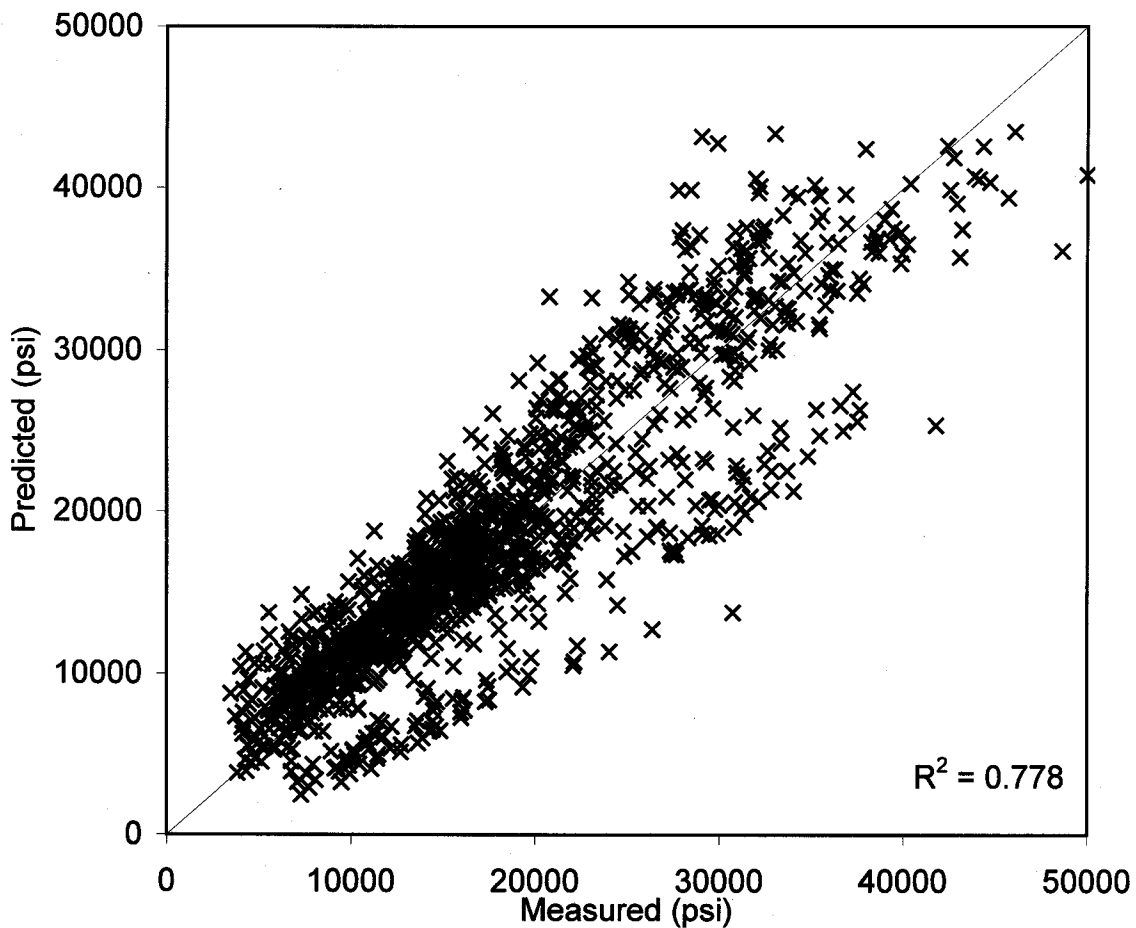


Figure 23: Predicted versus Measured Resilient Modulus With Based on Ni et al.'s (2002) Model and E_i/p_a Removed From the Subset of Predictor Variables.

5.3 Effects of Drying on Resilient Modulus

Three sets of resilient modulus tests were performed on the Wahiawa soil. The three sets differed in the way the samples were prepared. First, the soil is tested from wet to dry without drying below the target moisture content. This is referred to as the “in situ” set of tests. Second, a batch of the soil is air-dried to approximately half the in situ water content prior to resilient modulus testing. This soil is then rewetted to the target molding water content and compacted for testing. This set of tests is referred to as the “intermediate” soils. The “ovendry” specimens form the third set of tests. In this case, the samples were dried in the oven for 24 hours. The soil was then rewetted to the target moisture content prior to testing. Target compaction densities and water contents derived from Standard Proctor tests are shown in Table 11 of Section 4.3.1.

Values of K_i , based on both the Uzan (1985) and Ni et al (2002) models for the three different sets of Wahiawa specimens prepared at the optimum water content and maximum dry density are compared in Figure 24.

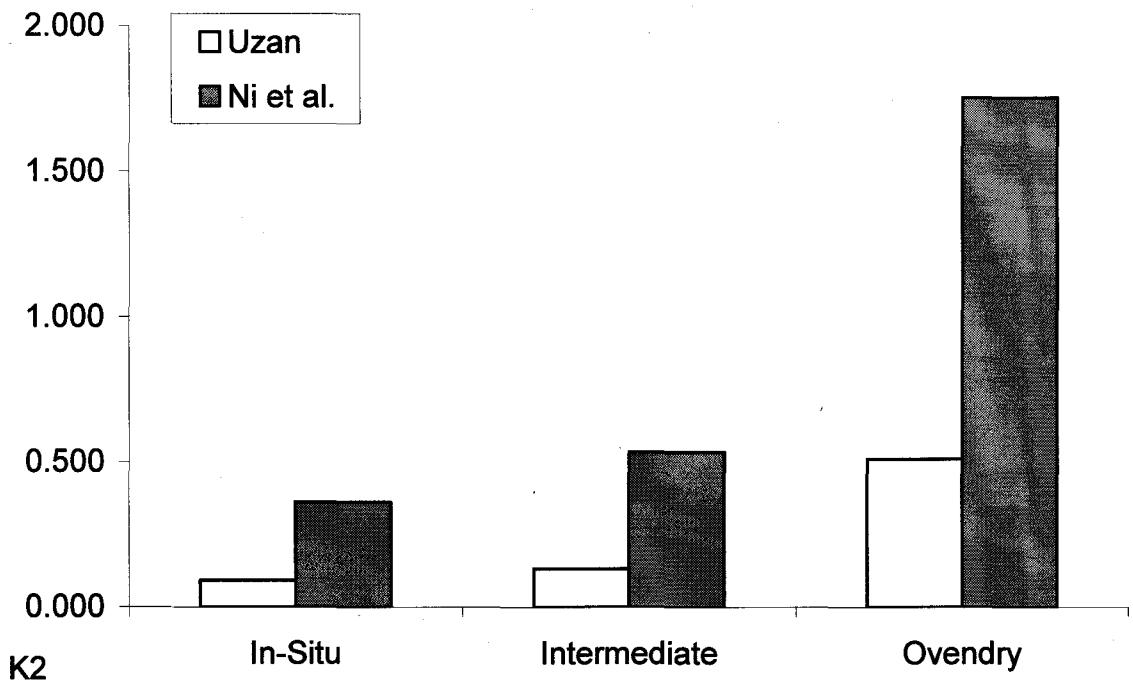
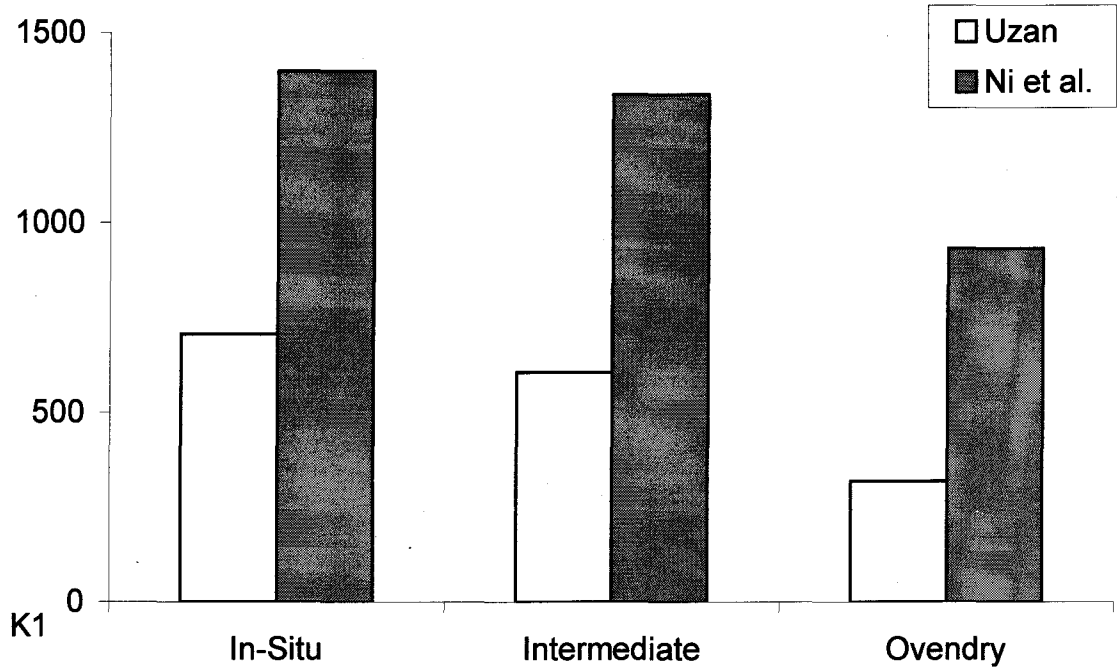


Figure 24: Average values of (a) K_1 , (b) K_2 and (c) K_3 for the Wahiawa soil.

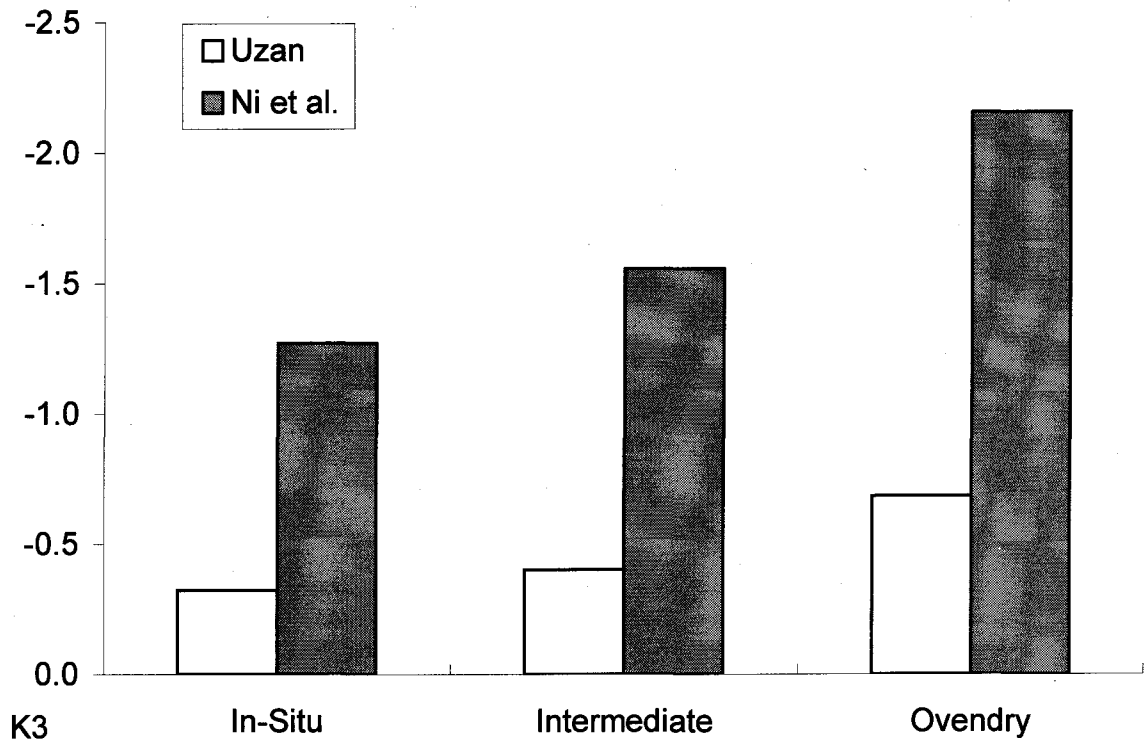


Figure 24: Average values of (a) K_1 , (b) K_2 and (c) K_3 for the Wahiawa soil.

The K_i values displayed in Figure 24 are average values obtained from multiple resilient modulus tests. For the in situ and intermediate soil, the K_i coefficients are the average values obtained from three separate resilient modulus tests. The owendry coefficients are obtained from resilient modulus tests on two duplicate samples.

It is observed that K_1 is largest for the in situ sample and smallest for the owendry sample. Higher K_1 coefficients would represent compacted soils with higher resilient modulus at similar stress states.

It is observed that K_2 is smallest for the in situ and largest for the owendry soils for both models. The K_2 coefficient is an exponent for the confining pressure (Ni et. al) and bulk

stress (Uzan). Intuitively, a smaller value for K_2 indicates a resilient modulus that is less influenced by changes in confining pressure or bulk stress.

The K_3 coefficient is an exponent for the deviator stress. The values of K_3 are negative in both the Ni et al and Uzan models. In either model, a value of K_3 closer to zero would indicate a soil that displays minimal decrease in resilient modulus under increasing deviatoric stress; i.e. a flatter curve on the resilient modulus versus deviatoric stress plot. The oven-dry soil has the smallest K_3 , indicating that the oven-dry resilient modulus is most sensitive to changes in deviatoric stress among the three soils.

A comparison of the resilient modulus at maximum dry density and optimum water content indicates that on average, the resilient modulus is largest for the "in situ" soils and smallest for the "oven-dry" soils. This is contradictory to intuition since the optimum water content is highest for the "in situ" (44.8%), 41.6% for the intermediate and lowest for the "oven-dry" at 38.4%. Similarly, the dry density at 100% relative compaction is lowest for the "in situ" soils and highest for the "oven-dry" soils. This trend in the variation of resilient modulus with increasing degree of drying is complicated by the fact that the oven-dry soils tend to behave in a more granular fashion where the resilient modulus is more sensitive to confining pressure, as evident by the high K_2 values.

Chapter 6: Summary and Conclusions

6.1 Summary

- Two constitutive models, Uzan (1985) and Ni et al. (2002), which express the relationship between resilient modulus and stress state were calibrated for several tropical Hawaiian fine-grained soils.
- The regression analyses involved relating the constants K_1 , K_2 and K_3 with common soil parameters.
- Four silts (two ML and two MH) of varying natural water contents (Kapolei – 19% to 23%; Waipio – 24% to 29%; Mililani Mauka – 28% to 33%; Wahiawa – 51% to 57%) were sampled for testing.
- Results of resilient modulus tests for the Wahiawa oven-dry soil were removed from the data set prior to developing the equations for correlating the resilient modulus with common soil parameters because the samples were dried to temperature extremes that regular soils do not experience, and therefore are judged to be inappropriate for inclusion in this work. Nevertheless, the oven-dry data did provide useful insight into the effects of drying on the resilient modulus.
- Parameters that provided the best correlation were selected from a process of elimination using statistical tools (the R^2 criterion). This method helped in the derivation of a model that provides reliable estimates of resilient modulus (high coefficient of determination) involving suitable combination of predictor variables.

- For the Uzan (1985) model, the R^2 obtained were 0.727 and 0.691, respectively when E_i/p_a was and was not included.
- For the Ni et al. (2002) model, the corresponding R^2 values were 0.810 and 0.779 respectively.
- Drying of the Wahiawa soils prior to testing results in lower Atterberg limits, a more granular grain size distribution and the compaction curve shifting up and to the left (i.e. increasing dry density and decreasing optimum water content).
- However, drying of the Wahiawa soil has several effects on the resilient modulus. While the resilient modulus of the oven-dry soil was lower than the in situ and intermediate on average, drying the soil appears to increase the influence of confining stress on the resilient modulus suggesting that it behaves more granular, i.e. a greater reduction in resilient modulus is obtained with a reduction in confining pressure. Also, the greater the degree of drying, the more sensitive is the resilient modulus to changes in deviatoric stress.
- The correlations for resilient properties provided in this thesis were developed based only upon four soils. These soils were tested under a limited range of moisture, density, and compactive method. Engineering judgment should be exercised when applying these correlations to soil physical state conditions outside of those tested in this study. Engineering judgment should also be exercised when applying these correlations to other soils.

6.2 Recommendations for Further Research

Topics for further research include:

- Investigate fit of proposed regression models for other Hawaiian tropical fine-grained soils.
- Investigate effects of compaction using a higher compaction effort i.e., modified proctor compaction.
- Investigate effects of other compaction methods (e.g., kneading) on the resilient modulus of tropical soils.
- Investigate effects of suction on the resilient modulus of tropical soils.
- Investigate the morphological changes of the Wahiawa soil upon drying to better understand the changes observed in the values of soil index and resilient modulus properties.
- Investigate any difference in resilient modulus between an in situ soil and the same soil reconstituted in the laboratory to the same physical state.

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Appendix A: Resilient Modulus Test Results

| Sample No. | σ_3 | σ_d | Resilient Modulus (psi) |
|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------|------------|----------------------------|
| | (psi) | | |
| Waipio γ_d (pcf) = 93.6 w (%) = 30.0 q_u (psi) = E_i (psi) = K_1 = 287 K_2 = 1.33 K_3 = -0.86 Note: All K_i Coefficients Shown in are Based on The Model Proposed by Uzan (1985). | 2 | 2.1 | 10403 |
| | 2 | 4.0 | 7248 |
| | 2 | 6.0 | 6851 |
| | 2 | 7.9 | 6783 |
| | 2 | 9.9 | 6781 |
| | 4 | 2.2 | 22047 |
| | 4 | 4.1 | 13981 |
| | 4 | 6.2 | 11453 |
| | 4 | 8.2 | 10860 |
| | 4 | 10.1 | 10117 |
| | 6 | 2.2 | 30725 |
| | 6 | 4.1 | 24036 |
| | 6 | 5.9 | 17345 |
| | 6 | 8.0 | 14529 |
| | 6 | 10.3 | 13490 |
| Waipio γ_d (pcf) = 93.7 w (%) = 29.3 q_u (psi) = 15.1 E_i (psi) = 1094 K_1 = 189 K_2 = 1.17 K_3 = -0.76 | 2 | 2.1 | 6652 |
| | 2 | 3.9 | 4809 |
| | 2 | 5.8 | 4194 |
| | 2 | 8.1 | 4157 |
| | 2 | 9.9 | 4101 |
| | 4 | 2.0 | 11424 |
| | 4 | 4.0 | 8195 |
| | 4 | 5.9 | 6860 |
| | 4 | 8.0 | 6126 |
| | 4 | 9.9 | 5753 |
| | 6 | 2.1 | 15606 |
| | 6 | 4.0 | 14284 |
| | 6 | 5.9 | 10595 |
| | 6 | 7.8 | 8748 |
| | 6 | 10.0 | 7844 |
| Waipio γ_d (pcf) = 93.7 w (%) = 29.3 q_u (psi) = 19.7 E_i (psi) = 1785 K_1 = 353 K_2 = 1.02 | 2 | 1.9 | 10288 |
| | 2 | 3.9 | 7815 |
| | 2 | 5.9 | 7136 |
| | 2 | 7.9 | 6991 |
| | 2 | 9.9 | 6968 |
| | 4 | 2.1 | 16279 |
| | 4 | 3.9 | 12763 |

| Sample No. | σ_3 | σ_d | Resilient Modulus (psi) |
|-------------------------------------------------------------------------------------------------------------------------------------------------|------------|------------|----------------------------|
| | (psi) | | |
| K ₃ = -0.62 | 4 | 6.0 | 10928 |
| | 4 | 7.9 | 10108 |
| | 4 | 9.7 | 9802 |
| | 6 | 2.1 | 20479 |
| | 6 | 4.0 | 19923 |
| | 6 | 5.7 | 17060 |
| | 6 | 7.8 | 13515 |
| | 6 | 9.9 | 12282 |
| Waipio γ_d (pcf) = 93.2 w (%) = 27.9 q_u (psi) = E_i (psi) = K_1 = 931 K_2 = 0.45 K_3 = -0.44 | 2 | 2.1 | 27147 |
| | 2 | 3.9 | 20954 |
| | 2 | 5.8 | 17994 |
| | 2 | 8.1 | 16376 |
| | 2 | 9.9 | 15299 |
| | 4 | 2.0 | 29508 |
| | 4 | 4.1 | 25451 |
| | 4 | 5.9 | 23518 |
| | 4 | 8.1 | 20240 |
| | 4 | 10.1 | 18907 |
| | 6 | 1.9 | 33161 |
| | 6 | 4.0 | 31903 |
| | 6 | 5.9 | 28153 |
| | 6 | 7.9 | 23299 |
| 6 | 10.1 | 21665 | |
| Waipio γ_d (pcf) = 93.9 w (%) = 27.1 q_u (psi) = 28.7 E_i (psi) = 3097 K_1 = 888 K_2 = 0.49 K_3 = -0.37 | 2 | 2.0 | 20083 |
| | 2 | 4.0 | 18110 |
| | 2 | 6.0 | 16646 |
| | 2 | 8.0 | 15755 |
| | 2 | 9.8 | 14732 |
| | 4 | 2.2 | 24851 |
| | 4 | 3.9 | 21246 |
| | 4 | 6.0 | 20773 |
| | 4 | 8.0 | 19233 |
| | 4 | 10.0 | 17927 |
| | 6 | 2.2 | 28911 |
| | 6 | 4.0 | 27202 |
| | 6 | 6.0 | 24716 |
| | 6 | 8.0 | 22015 |
| 6 | 10.0 | 19499 | |

| Sample No. | σ_3 | σ_d | Resilient Modulus (psi) |
|--------------------------------------------------------------------------------------------------------------------------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------|------------|----------------------------|
| | (psi) | | |
| Waipio γ_d (pcf) = 93.9 w (%) = 27.1 q_u (psi) = 29.3 E_i (psi) = 2803 K_1 = 905 K_2 = 0.50 K_3 = -0.45 | 2 | 2.1 | 23308 |
| | 2 | 4.2 | 20815 |
| | 2 | 6.0 | 18136 |
| | 2 | 7.7 | 16777 |
| | 2 | 9.8 | 15410 |
| | 4 | 2.5 | 27054 |
| | 4 | 4.1 | 24468 |
| | 4 | 6.0 | 22716 |
| | 4 | 7.8 | 20561 |
| | 4 | 9.9 | 18496 |
| | 6 | 2.0 | 35322 |
| | 6 | 4.1 | 31827 |
| | 6 | 5.9 | 27712 |
| | 6 | 8.1 | 22833 |
| | 6 | 10.0 | 20912 |
| | Waipio γ_d (pcf) = 93.6 w (%) = 25.5 q_u (psi) = 39.3 E_i (psi) = 4193 K_1 = 1653 K_2 = 0.29 K_3 = -0.39 | 2 | 2.0 |
| 2 | | 4.0 | 35760 |
| 2 | | 6.2 | 33109 |
| 2 | | 8.0 | 30822 |
| 2 | | 9.9 | 29655 |
| 4 | | 2.0 | 53499 |
| 4 | | 4.1 | 38533 |
| 4 | | 6.2 | 36020 |
| 4 | | 7.9 | 33714 |
| 4 | | 10.4 | 31605 |
| 6 | | 2.2 | 58356 |
| 6 | | 4.1 | 43824 |
| 6 | | 6.2 | 39451 |
| 6 | | 8.1 | 36266 |
| 6 | | 10.1 | 33040 |
| Waipio γ_d (pcf) = 93.6 w (%) = 25.5 q_u (psi) = 39.3 E_i (psi) = 4193 K_1 = 1522 K_2 = 0.30 K_3 = -0.33 | | 2 | 2.1 |
| | 2 | 4.1 | 31445 |
| | 2 | 6.0 | 28916 |
| | 2 | 7.8 | 26770 |
| | 2 | 9.8 | 24405 |
| | 4 | 1.9 | 39320 |
| | 4 | 4.1 | 34036 |
| | 4 | 6.0 | 32227 |

| Sample No. | σ_3 | σ_d | Resilient Modulus (psi) |
|----------------------------------------------------------------------------------------------------------------------------------------------|------------|------------|----------------------------|
| | (psi) | | |
| | 4 | 7.8 | 30513 |
| | 4 | 9.8 | 27320 |
| | 6 | 1.9 | 46046 |
| | 6 | 4.1 | 42878 |
| | 6 | 6.0 | 38643 |
| | 6 | 7.8 | 32054 |
| | 6 | 9.7 | 30232 |
| Waipio γ_d (pcf) = 93.5 w (%) = 25.7 q_u (psi) = E_i (psi) = K_1 = 1440 K_2 = 0.29 K_3 = -0.38 | 2 | 2.2 | 35878 |
| | 2 | 4.1 | 31990 |
| | 2 | 5.8 | 28823 |
| | 2 | 8.0 | 26016 |
| | 2 | 9.9 | 23629 |
| | 4 | 2.4 | 39143 |
| | 4 | 4.0 | 36101 |
| | 4 | 6.0 | 32443 |
| | 4 | 7.8 | 29543 |
| | 4 | 9.8 | 26908 |
| | 6 | 2.1 | 45901 |
| | 6 | 4.1 | 41825 |
| | 6 | 5.9 | 36653 |
| | 6 | 8.1 | 30941 |
| | 6 | 9.7 | 28037 |
| Waipio γ_d (pcf) = 88.6 w (%) = 29.9 q_u (psi) = 8.6 E_i (psi) = 1046 K_1 = 254 K_2 = 0.97 K_3 = -0.74 | 2 | 2.0 | 10048 |
| | 2 | 4.0 | 6768 |
| | 2 | 6.0 | 5733 |
| | 2 | 7.9 | 5372 |
| | 2 | 9.8 | 4930 |
| | 4 | 1.9 | 15270 |
| | 4 | 3.9 | 11202 |
| | 4 | 6.0 | 9353 |
| | 4 | 7.9 | 8348 |
| | 4 | 9.1 | 6391 |
| | 6 | 2.0 | 18220 |
| | 6 | 4.0 | 16196 |
| | 6 | 5.9 | 13057 |
| | 6 | 8.0 | 10664 |
| | 6 | 9.9 | 9641 |
| Waipio | 2 | 2.0 | 15549 |

| Sample No. | σ_3 | σ_d | Resilient Modulus (psi) |
|--------------------------------------------------------------------------------------------------------------------------------------------------------|------------|------------|----------------------------|
| | (psi) | | |
| γ_d (pcf) = 89.1 w (%) = 29.2 q_u (psi) = 13.9 E_i (psi) = 1617 K_1 = 566 K_2 = 0.74 K_3 = -0.49 | 2 | 3.9 | 11674 |
| | 2 | 6.2 | 10711 |
| | 2 | 7.9 | 10221 |
| | 2 | 9.9 | 9884 |
| | 4 | 2.1 | 19787 |
| | 4 | 4.0 | 17464 |
| | 4 | 5.8 | 16169 |
| | 4 | 7.9 | 14447 |
| | 4 | 9.8 | 13628 |
| | 6 | 2.1 | 24481 |
| | 6 | 4.0 | 22291 |
| | 6 | 5.9 | 19648 |
| | 6 | 8.0 | 17506 |
| | 6 | 9.9 | 15989 |
| Waipio γ_d (pcf) = 89.0 w (%) = 29.3 q_u (psi) = 13.8 E_i (psi) = 1932 K_1 = 502 K_2 = 0.81 K_3 = -0.55 | 2 | 2.0 | 14491 |
| | 2 | 4.0 | 11182 |
| | 2 | 6.0 | 10125 |
| | 2 | 7.9 | 9762 |
| | 2 | 9.8 | 9388 |
| | 4 | 2.1 | 18471 |
| | 4 | 4.1 | 16031 |
| | 4 | 5.9 | 14449 |
| | 4 | 7.8 | 13887 |
| | 4 | 10.0 | 12695 |
| | 6 | 2.3 | 26378 |
| | 6 | 4.0 | 22120 |
| | 6 | 5.8 | 19336 |
| | 6 | 8.1 | 15962 |
| 6 | 10.2 | 14853 | |
| Waipio γ_d (pcf) = 88.6 w (%) = 27.8 q_u (psi) = 17.9 E_i (psi) = 2156 K_1 = 821 K_2 = 0.50 K_3 = -0.38 | 2 | 1.9 | 19906 |
| | 2 | 4.0 | 17212 |
| | 2 | 5.9 | 15241 |
| | 2 | 8.0 | 14370 |
| | 2 | 10.1 | 13452 |
| | 4 | 1.8 | 24058 |
| | 4 | 3.9 | 21382 |
| | 4 | 5.8 | 19329 |
| 4 | 8.0 | 17851 | |

| Sample No. | σ_3 | σ_d | Resilient Modulus (psi) |
|--------------------------------------------------------------------------------------------------------------------------------------------------------|------------|------------|----------------------------|
| | (psi) | | |
| | 4 | 10.0 | 16087 |
| | 6 | 2.0 | 28336 |
| | 6 | 4.2 | 24245 |
| | 6 | 6.0 | 23800 |
| | 6 | 8.0 | 20837 |
| | 6 | 9.9 | 19358 |
| Waipio γ_d (pcf) = 88.6 w (%) = 27.9 q_u (psi) = 18.6 E_i (psi) = 2574 K_1 = 788 K_2 = 0.59 K_3 = -0.55 | 2 | 2.3 | 23883 |
| | 2 | 4.0 | 19128 |
| | 2 | 6.0 | 16679 |
| | 2 | 7.9 | 15576 |
| | 2 | 10.1 | 14152 |
| | 4 | 2.0 | 30837 |
| | 4 | 4.1 | 24850 |
| | 4 | 6.0 | 21634 |
| | 4 | 7.8 | 20210 |
| | 4 | 10.0 | 18514 |
| | 6 | 1.9 | 41753 |
| | 6 | 4.0 | 32806 |
| | 6 | 6.0 | 26077 |
| | 6 | 8.2 | 21896 |
| | 6 | 9.8 | 20160 |
| Waipio γ_d (pcf) = 88.8 w (%) = 27.7 q_u (psi) = 17.6 E_i (psi) = 2674 K_1 = 616 K_2 = 0.69 K_3 = -0.63 | 2 | 2.2 | 19291 |
| | 2 | 4.0 | 16020 |
| | 2 | 6.0 | 14120 |
| | 2 | 8.0 | 12776 |
| | 2 | 9.9 | 11993 |
| | 4 | 2.3 | 28163 |
| | 4 | 4.2 | 20888 |
| | 4 | 6.0 | 18651 |
| | 4 | 8.0 | 16338 |
| | 4 | 9.8 | 14983 |
| | 6 | 2.0 | 37262 |
| | 6 | 4.1 | 29130 |
| | 6 | 6.1 | 22826 |
| | 6 | 8.1 | 19261 |
| | 6 | 9.7 | 17625 |
| Waipio γ_d (pcf) = 88.9 | 2 | 2.1 | 35449 |
| | 2 | 4.0 | 30561 |

| Sample No. | σ_3 | σ_d | Resilient Modulus (psi) |
|------------------------------------------------------------------------------------------------------------------------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------|------------|----------------------------|
| | (psi) | | |
| w (%) = 25.5 q_u (psi) = 30.0 E_i (psi) = 3443 K_1 = 1382 K_2 = 0.33 K_3 = -0.39 | 2 | 6.2 | 28021 |
| | 2 | 8.2 | 25467 |
| | 2 | 10.1 | 23040 |
| | 4 | 2.1 | 39929 |
| | 4 | 4.1 | 33741 |
| | 4 | 5.9 | 30823 |
| | 4 | 8.2 | 29174 |
| | 4 | 10.0 | 26482 |
| | 6 | 2.1 | 49984 |
| | 6 | 4.1 | 39229 |
| | 6 | 6.0 | 36042 |
| | 6 | 8.1 | 30688 |
| | 6 | 10.0 | 27728 |
| | Waipio γ_d (pcf) = 88.3 w (%) = 26.3 q_u (psi) = 23.6 E_i (psi) = 3211 K_1 = 929 K_2 = 0.45 K_3 = -0.34 | 2 | 2.1 |
| 2 | | 4.2 | 18846 |
| 2 | | 5.9 | 17340 |
| 2 | | 7.9 | 15773 |
| 2 | | 9.8 | 14767 |
| 4 | | 2.2 | 25182 |
| 4 | | 4.0 | 23331 |
| 4 | | 5.8 | 21396 |
| 4 | | 7.9 | 19110 |
| 4 | | 10.0 | 17541 |
| 6 | | 1.1 | 33430 |
| 6 | | 3.8 | 28981 |
| 6 | | 5.8 | 25832 |
| 6 | | 8.0 | 21806 |
| 6 | 10.0 | 19501 | |
| Waipio γ_d (pcf) = 89.0 w (%) = 25.3 q_u (psi) = 28.9 E_i (psi) = 4330 K_1 = 1274 K_2 = 0.36 K_3 = -0.38 | 2 | 1.8 | 30623 |
| | 2 | 4.1 | 29024 |
| | 2 | 6.0 | 24905 |
| | 2 | 7.9 | 22885 |
| | 2 | 9.8 | 20921 |
| | 4 | 2.1 | 38411 |
| | 4 | 3.9 | 33449 |
| | 4 | 6.0 | 29896 |
| | 4 | 8.1 | 26444 |
| | 4 | 9.9 | 24421 |

| Sample No. | σ_3 | σ_d | Resilient Modulus (psi) |
|----------------------------------------------------------------------------------------------------------------------------------------------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------|------------|----------------------------|
| | (psi) | | |
| | 6 | 2.1 | 42701 |
| | 6 | 4.0 | 35558 |
| | 6 | 5.6 | 32691 |
| | 6 | 7.9 | 29150 |
| | 6 | 10.0 | 25958 |
| | Mililani γ_d (pcf) = 81.4 w (%) = 40.9 q_u (psi) = 21.5 E_i (psi) = 1719 K_1 = 411 K_2 = 0.37 K_3 = -0.58 | 2 | 2.1 |
| 2 | | 4.0 | 12349 |
| 2 | | 5.9 | 9714 |
| 2 | | 7.8 | 8098 |
| 2 | | 9.9 | 6821 |
| 4 | | 1.9 | 16611 |
| 4 | | 4.0 | 14462 |
| 4 | | 6.0 | 12089 |
| 4 | | 7.9 | 9861 |
| 4 | | 9.7 | 8308 |
| 6 | | 2.1 | 19415 |
| 6 | | 4.0 | 16863 |
| 6 | | 6.0 | 13658 |
| 6 | | 8.0 | 10698 |
| 6 | | 9.8 | 8855 |
| Mililani γ_d (pcf) = 81.4 w (%) = 40.9 q_u (psi) = 23.7 E_i (psi) = 1784 K_1 = 377 K_2 = 0.36 K_3 = -0.62 | | 2 | 2.2 |
| | 2 | 4.0 | 12004 |
| | 2 | 5.9 | 9397 |
| | 2 | 7.9 | 7586 |
| | 2 | 9.7 | 6532 |
| | 4 | 1.9 | 16336 |
| | 4 | 4.2 | 13701 |
| | 4 | 5.9 | 11259 |
| | 4 | 7.8 | 9173 |
| | 4 | 9.9 | 7573 |
| | 6 | 2.1 | 19391 |
| | 6 | 3.9 | 16914 |
| | 6 | 5.8 | 13458 |
| | 6 | 7.3 | 10728 |
| | 6 | 9.8 | 7941 |
| | Mililani γ_d (pcf) = 81.1 w (%) = 39.6 | 2 | 1.8 |
| 2 | | 4.1 | 19145 |
| 2 | | 6.2 | 17470 |

| Sample No. | σ_3 | σ_d | Resilient Modulus (psi) | |
|-------------------------------------------------------------------------------------------------------------------------------------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------|------------|----------------------------|----|
| | (psi) | | | |
| q_u (psi) = 30.4 E_i (psi) = 2522 K_1 = 825 K_2 = 0.19 K_3 = -0.37 | 2 | 8.1 | 15319 | |
| | 2 | 10.0 | 13381 | |
| | 4 | 2.1 | 23921 | |
| | 4 | 4.1 | 19973 | |
| | 4 | 6.1 | 17866 | |
| | 4 | 7.9 | 15996 | |
| | 4 | 9.9 | 14130 | |
| | 6 | 2.1 | 25820 | |
| | 6 | 4.2 | 23109 | |
| | 6 | 5.9 | 19598 | |
| | 6 | 8.0 | 16762 | |
| | 6 | 9.9 | 14273 | |
| | Mililani γ_d (pcf) = 81.3 w (%) = 39.1 q_u (psi) = 29.7 E_i (psi) = 2662 K_1 = 899 K_2 = 0.19 K_3 = -0.27 | 2 | -- | -- |
| | | 2 | -- | -- |
| 2 | | -- | -- | |
| 2 | | -- | -- | |
| 2 | | -- | -- | |
| 4 | | 2.0 | 21023 | |
| 4 | | 3.9 | 19436 | |
| 4 | | 5.9 | 18210 | |
| 4 | | 7.9 | 16868 | |
| 4 | | 9.8 | 14921 | |
| 6 | | 1.8 | 23747 | |
| 6 | | 3.8 | 21811 | |
| 6 | | 5.8 | 19903 | |
| 6 | | 8.0 | 17633 | |
| 6 | 10.0 | 14987 | | |
| Mililani γ_d (pcf) = 81.5 w (%) = 36.8 q_u (psi) = E_i (psi) = K_1 = 2065 K_2 = 0.01 K_3 = -0.10 | 2 | -- | -- | |
| | 2 | -- | -- | |
| | 2 | -- | -- | |
| | 2 | -- | -- | |
| | 2 | -- | -- | |
| | 4 | 2.1 | 36384 | |
| | 4 | 4.0 | 35751 | |
| | 4 | 5.8 | 34183 | |
| | 4 | 7.7 | 32066 | |
| | 4 | 10.0 | 30487 | |
| | 6 | 1.9 | 38068 | |

| Sample No. | σ_3 | σ_d | Resilient Modulus (psi) |
|-----------------------------------------------------------------------------------------------------------------------------------------------------------|------------|------------|----------------------------|
| | (psi) | | |
| | 6 | 3.6 | 33096 |
| | 6 | 5.9 | 35057 |
| | 6 | 8.0 | 33477 |
| | 6 | 9.8 | 31373 |
| Mililani γ_d (pcf) = 81.6 w (%) = 36.7 q_u (psi) = 35.3 E_i (psi) = 5242 K_1 = 1869 K_2 = 0.00 K_3 = -0.13 | 2 | 2.1 | 36578 |
| | 2 | 4.0 | 33361 |
| | 2 | 6.0 | 31318 |
| | 2 | 8.0 | 28728 |
| | 2 | 9.9 | 26585 |
| | 4 | 2.0 | 35262 |
| | 4 | 4.0 | 32632 |
| | 4 | 6.1 | 31234 |
| | 4 | 7.8 | 29758 |
| | 4 | 9.8 | 27303 |
| | 6 | 1.9 | 31843 |
| | 6 | 3.9 | 34811 |
| | 6 | 6.1 | 34026 |
| | 6 | 7.8 | 31408 |
| | 6 | 9.8 | 28306 |
| Mililani γ_d (pcf) = 81.2 w (%) = 37.3 q_u (psi) = 40.6 E_i (psi) = 2931 K_1 = 1743 K_2 = 0.03 K_3 = -0.15 | 2 | 2.2 | 33304 |
| | 2 | 4.0 | 30925 |
| | 2 | 6.0 | 29472 |
| | 2 | 8.0 | 26667 |
| | 2 | 9.8 | 25275 |
| | 4 | 2.0 | 37512 |
| | 4 | 4.0 | 32454 |
| | 4 | 6.0 | 29610 |
| | 4 | 7.8 | 29060 |
| | 4 | 9.8 | 27584 |
| | 6 | 2.3 | 30751 |
| | 6 | 3.9 | 29271 |
| | 6 | 5.8 | 31679 |
| | 6 | 7.9 | 30759 |
| | 6 | 9.9 | 27326 |
| Mililani γ_d (pcf) = 81.2 w (%) = 37.4 q_u (psi) = 35.3 | 2 | 2.2 | 36728 |
| | 2 | 4.2 | 30934 |
| | 2 | 6.1 | 29981 |
| | 2 | 8.1 | 29096 |

| Sample No. | σ_3 | σ_d | Resilient Modulus (psi) |
|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------|----------------------------|
| | (psi) | | |
| E_i (psi) = 5527 K₁ = 1777 K₂ = 0.04 K₃ = -0.18 | 2 | 9.7 | 27410 |
| | 4 | 2.5 | 35442 |
| | 4 | 4.2 | 32833 |
| | 4 | 6.3 | 31194 |
| | 4 | 8.3 | 29448 |
| | 4 | 9.9 | 27660 |
| | 6 | 1.5 | 37627 |
| | 6 | 4.3 | 33679 |
| | 6 | 6.0 | 32128 |
| | 6 | 8.3 | 29902 |
| | 6 | 9.9 | 27625 |
| | Mililani γ_d (pcf) = 77.1 w (%) = 41.4 q_u (psi) = 17.5 E_i (psi) = 1980 K₁ = 459 K₂ = 0.25 K₃ = -0.51 | 2 | 2.0 |
| 2 | | 4.0 | 12710 |
| 2 | | 5.9 | 10668 |
| 2 | | 7.9 | 8799 |
| 2 | | 9.8 | 7419 |
| 4 | | 1.8 | 17303 |
| 4 | | 3.9 | 14220 |
| 4 | | 5.9 | 11982 |
| 4 | | 7.9 | 9914 |
| 4 | | 9.7 | 8650 |
| 6 | | 2.0 | 18040 |
| 6 | | 3.8 | 16787 |
| 6 | | 5.8 | 13816 |
| 6 | | 7.9 | 10625 |
| 6 | | 9.9 | 9197 |
| Mililani γ_d (pcf) = 76.9 w (%) = 41.7 q_u (psi) = 17.0 E_i (psi) = 1388 K₁ = 441 K₂ = 0.34 K₃ = -0.50 | 2 | 2.0 | 14526 |
| | 2 | 3.9 | 11812 |
| | 2 | 6.0 | 9668 |
| | 2 | 7.8 | 8165 |
| | 2 | 9.7 | 7025 |
| | 4 | 1.9 | 16244 |
| | 4 | 3.8 | 14264 |
| | 4 | 5.8 | 11852 |
| | 4 | 7.7 | 9967 |
| | 4 | 9.7 | 8467 |
| | 6 | 1.5 | 19298 |
| | 6 | 4.1 | 16918 |

| Sample No. | σ_3 | σ_d | Resilient Modulus (psi) |
|----------------------------------------------------------------------------------------------------------------------------------------------------------|------------|------------|----------------------------|
| | (psi) | | |
| | 6 | 5.7 | 14138 |
| | 6 | 8.0 | 10503 |
| | 6 | 9.9 | 8959 |
| Mililani γ_d (pcf) = 76.8 w (%) = 39.5 q_u (psi) = 20.5 E_i (psi) = 2128 K_1 = 660 K_2 = 0.22 K_3 = -0.33 | 2 | 1.9 | 16221 |
| | 2 | 3.8 | 14393 |
| | 2 | 6.0 | 13094 |
| | 2 | 7.8 | 11508 |
| | 2 | 9.6 | 10330 |
| | 4 | 1.8 | 17648 |
| | 4 | 3.9 | 16720 |
| | 4 | 5.8 | 14329 |
| | 4 | 7.9 | 12483 |
| | 4 | -- | -- |
| | 6 | 1.5 | 22043 |
| | 6 | 4.0 | 18860 |
| | 6 | 5.8 | 16265 |
| | 6 | 7.8 | 13178 |
| | 6 | 9.8 | 11356 |
| Mililani γ_d (pcf) = 77.1 w (%) = 39.4 q_u (psi) = 18.4 E_i (psi) = 1739 K_1 = 576 K_2 = 0.29 K_3 = -0.46 | 2 | 2.0 | 16632 |
| | 2 | 4.0 | 14736 |
| | 2 | 5.9 | 12483 |
| | 2 | 7.8 | 11022 |
| | 2 | 9.7 | 9456 |
| | 4 | 2.1 | 19053 |
| | 4 | 4.1 | 16405 |
| | 4 | 6.0 | 14248 |
| | 4 | 7.9 | 12377 |
| | 4 | 9.7 | 10982 |
| | 6 | 2.0 | 21767 |
| | 6 | 3.9 | 18613 |
| | 6 | 6.0 | 16139 |
| | 6 | 7.9 | 13020 |
| | 6 | 9.8 | 11330 |
| Mililani γ_d (pcf) = 77.1 w (%) = 37.5 q_u (psi) = 29.5 E_i (psi) = 1384 | 2 | 1.9 | 23060 |
| | 2 | 4.0 | 21674 |
| | 2 | 6.0 | 20173 |
| | 2 | 7.8 | 18540 |
| | 2 | 9.7 | 16660 |

| Sample No. | σ_3 | σ_d | Resilient Modulus (psi) |
|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------|------------|----------------------------|
| | (psi) | | |
| K₁ = 1073 K₂ = 0.11 K₃ = -0.25 | 4 | 1.8 | 25488 |
| | 4 | 4.0 | 22220 |
| | 4 | 5.8 | 21193 |
| | 4 | 7.9 | 19277 |
| | 4 | 9.8 | 17252 |
| | 6 | 1.8 | 27261 |
| | 6 | 4.0 | 23292 |
| | 6 | 5.9 | 21976 |
| | 6 | 7.8 | 19783 |
| | 6 | 9.8 | 17515 |
| Mililani γ_d (pcf) = 76.9 w (%) = 37.7 q_u (psi) = 30.6 E_i (psi) = 1951 K₁ = 1057 K₂ = 0.08 K₃ = -0.19 | 2 | 1.9 | 20500 |
| | 2 | 4.0 | 20226 |
| | 2 | 6.0 | 18638 |
| | 2 | 7.9 | 17507 |
| | 2 | 9.6 | 16272 |
| | 4 | 2.3 | 20394 |
| | 4 | 4.1 | 20160 |
| | 4 | 5.9 | 19600 |
| | 4 | 8.1 | 18346 |
| | 4 | 9.8 | 16471 |
| | 6 | 2.1 | 23316 |
| | 6 | 4.2 | 21591 |
| | 6 | 5.9 | 19757 |
| | 6 | 8.0 | 18171 |
| | 6 | 9.9 | 16246 |
| Mililani γ_d (pcf) = 77.4 w (%) = 37.0 q_u (psi) = 29.5 E_i (psi) = 1384 K₁ = 1166 K₂ = 0.17 K₃ = -0.25 | 2 | 2.1 | 24291 |
| | 2 | 3.9 | 22589 |
| | 2 | 5.9 | 21521 |
| | 2 | 7.8 | 19290 |
| | 2 | 9.8 | 17960 |
| | 4 | 2.2 | 26204 |
| | 4 | 4.2 | 25586 |
| | 4 | 5.8 | 23080 |
| | 4 | 8.0 | 21558 |
| | 4 | 9.9 | 19291 |
| | 6 | 1.9 | 27725 |
| | 6 | 4.0 | 27141 |
| | 6 | 6.0 | 24792 |

| Sample No. | σ_3 | σ_d | Resilient Modulus (psi) |
|-----------------------------------------------------------------------------------------------------------------------------------------------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------|------------|----------------------------|
| | (psi) | | |
| | 6 | 8.1 | 21499 |
| | 6 | 10.0 | 19543 |
| Mililani γ_d (pcf) = 77.1 w (%) = 37.5 q_u (psi) = 22.4 E_i (psi) = 2508 K_1 = 1004 K_2 = 0.20 K_3 = -0.32 | 2 | 2.0 | 24629 |
| | 2 | 3.9 | 22926 |
| | 2 | 5.8 | 18810 |
| | 2 | 8.0 | 17406 |
| | 2 | 9.8 | 15057 |
| | 4 | 2.2 | 26078 |
| | 4 | 3.9 | 23239 |
| | 4 | 6.0 | 21767 |
| | 4 | 7.9 | 19370 |
| | 4 | -- | -- |
| | 6 | 1.9 | 27988 |
| | 6 | 3.9 | 26135 |
| | 6 | 6.0 | 22138 |
| | 6 | 7.9 | 20140 |
| | 6 | -- | -- |
| | Kapolei γ_d (pcf) = 100.3 w (%) = 27.0 q_u (psi) = 19.0 E_i (psi) = 1519 K_1 = 232 K_2 = 0.73 K_3 = -0.44 | 2 | 2.0 |
| 2 | | 3.9 | 4492 |
| 2 | | 6.0 | 4458 |
| 2 | | 7.8 | 4611 |
| 2 | | 10.1 | 4881 |
| 4 | | 2.0 | 7321 |
| 4 | | 4.0 | 5584 |
| 4 | | 5.9 | 5234 |
| 4 | | 7.9 | 5229 |
| 4 | | 9.9 | 5372 |
| 6 | | 2.0 | 11263 |
| 6 | | 4.0 | 9867 |
| 6 | | 5.9 | 7334 |
| 6 | | 8.0 | 6326 |
| 6 | | 9.9 | 6376 |
| Kapolei γ_d (pcf) = 100.2 w (%) = 27.1 q_u (psi) = 18.6 E_i (psi) = 1162 K_1 = 203 | 2 | 2.0 | 4033 |
| | 2 | 3.9 | 3491 |
| | 2 | 6.0 | 3747 |
| | 2 | 8.1 | 4141 |
| | 2 | 10.1 | 4445 |
| | 4 | 1.9 | 5566 |

| Sample No. | σ_3 | σ_d | Resilient Modulus (psi) |
|---------------------------------------------------------------------------------------------------------------------------------------------------|------------|------------|----------------------------|
| | (psi) | | |
| $K_2 = 0.88$ $K_3 = -0.41$ | 4 | 4.0 | 4316 |
| | 4 | 5.9 | 4427 |
| | 4 | 7.8 | 4653 |
| | 4 | 9.9 | 4827 |
| | 6 | 2.1 | 10374 |
| | 6 | 4.0 | 9157 |
| | 6 | 5.9 | 6787 |
| | 6 | 7.9 | 5750 |
| | 6 | 9.8 | 5903 |
| Kapolei γ_d (pcf) = 100.3 w (%) = 25.0 q_u (psi) = 30.0 E_i (psi) = 2495 $K_1 = 751$ $K_2 = 0.36$ $K_3 = -0.40$ | 2 | 2.1 | 18529 |
| | 2 | 4.0 | 16967 |
| | 2 | 6.0 | 15153 |
| | 2 | 8.0 | 13579 |
| | 2 | 9.9 | 12286 |
| | 4 | 2.1 | 22394 |
| | 4 | 3.7 | 20133 |
| | 4 | 6.1 | 17261 |
| | 4 | 8.0 | 15740 |
| | 4 | 10.0 | 14255 |
| | 6 | 2.1 | 25057 |
| | 6 | 4.2 | 23125 |
| | 6 | 6.0 | 20267 |
| | 6 | 8.0 | 17031 |
| | 6 | 10.0 | 15471 |
| Kapolei γ_d (pcf) = 100.2 w (%) = 25.2 q_u (psi) = 29.3 E_i (psi) = 2608 $K_1 = 720$ $K_2 = 0.29$ $K_3 = -0.34$ | 2 | 2.0 | 18170 |
| | 2 | 4.2 | 14802 |
| | 2 | 6.0 | 13613 |
| | 2 | 7.8 | 12635 |
| | 2 | 9.8 | 11510 |
| | 4 | 2.2 | 19109 |
| | 4 | 4.1 | 16519 |
| | 4 | 6.0 | 15712 |
| | 4 | 8.0 | 14020 |
| | 4 | 9.8 | 13476 |
| | 6 | 2.0 | 20783 |
| | 6 | 4.0 | 20139 |
| | 6 | 5.9 | 17693 |
| | 6 | 8.1 | 15235 |

| Sample No. | σ_3 | σ_d | Resilient Modulus (psi) |
|----------------------------------------------------------------------------------------------------------------------------------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------|------------|----------------------------|
| | (psi) | | |
| | 6 | 10.2 | 14107 |
| Kapolei γ_d (pcf) = 100.2 w (%) = 25.1 q_u (psi) = 31.5 E_i (psi) = 2430 K_1 = 803 K_2 = 0.37 K_3 = -0.45 | 2 | 2.0 | 23330 |
| | 2 | 4.1 | 18491 |
| | 2 | 5.9 | 16509 |
| | 2 | 7.8 | 14649 |
| | 2 | 9.8 | 13663 |
| | 4 | 2.0 | 27958 |
| | 4 | 4.0 | 22189 |
| | 4 | 6.0 | 19908 |
| | 4 | 7.7 | 17570 |
| | 4 | 9.9 | 15875 |
| | 6 | 2.1 | 28227 |
| | 6 | 4.1 | 26489 |
| | 6 | 6.0 | 22305 |
| | 6 | 7.9 | 19441 |
| | 6 | 10.1 | 17124 |
| | Kapolei γ_d (pcf) = 100.3 w (%) = 23.1 q_u (psi) = 53.5 E_i (psi) = 4105 K_1 = 1951 K_2 = 0.04 K_3 = -0.06 | 2 | 2.1 |
| 2 | | 4.0 | 31354 |
| 2 | | 6.0 | 30193 |
| 2 | | 8.1 | 28923 |
| 2 | | 9.9 | 27516 |
| 4 | | 2.5 | 32116 |
| 4 | | 4.1 | 32352 |
| 4 | | 5.9 | 31357 |
| 4 | | 8.1 | 29873 |
| 4 | | 10.1 | 28459 |
| 6 | | 2.1 | 29014 |
| 6 | | 4.4 | 33807 |
| 6 | | 6.3 | 32123 |
| 6 | | 8.1 | 30891 |
| 6 | | 10.2 | 29175 |
| Kapolei γ_d (pcf) = 100.3 w (%) = 23.0 q_u (psi) = 51.2 E_i (psi) = 3849 K_1 = 1726 K_2 = 0.19 | | 2 | 2.2 |
| | 2 | 4.2 | 28389 |
| | 2 | 6.1 | 27398 |
| | 2 | 8.1 | 26938 |
| | 2 | 9.9 | 26950 |
| | 4 | 2.0 | 31964 |
| | 4 | 4.1 | 32434 |

| Sample No. | σ_3 | σ_d | Resilient Modulus (psi) |
|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------|------------|----------------------------|
| | (psi) | | |
| K ₃ = -0.13 | 4 | 6.1 | 29929 |
| | 4 | 8.1 | 29440 |
| | 4 | 9.9 | 27371 |
| | 6 | 2.0 | 32989 |
| | 6 | 4.1 | 35155 |
| | 6 | 6.2 | 31464 |
| | 6 | 8.1 | 31300 |
| | 6 | 9.9 | 28414 |
| Kapolei γ_d (pcf) = 100.1 w (%) = 23.2 q_u (psi) = 52.4 E_i (psi) = 4346 K ₁ = 1809 K ₂ = 0.06 K ₃ = -0.08 | 2 | 2.4 | 31592 |
| | 2 | 4.0 | 28699 |
| | 2 | 5.9 | 29729 |
| | 2 | 7.8 | 26705 |
| | 2 | 9.9 | 25363 |
| | 4 | 1.8 | 28444 |
| | 4 | 4.0 | 30725 |
| | 4 | 5.9 | 29706 |
| | 4 | 7.9 | 29355 |
| | 4 | 9.9 | 26366 |
| | 6 | 1.9 | 29879 |
| | 6 | 3.9 | 34234 |
| | 6 | 5.9 | 32051 |
| | 6 | 7.9 | 29711 |
| | 6 | 9.8 | 27011 |
| Kapolei γ_d (pcf) = 100.1 w (%) = 23.2 q_u (psi) = 48.2 E_i (psi) = 3544 K ₁ = 1865 K ₂ = 0.00 K ₃ = -0.19 | 2 | 2.0 | 40205 |
| | 2 | 4.1 | 36405 |
| | 2 | 6.0 | 32895 |
| | 2 | 7.9 | 30104 |
| | 2 | 10.0 | 27025 |
| | 4 | 2.1 | 35379 |
| | 4 | 4.1 | 36444 |
| | 4 | 6.0 | 33191 |
| | 4 | 8.0 | 30534 |
| | 4 | 9.9 | 28380 |
| | 6 | 2.2 | 37918 |
| | 6 | 4.0 | 35451 |
| | 6 | 6.1 | 34401 |
| | 6 | 8.0 | 31336 |
| | 6 | 9.8 | 28821 |

| Sample No. | σ_3 | σ_d | Resilient Modulus (psi) |
|----------------------------------------------------------------------------------------------------------------------------------------------------|------------|------------|----------------------------|
| | (psi) | | |
| Kapolei γ_d (pcf) = 100.1 w (%) = 23.2 q_u (psi) = 43.2 E_i (psi) = 3548 K_1 = 1853 K_2 = 0.12 K_3 = -0.29 | 2 | 2.2 | 48639 |
| | 2 | 4.0 | 34622 |
| | 2 | 5.8 | 35412 |
| | 2 | 8.0 | 30873 |
| | 2 | 10.1 | 29276 |
| | 4 | 2.1 | 53224 |
| | 4 | 4.0 | 35840 |
| | 4 | 6.0 | 37796 |
| | 4 | 7.9 | 33751 |
| | 4 | 9.8 | 32756 |
| | 6 | 2.1 | 42372 |
| | 6 | 4.1 | 45699 |
| | 6 | 6.1 | 38234 |
| | 6 | 8.1 | 37607 |
| | 6 | 10.1 | 31894 |
| Kapolei γ_d (pcf) = 100.2 w (%) = 23.1 q_u (psi) = 55.3 E_i (psi) = 4148 K_1 = 1947 K_2 = 0.15 K_3 = -0.21 | 2 | 2.6 | 38265 |
| | 2 | 4.1 | 35541 |
| | 2 | 6.1 | 34187 |
| | 2 | 8.0 | 32683 |
| | 2 | 9.4 | 30852 |
| | 4 | 1.9 | 40351 |
| | 4 | 4.1 | 38588 |
| | 4 | 6.0 | 35918 |
| | 4 | 7.9 | 33583 |
| | 4 | 9.9 | 31574 |
| | 6 | 2.2 | 44306 |
| | 6 | 4.0 | 42521 |
| | 6 | 5.9 | 39862 |
| | 6 | 7.9 | 36053 |
| | 6 | 9.9 | 31929 |
| Kapolei γ_d (pcf) = 100.3 w (%) = 23.0 q_u (psi) = 55.3 E_i (psi) = 4396 K_1 = 1689 K_2 = 0.18 K_3 = -0.37 | 2 | 2.4 | 43175 |
| | 2 | 4.0 | 39837 |
| | 2 | 6.0 | 32668 |
| | 2 | 8.1 | 30498 |
| | 2 | 9.8 | 30257 |
| | 4 | 2.3 | 44678 |
| | 4 | 4.2 | 36898 |
| | 4 | 6.3 | 33720 |

| Sample No. | σ_3 | σ_d | Resilient Modulus (psi) |
|------------------------------------------------------------------------------------------------------------------------------------------------|------------|------------|----------------------------|
| | (psi) | | |
| | 4 | 8.3 | 31920 |
| | 4 | 9.8 | 30851 |
| | 6 | 2.1 | 56709 |
| | 6 | 4.0 | 44082 |
| | 6 | 6.0 | 38963 |
| | 6 | 7.9 | 34656 |
| | 6 | 10.1 | 30854 |
| Kapolei γ_d (pcf) = 95.3 w (%) = 27.0 q_u (psi) = 12.7 E_i (psi) = 1816 K_1 = 403 K_2 = 0.66 K_3 = -0.50 | 2 | 2.0 | 11380 |
| | 2 | 4.1 | 8933 |
| | 2 | 6.0 | 7949 |
| | 2 | 7.8 | 7624 |
| | 2 | 9.8 | 7101 |
| | 4 | 1.9 | 14671 |
| | 4 | 4.0 | 12195 |
| | 4 | 5.9 | 10931 |
| | 4 | 8.0 | 9804 |
| | 4 | 9.9 | 9254 |
| | 6 | 1.9 | 18760 |
| | 6 | 4.0 | 16131 |
| | 6 | 6.1 | 13612 |
| | 6 | 8.0 | 11773 |
| | 6 | 9.7 | 10989 |
| Kapolei γ_d (pcf) = 95.1 w (%) = 27.2 q_u (psi) = 13.4 E_i (psi) = 1815 K_1 = 424 K_2 = 0.58 K_3 = -0.46 | 2 | 2.0 | 11480 |
| | 2 | 3.9 | 9149 |
| | 2 | 6.0 | 8092 |
| | 2 | 7.8 | 7739 |
| | 2 | 9.9 | 7294 |
| | 4 | 2.1 | 14275 |
| | 4 | 3.9 | 12146 |
| | 4 | 6.1 | 10465 |
| | 4 | 7.9 | 9961 |
| | 4 | 9.8 | 9480 |
| | 6 | 2.0 | 17294 |
| | 6 | 4.0 | 14599 |
| | 6 | 6.0 | 12732 |
| | 6 | 8.1 | 11427 |
| | 6 | 10.0 | 11117 |
| Kapolei | 2 | 2.0 | 17138 |

| Sample No. | σ_3 | σ_d | Resilient Modulus (psi) |
|--------------------------------------------------------------------------------------------------------------------------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------|------------|----------------------------|
| | (psi) | | |
| γ_d (pcf) = 95.2 w (%) = 25.1 q_u (psi) = 21.3 E_i (psi) = 2685 K_1 = 694 K_2 = 0.35 K_3 = -0.35 | 2 | 4.1 | 14820 |
| | 2 | 6.0 | 13013 |
| | 2 | 7.9 | 11753 |
| | 2 | 9.9 | 11200 |
| | 4 | 2.0 | 18205 |
| | 4 | 4.0 | 17695 |
| | 4 | 5.9 | 15677 |
| | 4 | 8.0 | 13782 |
| | 4 | 9.8 | 12995 |
| | 6 | 2.0 | 20741 |
| | 6 | 4.1 | 20233 |
| | 6 | 5.9 | 18360 |
| | 6 | 7.8 | 15931 |
| | 6 | 10.2 | 13981 |
| | Kapolei γ_d (pcf) = 95.1 w (%) = 25.2 q_u (psi) = 21.6 E_i (psi) = 2449 K_1 = 570 K_2 = 0.44 K_3 = -0.43 | 2 | 2.0 |
| 2 | | 4.0 | 12625 |
| 2 | | 6.0 | 11300 |
| 2 | | 7.8 | 10439 |
| 2 | | 9.5 | 9704 |
| 4 | | 2.1 | 18304 |
| 4 | | 4.0 | 15103 |
| 4 | | 6.1 | 13798 |
| 4 | | 7.8 | 12483 |
| 4 | | 9.8 | 11775 |
| 6 | | 2.0 | 20999 |
| 6 | | 4.1 | 18236 |
| 6 | | 6.1 | 15781 |
| 6 | | 8.0 | 13931 |
| 6 | | 9.9 | 12954 |
| Kapolei γ_d (pcf) = 95.3 w (%) = 24.9 q_u (psi) = 22.5 E_i (psi) = 2719 K_1 = 644 K_2 = 0.42 K_3 = -0.50 | 2 | 2.3 | 19812 |
| | 2 | 4.2 | 15534 |
| | 2 | 6.1 | 13295 |
| | 2 | 7.9 | 12055 |
| | 2 | 9.9 | 11330 |
| | 4 | 2.3 | 21905 |
| | 4 | 4.3 | 18427 |
| | 4 | 6.0 | 16102 |
| | 4 | 8.1 | 14393 |

| Sample No. | σ_3 | σ_d | Resilient Modulus (psi) |
|----------------------------------------------------------------------------------------------------------------------------------------------------------|------------|------------|----------------------------|
| | (psi) | | |
| | 4 | 9.8 | 13376 |
| | 6 | 2.2 | 25727 |
| | 6 | 4.1 | 22962 |
| | 6 | 6.1 | 18937 |
| | 6 | 8.2 | 16343 |
| | 6 | 9.8 | 15328 |
| Kapolei γ_d (pcf) = 95.3 w (%) = 23.0 q_u (psi) = 38.0 E_i (psi) = 3779 K_1 = 1371 K_2 = 0.17 K_3 = -0.18 | 2 | 2.3 | 25674 |
| | 2 | 3.8 | 24429 |
| | 2 | 6.1 | 23845 |
| | 2 | 8.0 | 22044 |
| | 2 | 9.9 | 20315 |
| | 4 | 1.7 | 27848 |
| | 4 | 4.0 | 26440 |
| | 4 | 6.0 | 25010 |
| | 4 | 7.7 | 23321 |
| | 4 | 10.0 | 21554 |
| | 6 | 1.9 | 27752 |
| | 6 | 4.0 | 31157 |
| | 6 | 6.0 | 27782 |
| | 6 | 8.0 | 25710 |
| | 6 | 9.8 | 22351 |
| Kapolei γ_d (pcf) = 95.2 w (%) = 23.0 q_u (psi) = 32.6 E_i (psi) = 3197 K_1 = 1244 K_2 = 0.28 K_3 = -0.23 | 2 | 2.0 | 23079 |
| | 2 | 4.1 | 22975 |
| | 2 | 6.1 | 21326 |
| | 2 | 8.0 | 20867 |
| | 2 | 9.7 | 20143 |
| | 4 | 2.2 | 28135 |
| | 4 | 4.0 | 25094 |
| | 4 | 6.0 | 23864 |
| | 4 | 7.9 | 22833 |
| | 4 | 10.0 | 22461 |
| | 6 | 1.8 | 32186 |
| | 6 | 4.0 | 28478 |
| | 6 | 5.9 | 26458 |
| | 6 | 7.8 | 24776 |
| | 6 | 9.7 | 22801 |
| Kapolei γ_d (pcf) = 95.3 | 2 | 2.3 | 29792 |
| | 2 | 4.3 | 25292 |

| Sample No. | σ_3 | σ_d | Resilient Modulus (psi) | |
|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------|----------------------------|-------|
| | (psi) | | | |
| w (%) = 23.0 q _u (psi) = 37.7 E _i (psi) = 3990 K ₁ = 1194 K ₂ = 0.22 K ₃ = -0.34 | 2 | 6.3 | 22969 | |
| | 2 | 8.2 | 21114 | |
| | 2 | 9.9 | 19732 | |
| | 4 | 1.9 | 32296 | |
| | 4 | 4.1 | 27663 | |
| | 4 | 5.8 | 25130 | |
| | 4 | 8.0 | 23046 | |
| | 4 | 9.9 | 21309 | |
| | 6 | 2.1 | 36843 | |
| | 6 | 4.2 | 31454 | |
| | 6 | 6.1 | 27529 | |
| | 6 | 7.8 | 24535 | |
| | 6 | 10.0 | 22364 | |
| | Wahiawa In situ γ_d (pcf) = 75.4 w (%) = 46.8 q _u (psi) = 30.1 E _i (psi) = 1825 K ₁ = 487 K ₂ = 0.13 K ₃ = -0.45 | 2 | 2.1 | 14900 |
| | | 2 | 4.0 | 13089 |
| 2 | | 5.9 | 11099 | |
| 2 | | 7.8 | 9352 | |
| 2 | | 9.7 | 7978 | |
| 4 | | 2.2 | 15630 | |
| 4 | | 4.0 | 13613 | |
| 4 | | 5.8 | 11842 | |
| 4 | | 7.9 | 9781 | |
| 4 | | 9.8 | 8183 | |
| 6 | | 2.0 | 16635 | |
| 6 | | 4.1 | 14939 | |
| 6 | | 5.9 | 13210 | |
| 6 | | 7.9 | 10399 | |
| 6 | | 9.8 | 8332 | |
| Wahiawa In situ γ_d (pcf) = 75.3 w (%) = 47.0 q _u (psi) = 29.7 E _i (psi) = 1718 K ₁ = 419 K ₂ = 0.02 K ₃ = -0.42 | 2 | 2.1 | 13251 | |
| | 2 | 3.9 | 11383 | |
| | 2 | 5.8 | 9568 | |
| | 2 | 7.9 | 7418 | |
| | 2 | 9.7 | 6258 | |
| | 4 | 2.0 | 14236 | |
| | 4 | 4.1 | 11991 | |
| | 4 | 5.9 | 9820 | |
| | 4 | 7.8 | 7858 | |
| | 4 | 9.7 | 6491 | |

| Sample No. | σ_3 | σ_d | Resilient Modulus (psi) |
|--------------------------------------------------------------------------------------------------------------------------------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------|------------|----------------------------|
| | (psi) | | |
| | 6 | 0.9 | 16122 |
| | 6 | 4.0 | 13540 |
| | 6 | 5.7 | 11122 |
| | 6 | 7.8 | 8097 |
| | 6 | 9.8 | 6330 |
| Wahiawa In situ γ_d (pcf) = 75.3 w (%) = 46.9 q_u (psi) = 28.9 E_i (psi) = 1717 K_1 = 358 K_2 = 0.18 K_3 = -0.57 | 2 | 2.1 | 13262 |
| | 2 | 4.0 | 11347 |
| | 2 | 6.0 | 9054 |
| | 2 | 7.8 | 7364 |
| | 2 | 9.7 | 6144 |
| | 4 | 2.1 | 13590 |
| | 4 | 4.0 | 11631 |
| | 4 | 5.9 | 9458 |
| | 4 | 7.9 | 7717 |
| | 4 | 9.8 | 6418 |
| | 6 | 2.1 | 15659 |
| | 6 | 4.1 | 13622 |
| | 6 | 5.8 | 11215 |
| | 6 | 7.9 | 8360 |
| | 6 | 9.7 | 6566 |
| | Wahiawa In situ γ_d (pcf) = 75.4 w (%) = 44.8 q_u (psi) = 35.7 E_i (psi) = 2082 K_1 = 712 K_2 = 0.08 K_3 = -0.32 | 2 | 2.2 |
| 2 | | 4.1 | 15937 |
| 2 | | 5.9 | 14538 |
| 2 | | 7.8 | 12791 |
| 2 | | 9.7 | 11212 |
| 4 | | 2.0 | 17835 |
| 4 | | 4.1 | 16318 |
| 4 | | 5.9 | 14884 |
| 4 | | 7.7 | 13100 |
| 4 | | 9.8 | 11293 |
| 6 | | 2.0 | 19098 |
| 6 | | 4.1 | 17928 |
| 6 | | 5.9 | 16217 |
| 6 | | 7.9 | 13195 |
| 6 | | 9.7 | 11254 |
| Wahiawa In situ γ_d (pcf) = 75.3 w (%) = 44.9 | 2 | 2.4 | 16963 |
| | 2 | 4.2 | 15606 |
| | 2 | 5.9 | 14018 |

| Sample No. | σ_3 | σ_d | Resilient Modulus (psi) | |
|-----------------------------------------------------------------------------------------------------------------------------------------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------|------------|----------------------------|-------|
| | (psi) | | | |
| q_u (psi) = 33.7 E_i (psi) = 2453 K_1 = 710 K_2 = 0.14 K_3 = -0.32 | 2 | 7.8 | 12398 | |
| | 2 | 9.8 | 10774 | |
| | 4 | 2.3 | 18428 | |
| | 4 | 4.1 | 16210 | |
| | 4 | 5.9 | 14800 | |
| | 4 | 7.8 | 12840 | |
| | 4 | -- | -- | |
| | 6 | 2.0 | 18718 | |
| | 6 | 4.0 | 18053 | |
| | 6 | 5.9 | 15994 | |
| | 6 | 7.8 | 13472 | |
| | 6 | -- | -- | |
| | Wahiawa In situ γ_d (pcf) = 75.2 w (%) = 45.1 q_u (psi) = 35.9 E_i (psi) = 2518 K_1 = 701 K_2 = 0.06 K_3 = -0.33 | 2 | 2.1 | 17498 |
| | | 2 | 4.1 | 15798 |
| 2 | | 6.0 | 14229 | |
| 2 | | 7.9 | 12643 | |
| 2 | | 9.5 | 11129 | |
| 4 | | 2.2 | 18739 | |
| 4 | | 4.2 | 17066 | |
| 4 | | 5.9 | 15350 | |
| 4 | | 7.5 | 13524 | |
| 4 | | 9.9 | 11242 | |
| 6 | | 2.0 | 18597 | |
| 6 | | 4.0 | 17532 | |
| 6 | | 5.9 | 15456 | |
| 6 | | 7.9 | 13122 | |
| 6 | 9.9 | 10616 | | |
| Wahiawa In situ γ_d (pcf) = 75.5 w (%) = 42.5 q_u (psi) = 38.1 E_i (psi) = 2378 K_1 = 896 K_2 = 0.06 K_3 = -0.20 | 2 | 2.1 | 18363 | |
| | 2 | 4.0 | 17397 | |
| | 2 | 5.6 | 16287 | |
| | 2 | 7.7 | 14841 | |
| | 2 | 9.7 | 13713 | |
| | 4 | 1.8 | 18211 | |
| | 4 | 4.0 | 17596 | |
| | 4 | 5.6 | 16422 | |
| | 4 | 7.9 | 15411 | |
| | 4 | 9.9 | 13860 | |
| | 6 | 1.9 | 20075 | |

| Sample No. | σ_3 | σ_d | Resilient Modulus (psi) |
|-----------------------------------------------------------------------------------------------------------------------------------------------------------------|------------|------------|----------------------------|
| | (psi) | | |
| | 6 | 4.0 | 18732 |
| | 6 | 5.8 | 17144 |
| | 6 | 7.9 | 15478 |
| | 6 | 9.9 | 13829 |
| Wahiawa In situ γ_d (pcf) = 75.5 w (%) = 42.6 q_u (psi) = 38.2 E_i (psi) = 2597 K_1 = 982 K_2 = 0.14 K_3 = -0.25 | 2 | 2.1 | 20998 |
| | 2 | 4.0 | 19731 |
| | 2 | 6.0 | 17892 |
| | 2 | 7.8 | 16643 |
| | 2 | 9.8 | 15453 |
| | 4 | 2.1 | 22060 |
| | 4 | 4.1 | 20634 |
| | 4 | 6.1 | 19086 |
| | 4 | 7.8 | 17733 |
| | 4 | 9.8 | 16265 |
| | 6 | 2.2 | 23829 |
| | 6 | 4.1 | 22101 |
| | 6 | 6.0 | 20349 |
| | 6 | 7.8 | 18363 |
| | 6 | 9.9 | 16487 |
| Wahiawa In situ γ_d (pcf) = 71.7 w (%) = 46.5 q_u (psi) = 21.5 E_i (psi) = 1581 K_1 = 296 K_2 = 0.17 K_3 = -0.56 | 2 | 2.1 | 11165 |
| | 2 | 3.9 | 9141 |
| | 2 | 5.9 | 7433 |
| | 2 | 7.7 | 6067 |
| | 2 | 9.6 | 5087 |
| | 4 | 2.1 | 11684 |
| | 4 | 4.0 | 9941 |
| | 4 | 5.9 | 8064 |
| | 4 | 7.8 | 6563 |
| | 4 | 9.7 | 5523 |
| | 6 | 2.1 | 12724 |
| | 6 | 4.0 | 11183 |
| | 6 | 5.9 | 8733 |
| | 6 | 7.9 | 6564 |
| | 6 | 9.9 | 5529 |
| Wahiawa In situ γ_d (pcf) = 71.4 w (%) = 47.2 q_u (psi) = 21.5 | 2 | 2.0 | 11729 |
| | 2 | 3.9 | 9784 |
| | 2 | 5.8 | 7918 |
| | 2 | 7.8 | 6441 |

| Sample No. | σ_3 | σ_d | Resilient Modulus (psi) |
|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------|----------------------------|
| | (psi) | | |
| E_i (psi) = 1587 K_1 = 329 K_2 = 0.25 K_3 = -0.54 | 2 | 9.8 | 5337 |
| | 4 | 2.1 | 12424 |
| | 4 | 4.0 | 10556 |
| | 4 | 5.9 | 8821 |
| | 4 | -- | -- |
| | 4 | -- | -- |
| | 4 | 7.7 | 7115 |
| | 6 | 2.0 | 13984 |
| | 6 | 3.9 | 12392 |
| | 6 | 5.9 | 9675 |
| | 6 | 7.9 | 7218 |
| | Wahiawa In situ γ_d (pcf) = 71.7 w (%) = 44.6 q_u (psi) = 23.8 E_i (psi) = 1667 K_1 = 408 K_2 = 0.18 K_3 = -0.48 | 2 | 2.0 |
| 2 | | 3.9 | 11330 |
| 2 | | 5.9 | 9428 |
| 2 | | 7.8 | 7955 |
| 2 | | 9.7 | 6774 |
| 4 | | 2.2 | 13634 |
| 4 | | 4.1 | 11929 |
| 4 | | 5.9 | 10176 |
| 4 | | 7.8 | 8580 |
| 4 | | 9.8 | 7253 |
| 6 | | 2.0 | 15261 |
| 6 | | 4.0 | 13722 |
| 6 | | 5.9 | 11308 |
| 6 | | 7.9 | 8862 |
| 6 | | 10.0 | 7185 |
| Wahiawa In situ γ_d (pcf) = 71.8 w (%) = 44.5 q_u (psi) = 24.7 E_i (psi) = 1957 K_1 = 443 K_2 = 0.19 K_3 = -0.44 | 2 | 1.9 | 12936 |
| | 2 | 4.1 | 11639 |
| | 2 | 5.9 | 9943 |
| | 2 | 7.8 | 8508 |
| | 2 | 9.6 | 7347 |
| | 4 | 2.1 | 14330 |
| | 4 | 4.1 | 12344 |
| | 4 | 6.0 | 10808 |
| | 4 | 7.8 | 9122 |
| | 4 | 9.7 | 7779 |
| | 6 | 2.1 | 15400 |
| | 6 | 4.0 | 13767 |

| Sample No. | σ_3 | σ_d | Resilient Modulus (psi) |
|-----------------------------------------------------------------------------------------------------------------------------------------------------------------|------------|------------|----------------------------|
| | (psi) | | |
| | 6 | 5.8 | 11728 |
| | 6 | 7.9 | 9410 |
| | 6 | 9.9 | 7761 |
| Wahiawa In situ γ_d (pcf) = 71.7 w (%) = 42.7 q_u (psi) = 26.5 E_i (psi) = 1337 K_1 = 626 K_2 = 0.07 K_3 = -0.34 | 2 | -- | -- |
| | 2 | -- | -- |
| | 2 | -- | -- |
| | 2 | -- | -- |
| | 2 | -- | -- |
| | 4 | 2.3 | 16693 |
| | 4 | 4.2 | 14302 |
| | 4 | 6.1 | 12712 |
| | 4 | 7.9 | 11314 |
| | 4 | -- | -- |
| | 6 | 2.2 | 16955 |
| | 6 | 4.2 | 15675 |
| | 6 | 6.0 | 13658 |
| | 6 | 8.2 | 11584 |
| | 6 | 10.1 | 10115 |
| Wahiawa In situ γ_d (pcf) = 71.7 w (%) = 42.5 q_u (psi) = 30.6 E_i (psi) = 1815 K_1 = 696 K_2 = 0.21 K_3 = -0.35 | 2 | 2.2 | 17618 |
| | 2 | 4.1 | 15386 |
| | 2 | 5.9 | 13887 |
| | 2 | 7.8 | 12343 |
| | 2 | 9.6 | 11117 |
| | 4 | 2.2 | 18396 |
| | 4 | 4.1 | 16764 |
| | 4 | 6.0 | 15083 |
| | 4 | 7.9 | 13938 |
| | 4 | 9.8 | 12230 |
| | 6 | 2.2 | 20341 |
| | 6 | 4.1 | 18434 |
| | 6 | 5.9 | 16460 |
| | 6 | 7.8 | 14652 |
| | 6 | 9.8 | 12678 |
| Wahiawa In situ γ_d (pcf) = 71.8 w (%) = 42.3 q_u (psi) = 30.2 E_i (psi) = 2683 | 2 | 2.2 | 18070 |
| | 2 | 4.2 | 16262 |
| | 2 | 5.9 | 15016 |
| | 2 | 8.1 | 13702 |
| | 2 | 9.9 | 12641 |

| Sample No. | σ_3 | σ_d | Resilient Modulus (psi) |
|----------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------|------------|----------------------------|
| | (psi) | | |
| $K_1 = 794$ $K_2 = 0.08$ $K_3 = -0.27$ | 4 | 2.2 | 19026 |
| | 4 | 4.2 | 16343 |
| | 4 | 5.9 | 15273 |
| | 4 | 7.9 | 14093 |
| | 4 | 10.0 | 13016 |
| | 6 | 2.2 | 19465 |
| | 6 | 4.1 | 17879 |
| | 6 | 6.0 | 16026 |
| | 6 | 8.0 | 14301 |
| | 6 | 10.0 | 12970 |
| Wahiawa Intermediate γ_d (pcf) = 79.8 w (%) = 43.5 q_u (psi) = 28.5 E_i (psi) = 1758 $K_1 = 415$ $K_2 = 0.13$ $K_3 = -0.53$ | 2 | 1.9 | 15498 |
| | 2 | 4.0 | 12593 |
| | 2 | 5.9 | 10185 |
| | 2 | 7.8 | 8254 |
| | 2 | 9.7 | 6744 |
| | 4 | 2.1 | 15289 |
| | 4 | 4.1 | 12792 |
| | 4 | 6.0 | 10705 |
| | 4 | 7.8 | 8782 |
| | 4 | 9.7 | 7167 |
| | 6 | 1.9 | 16476 |
| | 6 | 4.0 | 14976 |
| | 6 | 5.8 | 12239 |
| | 6 | 7.9 | 9350 |
| | 6 | 9.7 | 7249 |
| Wahiawa Intermediate γ_d (pcf) = 79.9 w (%) = 43.3 q_u (psi) = 25.9 E_i (psi) = 1669 $K_1 = 327$ $K_2 = 0.20$ $K_3 = -0.62$ | 2 | 2.1 | 13381 |
| | 2 | 4.0 | 10882 |
| | 2 | 5.9 | 8748 |
| | 2 | 7.8 | 6954 |
| | 2 | 9.7 | 5663 |
| | 4 | 2.1 | 13714 |
| | 4 | 4.0 | 11774 |
| | 4 | 5.9 | 9403 |
| | 4 | 7.9 | 7356 |
| | 4 | 9.8 | 6043 |
| | 6 | 2.2 | 15507 |
| | 6 | 4.1 | 13765 |
| | 6 | 5.8 | 10942 |

| Sample No. | σ_3 | σ_d | Resilient Modulus (psi) |
|-------------------------------------------------------------------------------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------|------------|----------------------------|
| | (psi) | | |
| | 6 | 7.8 | 7895 |
| | 6 | 9.8 | 6210 |
| Wahiawa Intermediate γ_d (pcf) = 79.6 w (%) = 43.9 q_u (psi) = 27.4 E_i (psi) = 1838 K_1 = 391 K_2 = 0.08 K_3 = -0.51 | 2 | 2.1 | 13705 |
| | 2 | 4.1 | 11546 |
| | 2 | 5.9 | 9460 |
| | 2 | 7.9 | 7813 |
| | 2 | 9.6 | 6506 |
| | 4 | 2.2 | 14077 |
| | 4 | 3.9 | 11987 |
| | 4 | 5.8 | 10013 |
| | 4 | 7.8 | 8222 |
| | 4 | 9.7 | 6722 |
| | 6 | 2.1 | 14613 |
| | 6 | 3.9 | 13138 |
| | 6 | 6.0 | 10519 |
| | 6 | 7.9 | 8213 |
| | 6 | 9.8 | 6755 |
| | Wahiawa Intermediate γ_d (pcf) = 79.8 w (%) = 41.6 q_u (psi) = 28.1 E_i (psi) = 1445 K_1 = 557 K_2 = 0.14 K_3 = -0.42 | 2 | 2.1 |
| 2 | | 4.0 | 13053 |
| 2 | | 5.9 | 18050 |
| 2 | | 7.8 | 9873 |
| 2 | | 9.8 | 8402 |
| 4 | | 2.1 | 16882 |
| 4 | | 4.1 | 14563 |
| 4 | | 6.1 | 12904 |
| 4 | | 7.9 | 10895 |
| 4 | | 9.7 | 9168 |
| 6 | | 2.0 | 20002 |
| 6 | | 3.9 | 16696 |
| 6 | | 6.0 | 14395 |
| 6 | | 7.9 | 11584 |
| 6 | | 9.9 | 9296 |
| Wahiawa Intermediate γ_d (pcf) = 79.9 w (%) = 41.4 q_u (psi) = 31.6 E_i (psi) = 2433 K_1 = 829 | | 2 | 2.2 |
| | 2 | 4.1 | 17124 |
| | 2 | 5.9 | 15958 |
| | 2 | 7.7 | 14611 |
| | 2 | 9.8 | 12764 |
| | 4 | 2.0 | 20298 |

| Sample No. | σ_3 | σ_d | Resilient Modulus (psi) |
|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------|------------|----------------------------|
| | (psi) | | |
| K ₂ = 0.14 K ₃ = -0.29 | 4 | 3.9 | 18530 |
| | 4 | 6.0 | 17078 |
| | 4 | 8.0 | 15173 |
| | 4 | 9.7 | 13607 |
| | 6 | 2.0 | 20949 |
| | 6 | 4.0 | 20843 |
| | 6 | 6.0 | 18780 |
| | 6 | 7.9 | 16189 |
| | 6 | 9.9 | 13823 |
| Wahiawa Intermediate γ_d (pcf) = 79.6 w (%) = 41.9 q _u (psi) = 26.6 E _i (psi) = 1889 K ₁ = 435 K ₂ = 0.11 K ₃ = -0.49 | 2 | 2.2 | 14350 |
| | 2 | 4.1 | 12155 |
| | 2 | 6.0 | 10192 |
| | 2 | 7.8 | 8603 |
| | 2 | 9.6 | 7146 |
| | 4 | 2.1 | 14883 |
| | 4 | 4.2 | 12766 |
| | 4 | 5.9 | 10785 |
| | 4 | 7.8 | 8877 |
| | 4 | 9.7 | 7503 |
| | 6 | 2.0 | 15767 |
| | 6 | 4.1 | 14494 |
| | 6 | 6.0 | 12060 |
| | 6 | 7.7 | 9272 |
| | 6 | 9.7 | 7394 |
| Wahiawa Intermediate γ_d (pcf) = 79.9 w (%) = 39.4 q _u (psi) = 37.0 E _i (psi) = 2701 K ₁ = 951 K ₂ = 0.06 K ₃ = -0.24 | 2 | 1.9 | 20354 |
| | 2 | 4.1 | 18673 |
| | 2 | 5.8 | 17705 |
| | 2 | 7.9 | 16570 |
| | 2 | 10.0 | 14964 |
| | 4 | 2.1 | 21401 |
| | 4 | 3.9 | 19386 |
| | 4 | 5.9 | 18204 |
| | 4 | 7.9 | 16637 |
| | 4 | 9.8 | 14976 |
| | 6 | 2.2 | 21862 |
| | 6 | 4.0 | 20645 |
| | 6 | 6.1 | 18859 |
| | 6 | 7.8 | 16539 |

| Sample No. | σ_3 | σ_d | Resilient Modulus (psi) |
|-------------------------|------------|------------|----------------------------|
| | (psi) | | |
| | 6 | 10.0 | 14360 |
| Wahiawa Intermediate | 2 | 2.1 | 21497 |
| γ_d (pcf) = 80.7 | 2 | 4.1 | 19073 |
| w (%) = 39.2 | 2 | 6.1 | 17510 |
| q_u (psi) = 36.4 | 2 | 8.0 | 16197 |
| E_i (psi) = 2693 | 2 | 9.9 | 14677 |
| K_1 = 948 | 4 | 2.0 | 22254 |
| K_2 = 0.05 | 4 | 4.1 | 19655 |
| K_3 = -0.25 | 4 | 5.9 | 18159 |
| | 4 | 7.8 | 16565 |
| | 4 | 9.8 | 15100 |
| | 6 | 1.9 | 22266 |
| | 6 | 4.1 | 20911 |
| | 6 | 5.9 | 19034 |
| | 6 | 7.9 | 16996 |
| | 6 | 9.8 | 14886 |
| Wahiawa Intermediate | 2 | 2.0 | 9799 |
| γ_d (pcf) = 75.6 | 2 | 3.8 | 8056 |
| w (%) = 43.9 | 2 | 5.9 | 5839 |
| q_u (psi) = 17.4 | 2 | 7.8 | 4629 |
| E_i (psi) = 1258 | 2 | 9.7 | 3858 |
| K_1 = 211 | 4 | 2.1 | 10392 |
| K_2 = 0.30 | 4 | 4.0 | 8786 |
| K_3 = -0.71 | 4 | 5.9 | 6637 |
| | 4 | 7.7 | 5217 |
| | 4 | 9.8 | 4280 |
| | 6 | 2.1 | 12595 |
| | 6 | 4.0 | 10425 |
| | 6 | 5.9 | 7704 |
| | 6 | 7.8 | 5607 |
| | 6 | 9.8 | 4421 |
| Wahiawa Intermediate | 2 | 2.0 | 10393 |
| γ_d (pcf) = 75.7 | 2 | 3.9 | 8505 |
| w (%) = 43.8 | 2 | 5.7 | 6552 |
| q_u (psi) = 16.9 | 2 | 7.7 | 5161 |
| E_i (psi) = 1792 | 2 | 9.4 | 4334 |
| K_1 = 240 | 4 | 2.1 | 11414 |
| K_2 = 0.27 | 4 | 4.0 | 9422 |

| Sample No. | σ_3 | σ_d | Resilient Modulus (psi) |
|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------|------------|----------------------------|
| | (psi) | | |
| K ₃ = -0.67 | 4 | 5.9 | 7297 |
| | 4 | 7.7 | 5808 |
| | 4 | 9.6 | 4822 |
| | 6 | 2.1 | 12887 |
| | 6 | 4.0 | 11254 |
| | 6 | 5.9 | 8336 |
| | 6 | 7.8 | 6141 |
| | 6 | 9.7 | 4925 |
| Wahiawa Intermediate γ_d (pcf) = 75.8 w (%) = 41.6 q_u (psi) = 20.7 E_i (psi) = 1589 K ₁ = 375 K ₂ = 0.16 K ₃ = -0.52 | 2 | 2.1 | 13338 |
| | 2 | 4.0 | 10952 |
| | 2 | 5.9 | 8924 |
| | 2 | 7.7 | 7559 |
| | 2 | 9.9 | 6183 |
| | 4 | 2.0 | 13647 |
| | 4 | 4.0 | 11735 |
| | 4 | 5.9 | 9953 |
| | 4 | 7.8 | 7982 |
| | 4 | 9.8 | 6678 |
| | 6 | 2.0 | 14699 |
| | 6 | 4.1 | 13429 |
| | 6 | 5.9 | 10902 |
| | 6 | 7.8 | 8336 |
| | 6 | 9.9 | 6685 |
| Wahiawa Intermediate γ_d (pcf) = 75.7 w (%) = 41.7 q_u (psi) = 19.6 E_i (psi) = 1713 K ₁ = 343 K ₂ = 0.19 K ₃ = -0.54 | 2 | 2.0 | 12196 |
| | 2 | 4.1 | 10214 |
| | 2 | 5.9 | 8388 |
| | 2 | 7.8 | 6909 |
| | 2 | 9.7 | 5865 |
| | 4 | 2.2 | 12787 |
| | 4 | 4.1 | 10898 |
| | 4 | 5.9 | 9233 |
| | 4 | 7.8 | 7511 |
| | 4 | 9.7 | 6276 |
| | 6 | 2.2 | 13878 |
| | 6 | 4.0 | 12378 |
| | 6 | 5.9 | 10051 |
| | 6 | 7.8 | 7863 |
| | 6 | 9.9 | 6381 |

| Sample No. | σ_3 | σ_d | Resilient Modulus (psi) |
|----------------------------------------------------------------------------------------------------------------------------------------------------------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------|----------------------------|
| | (psi) | | |
| Wahiawa Intermediate γ_d (pcf) = 75.8 w (%) = 39.5 q_u (psi) = 24.4 E_i (psi) = 2521 K_1 = 567 K_2 = 0.07 K_3 = -0.37 | 2 | 2.1 | 15801 |
| | 2 | 4.0 | 13592 |
| | 2 | 5.9 | 11922 |
| | 2 | 7.8 | 10317 |
| | 2 | 9.9 | 9111 |
| | 4 | 2.1 | 16480 |
| | 4 | 4.0 | 13912 |
| | 4 | 5.9 | 12523 |
| | 4 | 8.0 | 10873 |
| | 4 | 9.8 | 9407 |
| | 6 | 2.0 | 16321 |
| | 6 | 3.9 | 15281 |
| | 6 | 5.9 | 13350 |
| | 6 | 8.0 | 10936 |
| | 6 | 10.0 | 9066 |
| | Wahiawa Intermediate γ_d (pcf) = 75.4 w (%) = 40.3 q_u (psi) = 22.4 E_i (psi) = 1930 K_1 = 455 K_2 = 0.15 K_3 = -0.46 | 2 | 2.1 |
| 2 | | 3.9 | 11976 |
| 2 | | 5.8 | 10198 |
| 2 | | 7.8 | 8877 |
| 2 | | 9.5 | 7610 |
| 4 | | 2.1 | 15280 |
| 4 | | 4.2 | 13133 |
| 4 | | 6.0 | 11015 |
| 4 | | 7.5 | 9801 |
| 4 | | 9.7 | 8267 |
| 6 | | 2.1 | 15840 |
| 6 | | 4.0 | 14234 |
| 6 | | 6.0 | 12126 |
| 6 | | 8.0 | 9333 |
| 6 | | 9.9 | 7821 |
| Wahiawa Intermediate γ_d (pcf) = 75.7 w (%) = 39.8 q_u (psi) = 26.4 E_i (psi) = 2419 K_1 = 639 K_2 = 0.11 K_3 = -0.35 | | 2 | 2.0 |
| | 2 | 4.1 | 14777 |
| | 2 | 6.0 | 13104 |
| | 2 | 7.9 | 11550 |
| | 2 | 9.8 | 10221 |
| | 4 | 2.1 | 17143 |
| | 4 | 4.0 | 15520 |
| | 4 | 5.9 | 13702 |

| Sample No. | σ_3 | σ_d | Resilient Modulus (psi) |
|-------------------------------------------------------------------------------------------------------------------------------------------------------------|------------|------------|----------------------------|
| | (psi) | | |
| | 4 | 7.9 | 12040 |
| | 4 | 9.8 | 10653 |
| | 6 | 2.2 | 17808 |
| | 6 | 4.0 | 16614 |
| | 6 | 5.9 | 14541 |
| | 6 | 7.8 | 12513 |
| | 6 | 9.8 | 10530 |
| Wahiawa Intermediate γ_d (pcf) = 75.4 w (%) = 40.2 q_u (psi) = 22.3 E_i (psi) = 2095 K_1 = 492 K_2 = 0.14 K_3 = -0.49 | 2 | 2.3 | 15396 |
| | 2 | 4.3 | 13198 |
| | 2 | 6.0 | 11173 |
| | 2 | 7.9 | 9672 |
| | 2 | 9.8 | 8278 |
| | 4 | 2.2 | 16996 |
| | 4 | 4.2 | 14321 |
| | 4 | 5.9 | 12233 |
| | 4 | 7.8 | 10319 |
| | 4 | 9.8 | 8677 |
| | 6 | 1.9 | 18824 |
| | 6 | 3.9 | 16667 |
| | 6 | 6.0 | 12744 |
| | 6 | 8.0 | 10229 |
| 6 | 9.9 | 8773 | |
| Wahiawa Ovendry γ_d (pcf) = 83.8 w (%) = 39.9 q_u (psi) = 15.7 E_i (psi) = 1321 K_1 = 170 K_2 = 0.81 K_3 = -0.80 | 2 | 2.0 | 7910 |
| | 2 | 4.0 | 5098 |
| | 2 | 5.9 | 4266 |
| | 2 | 7.8 | 3949 |
| | 2 | 9.8 | 3865 |
| | 4 | 2.2 | 10682 |
| | 4 | 4.0 | 7118 |
| | 4 | 5.8 | 5670 |
| | 4 | 7.8 | 5048 |
| | 4 | 9.7 | 4712 |
| | 6 | 2.2 | 14000 |
| | 6 | 3.9 | 11220 |
| | 6 | 6.0 | 8097 |
| | 6 | 7.8 | 6351 |
| 6 | 9.8 | 5778 | |
| Wahiawa Ovendry | 2 | 2.0 | 5961 |

| Sample No. | σ_3 | σ_d | Resilient Modulus (psi) |
|-----------------------------------------------------------------------------------------------------------------------------------------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------|------------|----------------------------|
| | (psi) | | |
| γ_d (pcf) = 83.9 w (%) = 39.8 q_u (psi) = 14.7 E_i (psi) = 1386 K_1 = 138 K_2 = 0.88 K_3 = -0.78 | 2 | 3.9 | 3814 |
| | 2 | 6.0 | 3411 |
| | 2 | 8.0 | 3309 |
| | 2 | 9.9 | 3331 |
| | 4 | 2.2 | 8189 |
| | 4 | 4.0 | 5347 |
| | 4 | 6.0 | 4325 |
| | 4 | 7.9 | 3984 |
| | 4 | 9.8 | 4042 |
| | 6 | 2.2 | 12297 |
| | 6 | 4.1 | 9532 |
| | 6 | 5.7 | 6932 |
| | 6 | 7.8 | 5039 |
| | 6 | 9.9 | 4539 |
| | Wahiawa Ovendry γ_d (pcf) = 83.7 w (%) = 38.4 q_u (psi) = 20.7 E_i (psi) = 1958 K_1 = 305 K_2 = 0.49 K_3 = -0.70 | 2 | 2.1 |
| 2 | | 4.0 | 9761 |
| 2 | | 5.9 | 7464 |
| 2 | | 7.8 | 6459 |
| 2 | | 9.9 | 5865 |
| 4 | | 2.2 | 14844 |
| 4 | | 4.0 | 11620 |
| 4 | | 5.9 | 9414 |
| 4 | | 7.8 | 7869 |
| 4 | | 9.8 | 7051 |
| 6 | | 2.3 | 17647 |
| 6 | | 4.2 | 15200 |
| 6 | | 5.8 | 11827 |
| 6 | | 7.8 | 9132 |
| 6 | | 10.0 | 7851 |
| Wahiawa Ovendry γ_d (pcf) = 83.2 w (%) = 39.2 q_u (psi) = 20.7 E_i (psi) = 2086 K_1 = 333 K_2 = 0.53 K_3 = -0.67 | 2 | 2.2 | 13706 |
| | 2 | 4.1 | 9985 |
| | 2 | 5.9 | 7984 |
| | 2 | 7.7 | 7057 |
| | 2 | 9.8 | 6408 |
| | 4 | 2.3 | 15577 |
| | 4 | 4.1 | 12084 |
| | 4 | 6.0 | 9717 |
| | 4 | 7.5 | 8409 |

| Sample No. | σ_3 | σ_d | Resilient Modulus (psi) |
|--------------------------------------------------------------------------------------------------------------------------------------------------------|------------|------------|----------------------------|
| | (psi) | | |
| | 4 | -- | -- |
| | 6 | 2.2 | 18868 |
| | 6 | 4.1 | 16265 |
| | 6 | 5.8 | 12877 |
| | 6 | 7.9 | 10011 |
| | 6 | -- | -- |
| Wahiawa Ovendry γ_d (pcf) = 83.5 w (%) = 36.6 q_u (psi) = 29.2 E_i (psi) = 2869 K_1 = 698 K_2 = 0.25 K_3 = -0.50 | 2 | 2.2 | 22912 |
| | 2 | 4.2 | 17981 |
| | 2 | 6.0 | 15535 |
| | 2 | 7.9 | 13596 |
| | 2 | 9.8 | 11993 |
| | 4 | 2.4 | 23901 |
| | 4 | 4.3 | 19795 |
| | 4 | 6.0 | 18042 |
| | 4 | 8.0 | 14561 |
| | 4 | 9.9 | 13123 |
| | 6 | 2.1 | 26759 |
| | 6 | 3.8 | 24512 |
| | 6 | 6.3 | 19907 |
| | 6 | 7.8 | 16419 |
| | 6 | 9.8 | 13730 |
| Wahiawa Ovendry γ_d (pcf) = 79.8 w (%) = 39.8 q_u (psi) = 11.3 E_i (psi) = 1229 K_1 = 154 K_2 = 1.01 K_3 = -0.83 | 2 | 2.1 | 6504 |
| | 2 | 3.9 | 4382 |
| | 2 | 5.9 | 3826 |
| | 2 | 7.9 | 3586 |
| | 2 | -- | -- |
| | 4 | 2.2 | 10307 |
| | 4 | 4.1 | 7160 |
| | 4 | 5.9 | 5790 |
| | 4 | 7.8 | 5164 |
| | 4 | 9.6 | 4823 |
| | 6 | 2.1 | 14547 |
| | 6 | 4.2 | 11107 |
| | 6 | 5.6 | 8448 |
| | 6 | 7.9 | 6184 |
| | 6 | 9.9 | 5593 |
| Wahiawa Ovendry γ_d (pcf) = 79.6 | 2 | 1.9 | 8010 |
| | 2 | 4.0 | 5035 |

| Sample No. | σ_3 | σ_d | Resilient Modulus (psi) |
|--------------------------------------------------------------------------------------------------------------------------------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------|------------|----------------------------|
| | (psi) | | |
| w (%) = 40.2 q_u (psi) = 12.4 E_i (psi) = 1327 K_1 = 180 K_2 = 0.85 K_3 = -0.76 | 2 | 5.8 | 4245 |
| | 2 | 7.9 | 4044 |
| | 2 | 9.8 | 3705 |
| | 4 | 1.8 | 10778 |
| | 4 | 4.0 | 7543 |
| | 4 | 5.9 | 6112 |
| | 4 | 7.8 | 5487 |
| | 4 | 9.7 | 4987 |
| | 6 | 2.1 | 14111 |
| | 6 | 4.0 | 11430 |
| | 6 | 6.0 | 8358 |
| | 6 | 7.7 | 6746 |
| | 6 | 9.8 | 6012 |
| | Wahiawa Ovendry γ_d (pcf) = 79.3 w (%) = 38.4 q_u (psi) = 14.7 E_i (psi) = 1634 K_1 = 256 K_2 = 0.63 K_3 = -0.69 | 2 | 2.6 |
| 2 | | 4.8 | 6747 |
| 2 | | 7.4 | 5377 |
| 2 | | 9.7 | 5070 |
| 2 | | 12.2 | 4856 |
| 4 | | 2.6 | 11306 |
| 4 | | 5.0 | 8404 |
| 4 | | 7.4 | 6863 |
| 4 | | 9.8 | 6363 |
| 4 | | 12.4 | 5978 |
| 6 | | 2.6 | 14629 |
| 6 | | 4.8 | 12292 |
| 6 | | 7.4 | 8706 |
| 6 | | 10.1 | 7248 |
| 6 | 12.5 | 6729 | |
| Wahiawa Ovendry γ_d (pcf) = 79.4 w (%) = 38.5 q_u (psi) = 13.2 E_i (psi) = 1742 K_1 = 241 K_2 = 0.77 K_3 = -0.70 | 2 | -- | -- |
| | 2 | -- | -- |
| | 2 | -- | -- |
| | 2 | -- | -- |
| | 2 | -- | -- |
| | 4 | 2.1 | 12544 |
| | 4 | 3.9 | 9783 |
| | 4 | 6.0 | 7968 |
| | 4 | 8.0 | 6828 |
| 4 | 10.0 | 6190 | |

| Sample No. | σ_3 | σ_d | Resilient Modulus (psi) |
|-----------------------------------------------------------------------------------------------------------------------------------------------------------------|------------|------------|----------------------------|
| | (psi) | | |
| | 6 | 2.3 | 15916 |
| | 6 | 4.0 | 13595 |
| | 6 | 5.8 | 10562 |
| | 6 | 7.8 | 8122 |
| | 6 | 9.8 | 7154 |
| Wahiawa Ovendry γ_d (pcf) = 79.6 w (%) = 36.2 q_u (psi) = 19.8 E_i (psi) = 2103 K_1 = 387 K_2 = 0.38 K_3 = -0.61 | 2 | 1.9 | 15095 |
| | 2 | 3.9 | 11320 |
| | 2 | 6.0 | 9359 |
| | 2 | 7.9 | 8105 |
| | 2 | 10.0 | 7218 |
| | 4 | 2.1 | 16707 |
| | 4 | 4.1 | 13024 |
| | 4 | 5.9 | 10638 |
| | 4 | 7.8 | 9271 |
| | 4 | 9.8 | 8146 |
| | 6 | 2.2 | 19734 |
| | 6 | 4.1 | 16015 |
| | 6 | 5.9 | 12586 |
| | 6 | 8.1 | 10111 |
| | 6 | 9.9 | 8613 |

Appendix B: Scatter Plots

