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The Effect of High Groundwater Level on Pavement Subgrade Performance

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THE EFFECT OF HIGH GROUNDWATER LEVEL
ON PAVEMENT SUBGRADE PERFORMANCE

By

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ABSTRACT

High groundwater table exerts detrimental effects on the roadway base and the whole pavement. Base clearance guidelines have been developed to prevent water from entering the pavement system in order to reduce its detrimental effects. This dissertation presents an experimental study to evaluate the effects of high groundwater and the moisture on determining pavement base clearance for granular subgrades. Full-scale in-lab and test-pit tests were conducted to simulate pavement profile and vehicle dynamic impact on the pavement. Eight types of granular subgrades were tested for this study. From the test, using layer theory, the results of the resilient modulus for each layer (layer resilient modulus) can be compared with the resilient modulus results from laboratory test. Multiple regression model will be established to predict soil resilient modulus without doing resilient modulus test. The dominant factor or factors of the effect of moisture to resilient modulus will be discussed.

The results showed that a 24-inch base clearance was considered adequate for the base protection of the A-3 and A-2 subgrades against high groundwater tables. The lab resilient modulus and layer resilient modulus have the same trend for each soil according to the moisture content change. The SR-70 A-2-4 (14% fines) soil was the most susceptible to the change of groundwater table than the other soils. The percent of fines or the percent of clays of subgrade soil is not good indicator to measure the influence of moisture effect on the resilient modulus. The coefficient of uniformity and coefficient of curvature of the subgrade gradations, which better represent the whole
shape of the gradation curve, are better indicators of the effect of moisture to modulus.
CHAPTER 1 INTRODUCTION

1.1 Problem Statement

A high groundwater table exerts detrimental effects on the roadway base and the whole pavement. The determination of design high groundwater elevation is one of the most important steps towards setting up grade lines in a roadway design. The pavement system must be designed in such a way that water is prevented from entering the places where it can cause damage. The Florida Department of Transportation (FDOT) has developed high groundwater clearance guidelines to prevent water from entering the pavement system in order to reduce its detrimental effects. In these guidelines a minimum height, the clearance, between a groundwater level and a particular elevation within the pavement system is specified. The guidelines are intended to satisfy two concerns: 1) to prevent potential damages to the roadway base due to ground water saturation or high moisture content from capillary suction; 2) to achieve the required compaction and stability during construction operations.

But the prevailing guideline (AASHTO, 1993) neglects the fact that each roadway is built with a different type of subgrade material. Subgrade materials used for construction are required to be selected materials (such as A-3, A-2-4 soils and Oolite in Florida) which covers a wide range of soils. There can be different geotechnical properties related with different subgrade soils such as permeability and suction in unsaturated state, which are critical for capillary behavior. Also this guideline does not take into account the effect of dynamic
loadings and some of the design criteria such as resilient modulus of subgrade materials. As a result, this prevailing guideline could be overly conservative in some cases, while for other cases the specified minimum base clearance could be inadequate. In view of the above, it is important to evaluate the effect of high groundwater level on pavement performance and the minimum base clearances for establishing the roadway grade lines. In addition, experimental data are needed to justify the design guidelines.

### 1.2 Scope of Study

The primary objective of this study was to evaluate the effect of high groundwater level on pavement subgrade performance. Eight typical subgrade soils used for real construction in Florida (including A-3, A-2-4 soils and Oolite) were obtained for evaluation. A full-scale laboratory evaluation of the subgrade performance was conducted in a test-pit facility. The subgrade and base profile of a full-scale flexible pavement system was simulated in the test-pit facility. Moisture condition was manipulated by raising and lowering the water level in the test-pit. The subgrade materials were tested in different moisture conditions that simulated different field conditions. The effect of the dynamic loadings was evaluated using the repeated plate load in the test-pit test.

In conjunction with the full-scale test-pit program, a laboratory triaxial test program was carried out to evaluate the resilient modulus of subgrade materials. The effect of moisture on the resilient properties of subgrade materials was evaluated using soil specimens with drying or soaking condition for resilient modulus test. In
addition, a field monitoring program was also performed at SR-70 (near Fort Pierce, Florida) to evaluate the moisture profile of subgrade soils under the influence of the seasonal variation of precipitation and air temperature in the field.

1.3 Report organization

This report summarizes the experimental program, test results, and analysis of the study to evaluate the effect of high groundwater level on pavement performance of eight typical Florida subgrade soils. The background and objectives of this research study are presented in this chapter. A literature review of the concepts and research related to the design high groundwater clearance is summarized in Chapter 2. The experimental program including a description of test equipment, test setup, and test procedure for full-scale test-pit and laboratory triaxial tests is presented in Chapter 3. Chapter 4 presents the test results of laboratory resilient modulus experimental program. The experimental results for test-pit test, suction test, and permeability test are summarized in Chapter 5. The analysis of laboratory resilient modulus results is established and discussed in Chapter 6. The analysis of test-pit experimental results is discussed in Chapter 7. The analysis of high groundwater effect is summarized in Chapter 8. Finally, the conclusions and recommendations of this research study are presented in Chapter 9.
CHAPTER 2 LITERATURE REVIEW

2.1 Sources of water in pavement

There are many sources of the water that reaches the pavement structure and its immediate vicinity. To evaluate the various sources, the pavement designer should consider the entire profile and cross section of the highway and the surface and subsurface drainage systems that are to be used for the operation and structural integrity of the overall facility. The pavement structure designer, who may not be directly involved with the other aspects of the facility, cannot predict the possible sources of water and amounts without knowledge of the surface and subsurface drainage geometry.

Free water enters the structural section and the adjacent area from many sources. Cedergren et al. state that the most abundant and often overlooked source is undoubtedly atmospheric precipitation, by which surface water is supplied from rain (usually the largest amount), snow, hail, condensing mist, dew, and melting ice. This water reaches the structural section in several ways:

1. Cracks in the pavement. New pavements can be constructed so that they are virtually impermeable, but they cannot be constructed without joints or without cracks forming well before the desired life of the pavement structure is attained.
2. Infiltration through the shoulders.
3. Infiltration from the side ditches.
4. Melting of an ice layer from a frost area during the thawing cycle.

5. Free water from pavement base. If the base is not properly drained, it may act as a source of free water for the subbase and subgrade.

6. High groundwater table.

7. Condensation of water vapor (small amounts).

The first five sources can be particularly significant if the surface drainage is not properly designed or maintained. Any free-water surface can act as a source of capillary water, which will move from the free-water surface when a capillary potential exists. The distance it moves depends primarily on the pore-size distribution in the soil. Capillary water can be changed to free water and vice versa. These changes may be affected by changes in temperature and changes in the pore-size distribution of the soil. Free-water surfaces and capillary fringe water are both sources for water vapor. Under changing temperature and pressure conditions, water vapor can change back to either free water or capillary water.

2.2 Establishing the free-water surface in the subgrade

By using the basic data of the original groundwater profile and the proposed highway geometry, surface drainage facilities, and subsurface drainage facilities, the free-water surface in the vicinity of the pavement can be predicted. Techniques for making these predictions are available. The location of the seasonal free-water surface is important because it affects the equilibrium moisture content, the bearing capacity, the frost susceptibility of the
subgrade, and the rate at which the infiltrated water can be drained from the base and subbase materials.

Recommendations on the minimum depth to the free-water surface from the pavement surface vary. Typical criteria are: Massachusetts-7 ft (2.1 m); Michigan and Minnesota-5 ft (1.5 m); Saskatchewan-8 to 12 ft (2.4 to 3.7 m); and Nebraska-3 to 4 ft (0.9 to 1.2 m) in granular materials and 7 ft (2.1 m) in cohesive soils.

Investigators in Germany concluded that a critical depth is 2 m (6.6 ft) below the pavement surface. Researchers in Sweden found significant reduction in bearing capacity when the water table is raised to within 70 cm (27 in.) of the surface, and further reduction when it is raised to within 30 cm (11 in.) of the surface. The research in Sweden is particularly significant because it shows the effect of the water table on subgrade strength independent of its relationship with frost-heave problems. This study was conducted using both a gravel base and a crushed-stone base on a frost-susceptible silt subgrade (no details on gradation or permeability were given).

Although no specific criteria considering these variables were found, the critical depth to the water table is probably a function of subgrade strength, subgrade permeability, subgrade capillarity, and the ratio of the design vertical live load stress to the live load plus dead load vertical stress. These items are important because the strength of the subgrade must be assessed at the effective stress level (i.e., the total stress less the pore pressure), whereas the driving force to cause failure is at the total stress level.
2.3 Resilient Modulus of Soils and Affecting Factors

The resilient modulus is defined as the deviator dynamic stress (due to the moving vehicular traffic) divided by the resilient axial (recoverable) strain. This concept is derived from the fact that the major component of deformation induced into a pavement structure under the traffic loading is not associated with plastic deformation or permanent deformation, but with elastic or resilient deformation. Thus, the resilient modulus is considered to be a required variable for determining the stress-strain characteristics of pavement structures subjected to traffic loading.

The resilient modulus of unstabilized granular base and subgrade soils is highly dependent upon the stress state to which the material is subjected within the pavement in addition to other variables. As a result, constitutive models must be used to present laboratory resilient modulus test results, including the effect of stress state, in a form suitable for use in pavement design. The resilient modulus depends on deviator stress and confining stress. Two popular and simple regression models are presented as follows:

1. When modulus is dependent on bulk stress:

\[ M_r = k_1 \theta^{k_2} \]  \hspace{1cm} (2-1)

2. When modulus is dependent on confining pressure:

\[ M_r = k_3 \sigma_3^{k_4} \]  \hspace{1cm} (2-2)

Where \( \theta \) = bulk stress, sum of the principal stresses, \((\sigma_1 + \sigma_2 + \sigma_3)\)

\( \sigma_3 \) = confining pressure or minor principal stress

\( k_1, k_2, k_3, k_4 \) = regression constants
Many factors influence the resilient modulus of soils. A brief review of the significant factors is discussed in this chapter. Moisture is one of the factors affecting the modulus of soils. A thorough review of the literature concerning the effect of moisture is provided accordingly.

The factors that influence the resilient modulus of soils include: soil type, soil properties, dry unit weight, water content, stain level, test procedures, and size effect. A brief review of the significant observations with regard to these factors is discussed in the following sections.

### 2.3.1 Soil Types

The resilient modulus is significantly influenced by the type of pavement soils. For instance, Chen et al. (1994) investigated the variability of resilient moduli due to aggregate type. The AASHTO T 292-91I test procedure was used to conduct tests on six selected aggregate types of soils. Conclusions show that for a given gradation, the differences in $M_r$ values due to aggregate sources were found to be from 20 to 50 percent.

### 2.3.2 Soil Properties

The resilient modulus is also significantly correlated with such soil properties as the liquid limit, plastic limit, and grain size distribution. Thompson and Robnett (1989) concluded that properties that tend to contribute to low resilient modulus values are low plasticity, high silt content, low clay content, and low specific
gravity. From the study, regression equations were developed for predicting $M_R$ based on soil properties.

2.3.3 Dry Density
Variations in the density of the laboratory test specimen with the same water content produce variable effects on the resilient response of subgrade soils. Theoretically, Young’s modulus of a soil is proportional to its density. Trollope et al. (1962) reported that the resilient modulus of dense sand might be 50 percent higher than that of loose sand.

2.3.4 Water Content
The effect of the water content on the resilient response of soils was noticed a long time ago. A general relationship between dry density, water content, and resilient modulus for subgrade soils is shown in Figure 2.1 (Monismith, 1989). The effect of moisture on the resilient modulus is the focus of this study.

2.3.5 Strain Amplitude
The strain level also has a significant effect on the resilient modulus. As the strain amplitude increases, the modulus of the soil decreases. Kim et al. (1991) identified the relationship of the strain amplitude versus the modulus of the compacted subgrade soils as shown in Figure 2.2. Figure 2.2 shows that the resilient modulus decreases with the increasing strain amplitude.
2.3.6 Test Procedure

T 292-91I and T 294-92 are two of the most extensively used test procedures in recent years. Because of the difference of confining pressure and test sequence, the two procedures normally produce different results. Zaman et al. (1994) found that the T 294-92 test procedure gave higher resilient modulus values than those obtained by using the T 292-91I test procedure. Ping and Hoang (1996) had similar results. This phenomenon was attributed to the stress sequence, which had a stiffening and strengthening effect on the specimen structure as the stress level increased.

2.3.7 Size Effect

Specimen size has influence on the resilient modulus of soils. The diameters of the specimen could be as small as 2.0 inches. However, the most common sizes are 4.0 and 6.0 inches in diameter. The ratio of height over diameter is usually 2.0.

The testing of materials composed of large particles demands larger specimens. T 292-92I specifies that a minimum 90% by material weight used to prepare the compacted specimen in the laboratory should have a maximum particle size finer than 1/6 the specimen diameter. The maximum particle size of the remaining material shall be no larger than 1/4 of the specimen diameter.

Zaman et al (1994) conducted a series of resilient modulus tests on six of the most commonly encountered aggregates that are used as base/sub-base of roadway in Oklahoma. The testing materials consisted of three limestones, one sandstone, one granite, and one rhyolite.
The specimens were prepared at three different levels of gradations. The maximum particle sizes varied from 0.75 inch to 1.5 inch. Vibration and compaction methods were employed in preparing specimens. The specimens were 4 inches and 6 inches in diameter. The test results of the 4-inch and the 6-inch samples were analyzed. In all cases, the resilient modulus for 4-inch specimens were higher (20-50%) than those for the 6-inch specimens.

2.4 Effect of Moisture
2.4.1 Detrimental Effect of Water
Experts recognized the detrimental effect of water on a pavement system. The detrimental effects of water, when entrapped in the pavement structure, can be summarized as follows:

1. It reduces the strength of unbounded granular material and subgrade soils.

2. It causes pumping of concrete pavements with subsequent faulting, cracking, and general shoulder deterioration. With the high hydrodynamic pressure generated by moving traffic, pumping of fines in the base course of flexible pavements may also occur with a resulting loss of support.

3. In northern climates with a depth of frost penetration greater than the pavement thickness, a high water table causes frost heave and the reduction of load-carrying capacity during the frost melting period.

5. Continuous contact with water causes stripping of asphalt mixture and durability or “D” cracking of concrete.

This study is focused on the first issue, the effect of water on the strength of granular material and subgrade soil.

2.4.2 Effect of Moisture on Resilient Modulus

Since the introduction of resilient modulus, the moisture content effect is considered a main factor which may change the value of resilient modulus.

Seed et al. (1962) noted a rapid increase in resilient deformations for specimens of the AASHO Road Test subgrade soils compacted at water content above the optimum level (Seed et al, 1962). For specimens compacted below optimum water content, resilient deformations were characteristically low.

Hicks and Monismith (1971) analyzed the factors that may affect the resilient modulus of granular material. They used two aggregates for the investigation: one was a well-graded, subangular, partially crushed gravel and the other a well-graded crushed rock. They found that the following factors may have a significant influence on the stress-deformation characteristics under short-duration repeated loads: (a) stress level (confining pressure), (b) degree of saturation, (c) dry density (or void ratio), (d) fines content (percent passing No.200 sieve), and (e) load frequency and duration. As for the effect of degree of saturation, the following is what Hicks and Monismith found:

\[ k_1 \text{ decreased from the dry to partially saturated test series where the comparisons were made on the basis of total stresses.} \]
dry test series, the cell pressure was approximately equal to the total stress and in this case only, the effective stress. For the partially saturated test series, the cell pressure was equal to the total stress and not the same as the effective stress. They did not attempt to measure the pore pressure; hence, effective stresses could not be properly defined in the tests for partially saturated materials. Figure 2.3 provides an indication of this effect for each aggregate at two levels of grading—coarse and fine.

When the data were plotted in the conventional manner in Figure 2.4, the modulus associated with the partially saturated test series was the lowest. This might be because of the manner in which the data were compared; data for the dry and partially saturated specimens were compared on the basis of total stresses, whereas data for the dry and saturated specimens were compared using effective stresses. It appears that, if all results were defined in terms of total stresses, the value of $k_i$ would steadily decrease with increasing degree of saturation (or water content) as shown in Figure 2.3. Although there were inherent differences in the dry density (mean value of 126.6 pcf for water content of 2.4 percent and 132.2 pcf for water content of 6.3 percent) for their tests, the reduction in $k_i$ with increasing water content was very apparent (Hicks et al, 1971). Thompson and Robnett (1976) summarized the effect of an AASHO road test on subgrade soil in 1976. A typical effect of moisture on resilient modulus is shown in Figure 2.5. The resilient modulus decreases as moisture increases (Thompson et al, 1976).

In “Research and Development of the Asphalt Institute’s Thickness Design Manual (MS-1) Ninth Edition” published in 1982, the Asphalt
Institute suggested “in order to retain a given value for the resilient modulus \( M_r \) the dry density must increase as the molding water content increases”. See Figure 2.1 for the general relationship between dry density, water content, and resilient modulus for subgrade soils. Pumphery and Lentz (1986) used repeated laboratory repeated load triaxial tests to estimate the effects of highway traffic on the permanent and resilient deformation of a subgrade sand commonly used as a foundation for a flexible highway pavement structure in Florida in 1986. Combinations of confining stress and cyclic principal stress difference (test variables) and of dry unit weight and moisture content (sample variables) were used for each sample and loaded to 10,000 cycles. Confining stress, cyclic principal stress difference, and dry unit weight were correlated with permanent strain and resilient modulus and thus affected deformation properties of these soils. However, moisture content correlated with neither permanent strain nor resilient modulus.

In this test, Pumphery and Lentz used a type of sand from a borrowed pit in Leon County, Tallahassee, Florida, as a sample, which was a uniform, fine sand. It was classified A-3 according to AASHTO classification. Standard (AASHTO T-99) and modified (AASHTO T-180) capaction tests were conducted to determine maximum dry unit weight and optimum moisture content.

Several of the test and sample variables, such as confining stress, cyclic principal stress difference, dry unit weight and moisture content were selected for study. Various combinations of these factors were tested in cyclic triaxial tests. A cyclic principal stress difference was set at different percentages of the peak static soil
strength determined from samples tested at similar dry unit weight, moisture content, and confining stress combinations. An inverted haversine wave form of 0.1-sec duration was used for all repeated load tests. This period is roughly equivalent to the time in which a vehicle traveling 30 mph affects a point in the top of the subgrade of a flexible pavement structure. The 0.1 second was followed by a 0.9-second rest period to allow proper damping of load before the following load was applied. Therefore, a frequency of one load per second resulted. All cyclic tests were continued to 10,250 cycles.

Tests were conducted on two different moisture content levels (3 percent below optimum and at optimum) of the sand. Preliminary plans included testing samples at three percent above optimum; however, samples could not be compacted to the required density using the tamping method, so this moisture condition was eliminated from the program.

The effect of moisture content on resilient modulus has been a particularly elusive characteristic for researchers to examine. Through analysis, no definite trend has developed for all materials in this area. Figure 2.6 contains comparisons of highway subgrade sand samples tested cyclically at different levels of moisture content in the sand. Because of the scatter in the points, no satisfactory relationships were found between moisture content and resilient modulus.

Thadkamalla and George (1995) studied the effect of saturation’s effect on the resilient modulus. Three modes of saturating (wetting) were investigated: (a) capillary saturating, (b) vacuum saturating,
and (c)molding at wet of optimum moisture content. Results showed that the degree of saturation above optimum moisture content had a nominal effect (20%) on resilient modulus of coarse-grain soils, whereas it had a severe effect (50 to 75 percent decrease) on the resilient modulus of fine-grain soils. Another finding was that both degree of saturation and saturating mode affected the resilient modulus of fine-grain soil. Vacuum saturation caused drastic decreases in resilient modulus.

In this study, Thadkamalla and George used two coarse-grain and two fine-grain soils. The two coarse-grain soils were A-2-4, 26% finer than a #200 sieve and A-2, 23% finer than a #200 sieve. The two fine-grain soils were A-7-5, 97% finer than a #200 sieve and A-4, 51% finer than a #200 sieve.

The percentage reduction of resilient modulus with degree of saturation, for typical coarse-grain and fine-grain soils is shown in Figure 2.7. As expected, resilient modulus decreased with saturation, resulting in the following observations:

1. The resilient modulus of coarse-grain soil was not significantly affected by the amount and manner of saturation; the reduction was approximately 20 percent.

2. The resilient modulus of fine-grain soils was drastically reduced by saturation, the reduction being 50 to 75 percent depending on the degree of saturation, and the saturating method used.

In the case of fine-grain soils, the saturating method used had a varying effect on the resilient modulus of the specimens tested. The resilient modulus value of the vacuum-saturated specimen decreased
exponentially with increasing degrees of saturation, where it decreased linearly with the capillary saturating and also with specimens molded at wet of optimum moisture content. In the case of fine-grain soils, the decrease in resilient modulus for both capillary saturated specimens and those molded at wet of optimum moisture content was nearly identical (Thadkamalla et al., 1995).

Barksdale, Alba, Khosla, Kim, Lambe, and Rahman (1996) prepared a report about the laboratory determination of resilient modulus for flexible pavement design. This report discussed the moisture sensitivity of resilient modulus. They found that achieving a saturated sample required the use of good equipment maintained by a meticulous laboratory technician. A much more practical approach was to simply initially preparing the specimen at the desired moisture content. Specimens could not be successfully prepared at moisture contents greater than 3 to 4% above optimum and achieve satisfactory dry densities. A moisture content 3% to 4% above optimum, however, was sufficient to show moisture sensitivity.

Figures 2.8, 2.9, and 2.10 show the important reduction in resilient modulus that occurred upon specimen soaking under a back pressure of 10 psi applied at the base and the corresponding increase in modulus after the water was partially drained from the specimen. The more cohesive clayey sand (Figure 2.8) subgrade soil was clearly much more moisture susceptible than the silty sand (Figure 2.9 and Figure 2.10) with the average retained resilient modulus upon soaking being about 40% and 75% respectively, of the impact compacted specimens at optimum moisture. Soaking the silty sand for up to 10 days only increased
the degree of saturation from 84% to 92% for the kneading compacted specimen. Achievement of a higher degree of saturation would have resulted in a larger reduction in resilient modulus (Barksdale et al., 1997).

Fredlund et al. (1997) also examined the effect of variations in deviator stress on the resilient modulus for specimens prepared at both dry and wet of optimum water contents. For wet of optimum specimens, the resilient modulus was shown to vary more with variations in deviator stress than those tested dry of optimum. Typical behavior showed a significant decrease in the resilient modulus with increasing deviator stress for wet of optimum test specimens. For those tested dry of optimum, the resilient modulus also decreased with increasing deviator stress, but to a much lesser extent than those tested wet of optimum.

In Florida, the State Department of Transportation (FDOT) has been using the repetitive rigid plate test to evaluate the characteristics of Florida pavement for more than 20 years. Ping, Yang, and Ho (1998) made a summary of these tests. Figures 2.11, 2.12, and 2.13 illustrate the moisture effect on resilient modulus. The five typical subgrade soils were all granular materials (sands). A test-pit facility was used to simulate the subgrade and base components of a flexible pavement system. By rising and lowering the water table, the moisture of the pavement was changed, which was called soaked or drained test. The drained and soaked test conditions were under somewhat lower and higher moisture than the optimum test conditions, respectively. As for the moisture effect on resilient modulus, a summary follows:
The resilient modulus and permanent deformation under various moisture conditions were compared to examine the effect of moisture. The resilient modulus and permanent deformation versus the moisture content are shown in Figures 2.11 and 2.13, respectively. As can be seen from the figures, the moisture has a significant effect on the resilient modulus and permanent deformation. As shown in Figure 2.11, an increase in moisture has a strong detrimental effect on the resilient modulus for all of the five subgrade soils. For Crawfordville sand, Ocala sand, and Brooksville sand, the modulus values were not changed very much with a change in moisture. For Alachua sand and Panama city sand, however, the moisture had a significant effect on the resilient modulus. The resilient modulus values were increased almost five times with the change in moisture from the soaked condition to the drained condition.

In addition, the figures also show that under the drained condition, major differences existed in the moduli among five subgrades, whereas under the soaked condition, relatively small differences were observed. Some subgrades (such as Alachua sand) are very sensitive to the change in moisture content.

The reduction in resilient modulus due to an increase in the degree of saturation is most significant for Alachua sand. One factor contributing to this effect may be due to the higher degree of saturation (75%) at the optimum condition for Alachua sand. The Crawfordville and Brooksville sands have lower degrees of saturation (59%) at the optimum condition and the detrimental effect on the resilient modulus due to the higher degree of saturation is found to be much less than that for the Alachua sand. Therefore, a degree of saturation, about 80% to 90% for a granular material (depending
on its optimum degree of saturation), may be sufficient to take the most critical moisture condition into consideration for determining the resilient modulus in laboratory. Based on the experience with this study, a laboratory specimen may not be able to be prepared when the degree of saturation is beyond 80% to 85% for a granular material (Ping et al., 1998).

Drumm, Reeves, Madgett, and Trolinger (1997) summarized their tests of the saturation effect on resilient modulus. A series of resilient modulus tests were designed to investigate the variation in resilient modulus due to post-compaction increases in water content. Triplicate specimens were prepared for 11 soils throughout Tennessee, with each specimen having target values of optimum water content and maximum dry density. One specimen was tested at optimum and the other two were tested at increasing levels of saturation. All soils exhibited a decrease in resilient modulus with an increase in saturation, but the magnitude of the decrease in resilient modulus was found to depend on the soil type. The soils with the highest resilient modulus for optimum conditions were found to experience the greatest decrease with saturation.

They realized that varying the moisture content at the time of saturation may not represent the actual variation in properties under field conditions. The moisture content at compaction affects the strength and stiffness properties of the soil due to the influence of particle orientations during compaction. These soil structure effects are known as important factors governing resilient response. Therefore, to accurately predict how subgrade soil will react with seasonal moisture changes, the specimens should first be compacted.
to near field conditions (such as optimum moisture content and maximum
dry density), and then the water content should be increased before
resilient modulus testing. Samples were selected from 11 active
construction projects in Tennessee. These soils were representative
of materials commonly found in pavement subgrades. Since the majority
of the subgrade soils in Tennessee are fine-grained, their research
was restricted to those with more than 50% passing the No. 200 sieve.
Drumm et al. did the cyclic tri-axial testing in general accordance
with the Strategic Highway Research Program (SHRP) Protocol P-46
(1989). The conditioning was 200 load repetitions. For each
combination of cell pressure and deviator stress, they applied 100
load repetitions. The load duration was 0.1 s and the cycle duration
was 1.0 s. Table 2.1 is a summary of specimen conditioning and loading
scheme (Strategic Highway Research Program 1989). The typical effects
of postcompaction saturation on Resilient Modulus are shown in Figures
2.14, 2.15, 2.16, and 2.17.
Figure 2.14 shows a typical reduction in resilient modulus with an
increase in the degree of saturation. The upper curve represents
triaxial results for a specimen compacted near the optimum moisture
content at 29.4% and a degree of saturation of 91.9%. The middle curve
represents a specimen saturated to a moisture content of 30.1% and
93.4% saturation. The lower curve represents a specimen saturated
to a moisture content of 30.7% and 95.4% saturation. Since the effect
of confining stress on the resilient modulus of these fine-grained
soils was small, smooth curves have been fitted to the data points,
and the resulting curve is the average of the results at confining
pressures of 41 kPa (6 psi), 28 kPa (4 psi), and 14 kPa (2 psi). Figure
2.14 shows that as the moisture content and degree of saturation increased, there was a corresponding decrease in resilient modulus values. This was observed for all 11 soils tested. To illustrate the magnitude of these changes by showing values from the triaxial curves at similar deviator stresses and confining pressures, Figure 2.15 shows a plot of $M_r$ versus moisture content at these stress conditions for the Knox County Station 4000 specimens. Figure 2.16 shows a plot of $M_r$ versus degree of saturation. Figure 2.17 summarizes the variation in resilient modulus with degrees of saturation for 11 subgrade soils. In general, the resilient modulus decreased with the increase of resilient modulus. The A-7-6 and A-7-5 soils have the highest resilient modulus at optimum water content and maximum dry density and they are most susceptible to changes in $M_r$ due to changes in water content or degrees of saturation. The lower resilient modulus A-4 and A-6 soils were less susceptible to decreases in $M_r$ with increases in water content (Drumm et al, 1997).

Andrew, Drumm, and Jackson (1998) measured the seasonal variation in subgrade resilient modulus by Falling Weight Deflectometer. They found the resilient modulus of fine-grained soil was dependent on moisture content. They suggested an effective roadbed soil resilient modulus, which incorporated the moisture variations and the corresponding resilient modulus. This effective modulus is equivalent to the combined effect of all the seasonal modulus values.

From the above researches, the following key points can be summarized:

1. The moisture effect on resilient modulus varies with the type of soil. Usually, it has a significant effect on fine-grained soil but not as much on coarse or granular soil and/or sand.
Moisture may have no significant effect on some sand, such as A-3 in Leon County, Florida.

2. The moisture has an effect on resilient modulus and in turn, the resilient modulus depends on deviator stress and confining pressure.

3. The moisture imbibition methods have an influence on the resilient modulus. The vacuum saturating severely affects the air-water interface in the soil. It cannot simulate moisture imbibition akin to field conditions. Capillary saturation and molding at wet may be more suitable (Andrew et al, 1998).

### 2.4.3 Explanation of Moisture Effect on Resilient Modulus

Edil and Motan (1979) studied the relationship between the resilient behavior of subgrade soil and soil-water potential (or soil suction), which gave some explanation of the effect of moisture on resilient modulus.

Soil suction causes an increase in effective stress in a subgrade or base as the material dries out. The increase in effective stress can cause a significant increase in resilient modulus. Soil suction decreases as the degree of saturation increases and is not present when the soil is saturated.

They found the energy of a soil-water system could be expressed as a function of its characteristic water retention curve, or the relationship between the free energy of water in the soil and that of pure water in a free surface condition.
Total soil-water potential or soil suction is defined as the work required to remove an infinitesimal quantity of water from the soil and provides a measure of the combined effects of the forces holding the water in the soil. With the exception of cementation bonds, it implicitly includes the effects of the fundamental interaction forces that influence the deformation characteristics of the soil. The total soil-water potential of a soil varies with its water content, mineralogy, solutes present in the pore water, and soil fabric, among other parameters.

The soil suction concept provides a fundamental soil parameter that reflects mechanical behavior. The few existing investigations that relate the mechanical response under repetitive loading conditions to soil suction indicate that soil suction is an important moisture variable for describing resilient behavior and relating it to the soil environment.

Edil et al. studied the relationship between the resilient modulus, residual strain, post-repetitive loading strength and moisture regime of two fine-grained soils and drew the following conclusions:

1. Characteristic water retention curves were useful for reflecting the susceptibility of compacted soils to moisture changes.

2. The resilient modulus and strength strongly depended on compaction moisture content on the dry side of optimum with insignificant dependency on the wet side (with the range of ±2% of optimum), whereas the residual strain exhibited the opposite behavior.
3. The moisture regime subsequent to compaction was expressed most suitably in terms of soil suction. It was an intrinsic parameter of the moisture equilibrium and reflected the effects of soil type and fabric, climate, and position of groundwater table on the mechanical response better than moisture content or degree of saturation alone.

4. Resilient modulus and post-repetitive loading strength were primarily related to soil suction. For silt loam soils investigated, variations in these properties were small for suction values less than 100 kPa. This suction corresponded roughly to 2% dry-of-optimum moisture content. For suction greater than this, however, significant increases in mechanical properties (on the order of three- to six- fold) were reached.

5. The opposite behavior was seen in the residual strain.

6. Resilient modulus increased monotonically for soil suctions from 100 kPa to a critical suction beyond which it decreased. This critical suction appeared to be about 800 kPa (116 psi) (corresponding moisture content was 2 percent dry of optimum) for the soil tested.

7. The number of loading cycles resulted in significant increases in resilient modulus and residual strain, and some increase in compressive strength (Edil et al, 1979).

2.5 Empirical Resilient Modulus Models
A very attractive approach for obtaining resilient moduli for use
in design, for at least most agencies, is to determine values of resilient modulus using generalized empirical relationships using statistically relevant, easy to measure physical properties of the material. Considering the large variation in resilient moduli along the route and important design changes in moisture with time, the use in design of empirical resilient modulus relationships is considered to be justified. A number of states have already developed generalized resilient modulus relationships for use in design, particularly for cohesive subgrade soils. Statistically based equations, graphs or charts would then be developed for each class of materials for the range of properties routinely used in design within the region of interest.

The following are selected models for resilient modulus or backcalculated layer modulus prediction. Using the power model to express resilient modulus is a practical alternative to the slightly more accurate bilinear model. The bilinear resilient modulus model for fine-grained soils has a distinct breakpoint as shown in Figure 2.18. The resilient modulus at the breakpoint can be estimated using the following expression developed by Thompson and LaGrow (1992):

\[
M_{r(\text{opt})} = 4.46 + 0.098(\text{% clay}) + 0.119(\text{PI})
\]  

(2-3)

where

\[
M_{r(\text{opt})} = \text{Breakpoint resilient modulus at optimum moisture content and 95% of AASHTO T99 maximum dry density}
\]

\[
\text{% clay} = \% \text{particles finer than the 2 micron size}
\]

\[
\text{PI} = \text{Plasticity index}
\]
Equation (2-3) is for cohesive soils compacted to 95% of AASHTO T99 maximum dry density at the optimum water content. Equation (2-3), although useful, has the important disadvantage that the resilient modulus is at only the breakpoint. The breakpoint is often, but not always, at or close to the minimum value of the resilient modulus. Thick pavement sections apply low deviator stress to the subgrade. As a result, the breakpoint resilient modulus is likely to be too low for strong sections resulting in unnecessary additional thickness.

Cheryl Allen Richter and Charles W. Schwartz (2002) did some research to develop empirical models to predict backcalculated pavement layer moduli as a function of moisture content and stress state. They also found that variation in moisture content is not always the most important factor causing seasonal variations in pavement layer moduli. In their study, 24 LTPP (Long Term Pavement Performance) seasonal monitoring test sections were considered in investigation. For 53 percent of the pavement layers, the correlation between modulus and moisture content is negative—i.e., increases in moisture correspond to decreases in modulus. The opposite is true for the remaining 47 percent of the pavement layers—i.e., increases in moisture correspond to increases in modulus. The backcalculated modulus is often less strongly correlated with moisture than with one or more of the stress parameters considered. The relative strength of the observed correlations between $\log M_r$ and the bulk and octahedral shear stress parameters is inconsistent with expectations based on laboratory resilient modulus test results. Lab data typically indicate that bulk stress is the more important predictor of modulus for granular
materials, whereas the correlations for the backcalculated moduli indicate that the octahedral shear stress is often the more important predictor for both granular and fine-grained materials. The study found that, in many instances, variations in moisture content are not the most important driver of seasonal variations in backcalculated layer moduli for unbound, non-frozen pavement layers. Given the present state-of-the-art, specifically the continued use of linear backcalculation procedures for the foreseeable future, the combined effects of stress and moisture on backcalculated pavement layer moduli may be approximately incorporated for practical design purposes using the constitutive model form as follows:

$$E / p_a = c_0 10^{(c_2 V_w / 100 + (c_1 + c_2 V_w / 100) \theta / p_a)} (\tau / p_a + 1)^{(c_1 + c_2 V_w / 100)}$$ \hspace{1cm} (2-4)

where

- $E$ = Backcalculated layer modulus
- $p_a$ = Atmospheric pressure
- $c_i$ = Regression Constant
- $V_w$ = Volumetric moisture content
- $\theta$ = Bulk stress
- $\tau$ = Octahedral shear stress

Model coefficients derived using backcalculated layer moduli are not applicable to laboratory resilient modulus data and vice versa (Richter et al, 2003).

Hassan M. Salem, Fouad M. Bayomy and metwally G. Al-Taher (2003) also did the research based on LTPP database.

Multiple regression analysis techniques were applied to relate the backcalculated elastic modulus to subgrade moisture content and other
soil properties such as Plastic Index and percentage passing sieve #200. The Statistical Analysis System (SAS) computer program was used to perform the multiple regression analysis.

For plastic soils, they developed the following equation:

$$\log(E) = 8.82 - 0.673X_1 - 2.44X_2 + 0.0084F - 0.11PI$$

(2-5)

where

- $E$ = Backcalculated elastic modulus
- $X_1 = \log(\text{gravimetric moisture content, } \%)$
- $X_2 = 1/(\text{gravimetric moisture content, } \%)$
- $F$ = Percentage passing sieve #200, %
- $PI$ = Plasticity index, %

It should be noted that this model could be applied only for plastic soils, as there is a term in the model for PI. For non-plastic soils, this model will be modified to account for soil properties other than PI. Generally, PI will be replaced by soil parameter D60, which is the soil size for 60% passing.

For non-plastic soils, they got the equation:

$$\log(E) = 13.01194 - 0.18922X_2 - 0.07845F - 38.03227D60$$

(2-6)

Figure 2.19 and Figure 2.20 show the predicted outcome versus the data observations for plastic and non-plastic soils correspondingly. Several other researchers have developed regression relationships between the resilient modulus of granular materials and water content. Each regression model is based on its own sample population. Alternatively speaking, each regression has its own application limitation. Each model would be practical in estimating a resilient modulus (either laboratory resilient modulus or backcalculated layer
modulus) value only for the similar soils liking those being used to develop the equation (Salem et al, 2003).
Table 2.1 Summary of Specimen Conditioning and Loading Scheme
(Strategic Highway Research Program 1989)

<table>
<thead>
<tr>
<th>Cyclic loading (1)</th>
<th>Cell Pressure $\sigma_c$ [kPa (psi)] (2)</th>
<th>Deviator Stress $\sigma_d$ [kPa (psi)] (3)</th>
<th>Number of load repetitions (4)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conditioning</td>
<td>41 (6)</td>
<td>28 (4)</td>
<td>200</td>
</tr>
<tr>
<td>Testing</td>
<td>41 (6)</td>
<td>7 (1)</td>
<td>100</td>
</tr>
<tr>
<td></td>
<td>41 (6)</td>
<td>14 (2)</td>
<td>100</td>
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<tr>
<td></td>
<td>41 (6)</td>
<td>28 (4)</td>
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<td>41 (6)</td>
<td>41 (6)</td>
<td>100</td>
</tr>
<tr>
<td></td>
<td>41 (6)</td>
<td>55 (8)</td>
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<td>14 (2)</td>
<td>69 (10)</td>
<td>100</td>
</tr>
</tbody>
</table>

Note: Load duration=0.1 s; cycle duration =1 s.
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- **Sandy Soil, Site 35-1112**
CHAPTER 3 EXPERIMENTAL PROGRAM

3.1 General
An experimental program was conducted to evaluate the effect of high groundwater level on pavement subgrade performance. The subgrade soils were selected or mixed in conjunction with Florida DOT personnel and were believed to be representative of typical Florida subgrade soils. The purpose of the experimental program was to test and evaluate the subgrade soils under different moisture condition for determination of high groundwater effect. The experimental program included a laboratory resilient modulus test program, a suction test program, a permeability test program, a full-scale test-pit test program, and a field monitoring program.

3.2 Subgrade Materials
The soils under investigation in this research were the typical A-3, A-2-4 subgrade materials in use in Florida representing the percent of fines passing No.200 sieve, which ranged from 4% to 30%. Total of eight types of soil were investigated, including Levy County A-3 (4% passing No.200), SR-70 A-3 (8% passing No.200), A-2-4 (14% passing No.200), A-2-4 (12% passing No.200), A-2-4 (20% passing No.200), A-2-4 (24% passing No.200), A-2-4 (30% passing No.200), and Oolite which are reported in this study. For those granular materials under evaluation, the compaction characteristics were determined in the laboratory using the modified Proctor (AASHTO T-180) method. The
pertinent characteristics of those subgrade soils are presented in Table 3.1.

3.3 Laboratory Resilient Modulus Test Program

3.3.1 Introduction

When a road is constructed, the subgrade is compacted at optimum moisture content. After the construction, the moisture will change due to rainfall, ground water, capillary rise and so on. An increase in moisture will have a detrimental effect on the resilient modulus of subgrade material.

In the tests mentioned in the literature review, back pressuring, de-air water flushing were used by researchers to saturate soil samples for testing. Usually, a high backpressure, which could be more than 100 psi, was used. However, in an actual field condition, the surrounding confining pressure of a typical subgrade pavement layer is around 2 psi.

In order to simulate the actual field condition, a laboratory test procedure using soil specimens with four to six-day soaking was used to evaluate the resilient modulus due to an increase in moisture. In addition, the Limerock Bearing Ratio (LBR) (Designation: FM 5-515) required the specimen to be soaked for 2 days before testing. Furthermore, the design high groundwater criteria required that a standing water duration should exceed 24 hours for traditional frequencies. A laboratory experimental program was undertaken to evaluate the effect of moisture on the resilient properties of subgrade materials.
3.3.2 Specimen Preparation

The primary objective of this test program was to evaluate the effect of moisture on the resilient modulus of granular subgrade soils. All soil materials were compacted in the laboratory to their optimum moisture and density conditions and then dried or soaked for resilient modulus test. The equipment and procedure for specimen preparation are described as follows:

Preparation Equipment

Split mold. A 10.2 cm in diameter by 20.3 cm in height (4-in. by 8-in.) split mold was chosen to prepare the laboratory test specimen. The mold assembly has a steel cylindrical split mold, a base, and a collar at the top. Threaded rods are used to hold the collar, mold, and base together.

Compaction machine. A mechanical soil compactor manufactured by Rainhart Company was used to compact the soil specimens. Different compaction energy levels can be achieved. The machine is designed to perform test methods AASHTO Designation T 99 and T 180.

Sample extruder. A sample extruder was also provided by Rainhart Company. This hydraulic extruder with a long travel length worked well with the split mold.

Miscellaneous apparatus. Apparatus used for specimen preparation also included rubber membranes for encasing the specimen, balances, ovens, a microwave oven, straight edges, a No. 4 sieve, filter papers, porous stones, mixing tools, and miscellaneous tools.

Specimen Compaction
The making of specimens follows the AASHTO Designation T180, Modified Proctor Compaction. The air-dried material (except the Oolite from Miami) was sieved through a #4 sieve (4.76 mm) and mixed with enough water to provide the optimum water content previously determined in accordance with AASHTO T-180. For the Oolite from Miami, it was crushed and then was sieved through a sieve of 3/8-inch opening. The mix was then compacted to give a resilient modulus specimen size of 4-inch in diameter and 8-inch in height, according to its optimum moisture and density conditions obtained from the modified Proctor Procedure. Because the specimen for modified Proctor is 4-inch in diameter and 4.586-inch in height, which is different in size from the resilient modulus specimen. A conversion was made to achieve the same compaction effort for the resilient modulus specimen. An equivalent compactive effect, with 8 layers at 27 blows for each layer, was applied to prepare for the resilient modulus specimen. The weight of the compactor and the height of the falling weight were kept the same as the modified Proctor. These specimens, at optimum compacted conditions, represent the actual subgrade layer in the field immediately after construction. During the compaction, the following value was used for calculation of dry density:

\[
\gamma_{d,\text{max}} = \frac{W_t - W_m}{V_m \cdot (1 + w/100)}
\]  

(3-1)

where \( \gamma_{d,\text{max}} \) = Maximum dry density

\( W_m \) = Weight of mold

\( W_t \) = Total weight of specimen and mold

\( w \) = Moisture content, in percent
\[ V_m = \text{Volume of mold} \]

### 3.3.3 Soaking and Drying

After compaction, specimens were subjected to soaking and drying to reach the desired moisture content for testing.

#### Soaking

The specimens were soaked in water with the mold. The soaking process is illustrated in Figure 3.1. In order to prevent soil particles from falling or leaking into the water, the follows measures were implemented. See Figure 3.2:

1. Two circular filter papers, which are larger in diameter than the mold, were placed on the top and bottom of the specimen, respectively. The outer edge of the filter paper was folded up around the end of the mold. A rubber band was placed outside the outer edge of the filter paper around the end of the mold, which tightly secured the filter paper and the mold. Some sealant was also placed at the joint of the split mold to prevent leakage.

2. Two circular porous stones were placed on both ends of the mold. During the entire soaking time, a surcharge, which is made of heavy steel ring with approximately the same outside diameter of the mold, was placed on the top of the mold. It exerted a force on the porous stones to prevent possible separation of the porous stone and the mold assembly. The whole mold assembly (Figure 3.1) was placed into a bucket of water for soaking. A porous cylinder stone was placed on the bottom of the mold assembly for a better flow of water to the specimen.
A test trial was carried out to find the suitable time of soaking. The specimen with the mold was taken out of the water bucket and weighted every day. It was found that the weight of A-3 specimen stopped increasing after two-day soaking. For the A-2-4 specimen, the weight was ceased to increase after 4 days. Therefore, the soaking time was set to be longer than 4 days.

The moisture content after soaking may be calculated using the following procedure:

1. The weight of soaked specimen may be calculated using the following equation:

\[ W_s = W_{st} - W_m \]  \hspace{1cm} (3-2)

where, \( W_s \) = Weight of soaked sample

\( W_{st} \) = Weight of the soaked sample with mold

\( W_m \) = Weight of the mold

2. The unit weight of the soaked sample, \( \gamma_s \), may be calculated as the following:

\[ \gamma_s = \frac{W_s}{V_m} \]  \hspace{1cm} (3-3)

Where, \( V_m \) = Volume of mold

3. The moisture content after soaking, \( w_s \), is obtained:

\[ w_s = \frac{\gamma_s - \gamma_d}{\gamma_d} \]  \hspace{1cm} (3-4)

Where, \( \gamma_d \) = Dry unit weight of sample

The degree of saturation, \( S \), can be calculated as:
\[ S = \frac{w \cdot G_s \cdot \gamma_d}{G_s \cdot \gamma_w - \gamma_d} \]  \hspace{1cm} (3-5)

where \( G_s \) = Specific gravity of soil solids

\( w \) = Moisture content

\( \gamma_w \) = Unit weight of water

\( \gamma_d \) = Dry unit weight of sample

**Drying**

The specimens were exposed to the air inside the laboratory room for drying, See Figure 3.3. The calculation equations for the moisture content are similar as the above for soaked sample except replacing the variables of the soaked specimen by the corresponding ones of the dried specimen. Therefore, it is not repeated hereafter.

### 3.3.4 Resilient Modulus Test Procedure

The resilient modulus test method adopted for this project was AASHTO T 292-91I, “Resilient Modulus of Subgrade Soils and Untreated Base/Sub-base Materials”. This method was considered an improvement to the AASHTO T 274-82 Method. The T292-91 method covered procedures for preparing and testing untreated subgrade and untreated base/sub-base materials for determination of resilient modulus under conditions representing a simulation of the physical conditions and stress states of materials beneath flexible pavements subjected to moving wheel loads. The resilient modulus testing equipment and procedures are described as follows.

**Test Equipment**
An MTS model 810 closed-loop servo-hydraulic testing system and a resilient modulus triaxial testing system were used in this study. The major components of these systems were: loading system, digital controller, workstation computer, triaxial cell, and linear variable differential transducer (LVDT) deformation measurements system. The resilient modulus testing equipment is schematically shown in Figure 3.4. The following sections describe some of the most noteworthy equipment with respect to loading system, triaxial cell, deformation measurement devices, and data acquisition and control systems.

Loading System
An MTS series 318 load unit consisting of a load frame, and a hydraulic actuator was provided by MTS System Corporation. An MTS TestStar System was used to control the loading system from a workstation computer (Figure 3.12). A repeated dynamic load was programmed by a function generator in the TestStar software from the computer. In this study, a haversine waveform of load shape was used. The loading pulse duration and the rest period were set at 0.1 and 0.9 second, respectively.

Triaxial Cell
The triaxial cell (Figure 3.5) and transducers were provided by Research Engineering Inc. The external chamber is made of cast acrylic and can resist the maximum confining pressure of 689 kPa (100 psi). The confining fluid is limited by the air only. The cell is fitted with a safety release valve that is set to release at approximately 758 kPa (110 psi).
The cell came equipped with two pore pressure lines to the cap and two to the base. These four lines are connected to the pore pressure transducer stand through a 3.2 mm (1/8") tube from the valves on the cell to the fittings. The pore pressure to the cap or the base or both at same time can be monitored during the test from the transducer panel meter. This pressure is the inside pore pressure of the test sample. There are two valves attached to the transducer stand to release the air in the testing sample.

The cell or chamber pressure is provided by an air compressor and is adjusted by a pressure regulator. There is also another pore pressure line connected from the valve on the bottom of the cell to the fitting on the pore pressure transducer stand. The cell pressure can be monitored by both a conventional gauge and a pressure transducer.

Deformation Measurement Devices
In this study, for the T 292-91I procedure, four LVDTs were mounted inside the triaxial cell. Two of them were positioned in the middle half length of the specimen (10.2-cm) by using of 180-degree diametrically-opposed clamps around the specimen's axis (Figure 3.5). The other two diametrically-opposed LVDTs were attached to the top platen of the test specimen and rested on the top of the cell. All four LVDTs were adjustable and arranged around the specimen evenly. Calibrations were made periodically during the laboratory testing program. This setup was used to compare the resilient modulus measurements obtained from the LVDT's at different locations. A ten-channel signal conditioner was used to condition, amplify, filter,
and transmit the signal from the LVDTs to the TestStar data recording system.

Data Acquisition and Control System
The TestStar control system is designed in such way that signal functioning, data acquisition, function generation, closed-loop servo-control, and hydraulic-pressure control are all provided within a single unit; thus, the user interacts with the control console entirely through the keyboard of a personal computer. A personal computer was used to control closed-loop servo feedback systems. The computer can be programmed to scan analog input channels, digitize the signal data, and compare the most recent data to the most current value of intended signal in a fracture of a millisecond.

There are three data modes to define how data is collected: 1) peak/valley levels of each cycle; 2) data at a specified time interval; and 3) data at each time an input channel signal changes a specified amount. Each of these modes can be used to acquire certain data. The mode of the peak and valley levels of each cycle was used in this study. The output of the data acquisition system included a graphic display of sampled dynamic load and displacement waveforms and a data file. The data file format was selected for use with spreadsheet programs (Excel). The collected data were further processed by analyzing, plotting, or a word processing program.

Resilient Modulus Test Procedures
The resilient modulus test procedures were basically followed from AASHTO T 292-91I (Table 3.2). A deviation from the test procedure
was made by using the two additional internally-mounted LVDTs for the full length measurements (T 292-91I). The test procedures are described in the following sections.

Test Setups (T 292-91I)

Prior to testing, the compacted soil specimen was removed from the mold using an extruder. Using a vacuum membrane expander, the membrane was pulled over the specimen and perforated stones. The membrane-enclosed soil specimen with the perforated stones on the top and the bottom was placed onto the bottom platen in the triaxial chamber. The top platen was fitted in place, and the specimen membrane ends were folded over the platens and secured with an O-ring. Two LVDT clamps were affixed to the upper and lower quarter points of the specimen (for 10.2-cm measurements). The LVDT clamps should be ensured to lie in horizontal planes. Then, two LVDTs were installed to the clamps. The other two LVDTs were mounted on the top platen to measure the resilient deformation of the entire 20.3-cm (8 in) long specimen. These four LVDTs were adjusted to the appropriate positions to permit enough travel distance during the testing. The assembly of the triaxial cell was completed by closing the triaxial chamber (Figure 3.5). The drainage valve to the specimen was left open.

Specimen Conditioning

Specimen conditioning was applied to simulate the stress history that exists in field conditions. The procedures for specimen conditioning are described as follows:
a. Load the MTS load frame to the triaxial load cell, be sure that the load frame is firmly contacted with the triaxial load cell.
b. Turn on the air compressor machine to produce a confining chamber pressure of:
   - 103.4 kPa (15 psi) for granular subgrade and embankment soils (T292-91I).
c. Zero the load reading from the control panel. Open a programmed template from Testware program according to the test material. The programmed templates enable the loading device to produce a haversine wave with a fixed load duration of 0.1 second with a 0.9 second period of relaxation.
d. Begin the conditioning by applying 1000 repetitions of a corresponding deviator stress. Monitor the permanent axial deformation occurring during conditioning.
e. After completion of the specimen conditioning phase, monitor the permanent axial deformation occurring to the specimen throughout the remainder of the test. If the permanent axial strain exceeds 5 percent, the test should be terminated.

Confining Pressure and Loading Sequences
AASHTO T292-91I specifies that after the specimen conditioning phase is completed, the testing phase should begin immediately. However, the resilient modulus values are very much affected by the deviator stresses in some cases, especially when a lower deviator stress follows a much higher one. Therefore, for this study, a 15 to 20 minute rest period was taken prior to the testing phase as suggested by Ping and Ge (1996).
Since the laboratory resilient modulus simulate the conditions in the pavement subgrade, the stress-state should be selected to cover the expected in-service range. Resilient properties of granular specimens should be tested over the range of confining pressures expected within the subgrade layer. A template was created in the TestStar software program to monitor the test sequence. In the test sequence (Table 3.3), the confining pressures decrease while the deviator stresses increase during each confining pressure stage.

Cyclic Loading Procedures
After 15 to 20 minutes of rest period after the specimen conditioning phase, the test phase was completed using the following procedures:

1. Open a template, apply 50 repetitions (T292-91I) of smallest deviator stress at the highest (T292-91I). The average recoverable deformation of each repetition is recorded automatically.

2. Apply the same repetitions of each of the remaining deviator stresses to be used at the present confining pressure.

3. Decrease (T292-91I) the confining pressure to the next desired level and adjust the deviator stress to the smallest value to be applied at this confining pressure. Prior to applying 50 repetitions (T292-91I) to the specimen, a 15 to 20-minute rest period was used.

4. Increase the deviator stress to the next desired level and continue the process of Steps 2 and 3 until testing has been completed for all desired stress states.

5. Disassemble the triaxial chamber and remove all apparatus from
3.3.5 Determination of Resilient Modulus

During the resilient modulus test, after finishing the specimen conditioning stage, a series of tests with different deviator stresses at different confining pressures were performed and the data were recorded for every cycle of each test. However, only the last five cycles of each test were used for analyses following the AASHTO T292-91I procedure.

The resilient modulus \( M_r \) was calculated from the load and deformation using the following equation:

\[
M_r = \frac{\sigma_d}{\varepsilon_R}
\]

Where \( \sigma_d \) is the deviator stress and \( \varepsilon_R \) is the resilient or recoverable strain.

3.3.6 Regression Analysis

The test results are reported in a tabular form and in plots of logarithmic graphs that show the variation of the \( M_r \) versus the bulk stress \( \theta \). In some cases, the plots required are logarithmic graphs showing the variation of the \( M_r \) versus the confining pressure. The regression models are presented as follows:

1. Modulus dependent on bulk stress:

\[
M_r = k_1 \theta^{k_2}
\]

2. Modulus dependent on confining pressure:

\[
M_r = k_3 \sigma_3^{k_4}
\]
Where $\theta = \text{Bulk stress, sum of the principal stresses}, (\sigma_1 + \sigma_2 + \sigma_3)$

$\sigma_1 = \text{Confining pressure or minor principal stress}$

$k_1, k_2, k_3, k_4 = \text{Regression constants}$

### 3.3.7 Testing Program

The laboratory resilient modulus testing program is summarized in Table 3.4. Eight types of pavement soils obtained from across the state of Florida were tested in the laboratory. Two replicate resilient modulus tests were conducted for each moisture condition of the soils. The soils specimens were tested at the optimum, dried, and soaked conditions.

### 3.4 Suction Test Program

The soil suction test was followed from the AASHTO Designation T273-86 to determine the soil suction value at different moisture contents for all the eight soil types.

#### 3.4.1 Methodology

The suction test (T273-86) method utilizes thermocouple psychrometers of the Spanner type for determining the total soil suction force. The thermocouple psychrometer measures relative humidity in soil through a technique called Peltier cooling. If a current is caused to flow through a single thermocouple junction in the proper direction, that particular junction will cool, causing water to condense on it when the dew point is reached. The voltage developed between the thermocouple and reference junction is proportional to the
temperature difference and is measured by a microvoltmeter. Because relative humidity is a function of the dew point and ambient temperature, the voltage output can be related to relative humidity or soil suction by a calibration curve. Laboratory measurements to evaluate total soil suction by thermocouple psychrometer may be made with the apparatus shown in Figure 3.6.

3.4.2 Test Devices

Thermocouple Psychrometer
Totally nine thermocouple psychrometers (PST-55-15-SF) of Spanner type with a known cooling coefficient \((\Pi_v)\) produced by Wescor Inc. were used in this test of water potential measurement. This psychrometer consisted of a sensing thermocouple junction, a chromel-constantan thermocouple, and two reference junctions of copper-constantan and copper-chromel. A PST-55-15-SF Psychrometer was specified as a psychrometer that was covered with a Dutch weave stainless thermocouple shield. SF is the connector with which the connection process can be completed by plugging this connector into the SUREFAST receptacle on the front panel of a microvoltmeter. To be accurate in water potential measurement, the psychrometer must be kept from contamination to achieve the right output of the evaporation rate. A contaminated junction will result in a reduction of accurate data readings.

Sample Chamber
This part of the equipment was comprised of a sample container, which
was a one-pint metal can with wax coated interior to prevent corrosion and sealed by a rubber stopper, and a polystyrene thermal container, which was an insulated box with 1.5 inch thickness of foamed polystyrene and wide enough to accommodate nine sample containers. In the suction test, the thermocouple psychrometer was inserted into a well-sealed sample container within which the soil specimen or calibration solution was placed. Then the whole sample chamber (an insulated box containing nine sample containers) was put into an environmental chamber to achieve the desired equilibrium for output recording.

**Microvoltmeter**

A microvoltmeter is also defined as a monitoring system. The type used here is WESCOR HR-33T dew point microvoltmeter. It is a self-contained electronic system specifically designed for the measurement of water potential force with thermocouple transducers. It can automatically maintain the temperature of the thermocouple junction at a dew point temperature when operating in dew point mode. The HR-33T shows the water potential information in either the dew point mode or psychrometric mode. In this research, the dew point mode was selected to obtain more accuracy in the water potential measurement.

**3.4.3 Calibration**

The calibration of the thermocouple psychrometer can be conveniently accomplished using known molalities of a salt solution (sodium chlorides) to correlate with microvoltmeter outputs from the
thermocouple. This process is conducted by suspending the psychrometer over a salt solution with a known osmotic suction under a constant temperature (isothermal). It requires the same set of apparatus as being illustrated in Figure 3.6 except that the soil specimen was substituted by one piece of filter papers (5.5 cm in diameter) saturated with a 2 ml sodium chlorides solution of known water potential. Salt solutions with specified concentration were sealed within sample containers. These cans were subsequently enclosed in an insulated box within an environmental chamber waiting for the humidity in the psychrometers in equilibrium with the relative humidity of the salt solution before the data collection began. Upon using an HR-33T microvoltmeter for data collection, eight amps of cooling current were applied for 30 seconds. The output of the psychrometer was approximately 0.75 microvolts per bar in dew point; these HR-33T readings \( (E_r) \) should be corrected to 25°C:

\[
E_{25} = \frac{E_r}{0.325 + 0.027T}
\]  

(3-7)

These microvoltmeter outputs, which are related with the humidity inside the cans, were recorded at least three times a day after equilibrium was achieved. The last three stabilized readings were averaged as the final output \( (E_r) \). The calibration curve of each psychrometer were expressed by a linear equation:

\[
\tau^o = A E_{25} - B
\]  

(3-8)

Where:  \( \tau^o \) = Total soil suction, kPa

\( A, B = \) Calibration constant

\( E_{25} = \) Psychrometric microvoltmeter readings corrected to 25°C, \( \mu V \)
The standard osmolality of 290, 1000, 1800 mOs/kg with a known sodium chloride concentration in the salt solution were introduced as a calibration standard. The calibration result is demonstrated from Figure 3.7 to Figure 3.13 and in Tables 3.5. The concentration of sodium chloride for standard osmolality and their related suction values under a certain temperature is shown below:

<table>
<thead>
<tr>
<th>NaCl/100g solution (gram)</th>
<th>0.9094</th>
<th>3.115</th>
<th>5.463</th>
</tr>
</thead>
<tbody>
<tr>
<td>Osmolality (mM/kg)</td>
<td>290</td>
<td>1000</td>
<td>1800</td>
</tr>
<tr>
<td>Suction at 25°C (kPa)</td>
<td>727.6</td>
<td>2509</td>
<td>4516</td>
</tr>
</tbody>
</table>

### 3.4.4 Sample Preparation

In a sample preparation for a suction test, sample soils were compacted under optimum moisture contents within a mold that had a height of 8 inches and a 4-inch diameter. The required energy was achieved by using a 10-pound hammer dropped from a height of 18 inches with 25 blows for each layer of eight equal layers. Dry density and optimum moisture were measured immediately after compaction of the sample. Nine 1.5x1.5x1.5 cubic in. samples of the specimen were cut from the compacted soil for suction measurement. Of those nine cubic specimens: two of them were directly sealed into sample containers representing the natural condition of soil; four of them were wetted by 1, 2, 3, and 4 ml of distilled water respectively right after these samples were cut, and then placed into sample containers; three of them were dried at room temperature for 1, 3, and 4.5 hours (5.5 hours for the Levy County A-3 soil) respectively before they were sealed into sample containers. Nine cans of specimens were enclosed within the insulated
box before they were stored in an environmental chamber for relative humidity equilibrium. Thus, a wide range of water content levels on specific soil was established for the water potential evaluation.

3.4.5 Test Procedure

The temperature equilibrium was attained within a few hours after closing the thermal container (insulated box). Equilibrium of the relative humidity of air measured by the psychrometer and the relative humidity in the soil specimen was acquired within 2 or 3 days. Upon using HR-33T for the psychrometer output recording, the $C^\circ/\mu V$ button was switched to $C^\circ$ and the RANGE button to $30^\circ$ to record temperature output ($T$) between $0^\circ C$ to $30^\circ C$. The switch was then changed to $\mu V$ (psychrometer), the meter was set to zero, cooling current ($8mA$) was applied for 30 seconds (identical to calibration), then the psychrometer output ($E_{\tau}$) was recorded in microvolts. The above process was repeated for every psychrometer in the equipment setup. The last three stabilized readings were averaged as the final output (the same procedure used in calibration). After the readings were completed, the specimen was removed from the containers. The water content was determined in each specimen using a microwave and electronic balance. The $E_{\tau}$ value was converted to $E_{25}$ by Equation (3-7), and the soil suction $\tau$ of each soil specimen was determined by entering the respective calibration curve with $E_{25}$.

For the accurate measurement of soil suction, results show that enough power supply should be secured. The RANGE switch was moved to +BATT for a battery check. Batteries were replaced when the voltage reading
fell below 16 volts.

3.5 Permeability Test Program

For SR-70 A-2-4 soil, the ASTM Designation D5084-90 Flexible Wall Permeameter (FWP) method was performed. This method was proved to be adequate for determining the hydraulic conductivity of compacted porous material like the SR-70 A-2-4 soil. The applicable permeability range for this test is less than or equal to $1.0 \times 10^{-5}$ m/s.

For SR-70 and Levy County A-3 soils, the ASTM Designation D2434-68 Constant Head method was adopted. This method was proved to be suitable for the establishment of the coefficient of permeability in disturbed granular sugrades like an A-3 soil having a permeability value higher than $1.0 \times 10^{-5}$ m/s and less than 10% fines passing the No.200 sieve.

For A-2-4 (12%), A-2-4 (20%), A-2-4 (24%), A-2-4 (30%) and Crushed Oolite, the ASTM Designation D5084-90 was adopted. The test equipment is HUMBOLDT Triaxial/Hydraulic Conductivity Testing Equipment. The constant head and flexible wall methods were used for permeability measurements.

3.6 Test-pit Experimental program

3.6.1 Introduction of Test-pit Test

The Florida DOT test-pit test facility has been adopted to determine the strengths and performance of Florida flexible pavement materials. The test-pit facility re-constructs and simulates the subgrade and base components of a flexible pavement system on a full-scale basis. The major concerns of test-pit test program are the deformation and equivalent resilient modulus of a layered system under the static
The cyclic loading of a circular plate is activated with a one-second interval within which the loading and resting periods would be 0.1 and 0.9 second respectively. For the evaluation of moisture influence on the performance of pavement material, the water table is adjusted within the pit while conducting a plate load test. The research program of DHW requires the ground water table to be adjusted from a drained to flooded condition with four stops. The TDR probes (the principle of which will be addressed in Appendix A) would be deployed within the test-pit for the monitor of moisture profile of pavement material.

The purpose of test-pit experimental program was to evaluate the capillary behavior and resilient modulus of the subgrade materials with changing groundwater levels. The test-pit evaluation of subgrade soils served the following advantages:

(A) The test-pit can be used to simulate the different material components of a pavement system on a full-scale basis.

(B) The test-pit can facilitate the change of water level so as to simulate the different moisture conditions in a practical situation.

(C) Together with a loading system, the test can be used to investigate the deformation characteristics of subgrade materials under the influence of static and dynamic loads.

The capillary action and resilient deformation of the materials under investigation were evaluated with three levels of groundwater elevation: -- flooded, intermediate levels between the embankment-subgrade interface, and 12 inches above the embankment.
To offset the loss due to capillary rise and evaporation, extra water had to be added within the pit to keep the water table constant at each designated elevation prior to the moisture equilibrium and plate load test.

### 3.6.2 Test-pit Setup

The complete setup of test-pit experiment is mainly comprised of two parts -- full-scale test-pit and loading system.

**Test-pit**

The FDOT test-pit for the research of design high water clearance is shaped like a rectangular reinforced concrete vessel that is twenty-four feet long, eight feet wide and seven feet deep. Below the subgrade material tested (three feet in thickness) was the standard embankment that was composed of three layers of different materials. The bottom layer was composed of a bed of 12-inch (305 mm) river-gravel that facilitated the upward percolation of ground water. A builder’s sand layer that was 12-inch (305 mm) thick rested upon the river gravel and was kept separated with gravel by a permeable filter fabric. The third layer was a 12-inch (305 mm) depth of standard A-3 soil (embankment) that was used as the top layer of simulated embankment.

**Loading System**

A hydraulic loading device was attached to an over hanging 24 WF beam which facilitated the transverse movement of the loading device, while the 24 WF beam itself traveled longitudinally above the test pit,
thus providing a two dimensional selection of loading location. A standard 12-inch diameter rigid plate was used to simulate the single wheel load upon the tested soil. Vertical deformations of the soil were measured through Linear Variable Displacement Transducer (LVDT). To best simulate the dynamic impact of moving vehicles on the subgrade, the plate loads were conducted in a cyclic manner, one-second per cycle with loading periods of 0.1 second and 0.9 seconds for the rebound of tested materials. This was consistent with the loading frequency used in laboratory triaxial resilient modulus tests. In order to achieve a certain deformation curve with respect to the number of load cycles, 30000 load cycles were conducted.

The loading system together with the cross sectional view of a test-pit is illustrated in Figure 3.14.

3.6.3 Method of Analysis
The resilient modulus obtained from the plate load tests on subgrade is based on Boussinesq’s theory of deflections at the center of a circular plate. Burmister has extended this theory to a two-layer elastic system. The layers are assumed to be homogeneous, isotropic, and elastic solid with a continuous interface with the bottom layer being infinite in depth. Under these circumstances, the equivalent single-layer resilient modulus under the cyclic loading on a two-layer system (base and subgrade layers) can be derived from the theory of elasticity:

\[ E_{er} = \frac{\pi pa}{\Delta_r}(1 - \nu^2) \]  

(3-9)

where: \( E_{er} \) = Equivalent resilient modulus of a two-layer system
\( \Delta_R \) = Resilient deflection of the two-layer system at \( N \) (number of cyclic load)
\( p \) = Surcharge pressure from the circular plate
\( a \) = Radius of the circular plate
\( \nu \) = Poisson’s ratio

If \( \nu = 0.35 \) and 0.5, Equation (3-9) will be as follow:

\[
E_{e_R} = \frac{1.38 pa}{\Delta_R} \quad (\nu = 0.35) \tag{3-10}
\]

\[
E_{e_R} = \frac{1.18 pa}{\Delta_R} \quad (\nu = 0.50) \tag{3-11}
\]

The equivalent modulus is an excellent criterion for the evaluation of the strength of pavement materials. With the decrease of equivalent modulus, deformation increases after the repeated loading. The magnitude of deformation does affect the potential rutting of the pavement. Thus, \( E_{eR} \) is a good index for the evaluation of potential pavement rutting. Design consideration of a minimum \( E_{eR} \) value can control potential excessive rutting of the pavement.

3.6.4 Time Domain Reflectometry (TDR)

The research of design high water clearances can only be conducted under a full awareness of seasonal water content under pavement. Time domain reflectometry (TDR) now serves as one of the most reliable nondestructive methods for monitoring both in situ and in lab soil moisture content. Measuring the time period for electric signal traveling through the guide-rod of a TDR probe as a mediate parameter, direct access to volumetric moisture content of subgrade soils was
gained using Campbell Scientific CS615 Water Content Reflectometer. TDR technique determines the changing moisture content of subgrade soil by measuring the proportionally changing conductivity profile; -- dielectric constant within subgrade soil mixture. The basic concept for a TDR probe was described in Appendix A.

The alternative equipment for the collection of moisture data is a moisture cell. It was used in the test-pit to justify the proper operation of CS615 probes and may not be worked as a prime access to moisture data because of its insensitivity to the moisture ranging from 4% to 16%. Time Domain Reflectometer is a relatively dependable approach for measuring the moisture content of granular soil.

Description of the Equipment

Manufactured by Campbell Scientific, the CS615 TDR probe (Figure 3.15) is also known as the Water Content Reflectometer. Its output is a square wave and can be connected to Campbell Scientific datalogger CR10X, CR10.

High-speed electronic components on the circuit board were configured as a bistable multivibrator. The output of the multivibrator was connected to the probe rod, which acted as a wave guide. The oscillation frequency of the multivibrator was dependent on dielectric constant of the soil measured. The dielectric constant was predominantly dependent on the water content. Digital circuitry scaled the multivibrator output to an appropriate frequency for measurement with a datalogger. The CS615 output was essentially a square wave with an amplitude swing of 0.25 VDC. The period of the square wave output ranged from 0.7 to 1.6 milliseconds and was used
for the calibration to water content. The measured period can be converted to moisture content using calibration value.

Two soil properties which can affect the response of the CS615 to changes in water content: high clay content (30% or above) and high electrical conductivity (more than dsm$^{-1}$, salted soil e.g.). In these cases, the required calibration must be generated for the specific soil.

**Conversion to Universal Model Form**

Instead of detecting the moisture content of soil through measuring apparent length $L_a$, CS615 TDR uses time period $t$ as a standard access to volumetric water content. A conversion deduction to universal model using parameter $t$ (travel time of the square wave along the CS615 TDR probe guide rod) helped to gain a better understanding of this equipment.

Refer to the Equation (A-1) in Appendix A, $K_a = (L_a/L_p V_p)^2$, where $L_a$: apparent length; $L_p$: actual length of CS615 TDR probe guide rod (0.3M), in this case, the travel distance should be two times the TDR length. $V_p$: the ratio of propagation velocity to the speed of light, usually 0.99 is used for maximum resolution. Here 1.0 is used for approximation, thus:

$$L_p \sqrt{K_a} = L_a \quad (3-12)$$

$$t = \frac{L_a}{C} = \frac{0.6 \sqrt{K_a}}{C} \quad (3-13)$$

Where $C =$ Speed of light ($3 \times 10^8$ m/s);

$t =$ Travel time on the rod. Also:
\[ V_w(\%) = 0.125\sqrt{K_u} - 0.125 - \frac{\gamma_d}{8G_s\gamma_w} \]  

(3-14)

\[ V_w(\%) = 0.125 \times C \times t + 0.6 - 0.125 - 0.08 = 0.208Ct - 0.205 \]  

(3-15)

It is evident that the above equation is the universal model for volumetric moisture content through use of the CS615 TDR probe.

The Calibration of the CS615 TDR Probe

As mentioned before, the sample soil for calibration represented the model form of all soil types of granular soils without losing accuracy. A standard equation was generated then for measuring each type of soil by using a specific CS615 TDR probe. Thus, the calibration process becomes one of calibrating each individual TDR probe. The following is the calibration data for each of the six TDR probes used in the test-pit test.

\[ V_w(\%) = C_0 + C_1 \times t + C_2 \times t^2 \]  

(3-16)

Where:  
\( t \) = Time period for the square wave traveling through the guide rod of TDR probe  
\( C_0, C_1, C_2 \) = Constant for mathematics modeling

The calibration data and calibration curves were presented in Table 3.6 and Figure 3.16.

Note: 1) Since the equipment cannot locate the time value that was in the order of magnitude about \( 10^{-9} \) second, all these period values were amplified at the unit of millisecond. Here Campbell Scientific took 256x128 as the time amplification factor. 2) The apparent length between two inflection points on the trace and TDR travel period were basically identical, the only difference rests upon different interpretation (Campbell Scientific Inc., 1998).
3.6.5 Test Arrangement

The test-pit investigation for all types of soils being discussed in this report was implemented in the FDOT Soil Materials Laboratory, Gainsville. This experimental program can be chronologically divided into eight Phases:

Phase I: Levy County A-3 subgrade (4% passing No.200) were compacted and experimented within one half of the test-pit (8 feet by 6 feet) from the date of 12/9/1998 to 4/8/1999.

Phases II & III: SR-70 A-3 (8% passing No.200) and A-2-4 (14% passing No.200) subgrades were compacted and experimented within one test-pit (8 feet by 12 feet) from the date of 4/13/1999 to 2/14/2000. Separated by wooden partitions, each of these subgrades accounted for one half of the test-pit area.

Phases IV, V & VI: A-2-4 (12%), A-2-4 (20%) and A-2-4 (24%) subgrades were compacted and experimented within one test-pit from the date of 6/20/2000 to 1/8/2001, separated by wooden partitions.

Phases VII & VIII: A-2-4 (30%) and Oolite were compacted and experimented within one test-pit from 6/20/2000 to 12/21/2000.

During the test, three feet of subgrade material was compacted within the test-pit under its optimum moisture condition. The subgrade materials were compacted into seven layers. With the exception of the first and last lifts three inches thick, each lift was six inches in thickness. The CS615 probe was embedded on each of these layers respectively staggering one another, whereas six moisture cells were placed vertically at six inches apart. The circular rigid loading plate was positioned on the mid-point between two columns of
vertically arranged CS615 probes.

The compaction data and procedure for tested soils are presented in Tables 3.7, 3.8, 3.9 and Table 3.10. The CS615 probe installation and test layout for the first three test phases are illustrated in Figure 3.17, Figure 3.18 and Figure 3.19.

The actual views of test-pit loading system and compaction equipment are illustrated in Figure 3.20 and Figure 3.21.

3.6.6 Test Procedure

Test Phase I (Levy County A-3 soil)

Sequence of Plate Load Test:

Water table 20 in. below embankment with plate load 20 psi (without limerock base)

Water table on the surface of embankment with plate load 20 psi (without limerock base)

Water table 12 in. above the embankment with plate load 20 psi (both with and without 5 in. limerock base) and plate load 50 psi (with 5 in. limerock Base);

Water table all the way up to the surface of subgrade (flooded case) with plate load 20 psi and 50 psi (with 5 in. limerock base)

Chronological record of the test procedure is summarized in Table 3.7.

Test Phase II & III (SR-70 A-3 & SR-70 A-2-4 soil)

Sequence of Plate Load Test:

Water table at the top of embankment with plate load 20 psi (without limerock base)
Water table at 12 in. above the embankment with plate load 20 psi (without limerock base)
Water table at 12 in. above the embankment with plate load 50 psi (with 5 in. limerock base)
Water table at 36 in. above the embankment with plate load 50 psi (with 5 in. limerock base)
Water table at 24 in. below the embankment with plate load 50 psi (with 5 in. limerock base), two sets of data recorded with one week apart (drained condition)
Water table back to 36 in. above the embankment with plate load 50 psi (with 5 in. limerock base)
Chronological record of the test procedure is summarized in Table 3.8.

Test Phase IV, V & VI (A-2-4 12%, 20%, 24%)
Sequence of Plate Load Test:
Water table on the surface of embankment with plate load 20 psi (without limerock base)
Water table 12 in. above the embankment with plate load 20 psi (both with and without 5 in. limerock base) and plate load 50 psi (with 5 in. limerock Base);
Water table all the way up to the surface of subgrade (flooded case) with plate load 50 psi (with 5 in. limerock base)
Chronological record of the test procedure is summarized in Table 3.9.
**Test Phase VII (A-2-4 30%)**

Sequence of Plate Load Test:
Water table on the surface of embankment with plate load 20 psi (without limerock base)
Water table 12 in. above the embankment with plate load 20 psi (without 5 in. limerock base) and plate load 50 psi (with 5 in. limerock Base);
Water table all the way up to the surface of subgrade (flooded case) with plate load 50 psi (with 5 in. limerock base)
Chronological record of the test procedure is summarized in Table 3.10.

**Test Phase VIII (Oolite)**

Sequence of Plate Load Test:
Water table 12 in. above the embankment with plate load 50 psi (without 5 in. limerock base);
Water table all the way up to the surface of subgrade (flooded case) with plate load 50 psi (with 5 in. limerock base)
Chronological record of the test procedure is summarized in Table 3.10.

### 3.7 Field Monitoring Program

The development of moisture within a subgrade material may exert a detrimental effect on the pavement while under the surcharge provided by moving vehicles. The main purpose for the research of design highwater clearances is to evaluate the influence of moisture within the subgrade material upon the soil modulus, so as to recommend an adequate distance of base clearance between the high ground water
table and the bottom of base layer. To achieve this objective, a field-monitoring test evaluating the moisture variations caused by the capillary rise behavior within actual field geologic strata was desirable. Being exposed to the open environment, the climatic factors such as precipitation and atmospheric temperature were introduced into the moisture measurement for SR-70 field monitoring program. The critical moisture conditions acquired through the field test can be correlated with the resilient behavior of same subgrade material sharing the similar moisture profile in a test-pit test, in order to predict the pavement performance. In the period of two years monitoring, due to the road construction and equipment problem, there is no data record for almost half a year. In summer season, according to sometime heavy precipitation, the water table will arise in the following days, then come back to original height.

3.7.1 Field Installation
The field test was conducted in State Road 70 near Fort Pierce, Florida. Two test sites, 300 feet apart, were selected for the installation of TDR probes. Each excavated test pit was installed with 12 TDR probes, from 0.5 ft. below the asphalt concrete layer down to 6 ft. below the asphalt concrete layer. All TDR probes were connected with a datalogger powered by a solar panel for data acquisition and data storage. The moisture data recorded within the datalogger can be transferred to an indoor terminal through a public telephone by activating PC208W software in the computer. To correlate the moisture condition of the pavement with the climatic factor such as precipitation, a rain gauge was also installed near the test site.
The acquisition interval for the precipitation data was fifteen minutes and activated in synchrony with the datalogger.
The installation and instrumentation for the field-monitoring program is described in detail in Appendix B. The results of this monitoring program are presented and discussed in Appendix C.

3.7.2 Discussion on Field Monitoring Program

One major question for the moisture measurement in SR-70 was to find out to what extent the test-pit study conducted in the laboratory could simulate the practical moisture variation along the pavement profile in the field. In the test-pit test, the ground water was taken as the only source of moisture within the pavement. In the field monitoring program conducted at State Road 70, both the downward moisture percolation as a result of precipitation and the upward moisture migration (capillary rise) as a result of the ground water table change were observed. But the moisture increase within the top layer of subgrade (A-3 soil, for both test site No. 1 and No. 2) incurred by precipitation was transient, and the degree of saturation was low according to the field test results. When compared with what was achieved in the test-pit test for the SR-70 A-3 soil, with roughly the same moisture content and the degree of saturation resulted from the water table adjustment, the effect of moisture damage on the subgrade stiffness (resilient modulus) was minimal. In addition, the asphalt concrete layer provided a protection against the seepage from precipitation.
The A-2-4 soil was not encountered within three feet below the base layer at the test sites. The moisture resulted from climatic change
in the A-2-4 soil layer fluctuated in a way quite similar to what was observed in the test-pit test subjected to ground water table adjustments. The moisture variation of the A-2-4 soil at SR-70 was relatively small compared with the A-3 soil. However the A-2-4 soil layer (with some organic content) existed between 3.5 ft and 4.5 ft below the asphalt concrete layer at test site No. 2, functioned as a barrier for both the downward and upward migration of moisture. The effect of hysterisis was quite obvious for the SR-70 A-2-4 soil due to high percentage of fines and higher soil suction. Discussions on the field monitoring results are presented in Appendix C.
### Table 3.1 Characteristics of Tested Subgrade Materials

<table>
<thead>
<tr>
<th>Material</th>
<th>No.200 Passing (%)</th>
<th>Clay Percentage (%)</th>
<th>Dry Density (kN/M$^3$)</th>
<th>Dry Density (pcf)</th>
<th>Optimum Moisture (%)</th>
<th>LBR*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Levy Co. A-3</td>
<td>4</td>
<td>N/A</td>
<td>16.7</td>
<td>106.5</td>
<td>10.0</td>
<td>22</td>
</tr>
<tr>
<td>SR-70 A-3</td>
<td>8</td>
<td>6</td>
<td>17.6</td>
<td>112.0</td>
<td>11.5</td>
<td>45</td>
</tr>
<tr>
<td>SR-70 A-2-4</td>
<td>14</td>
<td>10</td>
<td>19.2</td>
<td>122.0</td>
<td>10.5</td>
<td>124</td>
</tr>
<tr>
<td>A-2-4</td>
<td>12</td>
<td>3</td>
<td>17.3</td>
<td>110.6</td>
<td>12.1</td>
<td>30</td>
</tr>
<tr>
<td>A-2-4</td>
<td>20</td>
<td>8</td>
<td>19.5</td>
<td>124.4</td>
<td>10.0</td>
<td>146</td>
</tr>
<tr>
<td>A-2-4</td>
<td>24</td>
<td>5</td>
<td>18.2</td>
<td>116.3</td>
<td>10.7</td>
<td>69</td>
</tr>
<tr>
<td>A-2-4</td>
<td>30</td>
<td>N/A</td>
<td>18.2</td>
<td>116.0</td>
<td>12.0</td>
<td>72</td>
</tr>
<tr>
<td>Oolite</td>
<td>N/A</td>
<td>N/A</td>
<td>20.8</td>
<td>132.6</td>
<td>7.6</td>
<td>194</td>
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* LBR: Limerock Bearing Ratio
<table>
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<th>Test Procedure</th>
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<tr>
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<td>Subgrade Soils</td>
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<td></td>
<td>kPa</td>
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<tr>
<td>Specimen</td>
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</tr>
<tr>
<td>Condition</td>
<td></td>
</tr>
<tr>
<td>Testing</td>
<td>103.4</td>
</tr>
<tr>
<td></td>
<td>103.4</td>
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<tr>
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<td>68.9</td>
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<td>34.5</td>
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</tbody>
</table>

Table 3.2 Comparison of Three Mr Test Procedures for Granular Soils
Table 3.3 Raw Data and Calculation Procedure
M ATERIAL:
PANAM A SAND
OPT. M OISTURE:
8.5%
3
19.64 kN/m
M AX. DRY DEN.:

LOCATION: PANAM A CITY BEACH, FLORIDA
19.37 kN/m 3
DRY DENSITY:
M OISTURE:
7.63%

LBR:

TEST DATE:

88.00
Raw Data

Confining
Pressure
kPa
103.35
103.35
103.35
103.35
103.35
103.35
103.35
103.35
103.35
103.35
103.35
103.35
103.35
103.35
103.35
103.35
103.35
103.35
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103.35
103.35
103.35
103.35
103.35
103.35
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103.35
103.35
103.35
103.35
103.35

Axial
Load
kN
-0.3433
-0.0015
-0.3515
-0.0015
-0.356
-0.0032
-0.3589
-0.0025
-0.3645
-0.0019
-0.3718
-0.003
-0.3753
-0.0026
-0.3737
-0.0016
-0.3794
-0.0042
-0.3818
-0.0017
-0.3904
-0.005
-0.382
-0.0042
-0.3899
-0.0056
-0.3847
-0.0028
-0.3862
-0.0039
-0.3909
-0.0026
-0.3904
-0.0026
-0.3895
-0.005
-0.3889
-0.0064
-0.3917
-0.0045
-0.3935
0.0008
-0.3961
0.0005
-0.3918
-0.0039
-0.3892
-0.0036
-0.3925
-0.004

LVDT
(10.2-cm )
mm
0.902544
0.889247
0.902894
0.889247
0.902894
0.889597
0.902894
0.889422
0.903244
0.889247
0.903594
0.889597
0.903768
0.889422
0.903768
0.889422
0.903594
0.889772
0.904293
0.889422
0.904293
0.889772
0.904468
0.889597
0.904643
0.889772
0.904293
0.889422
0.904118
0.889422
0.904293
0.889422
0.904293
0.889597
0.904293
0.889597
0.904468
0.889772
0.904468
0.889422
0.904818
0.889597
0.904993
0.889597
0.904468
0.889597
0.904643
0.889772
0.904293
0.889772

LVDT
(10.2-cm )
mm
0.811618
0.798318
0.812143
0.797968
0.812143
0.798318
0.812318
0.798668
0.812843
0.798318
0.813018
0.798318
0.813193
0.798493
0.813193
0.798318
0.813368
0.798318
0.813543
0.798493
0.813893
0.798668
0.813543
0.798318
0.813718
0.798493
0.813893
0.798318
0.813718
0.798143
0.813893
0.798493
0.813718
0.798318
0.814068
0.798493
0.814068
0.798843
0.814068
0.798318
0.813893
0.798318
0.814593
0.798493
0.814068
0.798143
0.814243
0.798318
0.814243
0.798493

LVDT
(20.3-cm )
mm
6.466652
6.499898
6.466214
6.500335
6.465339
6.499898
6.465339
6.499898
6.465339
6.499460
6.463589
6.499898
6.464027
6.499460
6.463589
6.499460
6.463589
6.499023
6.463152
6.499898
6.462277
6.499460
6.461840
6.499023
6.462277
6.498148
6.462715
6.499023
6.463152
6.498585
6.461402
6.499023
6.461840
6.499460
6.460965
6.498585
6.461840
6.499023
6.461402
6.498585
6.460965
6.499023
6.461402
6.499460
6.461402
6.498585
6.460965
6.498585
6.461402
6.499023

5/9/95
Calculation Results

LVDT
(20.3-cm )
mm
6.903526
6.935017
6.902651
6.934580
6.902651
6.934143
6.902213
6.934580
6.901339
6.935017
6.900464
6.935017
6.900027
6.935454
6.901339
6.934580
6.900027
6.933705
6.900027
6.934143
6.899152
6.934580
6.899152
6.933705
6.898714
6.934143
6.900027
6.934580
6.899152
6.933705
6.898714
6.934143
6.899152
6.934143
6.898714
6.934143
6.898714
6.934143
6.898277
6.933268
6.897403
6.934580
6.897840
6.935017
6.898714
6.933268
6.899152
6.934580
6.898714
6.933705

85

Axial
Segm ents

Load Axial Strain Axial Strain
Cycles (10.2-cm ) (20.3-cm )

segm ents Cycles
1
2
1
4
5
2
7
8
3
10
11
4
13
14
5
16
17
6
19
20
7
22
23
8
25
26
9
28
29
10
31
32
11
34
35
12
37
38
13
40
41
14
43
44
15
46
47
16
49
50
17
52
54
18
55
56
19
58
59
20
61
62
21
64
66
22
67
68
23
70
71
24
73
74
25

Deviator
Stress
kPa

0.000131

0.000159

42.188

0.000137

0.000163

43.191

0.000133

0.000163

43.541

0.000133

0.000165

43.985

0.000140

0.000167

44.751

0.000141

0.000174

45.517

0.000143

0.000174

45.999

0.000144

0.000170

45.914

0.000142

0.000170

46.293

0.000147

0.000174

46.907

0.000146

0.000179

47.560

0.000148

0.000177

46.624

0.000148

0.000175

47.427

0.000150

0.000174

47.134

0.000149

0.000172

47.172

0.000149

0.000180

47.919

0.000148

0.000179

47.853

0.000149

0.000180

47.456

0.000147

0.000179

47.210

0.000152

0.000178

47.777

0.000152

0.000185

48.657

0.000155

0.000185

48.950

0.000152

0.000177

47.863

0.000152

0.000180

47.579

0.000149

0.000179

47.938


Table 3.3-continued
R aw D a ta
C onfining
P ressure
kP a
103 .35
103 .35
103 .35
103 .35
1 0 3 .3 5
1 0 3 .3 5
1 0 3 .3 5
1 0 3 .3 5
1 0 3 .3 5
1 0 3 .3 5
1 0 3 .3 5
1 0 3 .3 5
1 0 3 .3 5
1 0 3 .3 5
1 0 3 .3 5
1 0 3 .3 5
1 0 3 .3 5
1 0 3 .3 5
1 0 3 .3 5
1 0 3 .3 5
1 0 3 .3 5
1 0 3 .3 5
1 0 3 .3 5
1 0 3 .3 5
1 0 3 .3 5
1 0 3 .3 5
1 0 3 .3 5
1 0 3 .3 5
1 0 3 .3 5
1 0 3 .3 5
1 0 3 .3 5
1 0 3 .3 5
1 0 3 .3 5
1 0 3 .3 5
1 0 3 .3 5
1 0 3 .3 5
1 0 3 .3 5
1 0 3 .3 5
1 0 3 .3 5
1 0 3 .3 5
1 0 3 .3 5
1 0 3 .3 5
1 0 3 .3 5
1 0 3 .3 5
1 0 3 .3 5
1 0 3 .3 5
1 0 3 .3 5
1 0 3 .3 5

A xial
Load
kN
-0.38 84
-0.00 35
-0.39 44
-0.00 46
-0 .3 9 0 2
-0 .0 0 4 2
-0 .3 9 7 1
-0 .0 0 5 8
-0 .3 9 1 9
-0 .0 0 5 5
-0 .3 8 4 8
-0 .0 0 3 9
-0 .3 9 9 1
-0 .0 0 6 8
-0 .3 9 6 8
-0 .0 0 8 5
-0 .3 9 0 6
-0 .0 0 1 9
-0 .3 9 1 9
-0 .0 0 6 5
-0 .4 0 4 6
-0 .0 0 4 8
-0 .3 9 1 6
-0 .0 0 5 5
-0 .3 8 8 2
-0 .0 0 1 2
-0 .3 8 7 6
-0 .0 0 6 6
-0 .3 9 2 5
-0 .0 0 3 9
-0 .3 8 9 8
-0 .0 0 2 9
-0 .3 8 5 1
-0 .0 0 6 3
-0 .3 9 4 2
-0 .0 0 6 5
-0 .3 9 6 4
-0 .0 0 7 5
-0 .3 9 1 4
-0 .0 0 5 2
-0 .3 9 3 2
-0 .0 0 0 6
-0 .3 9 6
-0 .0 0 4 4
-0 .3 9 0 7
-0 .0 0 3 1
-0 .3 9 4 5
-0 .0 0 8 7

LV D T
(10.2-cm )

LVDT
(10 .2-cm )

LV D T
(20.3-cm )

C aculation R esults
LVDT
(20 .3-cm )

mm
0.904468
0.889597
0.904468
0.889772
0 .9 0 4 6 4 3
0 .8 8 9 7 7 2
0 .9 0 4 8 1 8
0 .8 8 9 9 4 7
0 .9 0 4 4 6 8
0 .8 8 9 7 7 2
0 .9 0 4 4 6 8
0 .8 8 9 2 4 7
0 .9 0 4 9 9 3
0 .8 8 9 7 7 2
0 .9 0 4 4 6 8
0 .8 8 9 7 7 2
0 .9 0 4 4 6 8
0 .8 8 9 5 9 7
0 .9 0 4 4 6 8
0 .8 8 9 7 7 2
0 .9 0 5 3 4 3
0 .8 8 9 7 7 2
0 .9 0 4 8 1 8
0 .8 8 9 7 7 2
0 .9 0 4 6 4 3
0 .8 8 9 5 9 7
0 .9 0 4 6 4 3
0 .8 8 9 9 4 7
0 .9 0 4 4 6 8
0 .8 8 9 9 4 7
0 .9 0 4 6 4 3
0 .8 8 9 5 9 7
0 .9 0 4 4 6 8
0 .8 9 0 1 2 2
0 .9 0 4 4 6 8
0 .8 8 9 7 7 2
0 .9 0 4 6 4 3
0 .8 8 9 7 7 2
0 .9 0 4 8 1 8
0 .8 8 9 7 7 2
0 .9 0 4 6 4 3
0 .8 8 9 5 9 7
0 .9 0 4 6 4 3
0 .8 8 9 5 9 7
0 .9 0 4 6 4 3
0 .8 8 9 2 4 7
0 .9 0 4 8 1 8
0 .8 8 9 7 7 2

mm
0.8138 93
0.7984 93
0.8142 43
0.7981 43
0 .8 1 3 8 9 3
0 .7 9 8 4 9 3
0 .8 1 4 4 1 8
0 .7 9 8 4 9 3
0 .8 1 4 0 6 8
0 .7 9 8 3 1 8
0 .8 1 3 7 1 8
0 .7 9 8 1 4 3
0 .8 1 4 0 6 8
0 .7 9 8 4 9 3
0 .8 1 4 2 4 3
0 .7 9 8 4 9 3
0 .8 1 4 0 6 8
0 .7 9 8 3 1 8
0 .8 1 4 2 4 3
0 .7 9 8 4 9 3
0 .8 1 4 5 9 3
0 .7 9 8 3 1 8
0 .8 1 4 0 6 8
0 .7 9 8 3 1 8
0 .8 1 3 8 9 3
0 .7 9 8 1 4 3
0 .8 1 3 7 1 8
0 .7 9 8 8 4 3
0 .8 1 4 0 6 8
0 .7 9 8 4 9 3
0 .8 1 3 8 9 3
0 .7 9 8 3 1 8
0 .8 1 3 7 1 8
0 .7 9 8 6 6 8
0 .8 1 4 4 1 8
0 .7 9 8 4 9 3
0 .8 1 4 2 4 3
0 .7 9 8 6 6 8
0 .8 1 4 2 4 3
0 .7 9 8 6 6 8
0 .8 1 4 4 1 8
0 .7 9 8 1 4 3
0 .8 1 3 8 9 3
0 .7 9 8 4 9 3
0 .8 1 4 2 4 3
0 .7 9 7 9 6 8
0 .8 1 3 8 9 3
0 .7 9 8 4 9 3

mm
6.461402
6.499023
6.460965
6.498585
6 .4 6 0 9 6 5
6 .4 9 8 1 4 8
6 .4 6 0 9 6 5
6 .4 9 8 1 4 8
6 .4 6 1 4 0 2
6 .4 9 8 5 8 5
6 .4 6 0 9 6 5
6 .4 9 8 5 8 5
6 .4 6 0 5 2 7
6 .4 9 8 1 4 8
6 .4 6 0 9 6 5
6 .4 9 8 5 8 5
6 .4 6 1 8 4 0
6 .4 9 8 5 8 5
6 .4 6 0 9 6 5
6 .4 9 9 0 2 3
6 .4 6 0 0 9 0
6 .4 9 9 0 2 3
6 .4 6 1 8 4 0
6 .4 9 8 5 8 5
6 .4 6 0 9 6 5
6 .4 9 8 5 8 5
6 .4 6 2 2 7 7
6 .4 9 7 7 1 1
6 .4 6 1 4 0 2
6 .4 9 9 0 2 3
6 .4 6 1 8 4 0
6 .4 9 9 0 2 3
6 .4 6 1 8 4 0
6 .4 9 9 0 2 3
6 .4 6 1 4 0 2
6 .4 9 8 1 4 8
6 .4 6 0 9 6 5
6 .4 9 8 1 4 8
6 .4 6 2 2 7 7
6 .4 9 8 5 8 5
6 .4 6 1 4 0 2
6 .4 9 9 4 6 0
6 .4 6 1 8 4 0
6 .4 9 8 5 8 5
6 .4 6 1 8 4 0
6 .4 9 8 5 8 5
6 .4 6 0 9 6 5
6 .4 9 7 7 1 1

mm
6.8991 52
6.9337 05
6.8987 14
6.9337 05
6 .8 9 8 7 1 4
6 .9 3 4 1 4 3
6 .8 9 7 4 0 3
6 .9 3 3 7 0 5
6 .8 9 8 2 7 7
6 .9 3 4 1 4 3
6 .8 9 8 7 1 4
6 .9 3 4 1 4 3
6 .8 9 7 4 0 3
6 .9 3 3 2 6 8
6 .8 9 7 4 0 3
6 .9 3 3 7 0 5
6 .8 9 8 2 7 7
6 .9 3 4 1 4 3
6 .8 9 8 7 1 4
6 .9 3 3 7 0 5
6 .8 9 7 4 0 3
6 .9 3 3 7 0 5
6 .8 9 8 2 7 7
6 .9 3 4 1 4 3
6 .8 9 9 1 5 2
6 .9 3 4 1 4 3
6 .8 9 8 7 1 4
6 .9 3 2 8 3 0
6 .8 9 7 8 4 0
6 .9 3 3 7 0 5
6 .8 9 8 2 7 7
6 .9 3 3 7 0 5
6 .8 9 8 2 7 7
6 .9 3 3 7 0 5
6 .8 9 8 7 1 4
6 .9 3 4 1 4 3
6 .8 9 8 7 1 4
6 .9 3 3 2 6 8
6 .8 9 8 2 7 7
6 .9 3 3 2 6 8
6 .8 9 7 8 4 0
6 .9 3 3 2 6 8
6 .8 9 8 2 7 7
6 .9 3 2 8 3 0
6 .8 9 8 2 7 7
6 .9 3 3 7 0 5
6 .8 9 8 2 7 7
6 .9 3 2 3 9 3

A verage of the last five cycles
1 0 3 .3 5 -0 .3 9 3 2
0 .9 0 4 7 1 3
1 0 3 .3 5 -0 .0 0 4 4
0 .8 8 9 5 9 7

0 .8 1 4 1 3 8
0 .7 9 8 3 5 3

6 .4 6 1 6 6 5
6 .4 9 8 5 8 5

6 .8 9 8 1 8 9
6 .9 3 3 0 9 3

A xial
S egm ents

L oad A xial S train A xial S train
C ycles (10 .2-cm ) (20.3-cm )

segm en ts C ycles
76
77
26
79
80
27
82
83
28
85
87
29
88
89
30
91
92
31
94
95
32
97
98
33
100
101
34
103
104
35
106
107
36
109
110
37
112
113
38
115
116
39
118
119
40
121
122
41
124
125
42
127
129
43
130
131
44
133
134
45
136
137
46
139
140
47
142
143
48
145
146
49

kP a
0.0001 49

0.000178

4 7.494

0.0001 52

0.000179

4 8.099

0 .0 0 0 1 4 9

0 .0 0 0 1 7 9

4 7 .6 2 6

0 .0 0 0 1 5 2

0 .0 0 0 1 8 1

4 8 .2 8 8

0 .0 0 0 1 5 0

0 .0 0 0 1 8 0

4 7 .6 8 3

0 .0 0 0 1 5 2

0 .0 0 0 1 8 0

4 7 .0 0 2

0 .0 0 0 1 5 2

0 .0 0 0 1 8 1

4 8 .4 1 1

0 .0 0 0 1 5 0

0 .0 0 0 1 8 2

4 7 .9 1 9

0 .0 0 0 1 5 1

0 .0 0 0 1 7 9

4 7 .9 7 6

0 .0 0 0 1 5 0

0 .0 0 0 1 8 0

4 7 .5 6 9

0 .0 0 0 1 5 7

0 .0 0 0 1 8 5

4 9 .3 3 8

0 .0 0 0 1 5 2

0 .0 0 0 1 7 9

4 7 .6 4 5

0 .0 0 0 1 5 2

0 .0 0 0 1 7 9

4 7 .7 5 8

0 .0 0 0 1 4 6

0 .0 0 0 1 7 1

4 7 .0 1 1

0 .0 0 0 1 4 8

0 .0 0 0 1 8 1

4 7 .9 5 7

0 .0 0 0 1 5 1

0 .0 0 0 1 7 9

4 7 .7 4 0

0 .0 0 0 1 4 5

0 .0 0 0 1 7 9

4 6 .7 4 7

0 .0 0 0 1 5 1

0 .0 0 0 1 7 8

4 7 .8 4 4

0 .0 0 0 1 5 0

0 .0 0 0 1 7 7

4 7 .9 9 5

0 .0 0 0 1 5 1

0 .0 0 0 1 7 5

4 7 .6 6 4

0 .0 0 0 1 5 4

0 .0 0 0 1 8 1

4 8 .4 5 8

0 .0 0 0 1 5 0

0 .0 0 0 1 7 5

4 8 .3 2 6

0 .0 0 0 1 5 6

0 .0 0 0 1 7 8

4 7 .8 3 4

0 .0 0 0 1 5 0

0 .0 0 0 1 7 4

4 7 .6 0 7

0 .0 0 0 1 5 2

0 .0 0 0 1 7 7

4 7 .9 7 8

R esilient m odu lus from 10.2-cm m easurem ent = 47.977/0.000152 = 3154 93.29 kP a = 315.20 M P a
R esilient m odu lus from 20.3-cm m easurem ent = 47.977/0.000176 = 2714 73.26 kP a = 271.22 M P a

86

D eviator
S tress


Table 3.4 Summary of Laboratory Tests

<table>
<thead>
<tr>
<th>Soil Types</th>
<th>Condition</th>
<th>Sample No.</th>
<th>Dry Density pcf</th>
<th>Moisture Content at Compaction</th>
<th>Moisture Content before Test</th>
</tr>
</thead>
<tbody>
<tr>
<td>A-3, Levy County</td>
<td>Dried</td>
<td>A3LEVYD1</td>
<td>106</td>
<td>9.50%</td>
<td>8.08%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>A3LEVYD2</td>
<td>105.8</td>
<td>9.60%</td>
<td>4.30%</td>
</tr>
<tr>
<td></td>
<td>Optimum</td>
<td>A3LEVYO1</td>
<td>105.6</td>
<td>9.50%</td>
<td>9.50%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>A3LEVYO2</td>
<td>105.8</td>
<td>9.60%</td>
<td>9.60%</td>
</tr>
<tr>
<td></td>
<td>Soaked</td>
<td>A3LEVYS1</td>
<td>105.8</td>
<td>9.50%</td>
<td>13.47%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>A3LEVYS2</td>
<td>105.27</td>
<td>9.50%</td>
<td>15.77%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>A3LEVYS3</td>
<td>105.4</td>
<td>9.60%</td>
<td>15%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>A3LEVYS4</td>
<td>105.1</td>
<td>9.60%</td>
<td>15.27%</td>
</tr>
<tr>
<td>A-3, SR70</td>
<td>Dried</td>
<td>A3SR70D1</td>
<td>111.6</td>
<td>11.40%</td>
<td>7.82%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>A3SR70D2</td>
<td>110.7</td>
<td>11.40%</td>
<td>5.31%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>A3SR70D3</td>
<td>108.8</td>
<td>11.40%</td>
<td>4.48%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>A3SR70D4</td>
<td>110.63</td>
<td>11.40%</td>
<td>4.00%</td>
</tr>
<tr>
<td></td>
<td>Optimum</td>
<td>A3SR70O1</td>
<td>111</td>
<td>11.40%</td>
<td>11.40%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>A3SR70O2</td>
<td>110.8</td>
<td>11.40%</td>
<td>11.40%</td>
</tr>
<tr>
<td></td>
<td>Soaked</td>
<td>A3SR70S1</td>
<td>109.7</td>
<td>11.40%</td>
<td>13.41%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>A3SR70S2</td>
<td>109.7</td>
<td>11.40%</td>
<td>13.69%</td>
</tr>
<tr>
<td>A-2-4, 12%</td>
<td>Dried</td>
<td>A2412%D1</td>
<td>110.6</td>
<td>12.10%</td>
<td>7.10%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>A2412%D2</td>
<td>110.7</td>
<td>12.10%</td>
<td>7.04%</td>
</tr>
<tr>
<td></td>
<td>Optimum</td>
<td>A2412%O1</td>
<td>109.3</td>
<td>12.10%</td>
<td>12.10%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>A2412%O2</td>
<td>109.8</td>
<td>12.10%</td>
<td>12.10%</td>
</tr>
<tr>
<td></td>
<td>Soaked</td>
<td>A2412%S1</td>
<td>109.6</td>
<td>12.10%</td>
<td>14.60%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>A2412%S2</td>
<td>109.6</td>
<td>12.10%</td>
<td>14.60%</td>
</tr>
<tr>
<td>A-2-4, SR70</td>
<td>Dried</td>
<td>A24SR70D1</td>
<td>120.3</td>
<td>10.60%</td>
<td>8.41%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>A24SR70D2</td>
<td>120.6</td>
<td>10.60%</td>
<td>7.76%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>A24SR70D3</td>
<td>120.9</td>
<td>10.60%</td>
<td>3.12%</td>
</tr>
<tr>
<td></td>
<td>Optimum</td>
<td>A24SR70O1</td>
<td>120.4</td>
<td>10.80%</td>
<td>10.80%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>A24SR70O2</td>
<td>119.8</td>
<td>10.39%</td>
<td>10.39%</td>
</tr>
<tr>
<td></td>
<td>Soaked</td>
<td>A24SR70S1</td>
<td>121.4</td>
<td>10.60%</td>
<td>11.23%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>A24SR70S2</td>
<td>120</td>
<td>10.60%</td>
<td>11.70%</td>
</tr>
<tr>
<td>Soil Types</td>
<td>Condition</td>
<td>Sample No.</td>
<td>Dry Density pcf</td>
<td>Moisture Content at Compaction</td>
<td>Moisture Content before Test</td>
</tr>
<tr>
<td>------------</td>
<td>-----------</td>
<td>------------</td>
<td>----------------</td>
<td>-------------------------------</td>
<td>-----------------------------</td>
</tr>
<tr>
<td>A-2-4, 20%</td>
<td>Dried</td>
<td>A2420%D1</td>
<td>117.3</td>
<td>10.00%</td>
<td>8.26%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>A2420%D2</td>
<td>117.9</td>
<td>10.00%</td>
<td>7.32%</td>
</tr>
<tr>
<td></td>
<td>Optimum</td>
<td>A2420%O1</td>
<td>117.9</td>
<td>10.00%</td>
<td>10.00%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>A2420%O2</td>
<td>118.9</td>
<td>10.00%</td>
<td>10.00%</td>
</tr>
<tr>
<td></td>
<td>Soaked</td>
<td>A2420%S1</td>
<td>119</td>
<td>10.00%</td>
<td>11.57%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>A2420%S2</td>
<td>118</td>
<td>10.00%</td>
<td>12.27%</td>
</tr>
<tr>
<td>A-2-4, 24%</td>
<td>Dried</td>
<td>A2424%D1</td>
<td>114</td>
<td>10.70%</td>
<td>7.65%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>A2424%D2</td>
<td>116</td>
<td>10.70%</td>
<td>7.72%</td>
</tr>
<tr>
<td></td>
<td>Optimum</td>
<td>A2424%O1</td>
<td>115.1</td>
<td>10.70%</td>
<td>10.70%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>A2424%O2</td>
<td>115.1</td>
<td>10.70%</td>
<td>10.70%</td>
</tr>
<tr>
<td></td>
<td>Soaked</td>
<td>A2424%S1</td>
<td>116.9</td>
<td>10.70%</td>
<td>12.00%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>A2424%S2</td>
<td>116.9</td>
<td>10.70%</td>
<td>11.45%</td>
</tr>
<tr>
<td>A-2-4, 30%</td>
<td>Dried</td>
<td>A2430%D1</td>
<td>116.1</td>
<td>12.00%</td>
<td>7.00%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>A2430%D2</td>
<td>115.12</td>
<td>12.00%</td>
<td>6.30%</td>
</tr>
<tr>
<td></td>
<td>Optimum</td>
<td>A2430%O1</td>
<td>115.8</td>
<td>12.00%</td>
<td>12.00%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>A2430%O2</td>
<td>115.1</td>
<td>12.00%</td>
<td>12.30%</td>
</tr>
<tr>
<td></td>
<td>Soaked</td>
<td>A2430%S1</td>
<td>116.4</td>
<td>12.00%</td>
<td>13.40%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>A2430%S2</td>
<td>116</td>
<td>12.00%</td>
<td>13.20%</td>
</tr>
<tr>
<td>Oolite</td>
<td>Dried</td>
<td>OOLITED1</td>
<td>131.35</td>
<td>7.80%</td>
<td>5.60%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>OOLITED2</td>
<td>131.3</td>
<td>7.80%</td>
<td>4.40%</td>
</tr>
<tr>
<td></td>
<td>Optimum</td>
<td>OOLITEO1</td>
<td>131.08</td>
<td>7.80%</td>
<td>7.80%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>OOLITEO2</td>
<td>131.22</td>
<td>7.80%</td>
<td>7.80%</td>
</tr>
<tr>
<td></td>
<td>Soaked</td>
<td>OOLITES1</td>
<td>131.52</td>
<td>7.80%</td>
<td>8.20%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>OOLITES2</td>
<td>131.2</td>
<td>7.80%</td>
<td>8.09%</td>
</tr>
</tbody>
</table>
Table 3.5 Equations of Calibration Line for Seven Psychrometers

<table>
<thead>
<tr>
<th>Psychrometer Number</th>
<th>Cooling Coefficient</th>
<th>Calibration Equation</th>
<th>R²</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>52</td>
<td>y = 262.74E25 + 359.83</td>
<td>0.9995</td>
</tr>
<tr>
<td>2</td>
<td>53</td>
<td>y = 152.68E25 - 138.37</td>
<td>0.9973</td>
</tr>
<tr>
<td>3</td>
<td>54</td>
<td>y = 191.31E25 + 307.75</td>
<td>1</td>
</tr>
<tr>
<td>4</td>
<td>55</td>
<td>y = 152.29E25 - 212.7</td>
<td>0.9984</td>
</tr>
<tr>
<td>5</td>
<td>56</td>
<td>y = 146.72E25 - 17.414</td>
<td>0.9998</td>
</tr>
<tr>
<td>6</td>
<td>56(B)</td>
<td>y = 160.51E25 - 267.39</td>
<td>1</td>
</tr>
<tr>
<td>7</td>
<td>58</td>
<td>y = 146.08E25 - 210.7</td>
<td>0.9995</td>
</tr>
</tbody>
</table>

Table 3.6 Calibration Data for CS615 Probes

<table>
<thead>
<tr>
<th>Probe No.</th>
<th>CS615 water content</th>
<th>CS615 Period</th>
<th>Gravimetric Water Content</th>
<th>Bulk Density (pcf)</th>
<th>Volumetric Water Content</th>
<th>C₀</th>
<th>C₁</th>
<th>C₂</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.422</td>
<td>1.297</td>
<td>0.122</td>
<td>113.1</td>
<td>0.22</td>
<td>-0.214</td>
<td>0.222</td>
<td>0.087</td>
</tr>
<tr>
<td>2</td>
<td>0.361</td>
<td>1.227</td>
<td>0.11</td>
<td>116.8</td>
<td>0.21</td>
<td>-0.214</td>
<td>0.195</td>
<td>0.123</td>
</tr>
<tr>
<td>3</td>
<td>0.442</td>
<td>1.319</td>
<td>0.09</td>
<td>117.9</td>
<td>0.17</td>
<td>-0.214</td>
<td>0.282</td>
<td>0.007</td>
</tr>
<tr>
<td>4</td>
<td>0.315</td>
<td>1.172</td>
<td>0.092</td>
<td>117.8</td>
<td>0.17</td>
<td>-0.214</td>
<td>0.215</td>
<td>0.096</td>
</tr>
<tr>
<td>5</td>
<td>0.277</td>
<td>1.123</td>
<td>0.092</td>
<td>115.6</td>
<td>0.17</td>
<td>-0.214</td>
<td>0.177</td>
<td>0.147</td>
</tr>
<tr>
<td>6</td>
<td>0.149</td>
<td>0.945</td>
<td>0.073</td>
<td>109.7</td>
<td>0.128</td>
<td>-0.214</td>
<td>0.009</td>
<td>0.373</td>
</tr>
</tbody>
</table>
Table 3.7 Test-pit Test Procedure for Levy County A-3 Soil

<table>
<thead>
<tr>
<th>Date</th>
<th>Test Procedure</th>
</tr>
</thead>
<tbody>
<tr>
<td>12/9/98--12/15/99</td>
<td>Levy County sand (A-3) was compacted in test pit with moisture sensor put in place.</td>
</tr>
<tr>
<td>12/15/98--12/22/98</td>
<td>Water in subgrade was allowed to drain and stabilize with elevation 20 in. below embankment</td>
</tr>
<tr>
<td>12/30/1998</td>
<td>First plate load was performed when moisture condition at each level came to their steady state.</td>
</tr>
<tr>
<td>1/5/99--1/26/99</td>
<td>Water table was raised gradually to the surface of embankment</td>
</tr>
<tr>
<td>2/5/1999</td>
<td>Moisture content stabilized, second plate load test was conducted.</td>
</tr>
<tr>
<td>2/5/1999--2/26/99</td>
<td>Water table was raised to 12 in. above embankment and moisture at each level reached to its steady state on 2/26/99, then the third plate load test was conducted.</td>
</tr>
<tr>
<td>2/26/99--3/3/99</td>
<td>5-inch thickness of lime rock base was built on the top of subgrade soil on 3/3/99,</td>
</tr>
<tr>
<td>3/23/1999</td>
<td>Moisture condition stabilized, plate load test with loading pressure 20 psi was conducted</td>
</tr>
<tr>
<td>3/24/1999</td>
<td>Plate load tests with loading pressure 50 psi was conducted</td>
</tr>
<tr>
<td>3/24/1999--3/31/99</td>
<td>Water table was raised to the top of subgrade. With moisture equilibrium achieved at each level</td>
</tr>
<tr>
<td>3/31/1999</td>
<td>Plate load tests were conducted under 50 psi</td>
</tr>
<tr>
<td>4/1/1999</td>
<td>Plate load tests were conducted under 50 psi</td>
</tr>
<tr>
<td>4/5/1999</td>
<td>Water was drained down to 20 in. below embankment</td>
</tr>
<tr>
<td>4/8/1999</td>
<td>Test pit was excavated</td>
</tr>
</tbody>
</table>
Table 3.8 Test-pit Test Procedures for SR-70 A-3 & A-2-4 Soil

<table>
<thead>
<tr>
<th>Date</th>
<th>Test Procedure</th>
</tr>
</thead>
<tbody>
<tr>
<td>4/13/99--4/29/99</td>
<td>SR-70 A-3 and A-2-4 soils were compacted in test-pit with CS615 probes put in place</td>
</tr>
<tr>
<td>4/29/99--5/17/99</td>
<td>Water in subgrade soil was allowed to drain and stabilized with elevation 24 in. below the embankment</td>
</tr>
<tr>
<td>5/17/99--6/10/99</td>
<td>Water table was raised to 12 in. below the embankment. Moisture content was stabilized</td>
</tr>
<tr>
<td>6/10/99--7/22/99</td>
<td>Water table was raised to the top of embankment. Moisture content was stabilized</td>
</tr>
<tr>
<td>7/19/1999</td>
<td>Plate load tests were conducted for A-2-4 (20 psi)</td>
</tr>
<tr>
<td>7/20/1999</td>
<td>Plate load tests were conducted for A-3 (20 psi)</td>
</tr>
<tr>
<td>7/22/99--9/3/99</td>
<td>Water table in subgrade was raised to 12 in. above the embankment</td>
</tr>
<tr>
<td>8/24/1999</td>
<td>Plate load tests were conducted for A-3 (20 psi)</td>
</tr>
<tr>
<td>8/25/1999</td>
<td>Plate load tests were conducted for A-2-4 (20 psi)</td>
</tr>
<tr>
<td>9/1/1999</td>
<td>5-inch thickness of limerock base was built on top of the subgrade soil</td>
</tr>
<tr>
<td>9/2/1999</td>
<td>Plate load tests were conducted for A-2-4 (50 psi)</td>
</tr>
<tr>
<td>9/3/1999</td>
<td>Plate load tests were conducted for A-3 (50 psi)</td>
</tr>
<tr>
<td>9/03/99--10/11/99</td>
<td>Water table was raised to the surface of subgrade.</td>
</tr>
<tr>
<td>9/29/1999</td>
<td>Plate load test was conducted for A-3 (50 psi)</td>
</tr>
<tr>
<td>9/30/1999</td>
<td>Plate load test was conducted for A-2-4 (50 psi)</td>
</tr>
<tr>
<td>10/5/1999</td>
<td>Another plate load test was conducted for A-3 (50 psi)</td>
</tr>
</tbody>
</table>
Table 3.8-continued

<table>
<thead>
<tr>
<th>Date</th>
<th>Test Procedure</th>
</tr>
</thead>
<tbody>
<tr>
<td>10/11/99--1/06/00</td>
<td>Water table dropped all the way down to 24 in. below the embankment</td>
</tr>
<tr>
<td>12/28/1999</td>
<td>Plate load tests were conducted for A-2-4 (50 psi)</td>
</tr>
<tr>
<td>12/29/1999</td>
<td>Plate load tests were conducted for A-3 (50 psi)</td>
</tr>
<tr>
<td>1/4/1999</td>
<td>Plate load tests were conducted A-3 (50 psi)</td>
</tr>
<tr>
<td>1/5/1999</td>
<td>Plate load tests were conducted A-2-4 (50 psi)</td>
</tr>
<tr>
<td>1/06/00--2/14/00</td>
<td>Water table moved back to the surface of subgrade soil</td>
</tr>
<tr>
<td>2/1/2000</td>
<td>Plate load tests were conducted for A-2-4 (50 psi)</td>
</tr>
<tr>
<td>2/2/2000</td>
<td>Plate load tests were conducted for A-3 (50 psi)</td>
</tr>
</tbody>
</table>
Table 3.9 Test-pit Test Procedures for A-2-4 (12%, 20% & 24%) Soil

<table>
<thead>
<tr>
<th>Date</th>
<th>Test Procedure</th>
</tr>
</thead>
<tbody>
<tr>
<td>6/20/2000</td>
<td>Water table dropped all the way down to 24 in. below the embankment</td>
</tr>
<tr>
<td>8/4/2000</td>
<td>Raise Water Table to top of embankment</td>
</tr>
<tr>
<td>9/19/00~9/26/00</td>
<td>Plate load tests were conducted for A-2-4 (12%, 20%, 24%) (20 psi)</td>
</tr>
<tr>
<td>9/26/2000</td>
<td>Raise Water Table to 12” above embankment</td>
</tr>
<tr>
<td>11/1/00~11/14/00</td>
<td>Plate load tests were conducted for A-2-4 (12%, 20%, 24%) (20 psi)</td>
</tr>
<tr>
<td>12/1/2000</td>
<td>Limerock cap placed</td>
</tr>
<tr>
<td>12/11/00~12/21/00</td>
<td>Plate load tests were conducted for A-2-4 (12%, 20%, 24%) (50 psi)</td>
</tr>
<tr>
<td>12/21/2000</td>
<td>Raise Water Table to bottom of limerock</td>
</tr>
<tr>
<td>2/26/01~3/8/01</td>
<td>Plate load tests were conducted for A-2-4 (12%, 20%, 24%) (50 psi)</td>
</tr>
</tbody>
</table>
Table 3.10 Test-pit Test Procedure for A-2-4 (30%) & Oolite

<table>
<thead>
<tr>
<th>Date</th>
<th>Test Procedure</th>
</tr>
</thead>
<tbody>
<tr>
<td>6/20/2000</td>
<td>Water table dropped all the way down to 24 in. below the embankment</td>
</tr>
<tr>
<td>7/7/2000</td>
<td>Raise Water Table to top of embankment</td>
</tr>
<tr>
<td>10/5/2000</td>
<td>Plate load tests were conducted for A-2-4 (30%) (20 psi)</td>
</tr>
<tr>
<td>10/5/2000</td>
<td>Raise Water Table to 12&quot; above embankment</td>
</tr>
<tr>
<td>10/6/00-10/17/00</td>
<td>Plate load tests were conducted for A-2-4 (30%) (20 psi) and Oolite (50psi)</td>
</tr>
<tr>
<td>11/28/2000</td>
<td>Limerock cap placed</td>
</tr>
<tr>
<td>12/11/00-12/18/00</td>
<td>Plate load tests were conducted for A-2-4 (30%) and Oolite (50 psi)</td>
</tr>
<tr>
<td>12/21/2000</td>
<td>Raise Water Table to bottom of limerock</td>
</tr>
<tr>
<td>2/7/01-2/12/02</td>
<td>Plate load tests were conducted for A-2-4 (30%) and Oolite (50 psi)</td>
</tr>
</tbody>
</table>
Figure 3.1 Samples under Soaking
Figure 3.2 Sample in Mold before Soaking
Figure 3.3 Samples under Drying
Figure 3.4 Sketch of the Resilient Modulus Testing Equipment
Figure 3.5 Triaxial Chamber with Internal LVDTs and Load Cell
Figure 3.6 A Schematic Illustration of T273-86 Soil Suction Test Setup
Calibration for Psychrometer #1

\[ y = 262.74x + 359.83 \]

\[ R^2 = 0.9995 \]

Figure 3.7 Calibration Line for Psychrometer No.1

Calibration for Psychrometer #2

\[ y = 152.68x - 138.37 \]

\[ R^2 = 0.9973 \]

Figure 3.8 Calibration Line for Psychrometer No.2
Figure 3.9 Calibration Line for Psychrometer No.3

Figure 3.10 Calibration Line for Psychrometer No.4
Calibration for Psychrometer #5

\[ y = 146.72x - 17.414 \]

\[ R^2 = 0.9998 \]

Figure 3.11 Calibration Line for Psychrometer No.5

Calibration for Psychrometer #6

\[ y = 160.51x - 267.39 \]

\[ R^2 = 1 \]

Figure 3.12 Calibration Line for Psychrometer No.6
Calibration for Psychrometer #7

\[ y = 146.08x - 210.7 \]

\[ R^2 = 0.9995 \]

Figure 3.13 Calibration Line for Psychrometer No.7
Figure 3.14 Schematic Diagram of Loading System & Cross Sectional View of Test-Pit
Figure 3.15 An Actual View of CS615 Probe

Figure 3.16 Calibration Curve for CS615 TDR Probe
Figure 3.17 Test-Pit Setup for Levy County A-3 Subgrade
(* Sequence of Water Table Adjustment)
Figure 3.18 Test-pit Setup for SR-70 A-3 & A-2-4 Subgrades
(* Sequence of Water Table Adjustment)
Figure 3.19 Phase II Plate Load Test Loading Position and Connection of Data Readout
Figure 3.20 An Actual View of Test-Pit Loading System
Figure 3.21 An Actual View of Test-Pit and Compaction Equipment
CHAPTER 4 PRESENTATION OF LABORATORY EXPERIMENTAL RESULTS

4.1 Laboratory Resilient Modulus Test Results

The soils consisted of eight types of granular subgrades. The T292-91I was used for all tests. During the resilient modulus test, specimen conditioning was conducted first. Then, a series of tests at different deviator stresses and confining pressures were performed, and the data were recorded for every cycle of the test. However, only the last five cycles were used for computation of resilient modulus. The resilient modulus ($M_r$) was calculated from the deviator stress and resilient strain using Equation (3-6).

Two resilient modulus tests were conducted for each moisture condition. The resilient modulus test results were reported in a tabular form including the deviator stress, axial strain, confining pressure, and bulk stress. A regression model was used to get the regression equation of $M_r$ from the confining pressure and bulk stress.

Typical resilient modulus test results on two samples for a soaked condition are summarized in Tables 4.1 and 4.2, and shown in Figures 4.1, 4.2, 4.3 and 4.4. The results included the confining pressure, deviator stress, bulk stress, axial strain, and their corresponding resilient modulus values. The resilient modulus test results for all materials are summarized and presented in Appendices E, F, G, H, I, J, K and L for the eight types of soils, respectively.

Please Note: In all of the regression equations in this study,
\[ M_r = k_1 \theta^{k_2} \]  
\[ M_r = k_3 \sigma_3^{k_4} \]  

The resilient modulus \( M_r \) is in units of MPa while the bulking stress \( \theta \) and the confining pressure \( \sigma_3 \) are in units of kPa.

4.1.1 Levy County A-3 soil with 4\% fines

The individual test results of the Levy County A-3 soil with 4\% fines are presented in detail in Appendix E. Seven samples were tested for resilient modulus. A summary of the regression models of \( M_r \) versus bulk stress is presented in Table 4.3 and shown in Figure 4.5. A summary of the regression models of \( M_r \) versus confining pressure is presented in Table 4.4 and illustrated in Figure 4.6. The effect of moisture on the resilient modulus was not significant.

4.1.2 SR-70 A-3 soil with 8\% fines

The individual test results of the SR-70 A-3 are presented in Appendix F. Eight samples were tested for resilient modulus. A summary of the regression models of \( M_r \) versus bulk stress is presented in Table 4.5 and demonstrated in Figure 4.7. A summary of the regression models of \( M_r \) versus confining pressure at different moisture contents is presented in Table 4.6 and illustrated in Figure 4.8. The moisture had a minor effect on the resilient modulus of SR70 A-3 soil.

4.1.3 A-2-4 soil with 12\% fines

The individual test results of the A-2-4 soil with 12\% fines are listed in Appendix G. Six samples were tested for resilient modulus. A summary of the regression models of \( M_r \) versus bulk stress at different
moisture contents is presented in Table 4.7 and illustrated in Figure 4.9. A summary of the regression models of \( M \), versus confining pressure at different moisture contents is presented in Table 4.8 and shown in Figure 4.10. The effect of moisture on the resilient modulus of A-2-4 soil with 12% fines was not very significant.

**4.1.4 SR-70 A-2-4 soil with 14% fines**

The test results of the SR-70 A-2-4 soil with 14% are listed in Appendix H. Six samples were tested for resilient modulus. A summary of the regression models of \( M \), versus bulk stress is presented in Table 4.9, and a summary of the regression models of \( M \), versus confining pressure is presented in Table 4.10. Figure 4.11 shows the \( M \), versus bulk stress at different moisture contents. Figure 4.12 shows the \( M \), versus confining pressure at different moisture contents. The moisture had a significant effect on the resilient modulus of SR-70 A-2-4 soil.

**4.1.5 A-2-4 soil with 20% fines**

The test results of the A-2-4 soil with 20% fines are listed in Appendix I. Six samples were tested. Table 4.11 presents a summary of the regression models of \( M \), versus bulk stress, and Table 4.12 presents a summary of the regression models of \( M \), versus confining pressure. Figure 4.13 shows the \( M \), versus bulk stress at different moisture contents. Figure 4.14 shows the \( M \), versus confining pressure at different moisture contents. The moisture has some effect on the resilient modulus of the A-2-4 soil with 20% fines.
4.1.6 A-2-4 soil with 24% fines

The test results of the A-2-4 soil with 24% fines are listed in Appendix J. Six samples were tested. Table 4.13 presents a summary of the regression models of $M$, versus bulk stress, and Table 4.14 presents a summary of the regression models of $M$, versus confining pressure. Figure 4.15 shows the $M$, versus bulk stress at different moisture contents. Figure 4.16 shows the $M$, versus confining pressure at different moisture contents. The moisture had some effect on the resilient modulus of the A-2-4 soil with 24% fines.

4.1.7 A-2-4 soil with 30% fines

The test results of the A-2-4 soil with 30% fines are listed in Appendix K. Totally, six samples were tested. Table 4.15 presents a summary of the regression models of $M$, versus bulk stress, and Table 4.16 presents a summary of the regression models of $M$, versus confining pressure. Figure 4.17 shows the $M$, versus bulk stress at different moisture contents. Figure 4.18 shows the $M$, versus confining pressure at different moisture contents. The effect of moisture on the resilient modulus was very significant.

4.1.8 Miami Oolite A-1 soil

Oolite of Miami is crushed in order to meet the laboratory requirement for resilient modulus test. The test results of Miami Oolite (A-1) soil are listed in Appendix L. Six samples were tested. Table 4.17 presents a summary of the regression models of $M$, versus bulk stress, and Table 4.18 presents a summary of the regression models of $M$, 

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versus confining pressure. Figure 4.19 shows the $M_r$ versus bulk stress at different moisture contents. Figure 4.20 shows the $M_r$ versus confining pressure at different moisture contents. The effect of moisture on the resilient modulus was very significant for the A-1 soil.

### 4.2 Soil Suction Test Results

The Figure 4.21 summarized the suction test results for the total eight soil types under different water contents. For each soil, there was a trend that when the moisture content increased, the suction value would decrease. The phenomena was agreed with the Soil-Water Characteristic Curve (SWCC), which defines the soil’s ability to store and release water.

For the two A-3 soils (Levy A-3 and SR-70 A-3), the suction value was small compared to A-2-4 soils. They were in range of 2 kPa to 60 kPa. The range of suction value for A-2-4 soils was from 30 kPa to 600 kPa around the optimum moisture content. This was because A-3 soils had little fines, so there was bigger pores in that soil. In A-2-4 soils, the more fines, the smaller pores. The smaller pores would contain and suck more water than bigger pores.

From the Figure 4.21, there was no much difference of the suction value change for these eight soils around the optimum moisture content. And the psychrometer method of measuring soil suction value would be more accurate on bigger values. So other test method would be better in this study for more accuracy such as filter paper test.
4.3 Permeability Test Results

All the permeability results were summarized in Table 4.19 and Figure 4.22. There obviously was a trend that with the increase of percent of fines, there was a decrease of the permeability. This result could be explained by size of pores in soils also. When there were more fines in the soil, the pore radius would be smaller, then made water more difficult to go through the pores.

The permeability results showed that the percent of fines was a good indicator of the permeability properties for soil.
Table 4.1 Sample Triaxial Test Results A-2-4 30% after Soaking (Sample # A2430%S2)

<table>
<thead>
<tr>
<th>Summary Resilient Modulus Test Result</th>
</tr>
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<tbody>
<tr>
<td><strong>Test Type:</strong> T292-91I</td>
</tr>
<tr>
<td><strong>Soil Identification</strong></td>
</tr>
<tr>
<td>Sample NdA2430%S2</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td><strong>Sample Number:</strong> A-2-4, 30% fine</td>
</tr>
<tr>
<td><strong>Lab. Moist.</strong></td>
</tr>
<tr>
<td>13.20% Opt. Moist. 12%</td>
</tr>
<tr>
<td><strong>Lab. Den.</strong></td>
</tr>
<tr>
<td>116 pcf Opt. Den. 115.7 pcf</td>
</tr>
<tr>
<td><strong>Conditioning Information</strong></td>
</tr>
<tr>
<td>Load Type: Dynamic</td>
</tr>
<tr>
<td>Dev. Stress: 82.74 kPa</td>
</tr>
<tr>
<td>Conf. Stress: 103.42 kPa</td>
</tr>
<tr>
<td>No. Reps.: 1000</td>
</tr>
</tbody>
</table>

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<thead>
<tr>
<th>Confining Pressure</th>
<th>Axial Load</th>
<th>Dev. Stress</th>
<th>Bulk Stress</th>
<th>Middle Strain</th>
<th>Full Length Strain</th>
<th>Middle Modulus</th>
<th>Full Length Modulus</th>
</tr>
</thead>
<tbody>
<tr>
<td>kPa</td>
<td>kN</td>
<td>kPa</td>
<td>kPa</td>
<td>MPa</td>
<td>Mpa</td>
<td></td>
<td></td>
</tr>
<tr>
<td>103.42</td>
<td>0.373</td>
<td>45.990</td>
<td>356.250</td>
<td>3.344E-05</td>
<td>0.000199</td>
<td>231.510</td>
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<td>0.00029</td>
<td>427.664</td>
<td>229.928</td>
</tr>
<tr>
<td>103.42</td>
<td>0.821</td>
<td>101.265</td>
<td>411.525</td>
<td>0.000324</td>
<td>0.00044</td>
<td>312.528</td>
<td>230.393</td>
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<td>32.237</td>
<td>239.087</td>
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<td>0.000193</td>
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<td>0.000281</td>
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<td>164.481</td>
</tr>
<tr>
<td>68.95</td>
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<td>0.000397</td>
<td>271.732</td>
<td>168.041</td>
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<tr>
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<td>101.199</td>
<td>308.049</td>
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<td>0.000594</td>
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<td>0.000612</td>
<td>161.353</td>
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</tr>
<tr>
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<td>0.150</td>
<td>18.477</td>
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Table 4.2 Sample Triaxial Test Results of SR-70 A-2-4 12% after Soaking (Sample # A24SR70S1)

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<th>Soil Identification</th>
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<td>Sample No. A24SR70S1</td>
<td>SR 70</td>
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<td>Moisture 11.23%</td>
<td>Opt. Moist. 10.60%</td>
</tr>
<tr>
<td>Lab. Den. 121.4 pcf</td>
<td>Opt. Den. 122.4 pcf</td>
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</table>

### Conditioning Information
- Load Type: Dynamic
- Dev. Stress: 82.74 kPa
- Conf. Stress: 103.42 kPa
- No. Reps.: 1000

<table>
<thead>
<tr>
<th>Confining Pressure</th>
<th>Axial Load</th>
<th>Dev. Stress</th>
<th>Bulk Stress</th>
<th>Middle Strain</th>
<th>Full Length Strain</th>
<th>Full Modulus</th>
<th>Middle Length Modulus</th>
</tr>
</thead>
<tbody>
<tr>
<td>kPa</td>
<td>kN</td>
<td>kPa</td>
<td>kPa</td>
<td>MPa</td>
<td>Mpa</td>
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<tr>
<td>103.42</td>
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<td>0.0001681</td>
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<td>0.0002424</td>
<td>320.088</td>
<td>275.847</td>
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<tr>
<td>103.42</td>
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</table>
Table 4.3 Resilient Modulus Test Results for Levy County A-3 4% (1)

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<th>Sample No.</th>
<th>Middle Half</th>
<th>Full Length</th>
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</thead>
<tbody>
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<td></td>
<td>$k_1$</td>
<td>$k_2$</td>
</tr>
<tr>
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<td>A3LEVYD1</td>
<td>31.2400</td>
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</tr>
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<td>4.30%</td>
<td>A3LEVYD2</td>
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<td>0.4316</td>
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<tr>
<td>9.50%</td>
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<td>0.4210</td>
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<tr>
<td>13.47%</td>
<td>A3LEVYS1</td>
<td>25.1780</td>
<td>0.4246</td>
</tr>
<tr>
<td>15.00%</td>
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</tr>
<tr>
<td>15.27%</td>
<td>A3LEVYS3</td>
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Table 4.4 Resilient Modulus Test Results for Levy County A-3 4\% (2)

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<tbody>
<tr>
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<td></td>
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<tr>
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<td>0.3262</td>
</tr>
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<tr>
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<td>A3LEVYO1</td>
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<td>0.3696</td>
</tr>
<tr>
<td>9.60%</td>
<td>A3LEVYO2</td>
<td>18.4610</td>
<td>0.3966</td>
</tr>
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<td>13.47%</td>
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<td>68.9590</td>
<td>0.4246</td>
</tr>
<tr>
<td>15.00%</td>
<td>A3LEVYS2</td>
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</tr>
<tr>
<td>15.27%</td>
<td>A3LEVYS3</td>
<td>56.9750</td>
<td>0.3884</td>
</tr>
<tr>
<td>Moisture Content</td>
<td>Sample No.</td>
<td>Middle Half</td>
<td>Full Length</td>
</tr>
<tr>
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<td>------------</td>
<td>-------------</td>
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</tr>
<tr>
<td></td>
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<td>$k_1$</td>
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</tr>
<tr>
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<td>Sample No.</td>
<td>Middle Half</td>
</tr>
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<td>-------------</td>
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<td>k₃</td>
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Table 4.7 Resilient Modulus Test Results for A-2-4 12% (1)

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<th>Middle Half</th>
<th>Full Length</th>
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</thead>
<tbody>
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<td></td>
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</tr>
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<td>A2412%D1</td>
<td>19.4130</td>
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</tr>
<tr>
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<td>A2412%D2</td>
<td>15.1390</td>
<td>0.5161</td>
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<td>A2412%O1</td>
<td>12.0340</td>
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<table>
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<th>k'₂</th>
<th>Formula ( y=\text{Mr}, x=\theta )</th>
<th>( R^2 )</th>
</tr>
</thead>
<tbody>
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<td>A2412%D1</td>
<td>7.0555</td>
<td>0.6066</td>
<td>( y=7.0555x^{0.6066} )</td>
<td>0.9924</td>
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<td>A2412%O1</td>
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<td>6.6733</td>
<td>0.6202</td>
<td>( y=6.6733x^{0.6202} )</td>
<td>0.9700</td>
</tr>
<tr>
<td>14.6%</td>
<td>A2412%S1</td>
<td>7.4721</td>
<td>0.5740</td>
<td>( y=7.4721x^{0.5740} )</td>
<td>0.9931</td>
</tr>
<tr>
<td>13.6%</td>
<td>A2412%S2</td>
<td>6.7001</td>
<td>0.6053</td>
<td>( y=6.7001x^{0.6053} )</td>
<td>0.9961</td>
</tr>
</tbody>
</table>
Table 4.8 Resilient Modulus Test Results for A-2-4 12\% (2)

<table>
<thead>
<tr>
<th>Moisture Content</th>
<th>Sample No.</th>
<th>Middle Half</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>k₃</td>
</tr>
<tr>
<td>7.1%</td>
<td>A2412%D1</td>
<td>49.1900</td>
</tr>
<tr>
<td>7.0%</td>
<td>A2412%D2</td>
<td>43.8560</td>
</tr>
<tr>
<td>12.1%</td>
<td>A2412%O1</td>
<td>35.5150</td>
</tr>
<tr>
<td>12.1%</td>
<td>A2412%O2</td>
<td>30.0830</td>
</tr>
<tr>
<td>14.6%</td>
<td>A2412%S1</td>
<td>29.2350</td>
</tr>
<tr>
<td>13.6%</td>
<td>A2412%S2</td>
<td>34.795</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Moisture Content</th>
<th>Sample No.</th>
<th>Full Length</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>k'₃</td>
</tr>
<tr>
<td>7.1%</td>
<td>A2412%D1</td>
<td>26.0570</td>
</tr>
<tr>
<td>7.0%</td>
<td>A2412%D2</td>
<td>21.594</td>
</tr>
<tr>
<td>12.1%</td>
<td>A2412%O1</td>
<td>21.7620</td>
</tr>
<tr>
<td>12.1%</td>
<td>A2412%O2</td>
<td>21.1340</td>
</tr>
<tr>
<td>14.6%</td>
<td>A2412%S1</td>
<td>24.5660</td>
</tr>
<tr>
<td>13.6%</td>
<td>A2412%S2</td>
<td>23.6990</td>
</tr>
</tbody>
</table>
Table 4.9 Resilient Modulus Test Results for SR70 A-2-4 (1)

<table>
<thead>
<tr>
<th>Moisture Content</th>
<th>Sample No.</th>
<th>k_1</th>
<th>k_2</th>
<th>Formula ((y=Mr, x=\theta))</th>
<th>(R^2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>8.41%</td>
<td>A24SR70D1</td>
<td>427.8900</td>
<td>0.0540</td>
<td>(y=427.89x^{0.054})</td>
<td>0.1721</td>
</tr>
<tr>
<td>7.76%</td>
<td>A24SR70D2</td>
<td>1211.8000</td>
<td>-0.1032</td>
<td>(y=1211.8x^{-0.1032})</td>
<td>0.1929</td>
</tr>
<tr>
<td>10.80%</td>
<td>A24SR70O1</td>
<td>132.9400</td>
<td>0.1698</td>
<td>(y=132.94x^{0.1698})</td>
<td>0.3393</td>
</tr>
<tr>
<td>10.39%</td>
<td>A24SR70O2</td>
<td>65.1530</td>
<td>0.2769</td>
<td>(y=65.153x^{0.2769})</td>
<td>0.6244</td>
</tr>
<tr>
<td>11.23%</td>
<td>A24SR70S1</td>
<td>24.8220</td>
<td>0.4310</td>
<td>(y=24.822x^{0.431})</td>
<td>0.877</td>
</tr>
<tr>
<td>11.70%</td>
<td>A24SR70S2</td>
<td>31.5620</td>
<td>0.4321</td>
<td>(y=31.562x^{0.4321})</td>
<td>0.4503</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Moisture Content</th>
<th>Sample No.</th>
<th>k'_1</th>
<th>k'_2</th>
<th>Formula ((y=Mr, x=\theta))</th>
<th>(R^2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>8.41%</td>
<td>A24SR70D1</td>
<td>57.4670</td>
<td>0.3861</td>
<td>(y=57.467x^{0.3861})</td>
<td>0.9121</td>
</tr>
<tr>
<td>7.76%</td>
<td>A24SR70D2</td>
<td>1.9460</td>
<td>0.9431</td>
<td>(y=1.946x^{0.9431})</td>
<td>0.9922</td>
</tr>
<tr>
<td>10.80%</td>
<td>A24SR70O1</td>
<td>42.3150</td>
<td>0.3332</td>
<td>(y=19.852x^{0.4414})</td>
<td>0.8241</td>
</tr>
<tr>
<td>10.39%</td>
<td>A24SR70O2</td>
<td>24.9300</td>
<td>0.4210</td>
<td>(y=24.930x^{0.4210})</td>
<td>0.8487</td>
</tr>
<tr>
<td>11.23%</td>
<td>A24SR70S1</td>
<td>9.6913</td>
<td>0.5608</td>
<td>(y=9.6913x^{0.5608})</td>
<td>0.932</td>
</tr>
<tr>
<td>11.70%</td>
<td>A24SR70S2</td>
<td>5.4516</td>
<td>0.6335</td>
<td>(y=5.4052x^{0.6335})</td>
<td>0.9716</td>
</tr>
<tr>
<td>Moisture Content</td>
<td>Sample No.</td>
<td>k_3</td>
<td>k_4</td>
<td>Formula (y=Mr, x=σ_3)</td>
<td>R^2</td>
</tr>
<tr>
<td>------------------</td>
<td>------------</td>
<td>-----</td>
<td>-----</td>
<td>-----------------------</td>
<td>-----</td>
</tr>
<tr>
<td><strong>Middle Half</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>8.41%</td>
<td>A24SR70D1</td>
<td>451.9800</td>
<td>0.0607</td>
<td>y=451.98x^{0.0607}</td>
<td>0.9849</td>
</tr>
<tr>
<td>7.76%</td>
<td>A24SR70D2</td>
<td>884.4900</td>
<td>-0.0571</td>
<td>y=884.49x^{0.0571}</td>
<td>0.8558</td>
</tr>
<tr>
<td>10.80%</td>
<td>A24SR70O1</td>
<td>171.5100</td>
<td>0.1698</td>
<td>y=39.914x^{0.439}</td>
<td>0.9311</td>
</tr>
<tr>
<td>10.39%</td>
<td>A24SR70O2</td>
<td>104.8700</td>
<td>0.2578</td>
<td>y=104.87x^{0.2578}</td>
<td>0.9937</td>
</tr>
<tr>
<td>11.23%</td>
<td>A24SR70S1</td>
<td>55.6000</td>
<td>0.3807</td>
<td>y=55.6x^{0.3807}</td>
<td>0.9994</td>
</tr>
<tr>
<td>11.70%</td>
<td>A24SR70S2</td>
<td>63.7580</td>
<td>0.4172</td>
<td>y=63.758x^{0.4172}</td>
<td>0.9996</td>
</tr>
<tr>
<td><strong>Full Length</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>8.41%</td>
<td>A24SR70D1</td>
<td>120.0400</td>
<td>0.3369</td>
<td>y=120.04x^{0.3369}</td>
<td>0.9978</td>
</tr>
<tr>
<td>7.76%</td>
<td>A24SR70D2</td>
<td>14.031</td>
<td>0.7789</td>
<td>y=14.031x^{0.7789}</td>
<td>0.9964</td>
</tr>
<tr>
<td>10.80%</td>
<td>A24SR70O1</td>
<td>78.6520</td>
<td>0.2962</td>
<td>y=45.686x^{0.3888}</td>
<td>0.9969</td>
</tr>
<tr>
<td>10.39%</td>
<td>A24SR70O2</td>
<td>54.9130</td>
<td>0.3727</td>
<td>y=54.913x^{0.3727}</td>
<td>0.9959</td>
</tr>
<tr>
<td>11.23%</td>
<td>A24SR70S1</td>
<td>28.5950</td>
<td>0.4870</td>
<td>y=28.595x^{0.487}</td>
<td>0.9998</td>
</tr>
<tr>
<td>11.70%</td>
<td>A24SR70S2</td>
<td>19.5280</td>
<td>0.5366</td>
<td>y=19.528x^{0.5366}</td>
<td>0.9936</td>
</tr>
</tbody>
</table>
Table 4.11 Resilient Modulus Test Results for A-2-4 20% (1)

| Moisture Content | Sample No.  | Middle Half |  | Full Length |  |
|------------------|-------------|-------------|-----------------|-----------------|
|                  |             | k<sub>1</sub> | k<sub>2</sub> | Formula (y=Mr, x= θ ) | R<sup>2</sup> |
| 8.3%             | A2420%D1    | 54.1420     | 0.3077          | y=54.142x<sup>0.3077</sup> | 0.9395 |
| 7.3%             | A2420%D2    | 45.1320     | 0.3647          | y=45.132x<sup>0.3647</sup> | 0.8629 |
| 10.0%            | A2420%O1    | 12.2060     | 0.5459          | y=12.206x<sup>0.5459</sup> | 0.9793 |
| 10.0%            | A2420%O2    | 10.397      | 0.5586          | y=10.397x<sup>0.5586</sup> | 0.9830 |
| 11.6%            | A2420%S1    | 13.8160     | 0.5163          | y=13.816x<sup>0.5163</sup> | 0.9749 |
| 12.3%            | A2420%S2    | 10.0030     | 0.5621          | y=10.003x<sup>0.5621</sup> | 0.9845 |

<table>
<thead>
<tr>
<th>Moisture Content</th>
<th>Sample No.</th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>k&lt;sub&gt;1&lt;/sub&gt;'</td>
<td>k&lt;sub&gt;2&lt;/sub&gt;'</td>
<td>Formula (y=Mr, x= θ )</td>
<td>R&lt;sup&gt;2&lt;/sup&gt;</td>
</tr>
<tr>
<td>8.3%</td>
<td>A2420%D1</td>
<td>11.0210</td>
<td>0.5807</td>
<td>y=11.021x&lt;sup&gt;0.5807&lt;/sup&gt;</td>
<td>0.9771</td>
</tr>
<tr>
<td>7.3%</td>
<td>A2420%D2</td>
<td>11.5170</td>
<td>0.5914</td>
<td>y=11.517x&lt;sup&gt;0.5914&lt;/sup&gt;</td>
<td>0.9612</td>
</tr>
<tr>
<td>10.0%</td>
<td>A2420%O1</td>
<td>7.7395</td>
<td>0.6080</td>
<td>y=7.7395x&lt;sup&gt;0.6080&lt;/sup&gt;</td>
<td>0.9881</td>
</tr>
<tr>
<td>10.0%</td>
<td>A2420%O2</td>
<td>6.5854</td>
<td>0.6529</td>
<td>y=6.5854x&lt;sup&gt;0.6529&lt;/sup&gt;</td>
<td>0.9867</td>
</tr>
<tr>
<td>11.6%</td>
<td>A2420%S1</td>
<td>7.8573</td>
<td>0.5907</td>
<td>y=7.8573x&lt;sup&gt;0.5907&lt;/sup&gt;</td>
<td>0.9825</td>
</tr>
<tr>
<td>12.3%</td>
<td>A2420%S2</td>
<td>6.9320</td>
<td>0.6137</td>
<td>y=6.9320x&lt;sup&gt;0.6137&lt;/sup&gt;</td>
<td>0.9893</td>
</tr>
</tbody>
</table>
### Table 4.12 Resilient Modulus Test Results for A-2-4 20% (2)

<table>
<thead>
<tr>
<th>Moisture Content</th>
<th>Sample No.</th>
<th>Middle Half</th>
<th>Full Length</th>
</tr>
</thead>
<tbody>
<tr>
<td>Moisture Content</td>
<td>Sample No.</td>
<td>Middle Half</td>
<td>Full Length</td>
</tr>
<tr>
<td>Moisture Content</td>
<td>Sample No.</td>
<td>k&lt;sub&gt;3&lt;/sub&gt;</td>
<td>k&lt;sub&gt;4&lt;/sub&gt;</td>
</tr>
<tr>
<td>8.3% A2420%D1</td>
<td>99.0040</td>
<td>0.2652</td>
<td>y=99.004x&lt;sup&gt;0.2652&lt;/sup&gt;</td>
</tr>
<tr>
<td>7.3% A2420%D2</td>
<td>89.7970</td>
<td>0.3218</td>
<td>y=89.797x&lt;sup&gt;0.3218&lt;/sup&gt;</td>
</tr>
<tr>
<td>10.0% A2420%O1</td>
<td>38.2730</td>
<td>0.4519</td>
<td>y=38.273x&lt;sup&gt;0.4519&lt;/sup&gt;</td>
</tr>
<tr>
<td>10.0% A2420%O2</td>
<td>34.2940</td>
<td>0.4928</td>
<td>y=34.294x&lt;sup&gt;0.4928&lt;/sup&gt;</td>
</tr>
<tr>
<td>11.6% A2420%S1</td>
<td>39.2840</td>
<td>0.4361</td>
<td>y=39.284x&lt;sup&gt;0.4361&lt;/sup&gt;</td>
</tr>
<tr>
<td>12.3% A2420%S2</td>
<td>31.8970</td>
<td>0.4694</td>
<td>y=31.897x&lt;sup&gt;0.4694&lt;/sup&gt;</td>
</tr>
</tbody>
</table>
Table 4.13 Resilient Modulus Test Results for A-2-4 24% (1)

<table>
<thead>
<tr>
<th>Moisture Content</th>
<th>Sample No.</th>
<th>Middle Half</th>
<th>Full Length</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>$k_1$</td>
<td>$k_2$</td>
</tr>
<tr>
<td>7.72%</td>
<td>A2424%D1</td>
<td>16.7250</td>
<td>0.4530</td>
</tr>
<tr>
<td>7.65%</td>
<td>A2424%D2</td>
<td>18.7130</td>
<td>0.4522</td>
</tr>
<tr>
<td>10.70%</td>
<td>A2424%O1</td>
<td>21.5070</td>
<td>0.3889</td>
</tr>
<tr>
<td>10.70%</td>
<td>A2424%O2</td>
<td>15.5120</td>
<td>0.4671</td>
</tr>
<tr>
<td>12.00%</td>
<td>A2424%S1</td>
<td>4.9754</td>
<td>0.6255</td>
</tr>
<tr>
<td>12.00%</td>
<td>A2424%S2</td>
<td>8.2687</td>
<td>0.6080</td>
</tr>
</tbody>
</table>
Table 4.14 Resilient Modulus Test Results for A-2-4 24% (2)

<table>
<thead>
<tr>
<th>Moisture Content</th>
<th>Sample No.</th>
<th>Sample No.</th>
<th>Middle Half</th>
<th>Full Length</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Formula ($y=\text{Mr}, x=\sigma_3$)</td>
<td>$R^2$</td>
</tr>
<tr>
<td><strong>Moisture</strong></td>
<td><strong>Sample No.</strong></td>
<td><strong>k</strong></td>
<td><strong>$k_4$</strong></td>
<td><strong>R^2</strong></td>
</tr>
<tr>
<td><strong>Content</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>7.72%</td>
<td>A2424%D1</td>
<td>41.4400</td>
<td>0.3859</td>
<td>y=41.44$x^{0.3859}$</td>
</tr>
<tr>
<td>7.65%</td>
<td>A2424%D2</td>
<td>45.9930</td>
<td>0.3865</td>
<td>y=45.993$x^{0.3865}$</td>
</tr>
<tr>
<td>10.70%</td>
<td>A2424%O1</td>
<td>47.0930</td>
<td>0.3291</td>
<td>y=47.093$x^{0.3291}$</td>
</tr>
<tr>
<td>10.70%</td>
<td>A2424%O2</td>
<td>38.8840</td>
<td>0.4017</td>
<td>y=38.884$x^{0.4017}$</td>
</tr>
<tr>
<td>12.00%</td>
<td>A2424%S1</td>
<td>17.5770</td>
<td>0.5290</td>
<td>y=17.577$x^{0.529}$</td>
</tr>
<tr>
<td>11.40%</td>
<td>A2424%S2</td>
<td>25.5980</td>
<td>0.5399</td>
<td>y=25.598$x^{0.5399}$</td>
</tr>
</tbody>
</table>

| **Moisture**     | **Sample No.** | **k'_3** | **k'_4** | **Formula ($y=\text{Mr}, x=\sigma_3$) | **R^2** |
| **Content**      |             |             |             |             |             |
| 7.72%            | A2424%D1    | 31.0020     | 0.4415      | y=31.002$x^{0.4415}$ | 0.9901 |
| 7.65%            | A2424%D2    | 36.8590     | 0.4196      | y=36.859$x^{0.4196}$ | 0.9935 |
| 10.70%           | A2424%O1    | 26.6810     | 0.4528      | y=26.681$x^{0.4528}$ | 0.997 |
| 10.70%           | A2424%O2    | 23.7020     | 0.5039      | y=23.702$x^{0.5039}$ | 0.9859 |
| 12.00%           | A2424%S1    | 14.2170     | 0.5319      | y=14.217$x^{0.5319}$ | 0.994 |
| 11.40%           | A2424%S2    | 15.9130     | 0.5977      | y=15.913$x^{0.5977}$ | 0.9804 |
Table 4.15 Resilient Modulus Test Results for A-2-4 30% (1)

<table>
<thead>
<tr>
<th>Moisture Content</th>
<th>Sample No.</th>
<th>k&lt;sub&gt;1&lt;/sub&gt;</th>
<th>k&lt;sub&gt;2&lt;/sub&gt;</th>
<th>Formula (y = Mr, x = θ)</th>
<th>R&lt;sup&gt;2&lt;/sup&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td>6.30%</td>
<td>A2430%D1</td>
<td>596.33</td>
<td>0.0647</td>
<td>y = 596.33x&lt;sup&gt;0.0647&lt;/sup&gt;</td>
<td>0.0379</td>
</tr>
<tr>
<td>7.00%</td>
<td>A2430%D2</td>
<td>540.26</td>
<td>0.0793</td>
<td>y = 540.26x&lt;sup&gt;0.0793&lt;/sup&gt;</td>
<td>0.0564</td>
</tr>
<tr>
<td>12.00%</td>
<td>A2430%O1</td>
<td>10.877</td>
<td>0.5973</td>
<td>y = 10.877x&lt;sup&gt;0.5973&lt;/sup&gt;</td>
<td>0.3938</td>
</tr>
<tr>
<td>12.30%</td>
<td>A2430%O2</td>
<td>9.9673</td>
<td>0.5778</td>
<td>y = 9.9673x&lt;sup&gt;0.5778&lt;/sup&gt;</td>
<td>0.4464</td>
</tr>
<tr>
<td>13.40%</td>
<td>A2430%S1</td>
<td>12.556</td>
<td>0.5469</td>
<td>y = 12.556x&lt;sup&gt;0.5469&lt;/sup&gt;</td>
<td>0.712</td>
</tr>
<tr>
<td>13.20%</td>
<td>A2430%S2</td>
<td>13.122</td>
<td>0.5448</td>
<td>y = 13.122x&lt;sup&gt;0.5448&lt;/sup&gt;</td>
<td>0.6345</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Moisture Content</th>
<th>Sample No.</th>
<th>k'&lt;sub&gt;1&lt;/sub&gt;</th>
<th>k'&lt;sub&gt;2&lt;/sub&gt;</th>
<th>Formula (y = Mr, x = θ)</th>
<th>R&lt;sup&gt;2&lt;/sup&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td>6.30%</td>
<td>A2430%D1</td>
<td>19.176</td>
<td>0.6226</td>
<td>y = 19.176x&lt;sup&gt;0.6226&lt;/sup&gt;</td>
<td>0.9343</td>
</tr>
<tr>
<td>7.00%</td>
<td>A2430%D2</td>
<td>21.326</td>
<td>0.6001</td>
<td>y = 21.326x&lt;sup&gt;0.6001&lt;/sup&gt;</td>
<td>0.9418</td>
</tr>
<tr>
<td>12.00%</td>
<td>A2430%O1</td>
<td>3.3241</td>
<td>0.7184</td>
<td>y = 3.3241x&lt;sup&gt;0.7184&lt;/sup&gt;</td>
<td>0.9353</td>
</tr>
<tr>
<td>12.30%</td>
<td>A2430%O2</td>
<td>3.2058</td>
<td>0.7096</td>
<td>y = 3.2058x&lt;sup&gt;0.7096&lt;/sup&gt;</td>
<td>0.9459</td>
</tr>
<tr>
<td>13.40%</td>
<td>A2430%S1</td>
<td>2.7408</td>
<td>0.7601</td>
<td>y = 2.7408x&lt;sup&gt;0.7601&lt;/sup&gt;</td>
<td>0.9590</td>
</tr>
<tr>
<td>13.20%</td>
<td>A2430%S2</td>
<td>3.2634</td>
<td>0.7073</td>
<td>y = 3.2634x&lt;sup&gt;0.7073&lt;/sup&gt;</td>
<td>0.9681</td>
</tr>
</tbody>
</table>
Table 4.16 Resilient Modulus Test Results for A-2-4 30% (2)

<table>
<thead>
<tr>
<th>Moisture Content</th>
<th>Sample No.</th>
<th>k&lt;sub&gt;3&lt;/sub&gt;</th>
<th>k&lt;sub&gt;4&lt;/sub&gt;</th>
<th>Formula (y=Mr, x=σ&lt;sub&gt;1&lt;/sub&gt;)</th>
<th>R&lt;sup&gt;2&lt;/sup&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td>Middle Half</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6.30%</td>
<td>A2430%D1</td>
<td>578.4</td>
<td>0.1012</td>
<td>y=578.4x&lt;sup&gt;0.1012&lt;/sup&gt;</td>
<td>0.8096</td>
</tr>
<tr>
<td>7.00%</td>
<td>A2430%D2</td>
<td>537.35</td>
<td>0.1142</td>
<td>y=537.35x&lt;sup&gt;0.1142&lt;/sup&gt;</td>
<td>0.8753</td>
</tr>
<tr>
<td>12.00%</td>
<td>A2430%O1</td>
<td>27.255</td>
<td>0.6002</td>
<td>y=27.255x&lt;sup&gt;0.6002&lt;/sup&gt;</td>
<td>0.9982</td>
</tr>
<tr>
<td>12.30%</td>
<td>A2430%O2</td>
<td>25.023</td>
<td>0.5683</td>
<td>y=25.023x&lt;sup&gt;0.5683&lt;/sup&gt;</td>
<td>0.9932</td>
</tr>
<tr>
<td>13.40%</td>
<td>A2430%S1</td>
<td>33.301</td>
<td>0.5059</td>
<td>y=33.301x&lt;sup&gt;0.5059&lt;/sup&gt;</td>
<td>0.993</td>
</tr>
<tr>
<td>13.20%</td>
<td>A2430%S2</td>
<td>34.09</td>
<td>0.5106</td>
<td>y=34.09x&lt;sup&gt;0.5106&lt;/sup&gt;</td>
<td>0.9944</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Moisture Content</th>
<th>Sample No.</th>
<th>k'&lt;sub&gt;3&lt;/sub&gt;</th>
<th>k'&lt;sub&gt;4&lt;/sub&gt;</th>
<th>Formula (y=Mr, x=σ&lt;sub&gt;1&lt;/sub&gt;)</th>
<th>R&lt;sup&gt;2&lt;/sup&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td>Full Length</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6.30%</td>
<td>A2430%D1</td>
<td>64.499</td>
<td>0.5363</td>
<td>y=64.499x&lt;sup&gt;0.5363&lt;/sup&gt;</td>
<td>0.9942</td>
</tr>
<tr>
<td>7.00%</td>
<td>A2430%D2</td>
<td>68.457</td>
<td>0.5188</td>
<td>y=68.457x&lt;sup&gt;0.5188&lt;/sup&gt;</td>
<td>0.9996</td>
</tr>
<tr>
<td>12.00%</td>
<td>A2430%O1</td>
<td>13.503</td>
<td>0.6208</td>
<td>y=13.503x&lt;sup&gt;0.6208&lt;/sup&gt;</td>
<td>0.9943</td>
</tr>
<tr>
<td>12.30%</td>
<td>A2430%O2</td>
<td>12.879</td>
<td>0.6112</td>
<td>y=12.879x&lt;sup&gt;0.6112&lt;/sup&gt;</td>
<td>0.9965</td>
</tr>
<tr>
<td>13.40%</td>
<td>A2430%S1</td>
<td>12.42</td>
<td>0.6492</td>
<td>y=12.42x&lt;sup&gt;0.6492&lt;/sup&gt;</td>
<td>0.9941</td>
</tr>
<tr>
<td>13.20%</td>
<td>A2430%S2</td>
<td>13.528</td>
<td>0.6004</td>
<td>y=13.528x&lt;sup&gt;0.6004&lt;/sup&gt;</td>
<td>0.989</td>
</tr>
<tr>
<td>Moisture Content</td>
<td>Sample No.</td>
<td>Middle Half</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>------------------</td>
<td>------------</td>
<td>-------------</td>
<td>----</td>
<td>----</td>
<td>----</td>
</tr>
<tr>
<td></td>
<td></td>
<td>k₁</td>
<td>k₂</td>
<td>Formula (y=Mr, x= θ)</td>
<td>R²</td>
</tr>
<tr>
<td>5.60%</td>
<td>OOLITED1</td>
<td>24.9270</td>
<td>0.5514</td>
<td>y=24.927x⁰.⁵⁵¹⁴</td>
<td>0.9343</td>
</tr>
<tr>
<td>4.40%</td>
<td>OOLITED2</td>
<td>34.2920</td>
<td>0.5020</td>
<td>y=34.292x⁰.⁵⁰²</td>
<td>0.8909</td>
</tr>
<tr>
<td>7.80%</td>
<td>OOLITEO1</td>
<td>5.0349</td>
<td>0.7568</td>
<td>y=5.0349x⁰.⁷⁵⁶⁸</td>
<td>0.9182</td>
</tr>
<tr>
<td>7.80%</td>
<td>OOLITEO2</td>
<td>5.9633</td>
<td>0.7204</td>
<td>y=5.9633x⁰.⁷²⁰⁴</td>
<td>0.9199</td>
</tr>
<tr>
<td>8.20%</td>
<td>OOLITES1</td>
<td>1.6414</td>
<td>0.8946</td>
<td>y=1.6414x⁰.⁸⁹⁴⁶</td>
<td>0.9429</td>
</tr>
<tr>
<td>8%</td>
<td>OOLITES2</td>
<td>3.8590</td>
<td>0.7655</td>
<td>y=3.859x⁰.⁷⁶⁵⁵</td>
<td>0.9588</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Moisture Content</td>
<td>Sample No.</td>
<td>Full Length</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>k'₁</td>
<td>k'₂</td>
<td>Formula (y=Mr, x= θ)</td>
<td>R²</td>
</tr>
<tr>
<td>5.60%</td>
<td>OOLITED1</td>
<td>4.9032</td>
<td>0.7596</td>
<td>y=4.9032x⁰.⁷⁵⁹⁶</td>
<td>0.9807</td>
</tr>
<tr>
<td>4.40%</td>
<td>OOLITED2</td>
<td>9.9158</td>
<td>0.5774</td>
<td>y=9.9158x⁰.⁵⁷⁷⁴</td>
<td>0.9637</td>
</tr>
<tr>
<td>7.80%</td>
<td>OOLITEO1</td>
<td>3.0146</td>
<td>0.8194</td>
<td>y=3.0146x⁰.⁸₁⁹⁴</td>
<td>0.9552</td>
</tr>
<tr>
<td>7.80%</td>
<td>OOLITEO2</td>
<td>3.5722</td>
<td>0.7921</td>
<td>y=3.5722x⁰.⁷⁹²¹</td>
<td>0.9545</td>
</tr>
<tr>
<td>8.20%</td>
<td>OOLITES1</td>
<td>0.9275</td>
<td>0.9888</td>
<td>y=0.9275x⁰.⁹₈₈₈</td>
<td>0.9728</td>
</tr>
<tr>
<td>8%</td>
<td>OOLITES2</td>
<td>2.4621</td>
<td>0.8330</td>
<td>y=2.4621x⁰.⁸₃₃</td>
<td>0.9593</td>
</tr>
</tbody>
</table>
Table 4.18 Resilient Modulus Test Results for A-1 Oolite (2)

<table>
<thead>
<tr>
<th>Moisture Content</th>
<th>Sample No.</th>
<th>$k_3$</th>
<th>$k_4$</th>
<th>Formula (y=\text{Mr}, x=\sigma_3)</th>
<th>(R^2)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Middle Half</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5.60%</td>
<td>OOLITED1</td>
<td>75.8540</td>
<td>0.4682</td>
<td>(y=75.854x^{0.4682})</td>
<td>0.9653</td>
</tr>
<tr>
<td>4.40%</td>
<td>OOLITED2</td>
<td>90.4880</td>
<td>0.4371</td>
<td>(y=90.488x^{0.4371})</td>
<td>0.9739</td>
</tr>
<tr>
<td>7.80%</td>
<td>OOLITEO1</td>
<td>24.0410</td>
<td>0.6205</td>
<td>(y=24.041x^{0.6205})</td>
<td>0.9254</td>
</tr>
<tr>
<td>7.80%</td>
<td>OOLITEO2</td>
<td>27.3050</td>
<td>0.5951</td>
<td>(y=27.3050x^{0.5951})</td>
<td>0.9269</td>
</tr>
<tr>
<td>8.20%</td>
<td>OOLITES1</td>
<td>10.9870</td>
<td>0.7349</td>
<td>(y=678.53x^{0.0469})</td>
<td>0.9429</td>
</tr>
<tr>
<td>8%</td>
<td>OOLITES2</td>
<td>18.3600</td>
<td>0.6454</td>
<td>(y=18.36x^{0.6454})</td>
<td>0.9759</td>
</tr>
<tr>
<td><strong>Full Length</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5.60%</td>
<td>OOLITED1</td>
<td>23.4790</td>
<td>0.6349</td>
<td>(y=23.479x^{0.6349})</td>
<td>0.9872</td>
</tr>
<tr>
<td>4.40%</td>
<td>OOLITED2</td>
<td>38.8570</td>
<td>0.5740</td>
<td>(y=38.857x^{0.574})</td>
<td>0.9870</td>
</tr>
<tr>
<td>7.80%</td>
<td>OOLITEO1</td>
<td>16.4290</td>
<td>0.6842</td>
<td>(y=16.429x^{0.6842})</td>
<td>0.9642</td>
</tr>
<tr>
<td>7.80%</td>
<td>OOLITEO2</td>
<td>18.6200</td>
<td>0.6585</td>
<td>(y=18.62x^{0.6585})</td>
<td>0.9603</td>
</tr>
<tr>
<td>8.20%</td>
<td>OOLITES1</td>
<td>7.3804</td>
<td>0.8180</td>
<td>(y=7.3804x^{0.818})</td>
<td>0.971</td>
</tr>
<tr>
<td>8%</td>
<td>OOLITES2</td>
<td>13.3310</td>
<td>0.7043</td>
<td>(y=13.331x^{0.7043})</td>
<td>0.9784</td>
</tr>
</tbody>
</table>
Table 4.19 Permeability Values for 8 Soils

<table>
<thead>
<tr>
<th>Soil Type</th>
<th>Percent of Passing #200 sieve</th>
<th>Permeability (cm/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Levy A-3</td>
<td>4%</td>
<td>5.52*10^-3</td>
</tr>
<tr>
<td>SR-70 A-3</td>
<td>8%</td>
<td>2.06*10^-3</td>
</tr>
<tr>
<td>A-2-4 (12%)</td>
<td>12%</td>
<td>3.05*10^-4</td>
</tr>
<tr>
<td>SR-70 A-2-4</td>
<td>14%</td>
<td>2.5*10^-4</td>
</tr>
<tr>
<td>A-2-4 (20%)</td>
<td>20%</td>
<td>1.04*10^-4</td>
</tr>
<tr>
<td>A-2-4 (24%)</td>
<td>24%</td>
<td>6.50*10^-5</td>
</tr>
<tr>
<td>A-2-4 (30%)</td>
<td>30%</td>
<td>2.01*10^-5</td>
</tr>
</tbody>
</table>
Figure 4.1 Sample Resilient Modulus versus bulk stress for A-2-4 30% after soaking (Sample # A2430%S2)

Figure 4.2 Sample Resilient Modulus versus confining stress for A-2-4 30% after soaking (Sample # A2430%S2)
Figure 4.3 Sample Resilient Modulus versus bulk stress for SR70 A-2-4 after soaking (Sample # A24SR70S1)

Figure 4.4 Sample Resilient Modulus versus confining stress for SR70 A-2-4 after soaking (Sample # A24SR70S1)
Figure 4.5 Mr vs. Bulk Stress for Levy County A-3 at Different Moisture Contents

Figure 4.6 Mr vs. Confining Pressure of Levy County A-3 at Different Moisture Contents
Figure 4.7 Mr vs. Bulk Stress at Different Moisture Contents of SR70 A-3

Figure 4.8 Mr vs. Confining Pressure at Different Moisture Contents of SR70 A-3
Figure 4.9 Mr vs. Bulk Stress at Different Moisture Contents of A-2-4, 12%

Figure 4.10 Mr vs. Confining Pressure at Different Moisture Contents of A-2-4, 12%
Figure 4.11 Mr vs. Bulk Stress at Different Moisture Contents of SR70 A-2-4

Figure 4.12 Mr vs. Bulk Stress at Different Moisture Contents of SR70 A-2-4
Figure 4.13 Mr vs. Bulk Stress at Different Moisture Contents of A-2-4 20%

Figure 4.14 Mr vs. Confining Stress at Different Moisture Contents of A-2-4 20%
Figure 4.15 Mr vs. Bulk Stress at Different Moisture Contents of A-2-4

24%

Figure 4.16 Mr vs. Confining Pressure Different Moisture Contents of A-2-4 24%
Figure 4.17 Mr vs. Bulk Stress at Different Moisture Contents of A-2-4 30%

Figure 4.18 Mr vs. Confining Pressure at Different Moisture Contents of A-2-4 30%
Figure 4.19 Mr vs. Bulk Stress at Different Moisture Contents of Oolite, Miami

Figure 4.20 Mr vs. Bulk Stress at Different Moisture Contents of Oolite, Miami
Soil Suction vs. Water Content

Figure 4.21 Suction Value for Each Soil at Different Moisture Content

Permeability vs. %fines

Figure 4.22 Permeability vs. Percentage of Fines for 8 Soil Types
CHAPTER 5 PRESENTATION OF TEST-PIT EXPERIMENTAL RESULTS

5.1 Test-pit Experimental Results

Eight types of soil representing Florida subgrade materials were tested in the test-pit within a period of 27 months. The experimental program can be grouped into eight phases with each one focusing on one soil type. For each soil, static and cyclic (30,000 cycles for simulation of the dynamic effect) plate load tests were conducted under different water table levels. Since the resilient behavior of subgrade soil under the dynamic loading was influenced by the soil properties as well as moisture conditions, a detailed evaluation was made of the moisture profile under different ground water levels. The test-pit experimental results were presented in reference to different ground water table levels.

5.1.1 Phase I: Levy County A-3 Soil

A series of plate load tests were conducted at each time when the moisture equilibrium was achieved for Levy County A-3 soil after adjusting the water table level. The designated test numbers and their corresponding loading conditions for phase I are shown below:
One of the main purposes of this study was to evaluate the influence of different water table levels on the deformation and resilient modulus of tested subgrade soils. To correlate the moisture profile as a result of water level adjustment with the resilient behavior of the tested subgrade soil, an accurate moisture profile was obtained of the subgrade soil under the plate load test. All volumetric water content measured through the TDR probe was converted into gravimetric water content according to Equation (B-1) (refer to Appendix B). The dry unit weight ($\gamma_d$) of each layer of the subgrade soil was measured when the soil was initially compacted in the test pit. Thus, the dry unit weight ($\gamma_d$) of the subgrade at a corresponding elevation for the TDR probe was approximated during the experiment. A linear

<table>
<thead>
<tr>
<th>Water Table (inch)</th>
<th>Test Number</th>
<th>Plate Load (psi)</th>
<th>5-inch Base Layer (Limerock)</th>
<th>Test Date Mo./Day/Year</th>
</tr>
</thead>
<tbody>
<tr>
<td>-20</td>
<td>1-1</td>
<td>20</td>
<td>No</td>
<td>12/30/1998</td>
</tr>
<tr>
<td>0</td>
<td>1-2</td>
<td>20</td>
<td>No</td>
<td>2/5/1999</td>
</tr>
<tr>
<td>+12</td>
<td>1-3</td>
<td>20</td>
<td>No</td>
<td>2/26/1999</td>
</tr>
<tr>
<td>+12</td>
<td>1-4</td>
<td>20</td>
<td>Yes</td>
<td>3/23/1999</td>
</tr>
<tr>
<td>+12</td>
<td>1-5</td>
<td>50</td>
<td>Yes</td>
<td>3/24/1999</td>
</tr>
<tr>
<td>+36</td>
<td>1-6</td>
<td>50</td>
<td>Yes</td>
<td>3/31/1999</td>
</tr>
<tr>
<td>+36</td>
<td>1-7</td>
<td>20</td>
<td>Yes</td>
<td>4/1/1999</td>
</tr>
</tbody>
</table>

*Note: The relative elevation 0.0 in. is set at the interface between the stabilized subgrade and embankment.*
interpolation was used to indicate the water content at each increment level of the subgrade within a specific test.

5.1.2 Phase II: SR-70 A-3 Soil

A total of eight plate load tests were conducted for SR-70 A-3 soil in the test-pit study after the establishment of moisture equilibrium. The designated test numbers and their corresponding loading conditions for phase II are shown in the following table:

<table>
<thead>
<tr>
<th>Water Table (inch)</th>
<th>Test Number</th>
<th>Plate Load (psi)</th>
<th>5-inch Base Layer (Limerock)</th>
<th>Test Date Mo./Day/Year</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>2-1</td>
<td>20</td>
<td>No</td>
<td>7/19/1999</td>
</tr>
<tr>
<td>+12</td>
<td>2-2</td>
<td>20</td>
<td>No</td>
<td>8/25/1999</td>
</tr>
<tr>
<td>+12</td>
<td>2-3</td>
<td>50</td>
<td>Yes</td>
<td>9/3/1999</td>
</tr>
<tr>
<td>+36</td>
<td>2-4</td>
<td>50</td>
<td>Yes</td>
<td>9/29/1999</td>
</tr>
<tr>
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<td>2-5</td>
<td>50</td>
<td>Yes</td>
<td>10/5/1999</td>
</tr>
<tr>
<td>-24</td>
<td>2-6</td>
<td>50</td>
<td>Yes</td>
<td>12/29/1999</td>
</tr>
<tr>
<td>-24</td>
<td>2-7</td>
<td>50</td>
<td>Yes</td>
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<tr>
<td>+36</td>
<td>2-8</td>
<td>50</td>
<td>Yes</td>
<td>2/2/2000</td>
</tr>
</tbody>
</table>

5.1.3 Phase III: SR-70 A-2-4 Soil

A total of seven plate load tests were conducted for SR-70 A-2-4 soil in the test-pit study after the establishment of moisture equilibrium. The designated test numbers and their corresponding loading conditions for phase III are shown in the following table:
### 5.1.4 Phase IV: A-2-4 (12%)

A total of five plate load tests were conducted for A-2-4 (12%) soils in the test-pit study after the establishment of moisture equilibrium. The designated test numbers and their corresponding loading conditions for phase IV are shown in the following table:

<table>
<thead>
<tr>
<th>Water Table (inch)</th>
<th>Test Number</th>
<th>Plate Load (psi)</th>
<th>5-inch Base Layer (Limerock)</th>
<th>Test Date Mo./Day/Year</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>3-1</td>
<td>20</td>
<td>No</td>
<td>7/20/1999</td>
</tr>
<tr>
<td>+12</td>
<td>3-2</td>
<td>20</td>
<td>No</td>
<td>8/24/1999</td>
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<tr>
<td>+12</td>
<td>3-3</td>
<td>50</td>
<td>Yes</td>
<td>9/2/1999</td>
</tr>
<tr>
<td>+36</td>
<td>3-4</td>
<td>50</td>
<td>Yes</td>
<td>9/30/1999</td>
</tr>
<tr>
<td>-24</td>
<td>3-5</td>
<td>50</td>
<td>Yes</td>
<td>12/28/1999</td>
</tr>
<tr>
<td>-24</td>
<td>3-6</td>
<td>50</td>
<td>Yes</td>
<td>1/5/2000</td>
</tr>
<tr>
<td>+36</td>
<td>3-7</td>
<td>50</td>
<td>Yes</td>
<td>2/1/2000</td>
</tr>
</tbody>
</table>

### 5.1.5 Phase V: A-2-4 (20%)

A total of five plate load tests were conducted for A-2-4 (20%) soils in the test-pit study after the establishment of moisture equilibrium. The designated test numbers and their corresponding loading conditions for phase V are shown in the following table:

<table>
<thead>
<tr>
<th>Water Table (inch)</th>
<th>Test Number</th>
<th>Plate Load (psi)</th>
<th>5-inch Base Layer (Limerock)</th>
<th>Test Date Mo./Day/Year</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>4-1</td>
<td>20</td>
<td>No</td>
<td>9/19/2000</td>
</tr>
<tr>
<td>+12</td>
<td>4-2</td>
<td>20</td>
<td>No</td>
<td>11/1/2000</td>
</tr>
<tr>
<td>+12</td>
<td>4-3</td>
<td>50</td>
<td>Yes</td>
<td>12/14/2000</td>
</tr>
<tr>
<td>+12</td>
<td>4-4</td>
<td>50</td>
<td>Yes</td>
<td>12/21/2000</td>
</tr>
<tr>
<td>+36</td>
<td>4-5</td>
<td>50</td>
<td>Yes</td>
<td>2/26/2000</td>
</tr>
</tbody>
</table>
A total of six plate load tests were conducted for A-2-4 (20%) soils in the test-pit study after the establishment of moisture equilibrium. The designated test numbers and their corresponding loading conditions for phase V are shown in the following table:

<table>
<thead>
<tr>
<th>Water Table (inch)</th>
<th>Test Number</th>
<th>Plate Load (psi)</th>
<th>5-inch Base Layer (Limerock)</th>
<th>Test Date Mo./Day/Year</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>5-1</td>
<td>20</td>
<td>No</td>
<td>9/22/2000</td>
</tr>
<tr>
<td>+12</td>
<td>5-2</td>
<td>20</td>
<td>No</td>
<td>11/6/2000</td>
</tr>
<tr>
<td>+12</td>
<td>5-3</td>
<td>20</td>
<td>No</td>
<td>11/8/2000</td>
</tr>
<tr>
<td>+12</td>
<td>5-4</td>
<td>50</td>
<td>Yes</td>
<td>12/11/2000</td>
</tr>
<tr>
<td>+12</td>
<td>5-5</td>
<td>50</td>
<td>Yes</td>
<td>12/13/2000</td>
</tr>
<tr>
<td>+36</td>
<td>5-6</td>
<td>50</td>
<td>Yes</td>
<td>3/5/2001</td>
</tr>
</tbody>
</table>

5.1.6 Phase VI: A-2-4 (24%)

A total of six plate load tests were conducted for A-2-4 (24%) soils in the test-pit study after the establishment of moisture equilibrium. The designated test numbers and their corresponding loading conditions for phase VI are shown in the following table:
A total of six plate load tests were conducted for A-2-4 (30%) soils in the test-pit study after the establishment of moisture equilibrium. The designated test numbers and their corresponding loading conditions for phase VII are shown in the following table:

<table>
<thead>
<tr>
<th>Water Table (inch)</th>
<th>Test Number</th>
<th>Plate Load (psi)</th>
<th>5-inch Base Layer (Limerock)</th>
<th>Test Date Mo./Day/Year</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>6-1</td>
<td>20</td>
<td>No</td>
<td>9/26/2000</td>
</tr>
<tr>
<td>+12</td>
<td>6-2</td>
<td>20</td>
<td>No</td>
<td>11/9/2000</td>
</tr>
<tr>
<td>+12</td>
<td>6-3</td>
<td>20</td>
<td>No</td>
<td>11/14/2000</td>
</tr>
<tr>
<td>+12</td>
<td>6-4</td>
<td>50</td>
<td>Yes</td>
<td>12/18/2000</td>
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<td>+12</td>
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</tr>
<tr>
<td>+36</td>
<td>6-6</td>
<td>50</td>
<td>Yes</td>
<td>3/8/2001</td>
</tr>
</tbody>
</table>

**5.1.7 Phase VII: A-2-4 (30%)**

A total of six plate load tests were conducted for A-2-4 (30%) soils in the test-pit study after the establishment of moisture equilibrium. The designated test numbers and their corresponding loading conditions for phase VII are shown in the following table:

<table>
<thead>
<tr>
<th>Water Table (inch)</th>
<th>Test Number</th>
<th>Plate Load (psi)</th>
<th>5-inch Base Layer (Limerock)</th>
<th>Test Date Mo./Day/Year</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>7-1</td>
<td>20</td>
<td>No</td>
<td>10/5/2000</td>
</tr>
<tr>
<td>+12</td>
<td>7-2</td>
<td>20</td>
<td>No</td>
<td>10/6/2000</td>
</tr>
<tr>
<td>+12</td>
<td>7-3</td>
<td>20</td>
<td>No</td>
<td>10/19/2000</td>
</tr>
<tr>
<td>+12</td>
<td>7-4</td>
<td>50</td>
<td>Yes</td>
<td>12/13/2000</td>
</tr>
<tr>
<td>+12</td>
<td>7-5</td>
<td>50</td>
<td>Yes</td>
<td>12/14/2000</td>
</tr>
<tr>
<td>+36</td>
<td>7-6</td>
<td>50</td>
<td>Yes</td>
<td>2/12/2001</td>
</tr>
</tbody>
</table>

**5.1.8 Phase VIII: Oolite**

A total of six plate load tests were conducted for Oolite soils in the test-pit study after the establishment of moisture equilibrium. The designated test numbers and their corresponding loading conditions for phase VIII are shown in the following table:

<table>
<thead>
<tr>
<th>Water Table (inch)</th>
<th>Test Number</th>
<th>Plate Load (psi)</th>
<th>5-inch Base Layer (Limerock)</th>
<th>Test Date Mo./Day/Year</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>8-1</td>
<td>20</td>
<td>No</td>
<td>11/10/2000</td>
</tr>
<tr>
<td>+12</td>
<td>8-2</td>
<td>20</td>
<td>No</td>
<td>11/11/2000</td>
</tr>
<tr>
<td>+12</td>
<td>8-3</td>
<td>50</td>
<td>Yes</td>
<td>12/15/2000</td>
</tr>
<tr>
<td>+12</td>
<td>8-4</td>
<td>50</td>
<td>Yes</td>
<td>12/16/2000</td>
</tr>
<tr>
<td>+36</td>
<td>8-5</td>
<td>50</td>
<td>Yes</td>
<td>2/12/2001</td>
</tr>
</tbody>
</table>
conditions for phase VIII are shown in the following table:

<table>
<thead>
<tr>
<th>Water Table (inch)</th>
<th>Test Number</th>
<th>Plate Load (psi)</th>
<th>5-inch Base Layer (Limerock)</th>
<th>Test Date Mo./Day/Year</th>
</tr>
</thead>
<tbody>
<tr>
<td>+12</td>
<td>B-1</td>
<td>50</td>
<td>No</td>
<td>10/9/2000</td>
</tr>
<tr>
<td>+12</td>
<td>B-2</td>
<td>50</td>
<td>No</td>
<td>10/10/2000</td>
</tr>
<tr>
<td>+12</td>
<td>B-3</td>
<td>50</td>
<td>No</td>
<td>10/17/2000</td>
</tr>
<tr>
<td>+12</td>
<td>B-4</td>
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<td>12/11/2000</td>
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<td>B-5</td>
<td>50</td>
<td>Yes</td>
<td>12/18/2000</td>
</tr>
<tr>
<td>+36</td>
<td>B-6</td>
<td>50</td>
<td>Yes</td>
<td>2/7/2001</td>
</tr>
</tbody>
</table>

5.1.9 Moisture Profile

For the Levy County A-3 soil, the moisture profiles in an equilibrium state under different water table levels are presented in Table 5.1 and shown in Figure 5.1. The moisture profiles at the time of plate load test are summarized in Table 5.2.

For the SR-70 A-3 soil, the moisture profiles in an equilibrium state after the adjustment of water table levels are presented in Table 5.3 and shown in Figure 5.2. The moisture profiles at the time of plate load test are summarized in Table 5.4.

For the SR-70 A-2-4 soil, the moisture profiles under different water table levels are presented in Table 5.5 and shown in Figure 5.3. The moisture profiles at the time of plate load test are summarized in Table 5.6.

For the A-2-4 (12%) soil, the moisture profiles under different water table levels are presented in Table 5.7 and shown in Figure 5.4. The moisture profiles at the time of plate load test are summarized in Table 5.8.
For the A-2-4 (20%) soil, the moisture profiles under different water table levels are presented in Table 5.9 and shown in Figure 5.5. The moisture profiles at the time of plate load test are summarized in Table 5.10.

For the A-2-4 (24%) soil, the moisture profiles under different water table levels are presented in Table 5.11 and shown in Figure 5.6. The moisture profiles at the time of plate load test are summarized in Table 5.12.

For the A-2-4 (30%) soil, the moisture profiles under different water table levels are presented in Table 5.13 and shown in Figure 5.7. The moisture profiles at the time of plate load test are summarized in Table 5.14.

For the Oolite soil, the moisture profiles under different water table levels are presented in Table 5.15 and shown in Figure 5.8. The moisture profiles at the time of plate load test are summarized in Table 5.16.

The moisture profiles for the eight subgrade soils are combined together and presented in Figures 5.9, 5.10 and 5.11 for the water table level at 0.0 in., +12.0 in., and +36 in., respectively.

### 5.1.10 Plate Load Test Results

The equivalent modulus values under different loading conditions and number of load cycles are presented in Tables 5.17, 5.18, 5.19, 5.20, 5.21, 5.22, 5.23 and 5.24 for the Levy County A-3, SR-70 A-3, SR-70 A-2-4 soils, A-2-4 (12%), A-2-4 (20%), A-2-4 (24%), A-2-4 (30%) and Oolite respectively. For each plate load test conducted, two figures are grouped together to represent a specific set of plate load test
results. The figure series “A” represents the equivalent modulus versus the number of load cycles (for example: Figure 5.12 A), figure series “B” represents the moisture profiles on the condition of this plate load test (for example: Figure 5.12 B).

The phase I plate load test results are presented in Figures 5.12 A & B, 5.13 A & B, 5.14 A & B for the Levy County A-3 soil, representing the three cases of 20 psi test load without limerock base layer, 20 psi test load with limerock base layer, and 50 psi test load with limerock base layer, respectively.

The phase II plate load test results are presented in Figures 5.15, 5.16, 5.17, and 5.18 for the SR-70 A-3 soil. The data for the phase II tests are grouped into four cases: a) 20 psi test load without limerock base layer, b) 50 psi test load with limerock base layer under different water table levels, c) 50 psi plate load with limerock base layer under drained conditions, and d) 50 psi test load with limerock base layer under flooded conditions.

The phase III plate load test results are presented in Figures 5.19, 5.20, 5.21, and 5.22 for the SR-70 A-2-4 soil. The data for the phase III tests are grouped into four cases: a) 20 psi test load without limerock base layer, b) 50 psi test load with limerock base layer under different water table levels, c) 50 psi plate load with limerock base layer under drained conditions, and d) 50 psi test load with limerock base layer under flooded conditions.

The phase IV plate load test results are presented in Figures 5.23 and 5.24 for the A-2-4 (12%) soil. The data for the phase IV tests are grouped into two cases: a) 20 psi test load without limerock base layer, b) 50 psi test load with limerock base layer under different
The phase V plate load test results are presented in Figures 5.25 and 5.26 for the A-2-4 (20%) soil. The data for the phase V tests are grouped into two cases: a) 20 psi test load without limerock base layer, b) 50 psi test load with limerock base layer under different water table levels.

The phase VI plate load test results are presented in Figures 5.27 and 5.28 for the A-2-4 (24%) soil. The data for the phase VI tests are grouped into two cases: a) 20 psi test load without limerock base layer, b) 50 psi test load with limerock base layer under different water table levels.

The phase VII plate load test results are presented in Figures 5.29 and 5.30 for the A-2-4 (30%) soil. The data for the phase VII tests are grouped into two cases: a) 20 psi test load without limerock base layer, b) 50 psi test load with limerock base layer under different water table levels.

The phase VIII plate load test results are presented in Figure 5.31 for the Oolite soil. The data for the phase VIII tests are only grouped into one case: 50 psi test load with limerock base layer under different water table levels.

5.2 Capillary Rise Results

Capillary rise was the vertical distance between the water table and the highest elevation where the moisture increase exists. When water table changed from a level below 0 in. (the interface between subgrade and embankment) to 0 in., the moisture profile and the time were recorded. For Levy A-3 soil, the water table was raised from -20 in.
to 0 in. For SR-70 A-3 soil, water table was raised from –12 in. to 0 in. For the other six soil types (SR-70 A-2-4, A-2-4 12%, A-2-4 20%, A-2-4 24%, A-2-4 30% and Oolite), water table was raised from –24 in. to 0 in. The moisture profile with time can be found in Figure 5.1 to Figure 5.8.

According to the assumption that capillary rise was at uniform speed, the capillary rise speed for 8 soils can be gotten in Figure 5.32. From the Figure 5.32, the capillary rise speed was from 0 in./day to 0.87 in./day. The capillary rise speed was affect by so many factors such as permeability, porosity, etc. Levy County A-3 (4%) had the biggest permeability value; its capillary rise speed was also the highest one. But there is no such a relation that the capillary rise speed increase with the permeability value increase. This study could not be determined accurately, because the moisture profile in a whole test-pit could not be uniform. And we only installed 6 TDR to record the moisture content in 6 levels (the elevation difference was 6 in.). From the recorded moisture profile for 8 soils, probably there was some malfunction happened to some TDR in some time. So the accurate theoretical model (Terzaghi’s Model) would not be used to predict the capillary speed in this research. The accurate prediction of the capillary rise speed demanded a successful permeability modeling which simulates the variation of unsaturated permeability as moisture developed within capillary fringe and the accurate moisture content profile with time.

This study could give us a reasonable range of capillary rise rate in the field for these 8 soils, which will be helpful to guide the design and construction for some sudden water table increase by some
reason.
Table 5.1 Moisture Profile of Levy County A-3 Soil

<table>
<thead>
<tr>
<th>Water Table (in.)</th>
<th>Moisture Content (%) @ Each Elevation (in. above Embankment)</th>
<th>Date Recorded</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>3</td>
<td>9</td>
</tr>
<tr>
<td>-20</td>
<td>12.5</td>
<td>9.6</td>
</tr>
<tr>
<td>0</td>
<td>15.1</td>
<td>14.5</td>
</tr>
<tr>
<td>+12</td>
<td>16.5</td>
<td>15.7</td>
</tr>
<tr>
<td>+36</td>
<td>16.6</td>
<td>16.4</td>
</tr>
<tr>
<td>Drain</td>
<td>15.6</td>
<td>12.3</td>
</tr>
</tbody>
</table>

Table 5.2 Moisture Profile of Levy County A-3 Soil (During Plate Load Test)

<table>
<thead>
<tr>
<th>Test No.</th>
<th>Water Table (in.)</th>
<th>Test Load (psi)</th>
<th>Limerock</th>
<th>Moisture Content (%) @ Each Elevation (in. above Embankment)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>3</td>
</tr>
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<td>1-1</td>
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<td>12.9</td>
</tr>
<tr>
<td>1-2</td>
<td>0</td>
<td>20</td>
<td>NO</td>
<td>15.1</td>
</tr>
<tr>
<td>1-3</td>
<td>+12</td>
<td>20</td>
<td>NO</td>
<td>15.8</td>
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<td>1-5</td>
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<td>50</td>
<td>YES</td>
<td>16.3</td>
</tr>
<tr>
<td>1-6</td>
<td>+36</td>
<td>50</td>
<td>YES</td>
<td>16.7</td>
</tr>
<tr>
<td>1-7</td>
<td>+36</td>
<td>20</td>
<td>YES</td>
<td>16.7</td>
</tr>
</tbody>
</table>
Table 5.3 Moisture Profile of SR-70 A-3 Soil

<table>
<thead>
<tr>
<th>Water Table (in.)</th>
<th>Moisture Content (%) @ Each Elevation (in. above Embankment)</th>
<th>Date Recorded</th>
</tr>
</thead>
<tbody>
<tr>
<td>-24</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>9</td>
</tr>
<tr>
<td>-12</td>
<td>9.5</td>
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<td>13.4</td>
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<td>20.4</td>
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<tr>
<td>+36</td>
<td>16.9</td>
<td>20.2</td>
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<tr>
<td>Drain</td>
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<td>10.5</td>
</tr>
<tr>
<td>Drain</td>
<td>13.9</td>
<td>18.2</td>
</tr>
</tbody>
</table>

Table 5.4 Moisture Profile of SR-70 A-3 Soil (During Plate Load Test)

<table>
<thead>
<tr>
<th>Test No.</th>
<th>Water Table (in.)</th>
<th>Test Load psi</th>
<th>Limerock</th>
<th>Moisture Content (%) @ Each Elevation (in. above Embankment)</th>
<th>Date Recorded</th>
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</thead>
<tbody>
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<td>2-1</td>
<td>-24</td>
<td>50</td>
<td>YES</td>
<td>8.6</td>
<td>10.6</td>
</tr>
<tr>
<td>2-2</td>
<td>-24</td>
<td>50</td>
<td>YES</td>
<td>8.6</td>
<td>10.5</td>
</tr>
<tr>
<td>2-3</td>
<td>0</td>
<td>20</td>
<td>NO</td>
<td>17.2</td>
<td>13.4</td>
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<td>+12</td>
<td>20</td>
<td>NO</td>
<td>16.7</td>
<td>20.6</td>
</tr>
<tr>
<td>2-5</td>
<td>+12</td>
<td>50</td>
<td>YES</td>
<td>16.7</td>
<td>20.4</td>
</tr>
<tr>
<td>2-6</td>
<td>+36</td>
<td>50</td>
<td>YES</td>
<td>16.9</td>
<td>20.2</td>
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<tr>
<td>2-7</td>
<td>+36</td>
<td>50</td>
<td>YES</td>
<td>16.9</td>
<td>20</td>
</tr>
<tr>
<td>2-8</td>
<td>+36</td>
<td>50</td>
<td>YES</td>
<td>15.4</td>
<td>17.9</td>
</tr>
</tbody>
</table>
Table 5.5 Moisture Profile of SR-70 A-2-4 Soil

<table>
<thead>
<tr>
<th>Water Table (in.)</th>
<th>Moisture Content (%) @ Each Elevation (in. above Embankment)</th>
<th>Date Recorded</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>3</td>
<td>9</td>
</tr>
<tr>
<td>-24</td>
<td>12.1</td>
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<td>-12</td>
<td>12.4</td>
<td>11.4</td>
</tr>
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<td>14.5</td>
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<td>18.3</td>
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<tr>
<td>+36</td>
<td>14.6</td>
<td>18</td>
</tr>
<tr>
<td>Drain</td>
<td>14</td>
<td>14.6</td>
</tr>
<tr>
<td>Drain</td>
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</tr>
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</table>

Table 5.6 Moisture Profile of SR-70 A-2-4 Soil (During Plate Load Test)

<table>
<thead>
<tr>
<th>Test No.</th>
<th>Water Table (in.)</th>
<th>Test Load (psi)</th>
<th>Limerock</th>
<th>Moisture Content (%) @ Each Elevation (in. above Embankment)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>3</td>
</tr>
<tr>
<td>3-1</td>
<td>-24</td>
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<tr>
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<td>-24</td>
<td>50</td>
<td>YES</td>
<td>14</td>
</tr>
<tr>
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<td>0</td>
<td>20</td>
<td>NO</td>
<td>14.4</td>
</tr>
<tr>
<td>3-4</td>
<td>+12</td>
<td>20</td>
<td>NO</td>
<td>14.6</td>
</tr>
<tr>
<td>3-5</td>
<td>+12</td>
<td>50</td>
<td>YES</td>
<td>14.6</td>
</tr>
<tr>
<td>3-6</td>
<td>+36</td>
<td>50</td>
<td>YES</td>
<td>14.6</td>
</tr>
<tr>
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Table 5.7 Moisture Profile of A-2-4 (12%) Soil

<table>
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<th>Water Table (in.)</th>
<th>Moisture Content (%) @ Each Elevation (in. above Embankment)</th>
<th>Date Recorded</th>
</tr>
</thead>
<tbody>
<tr>
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<td>3</td>
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</tr>
<tr>
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<td>5.09</td>
<td>5.06</td>
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<td>12.05</td>
</tr>
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<td>12.95</td>
</tr>
<tr>
<td>+36</td>
<td>11.36</td>
<td>13.26</td>
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<td>+41</td>
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<td>13.33</td>
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Table 5.8 Moisture Profile of A-2-4 (12%) Soil (During Plate Load Test)

<table>
<thead>
<tr>
<th>Test No.</th>
<th>Water Table (in.)</th>
<th>Test Load (ps)</th>
<th>Limerock</th>
<th>Moisture Content (%) @ Each Elevation (in. above Embankment)</th>
<th>Date Recorded</th>
</tr>
</thead>
<tbody>
<tr>
<td>4-1</td>
<td>0</td>
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<td>NO</td>
<td>10.38</td>
<td>12.02</td>
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<td>+12</td>
<td>20</td>
<td>NO</td>
<td>10.77</td>
<td>12.68</td>
</tr>
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<td>4-3</td>
<td>+12</td>
<td>50</td>
<td>YES</td>
<td>11.11</td>
<td>12.93</td>
</tr>
<tr>
<td>4-4</td>
<td>+12</td>
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<td>YES</td>
<td>11.15</td>
<td>12.95</td>
</tr>
<tr>
<td>4-5</td>
<td>+36</td>
<td>50</td>
<td>YES</td>
<td>11.3</td>
<td>13.16</td>
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Table 5.9 Moisture Profile of A-2-4 (20%) Soil

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<th>Moisture Content (%) @ Each Elevation (in. above Embankment)</th>
<th>Date Recorded</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
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<tr>
<td>+12</td>
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<td>9.43</td>
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<td>9.66</td>
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Table 5.10 Moisture Profile of A-2-4 (20%) Soil (During Plate Load Test)

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<th>Water Table (in.)</th>
<th>Test Load psi</th>
<th>Lime rock</th>
<th>Moisture Content (%) @ Each Elevation (in. above Embankment)</th>
<th>Date Recorded</th>
</tr>
</thead>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
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<td>9.32</td>
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<tr>
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<td>+12</td>
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<td>+12</td>
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<td>9.6</td>
<td>9.51</td>
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Table 5.11 Moisture Profile of A-2-4 (24%) Soil

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<th>Moisture Content (%) @ Each Elevation (in. above Embankment)</th>
<th>Date Recorded</th>
</tr>
</thead>
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<tr>
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<tr>
<td>+12</td>
<td>7.39</td>
<td>8.62</td>
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</table>

Table 5.12 Moisture Profile of A-2-4 (24%) Soil (During Plate Load Test)

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<th>Water Table (in.)</th>
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<th>Limerock</th>
<th>Moisture Content (%) @ Each Elevation (in. above Embankment)</th>
<th>Date Recorded</th>
</tr>
</thead>
<tbody>
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<td></td>
</tr>
<tr>
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<td>ND</td>
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<tr>
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<td>+12</td>
<td>20</td>
<td>ND</td>
<td>7.29</td>
<td>8.56</td>
</tr>
<tr>
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<td>+12</td>
<td>20</td>
<td>ND</td>
<td>7.33</td>
<td>8.6</td>
</tr>
<tr>
<td>6-4</td>
<td>+12</td>
<td>50</td>
<td>YES</td>
<td>7.36</td>
<td>8.6</td>
</tr>
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<td>6-5</td>
<td>+12</td>
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<td>YES</td>
<td>7.39</td>
<td>8.62</td>
</tr>
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<td>8.76</td>
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Table 5.13 Moisture Profile of A-2-4 (30%) Soil

<table>
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<tr>
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<th>Moisture Content (%) @ Each Elevation (in. above Embankment)</th>
<th>Date Recorded</th>
</tr>
</thead>
<tbody>
<tr>
<td>-24</td>
<td>11.93 12.17 11.73 12.48 10.82 7.87</td>
<td>7/6/00</td>
</tr>
<tr>
<td>0</td>
<td>16.01 13.90 12.57 13.02 10.90 8.04</td>
<td>8/14/00</td>
</tr>
<tr>
<td>+12</td>
<td>15.55 16.80 16.16 14.04 11.24 8.06</td>
<td>12/20/00</td>
</tr>
<tr>
<td>+36</td>
<td>15.66 16.97 16.43 14.92 11.46 8.55</td>
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Table 5.14 Moisture Profile of A-2-4 (30%) Soil (During Plate Load Test)

<table>
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<th>Water Table (in.)</th>
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<th>Limerock</th>
<th>Moisture Content (%) @ Each Elevation (in. above Embankment)</th>
<th>Date Recorded</th>
</tr>
</thead>
<tbody>
<tr>
<td>7-1</td>
<td>0</td>
<td>20</td>
<td>NO</td>
<td>15.75 16.76 16.3 13.83 11.23 8.04</td>
<td>10/5/00</td>
</tr>
<tr>
<td>7-2</td>
<td>+12</td>
<td>20</td>
<td>NO</td>
<td>15.76 16.77 16.29 13.82 11.22 8.02</td>
<td>10/6/00</td>
</tr>
<tr>
<td>7-3</td>
<td>+12</td>
<td>20</td>
<td>NO</td>
<td>15.68 16.82 16.24 13.86 11.2 7.92</td>
<td>10/19/00</td>
</tr>
<tr>
<td>7-4</td>
<td>+12</td>
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<td>YES</td>
<td>15.53 16.75 16.19 14.01 11.28 8.1</td>
<td>12/13/00</td>
</tr>
<tr>
<td>7-5</td>
<td>+12</td>
<td>50</td>
<td>YES</td>
<td>15.54 16.76 16.19 13.99 11.29 8.09</td>
<td>12/14/00</td>
</tr>
<tr>
<td>7-6</td>
<td>+36</td>
<td>50</td>
<td>YES</td>
<td>15.66 16.96 16.43 14.92 11.47 8.64</td>
<td>2/12/01</td>
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### Table 5.15 Moisture Profile of Oolite Soil

<table>
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<th>Water Table (in.)</th>
<th>Moisture Content (%) @ Each Elevation (in. above Embankment)</th>
<th>Date Recorded</th>
</tr>
</thead>
<tbody>
<tr>
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<td>2.94</td>
<td>2.53</td>
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<td>3.24</td>
</tr>
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### Table 5.16 Moisture Profile of Oolite Soil (During Plate Load Test)

<table>
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<th>Test No.</th>
<th>Water Table (in.)</th>
<th>Test Load (psi)</th>
<th>Limerock</th>
<th>Moisture Content (%) @ Each Elevation (in. above Embankment)</th>
<th>Date Recorded</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>8-1</td>
<td>+12</td>
<td>50</td>
<td>NO</td>
<td>3.18</td>
<td>3.23</td>
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<tr>
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<td>+12</td>
<td>50</td>
<td>NO</td>
<td>3.18</td>
<td>3.23</td>
</tr>
<tr>
<td>8-3</td>
<td>+12</td>
<td>50</td>
<td>NO</td>
<td>3.18</td>
<td>3.23</td>
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<tr>
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<td>+12</td>
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<td>3.18</td>
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<td>3.22</td>
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<tr>
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### Table 5.17 Equivalent Modulus of Levy County A-3 Soil

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<th>1-4</th>
<th>1-7</th>
<th>1-5</th>
<th>1-6</th>
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<td>NO</td>
<td>YES</td>
<td>YES</td>
<td>YES</td>
<td>YES</td>
</tr>
<tr>
<td>No. of Plate Load Cycles</td>
<td>E.M. under Drained Cond.</td>
<td>E.M. with W.T. at 0.0in.</td>
<td>E.M. with W.T. at +12.0in.</td>
<td>E.M. with W.T. at +24.0in.</td>
<td>E.M. with W.T. at +36in.</td>
<td></td>
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</tr>
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<td>MPa</td>
<td>MPa</td>
<td>MPa</td>
<td>MPa</td>
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Table 5.18 Equivalent Modulus of SR-70 A-3 Soil

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<td>50 psi</td>
<td>50 psi</td>
<td>50 psi</td>
<td>50 psi</td>
<td>50 psi</td>
<td>50 psi</td>
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<td>YES</td>
<td>YES</td>
<td>YES</td>
<td>YES</td>
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Table 5.19 Equivalent Modulus of SR-70 A-2-4 Soil

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Table 5.20 Equivalent Modulus of A-2-4 (12%)

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### Table 5.21 Equivalent Modulus of A-2-4 (20%)

**EQ Modulus : 1.38 pa/(Resilient Deformation)**

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**Average from 10,000 Cycles**

<p>|                  | 154.43 | 144.15 | 189.74 | 237.16 | 210.64 |</p>
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</tr>
<tr>
<td>Average from 10,000 Cycles</td>
<td>169.12</td>
<td>120.18</td>
</tr>
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</table>

Table 5.22 Equivalent Modulus of A-2-4 (24%)
<table>
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<tr>
<th>No. of Plate Load Cycles</th>
<th>E.M. with W.T. at 0.0in.</th>
<th>E.M. with W.T. at +12.0in.</th>
<th>E.M. with W.T. at +12.0in.</th>
<th>E.M. with W.T. at +12.0in.</th>
<th>E.M. with W.T. at +12.0in.</th>
<th>E.M. with W.T. at +36.0in.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mpa</td>
<td>Mpa</td>
<td>Mpa</td>
<td>Mpa</td>
<td>Mpa</td>
<td>Mpa</td>
</tr>
<tr>
<td>1</td>
<td>133.07</td>
<td>107.56</td>
<td>213.40</td>
<td>119.56</td>
<td>172.65</td>
<td>82.89</td>
</tr>
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<td>4</td>
<td>148.66</td>
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<td>127.07</td>
<td>150.45</td>
<td>216.85</td>
<td>118.85</td>
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<td>5</td>
<td>145.97</td>
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<td>119.84</td>
<td>151.35</td>
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<td>10</td>
<td>140.93</td>
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<td>119.84</td>
<td>159.55</td>
<td>220.02</td>
<td>108.98</td>
</tr>
<tr>
<td>25</td>
<td>151.48</td>
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<td>115.42</td>
<td>148.17</td>
<td>205.61</td>
<td>103.04</td>
</tr>
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<td>148.17</td>
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<td>100</td>
<td>171.20</td>
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<td>107.56</td>
<td>151.69</td>
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<td>200</td>
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<td>106.94</td>
<td>152.52</td>
<td>198.16</td>
<td>94.01</td>
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<tr>
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<td>134.59</td>
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<td>203.82</td>
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</tr>
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<td>1000</td>
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</tr>
<tr>
<td>2000</td>
<td>147.21</td>
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<td>105.70</td>
<td>174.44</td>
<td>210.23</td>
<td>86.86</td>
</tr>
<tr>
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<td>106.32</td>
<td>179.82</td>
<td>218.99</td>
<td>85.29</td>
</tr>
<tr>
<td>10000</td>
<td>160.52</td>
<td>143.48</td>
<td>110.46</td>
<td>184.44</td>
<td>222.78</td>
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</tr>
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<td>159.21</td>
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<td>110.04</td>
<td>218.64</td>
<td>258.08</td>
<td>74.76</td>
</tr>
<tr>
<td>Average from 10,000 Cycles</td>
<td>158.67</td>
<td>154.20</td>
<td>113.30</td>
<td>203.68</td>
<td>240.32</td>
<td>79.94</td>
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Table 5.24 Equivalent Modulus of Oolite

<table>
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<th>Loads</th>
<th>Plate Load 50 psi</th>
<th>Plate Load 50 psi</th>
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</thead>
<tbody>
<tr>
<td>Lime Rock</td>
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<td>NO</td>
</tr>
<tr>
<td>No.of Plate Load Cycles</td>
<td>MPa</td>
<td>MPa</td>
</tr>
<tr>
<td>1</td>
<td>323.01</td>
<td>455.05</td>
</tr>
<tr>
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<tr>
<td>30000</td>
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<td>485.26</td>
</tr>
<tr>
<td>Average from 10,000 Cycles</td>
<td>541.04</td>
<td>476.49</td>
</tr>
</tbody>
</table>

EQ Modulus : 1.38 pa/(Resilient Deformation)

Plate Load 50 psi Plate Load 50 psi
Figure 5.1 Levy County A-3 Soil Moisture Profile under Different Water Table

Figure 5.2 SR-70 A-3 Soil Moisture Profile under Different Water Table
(Moisture nearly stabilized from 9/29/99 to 10/11/99)
Figure 5.3 SR-70 A-2-4 Soil Moisture profile under Different Water Table (Moisture nearly stabilized from 9/29/99 to 10/11/99)

Figure 5.4 A-2-4 (12%) Soil Moisture profile under Different Water Table
Figure 5.5 A-2-4 (20%) Soil Moisture profile under Different Water Table

Figure 5.6 A-2-4 (24%) Soil Moisture profile under Different Water Table
Figure 5.7 A-2-4 (30%) Soil Moisture profile under Different Water Table

Figure 5.8 Oolite Soil Moisture profile under Different Water Table
Figure 5.9 8 Soils Moisture Profiles (Water Table at 0.0 in.)

Figure 5.10 8 Soils Moisture Profiles (Water Table at +12.0 in.)
Figure 5.11 8 Soils Moisture Profiles (Water Table at +36.0 in.)
Figure 5.12A Levy County A-3 Soil EQ Modulus vs. Number of Cycles under Different Water Tables (20 psi without Lime Rock)

Figure 5.12B Levy County A-3 Soil Moisture Profile under Plate Load Test (20 psi without Lime Rock)
Figure 5.13A Levy County A-3 Soil EQ Modulus vs. Number of Cycles under Different Water Tables (20 psi with Limerock)

Figure 5.13B Levy County A-3 Soil Moisture Profile under Plate Load Test (20 psi with Limerock)
Figure 5.14A Levy County A-3 Soil EQ Modulus vs. Number of Cycles under Different Water Tables (50 psi with Limerock)

Figure 5.14B Levy County A-3 Soil Moisture Profile under Plate Load Test (50 psi with Limerock)
Figure 5.15A SR-70 A-3 Soil EQ Modulus vs. Number of Cycles under Different Water Tables (20 psi without Limerock)

Figure 5.15B SR-70 A-3 Soil Moisture Profile under Plate Load Test (20 psi without Limerock)
Figure 5.16A SR-70 A-3 Soil EQ Modulus vs. Number of Cycles under Different Water Tables (50 psi with Limerock)

Figure 5.16B SR-70 A-3 Soil Moisture Profile under Plate Load Test (50 psi with Limerock)
Figure 5.17A SR-70 A-3 Soil EQ Modulus vs. Number of Cycles under Different Water Tables (50 psi with Limerock)

Figure 5.17B SR-70 A-3 Soil Moisture Profile under Plate Load Test (50 psi with Limerock)
Figure 5.18A SR-70 A-3 Soil EQ Modulus vs. Number of Cycles under Different Water Tables (50 psi with Limerock)

Figure 5.18B SR-70 A-3 Soil Moisture Profile under Plate Load Test (50 psi with Limerock)
Figure 5.19A SR-70 A-2-4 Soil EQ Modulus vs. Number of Cycles under Different Water Tables (20 psi without Limerock)

Figure 5.19B SR-70 A-2-4 Soil Moisture Profile under Plate Load Test (20 psi without Limerock)
Figure 5.20A SR-70 A-2-4 Soil EQ Modulus vs. Number of Cycles under Different Water Tables (50 psi with Limerock)

Figure 5.20B SR-70 A-2-4 Soil Moisture Profile under Plate Load Test (50 psi with Limerock)
Figure 5.21A SR-70 A-2-4 Soil EQ Modulus vs. Number of Cycles under Different Water Tables (50 psi with Limerock)

Figure 5.21B SR-70 A-2-4 Soil Moisture Profile under Plate Load Test (50 psi with Limerock)
Figure 5.22A SR-70 A-2-4 Soil EQ Modulus vs. Number of Cycles under Different Water Tables (50 psi with Limerock)

Figure 5.22B SR-70 A-2-4 Soil Moisture Profile under Plate Load Test (50 psi with Limerock)
A-2-4 (12%) Soil, EQ Modulus vs. Number of Cycles

Figure 5.23A A-2-4 (12%) EQ Modulus vs. Number of Cycles under Different Water Tables (20 psi without Limerock)

A-2-4(12%) Moisture Profile under Plate Load Test

Figure 5.23B A-2-4 (12%) Moisture Profile under Plate Load Test (20 psi without Limerock)
Figure 5.24A A-2-4 (12%) EQ Modulus vs. Number of Cycles under Different Water Tables (50 psi with Limerock)

Figure 5.24B A-2-4 (12%) Moisture Profile under Plate Load Test (50 psi with Limerock)
Figure 5.25A A-2-4 (20%) EQ Modulus vs. Number of Cycles under Different Water Tables (20 psi without Limerock)

Figure 5.25B A-2-4 (20%) Moisture Profile under Plate Load Test (20 psi without Limerock)
Figure 5.26A A-2-4 (20%) EQ Modulus vs. Number of Cycles under Different Water Tables (50 psi with Limerock)

Figure 5.26B A-2-4 (20%) Moisture Profile under Plate Load Test (50 psi with Limerock)
Figure 5.27A A-2-4 (24%) EQ Modulus vs. Number of Cycles under Different Water Tables (20 psi without Limerock)

Figure 5.27B A-2-4 (24%) Moisture Profile under Plate Load Test (20 psi without Limerock)
Figure 5.28A A-2-4 (24%) EQ Modulus vs. Number of Cycles under Different Water Tables (50 psi with Limerock)

Figure 5.28B A-2-4 (24%) Moisture Profile under Plate Load Test (50 psi with Limerock)
Figure 5.29A A-2-4 (30%) EQ Modulus vs. Number of Cycles under Different Water Tables (20 psi without Limerock)

Figure 5.29B A-2-4 (30%) Moisture Profile under Plate Load Test (20 psi without Limerock)
Figure 5.30A A-2-4 (30%) EQ Modulus vs. Number of Cycles under Different Water Tables (50 psi with Limerock)

Figure 5.30B A-2-4 (30%) Moisture Profile under Plate Load Test (50 psi with Limerock)
Figure 5.31A Oolite EQ Modulus vs. Number of Cycles under Different Water Tables (50 psi with Limerock)

Figure 5.31B Oolite Moisture Profile under Plate Load Test (50 psi with Limerock)
Figure 5.32 Rate of Capillary Rise for 8 Soils

Capillary Rise Assumed to be Uniform.

1 Capillary Rise Assumed to be Uniform.
CHAPTER 6 ANALYSIS OF LABORATORY EXPERIMENTAL RESULTS

6.1 Laboratory Resilient Modulus Test

The results of the laboratory tests are further analyzed in this chapter. The individual test results are summarized and presented in Appendices for each of the eight soil types.

A significant difference existed between the resilient modulus values computed from deformations measured by middle length LVDTs and full length LVDTs. The discrepancy was mainly caused by the end effect and the end friction. The end effect was caused by the uneven contact between the end platens and specimen resulting in unwanted deformation (i.e. compliance) at the interface. The end effect became more pronounced when the increase in resilient modulus due to the drying effect was very high. Due to the end effect, the resilient modulus values measured by the full length LVDTs were not representative of the actual resilient modulus of the soils. Thus, the resilient modulus measured by the LVDTs at the middle half was chosen for the analysis.

During the analysis, the effect of moisture on resilient modulus was mainly evaluated according to the following aspects:

1. To compare the regression curves of resilient modulus versus bulk stress at different moisture contents;

2. To compare the regression curves of resilient modulus versus confining pressure at different moisture contents;
3. To evaluate the effect of moisture on the constants of the regression models;
4. To compare the resilient modulus values versus moisture contents at different confining pressures;
5. To compare the resilient modulus values versus moisture contents at different deviator stresses;
6. To evaluate the reduction in resilient modulus due to soaking at the confining pressure of 13 kPa (2 psi) and deviator stress of 46.2 kPa (7 psi).

The analyses of the moisture effect on the resilient modulus for each of the eight soils are presented as follows (Lan, 2001).

6.1.1 Levy County A-3 4% Soil

Two regression models for the resilient modulus of granular soils were presented, one was dependent on bulk stress (Equation 2-1) and the other was dependent on confining pressure (Equation 2-2). The four regression constants are presented in Tables 4.3 and 4.4 for the Levy County A-3 soil. The resilient modulus versus bulk stress at different moisture contents is presented in Figure 4.5, while the resilient modulus versus confining pressure at different moisture contents is presented in Figure 4.6. The results showed that the moisture had no significant effect on the resilient modulus.

Figure 6.1 shows the moisture effect on the constants $k_1$ and $k_3$ of the regression models. The Regression constants $k_1$ and $k_3$ are the y-intercept of resilient modulus in Figure 4.5 and Figure 4.6. The data showed that the moisture had a little effect on the $k_1$ and $k_3$. 
Figure 6.2 shows the moisture effect on the constants $k_2$ and $k_4$. The data showed that the moisture had a slight effect on the constants. The regression constants $k_2$ and $k_4$ are the slopes of regression equations in Figure 4.5 and Figure 4.6.

The effects of moisture on the resilient modulus at different confining pressures and deviator stresses are demonstrated in Figures 6.3 and 6.4, respectively. The data showed that the resilient modulus decreased somewhat with an increase in moisture content.

The laboratory resilient modulus was stress dependent. The resilient modulus value increased with an increase in confining pressure for granular soils. In actual field conditions, the confining pressure at subgrade layers was found to be approximately 13.79 kPa (2 psi). In a laboratory resilient modulus test, the resilient modulus value obtained at a deviator stress of 46.2 kPa (7 psi) under the confining pressure 13.79 kPa (2 psi) was considered representative of the in-situ subgrade modulus. The resilient modulus values under the condition of confining pressure 13.79 kPa and deviator stress 46.2 kPa are summarized and presented in Table 6.1 at various moisture conditions for the Levy County A-3 soil. The effect of moisture on the resilient modulus under these conditions is shown in Figure 6.5. The data showed that the moisture content had some effect on the resilient modulus but the effect was not very significant.

The resilient modulus values at the optimum and soaked conditions are compared and illustrated in Figure 6.6. The reduction of resilient modulus due to soaking was not significant.
In a summary, the moisture had a slight effect on the resilient modulus of the Levy County A-3 soil. The resilient modulus increased with an increase in confining pressure for the A-3 soil.

6.1.2 SR-70 A-3 8% Soil

Two regression models for the resilient modulus of SR-70 A-3 soil with 8% fines were presented, one was dependent on bulk stress (Equation 2-1) and the other was dependent on confining pressure (Equation 2-2). The four regression constants are presented in Tables 4.5 and 4.6 for the SR-70 A-3 soil. The resilient modulus versus bulk stress at different moisture contents is presented in Figure 4.7, while the resilient modulus versus confining pressure at different moisture contents is presented in Figure 4.8. The results showed that the moisture had a slight effect on the resilient modulus.

Figure 6.7 shows the moisture effect on the constants $k_1$ and $k_3$ of the regression models. Regression constants $k_1$ and $k_3$ are the y-intercept of the resilient modulus in Figure 4.7 and Figure 4.8. The data showed that the moisture had a slight effect on the $k_1$ and $k_3$.

Figure 6.8 shows the moisture effect on the constants $k_2$ and $k_4$. The data showed that the moisture had a slight effect on the constants. The regression constants $k_2$ and $k_4$ are the slopes of regression equations in Figure 4.7 and Figure 4.8.

The effects of moisture on the resilient modulus at different confining pressures and deviator stresses are demonstrated in Figures 6.9 and 6.10, respectively. The data showed that the resilient modulus decreased slightly with an increase in moisture content.
Due to the same reason as described in the section for the Levy County A-3 soil with 4% fines, the resilient modulus value obtained at a deviator stress of 46.2 kPa (7 psi) under the confining pressure 13.79 kPa (2 psi) was selected to be representative of the in-situ subgrade modulus. The resilient modulus values under the condition of confining pressure 13.79 kPa and deviator stress 46.2 kPa are summarized and presented in Table 6.2 at various moisture conditions for the SR-70 A-3 soil. The effect of moisture on the resilient modulus under these conditions is shown in Figure 6.11. The data showed that the moisture content had some effect on the resilient modulus, but the effect not very significant.

The resilient modulus values at the optimum and soaked conditions are compared and illustrated in Figure 6.12. The reduction rate of resilient modulus due to soaking was 12.2%.

In a summary, the moisture had some effect on the resilient modulus of the SR-70 A-3 soil. The drying process caused some increase in the resilient modulus of the A-3 soil. The soaking process decreased the resilient modulus by about 12%. The effect of moisture was not very significant.

### 6.1.3 A-2-4 12% Soil

Two regression models for the resilient modulus of the A-2-4 soil with 12% fines were presented, one was dependent on bulk stress (Equation 2-1) and the other was dependent on confining pressure (Equation 2-2). The four regression constants are presented in Tables 4.7 and 4.8 for the A-2-4 12% soil. The resilient modulus versus bulk stress at different moisture contents is presented in Figure 4.9,
while the resilient modulus versus confining pressure at different moisture contents is presented in Figure 4.10. The results showed that the moisture had some effect on the resilient modulus. Figure 6.13 shows the moisture effect on the constants $k_1$ and $k_3$ of the regression models. The regression constants $k_1$ and $k_3$ are the y-intercept of the resilient modulus in Figure 4.9 and Figure 4.10. The data showed that the moisture had some effect on the $k_1$ and $k_3$. Figure 6.14 shows the moisture effect on the constants $k_2$ and $k_4$. The data showed that the moisture had some effect on the constants. The regression constants $k_2$ and $k_4$ are the slopes of regression equations in Figure 4.9 and Figure 4.10. The effects of moisture on the resilient modulus at different confining pressures and different deviator stresses are demonstrated in Figures 6.15 and 6.16, respectively. The data showed that the resilient modulus decreased with an increase in moisture content. The resilient modulus value obtained at a deviator stress of 46.2 kPa (7 psi) under the confining pressure 13.79 kPa (2 psi) was selected to be representative of the in-situ subgrade modulus. The resilient modulus values under the condition of confining pressure 13.79 kPa and deviator stress 46.2 kPa are presented in Table 6.3 at various moisture conditions for the A-2-4 12% soil. The effect of moisture on the resilient modulus under these conditions is shown in Figure 6.17. The data showed that the moisture content had some effect on the resilient modulus. The resilient modulus values at the optimum and soaked conditions are compared and illustrated in Figure 6.18. The reduction rate of resilient modulus due to soaking was 8.2%.
In a summary, the moisture has some effect on the resilient modulus of the A-2-4 soil with 12% fines. The drying caused an increase in the resilient modulus, while the soaking decreased the resilient modulus by 8.2%.

6.1.4 SR-70 A-2-4 14% Soil

The four regression constants are presented in Tables 4.9 and 4.10 for the SR-70 A-2-4 soil with 14% fines. The resilient modulus versus bulk stress at different moisture contents is presented in Figure 4.11, while the resilient modulus versus confining pressure at different moisture contents is presented in Figure 4.12. The results showed that the moisture had a significant effect on the resilient modulus.

Figure 6.19 shows the moisture effect on the constants $k_1$ and $k_3$ of the regression models. The regression constants $k_1$ and $k_3$ are the y-intercept of the resilient modulus in Figure 4.11 and Figure 4.12. The data showed that the moisture had a significant effect on the $k_1$ and $k_3$.

Figure 6.20 shows the moisture effect on the constants $k_2$ and $k_4$. The data showed that the moisture had a significant effect on the constants. The regression constants $k_2$ and $k_4$ are the slopes of regression equations in Figure 4.11 and Figure 4.12.

The effects of moisture on the resilient modulus at different confining pressures and deviator stresses are demonstrated in Figures 6.21 and 6.22, respectively. The data showed that the resilient modulus decreased with an increase in moisture content.
The resilient modulus value obtained at a deviator stress of 46.2 kPa (7 psi) under the confining pressure 13.79 kPa (2 psi) was selected to be representative of the in-situ subgrade modulus. The resilient modulus values under the condition of confining pressure 13.79 kPa and deviator stress 46.2 kPa are presented in Table 6.4 at various moisture conditions for the SR-70 A-2-4 14% soil. The effect of moisture on the resilient modulus under these conditions is shown in Figure 6.23. The data showed that the moisture content had a significant effect on the resilient modulus.

The resilient modulus values at the optimum and soaked conditions are compared and illustrated in Figure 6.24. The reduction rate of resilient modulus due to soaking was 37.8%.

In a summary, the moisture had a significant effect on the resilient modulus of the SR-70 A-2-4 soil with 14% fines. The drying process caused a significant increase in the resilient modulus. The soaking decreased the resilient modulus by 37.8%.

6.1.5 A-2-4 20% Soil

The four regression constants are presented in Tables 4.11 and 4.12 for the A-2-4 20% soil. The resilient modulus versus bulk stress at different moisture contents is presented in Figure 4.13, while the resilient modulus versus confining pressure at different moisture contents is presented in Figure 4.14. The results showed that the moisture had some effect on the resilient modulus.

Figure 6.25 shows the moisture effect on the constants $k_1$ and $k_3$ of the regression models. The regression constants $k_1$ and $k_3$ are the
y-intercept of the resilient modulus in Figure 4.13 and Figure 4.14. The data showed that the moisture had some effect on the $k_1$ and $k_3$. Figure 6.26 shows the moisture effect on the constants $k_2$ and $k_4$. The data showed that the moisture had some effect on the constants. The regression constants $k_2$ and $k_4$ are the slopes of regression equations in Figure 4.13 and Figure 4.14.

The effects of moisture on the resilient modulus at different confining pressures and deviator stresses are demonstrated in Figures 6.27 and 6.28, respectively. The data showed that the resilient modulus decreased with an increase in moisture content.

The resilient modulus value obtained at a deviator stress of 46.2 kPa (7 psi) under the confining pressure 13.79 kPa (2 psi) was selected to be representative of the in-situ subgrade modulus. The resilient modulus values under the condition of confining pressure 13.79 kPa and deviator stress 46.2 kPa are presented in Table 6.5 at various moisture conditions for the A-2-4 20% soil. The effect of moisture on the resilient modulus under these conditions is shown in Figure 6.29. The data showed that the moisture content had some effect on the resilient modulus.

The resilient modulus values at the optimum and soaked conditions are compared and illustrated in Figure 6.30. The reduction rate of resilient modulus due to soaking was 3.8%.

In a summary, the moisture had some effect on the resilient modulus of the A-2-4 soil with 20% fines. The drying caused an increase in the resilient modulus, while the soaking decreased the resilient modulus by 3.8%.
6.1.6 A-2-4 24% Soil

The four regression constants are presented in Table 4.13 and 4.14 for the A-2-4 24% soil. The resilient modulus versus bulk stress at different moisture contents is presented in Figure 4.15, while the resilient modulus versus confining pressure at different moisture contents is presented in Figure 4.16. The results showed that the moisture had some effect on the resilient modulus.

Figure 6.31 shows the moisture’s effect on the constants k1 and k3 of the regression models. The regression constants k1 and k3 are the y-intercept of the resilient modulus in Figure 4.15 and Figure 4.16. The data showed that the moisture had a significant effect on the k1 and k3.

Figure 5.54 shows the moisture effect on the constants k2 and k4. The data showed that the moisture had some effect on the constants. The regression constants k2 and k4 are the slopes of regression equations in Figure 4.15 and Figure 4.16.

The effects of moisture on the resilient modulus at different confining pressures and deviator stresses are demonstrated in Figures 6.33 and 6.34, respectively. The data showed that the resilient modulus decreased with an increase in moisture content.

The resilient modulus value obtained at a deviator stress of 46.2 kPa (7 psi) under the confining pressure 13.79 kPa (2 psi) was selected to be representative of the in-situ subgrade modulus. The resilient modulus values under the condition of confining pressure 13.79 kPa and deviator stress 46.2 kPa are presented in Table 6.6 at various moisture conditions for the A-2-4 24% soil. The effect of moisture on the resilient modulus under these conditions is shown in Figure
6.35. The data showed that the moisture content had a significant effect on the resilient modulus. The resilient modulus values at the optimum and soaked conditions are compared and illustrated in Figure 6.36. The reduction rate of resilient modulus due to soaking was 21.6%.

In a summary, the moisture had a significant effect on the resilient modulus of the A-2-4 soil with 24% fines. The drying caused a significant increase in the resilient modulus, while the soaking decreased the resilient modulus by 21.6%.

6.1.7 A-2-4 30% Soil

The four regression constants are presented in Tables 4.15 and 4.16 for the A-2-4 30% soil. The resilient modulus versus bulk stress at different moisture contents is presented in Figure 4.17, while the resilient modulus versus confining pressure at different moisture contents is presented in Figure 4.18. The results showed that the moisture had a significant effect on the resilient modulus.

Figure 6.37 shows the moisture effect on the constants k1 and k3 of the regression models. The regression constants k1 and k3 are the y-intercept of the resilient modulus in the Figure 4.17 and Figure 4.18. The data showed that the moisture had a significant effect on the k1 and k3.

Figure 6.38 shows the moisture effect on the constants k2, and k4. The data showed that the moisture had a significant effect on the constants. The regression constants k2 and k4 are the slopes of regression equations in Figure 4.17 and Figure 4.18.
The effects of moisture on the resilient modulus at different confining pressures and different deviator stresses are demonstrated in Figures 6.39 and 6.40, respectively. The data showed that the resilient modulus decreased with an increase in moisture content. The resilient modulus value obtained at a deviator stress of 46.2 kPa (7 psi) under the confining pressure 13.79 kPa (2 psi) was selected to be representative of the in-situ subgrade modulus. The resilient modulus values under the condition of confining pressure 13.79 kPa and deviator stress 46.2 kPa are presented in Table 6.7 at various moisture conditions for the A-2-4 30% soil. The effect of moisture on the resilient modulus under these conditions is shown in Figure 6.41. The data showed that the moisture content had a significant effect on the resilient modulus.

The resilient modulus values at the optimum and soaked conditions are compared and illustrated in Figure 6.42. The reduction rate of resilient modulus due to soaking was 18.8%.

In a summary, the effect of moisture was very significant on the resilient modulus of the A-2-4 soil with 30% fines. The decrease of moisture content due to drying caused a great increase in the resilient modulus. The increase of moisture due to soaking reduced the resilient modulus by 18.8%.

6.1.8 Miami Oolite A-1 Soil

The four regression constants are presented in Tables 4.17 and 4.18 for the Oolite soil. The resilient modulus versus bulk stress at different moisture contents is presented in Figure 4.19, while the resilient modulus versus confining pressure at different moisture
contents is presented in Figure 4.20. The results showed that the moisture had a significant effect on the resilient modulus.

Figure 6.43 shows the moisture effect on the constants k1 and k3 of the regression models. The regression constants k1 and k3 are the y-intercept of the resilient modulus in Figure 4.19 and Figure 4.20. The data showed that the moisture had a significant effect on the k1 and k3.

Figure 6.44 shows the moisture effect on the constants k2 and k4. The data showed that the moisture had a significant effect on the constants. The regression constants k2 and k4 are the slopes of regression equations in Figure 4.19 and Figure 4.20.

The effects of moisture on the resilient modulus at different confining pressures and deviator stresses are demonstrated in Figures 6.45 and 6.46, respectively. The data showed that the resilient modulus decreased with an increase in moisture content.

The resilient modulus value obtained at a deviator stress of 46.2 kPa (7 psi) under the confining pressure 13.79 kPa (2 psi) was selected to be representative of the in-situ subgrade modulus. The resilient modulus values under the condition of confining pressure 13.79 kPa and deviator stress 46.2 kPa are presented in Table 6.8 at various moisture conditions for the Miami Oolite A-1 soil. The effect of moisture on the resilient modulus under these conditions is shown in Figure 6.47. The data showed that the moisture content had a significant effect on the resilient modulus.

The resilient modulus values at the optimum and soaked conditions are compared and illustrated in Figure 6.48. The reduction rate of resilient modulus due to soaking was 37%.
In a summary, the effect of moisture was significant on the resilient modulus of the Miami Oolite A-1 soil. The decrease of moisture content due to drying caused a significant increase in the resilient modulus. The increase of moisture due to soaking reduced the resilient modulus by 37%.

6.1.9 Summary and Discussion
From the above analysis, the results showed that the moisture had a detrimental effect on the resilient modulus of subgrade soils. In general, the increase of moisture caused a reduction in the resilient modulus. The degree of reduction was different among various types of soils. The degree of reduction for A-2-4 soils was more apparent than that of A-3 soils.

The increase of the constant k2 and k4 with increasing moisture content indicated that the resilient modulus became more sensitive to confining pressure and bulk stress with an increase in moisture content. The increase of moisture reduced the rigidity of the soil structure and made it more sensitive to the surrounding pressure. The increase of moisture could also increase the Poisson’s ratio of the soil.

The reduction rates of the eight granular soils are summarized in Table 6.9. The reduction rates were calculated from optimum water content to soaked condition based on the resilient modulus under a confining pressure of 13.79 kPa (2 psi) and a deviator stress of 46.2 kPa (7 psi), which was considered to be representative of the in-situ subgrade modulus. The test results showed that the soaking did not have a significant effect on the A-3 soils.
According to their reduction rates, the eight soils were further classified into four categories based on their susceptibility to the moisture. The classification of the moisture effect by the rate of reduction in resilient modulus is summarized in Table 6.10. Table 6.11 summarized the resilient modulus in optimum and soaked conditions with degree of saturation. When in saturation condition, the moisture contents for SR70 A-2-4 (14%), A-2-4 (20%), A-2-4 (30%) and Oolite were over 80%. In the above four soils, except A-2-4 (20%), the other three had large reduction rates.

Generally, the percentage of fines passing sieve #200 of a subgrade soil can significantly influence its moisture effect on the resilient modulus. The A-2-4 soils with relatively high percent of fines are more susceptible to the increase of moisture than the A-3 soils (Figure 6.49). However, as shown in Figures 6.49 with different percentage of fines for the A-2-4 and A-3 soils, the percentage of passing #200 fines may not be a dominant factor on the reduction of resilient modulus due to the effect of moisture.

Figure 6.50 summarizes the laboratory resilient moduli for seven soils at dry, optimum moisture and soaked conditions. It will be compared with the layer moduli in Chapter 8. From Figure 6.50, two soil types (SR 70 A-2-4 and A-2-4 30%) are very sensitive to the moisture change. From this figure, the reduction rate can be gotten in Figure 6.52. Figure 6.51 shows the relationship of the resilient modulus versus the dry unit weight of the eight soils. It demonstrated that the resilient modulus was not dependent upon the dry unit weight of the soil.
The reduction rates of resilient modulus due to soaking versus the percentages of fines passing sieve #200 are illustrated in Figure 6.52 for the eight soils. A-2-4 (30%) reduction rate was calculated by the regression equation of the resilient modulus vs. moisture content. The test showed a little increase of resilient modulus of A-2-4 (30%) from the optimum condition to soaked condition. This was due to the test “error” such as soil sample difference, test results variance, etc. The data showed that the percentage of fines was not a dominant factor for the reduction rate of resilient modulus. The LBR values versus the percentages of fines passing sieve #200 are also presented in Figure 6.53 for the eight soils. Comparing the data shown in Figures 6.52 and 6.53, with the exception of the A-2-4 soil with 20% fines, the reduction rates are proportional to the LBR values for seven of the eight soils. Due to the effect of moisture, the data showed that the reduction rate of resilient modulus increased with increasing LBR value of the soil (Lan, 2001).

6.2 Soil Resilient Modulus Prediction Model

6.2.1 Multiple Regression Model

The general purpose of multiple regression is to learn more about the relationship between several independent or predictor variables and a dependent or criterion variable. In general, multiple regression allows the researcher to ask (and hopefully answer) the general question “what is the best predictor of ...?”. In the multivariate case, when there is more than one independent variable, the regression line cannot be visualized in the two
dimensional space, but can be computed just as easily. In general then, multiple regression procedures will estimate a linear equation of the form:

$$y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \cdots + \beta_k x_k + \epsilon$$  \hspace{1cm} (6-1)

The smaller the variability of the residual values around the regression line relative to the overall variability, the better is our prediction. The R-square value is an indicator of how well the model fits the data (e.g., an R-square value close to 1.0 indicates that almost all of the variability with the variables specified in the model have been accounted for). More information about multiple regression can be found in Appendix M (McClave et al, 2000) (StatSoft, 1984-2003).

6.2.2 Model Sample Population
There are totally eight soil types in the laboratory resilient modulus test program. But only five soils' gradation curves are available. So the resilient modulus multiple regression model will only include five soil types with some parameters coming from the gradation curves as predictors in the model. Generally, there are 6 resilient modulus test results for each soil type. For each of dry, optimum moisture and saturated conditions, there are two resilient modulus data points existing for checking with each other. So there will be 6*5=30 data available to set up the regression model. If the number of predictors is only 2 or 3, the sample size (30) is enough to build the model. For some soils, more than six laboratory resilient modulus tests are available. So, the actual sample size is 33.
6.2.3 Selection of Predictors

The soils under investigation in this model building study were one A-3 and four A-2-4 subgrade materials in use in Florida representing the percent of fines passing No.200 sieve, which ranged from 8% to 24%. The five soils included SR-70 A-3 (8% passing No.200), SR-70 A-2-4 (14% passing No.200), A-2-4 (12% passing No.200), A-2-4 (20% passing No.200) and A-2-4 (24% passing No.200). The compaction characteristics were determined in the laboratory using the modified Proctor (AASHTO T-180) method. The pertinent characteristics of those subgrade soils are presented in Table 6.12.

For the gradation analysis of each soil, sieve analysis and hydrometer analysis test were conducted. The gradation curves for the subgrades were presented in Figure 6.54. From Figure 6.54, the particle size parameters (D10, D30, D60) and the coefficient of uniformity ($C_u$) and coefficient of curvature ($C_c$) can be determined and are summarized in Table 6.13. For well-graded soils, $C_c$ values should be between about 1 and 3 and $C_u$ should be equal to or over 5. For these five Florida subgrade soils, they were all not well-graded. Especially, SR-70 A-2-4 (14%) soil had extremely high $C_c$ value. That means this soil was gap-graded because it was missing particles in a certain size range. Gap-graded soils were sometimes considered a type of poorly graded soil.

The purpose of regression model is using some parameters to predict another value (called response). In laboratory resilient modulus test program, it is difficult and time consuming to conduct a resilient modulus test. But it is easy to get some other soil properties such
as percentage of fines, gradation curves, moisture content, etc. If more parameters are added in the model, the prediction model will be more accurate. But for each predictor, some tests are needed to determine whether it is simple or not to get the values. So in the study, parameters such as percentage of fines, moisture content, maximum dry density, clay percentage, coefficient of uniformity ($C_u$) and coefficient of curvature ($C_c$) are candidate predictors for the model. The soil suction value, permeability, and other parameters of each soil will not be included in our resilient modulus regression model. Another consideration is that the soil suction value, permeability value and other properties are related with individual soil’s percentage of fines and/or moisture contents. The predictors should be independent.

6.2.4 Selection of Multiple Regression Equation Form

In the multiple regression model, if the model coefficient of determination is more close to 1, the form of the response and predictors can be changed to reciprocal value, logarithm value or others.

The selection of multiple regression equation form process is by trials and referring to other researchers’ findings. The following are some trials results by statistic software Minitab.

In the laboratory resilient modulus test program, different resilient modulus values were obtained for each soil according to different conditions. The full-length resilient modulus under 13.79kPa confining pressure, 0.37kN axial load, 46kPa deviator stress and 87kPa bulk stress was chosen as model responses.
The maximum dry density, gradation curve and moisture content are basic soil properties. They can be gotten with simple tests. We tried to use logarithm value of response and/or predictors. The following are the Minitab results for trials. Many other trials are not included here because they got even worse regression results.

Model (1):

\[
\ln(M_r) = \beta_0 + \beta_1 \omega + \beta_2 \rho + \beta_3 (C_u) + \beta_4 (C_c) + \beta_5 \alpha
\]  

(6-2)

where \( M_r \) = Resilient modulus in ksi, at 2 psi confining pressure

\( \omega \) = Gravimetric moisture content in percentage (0~100)

\( \rho \) = Maximum dry density in pcf

\( \alpha \) = Clay percentage in percentage (0~100)

\( \beta_i \) = Regression constants

The regression equation is

\[
\ln(E(ksi)) = 2.07 - 0.0409 \text{ moisture content}(\%) + 0.0102 \text{ Max Dry Density} + 0.0239 \text{ Cu} - 0.117 \text{ Cc} + 0.0020 \text{ clay percent}
\]

Predictor | Coef   | SE Coef | T    | P       |
-----------|--------|---------|------|---------|
Constant   | 2.065  | 1.768   | 1.17 | 0.253   |
moisture   | -0.04086 | 0.01262 | -3.24| 0.003   |
Max Dry    | 0.01016 | 0.01813 | 0.56 | 0.580   |
Cu         | 0.02386 | 0.01585 | 1.51 | 0.144   |
Cc         | -0.11666 | 0.07856 | -1.49| 0.149   |
clay per   | 0.00203 | 0.05369 | 0.04 | 0.970   |

S = 0.2029  \( \text{R-Sq} = 54.2\% \)  \( \text{R-Sq(adj)} = 45.7\% \)

Analysis of Variance

Source | DF | SS       | MS      | F     | P       |
--------|----|----------|---------|-------|---------|
Regression | 5  | 1.31559  | 0.26312 | 6.39  | 0.000   |
Residual Error | 27 | 1.11120  | 0.04116 |       |         |
Total     | 32 | 2.42679  |         |       |         |

Source | DF | Seq SS   |
--------|----|---------|
moisture | 1  | 0.65991 |
Max Dry   | 1  | 0.22191 |
Cu        | 1  | 0.25283 |
Cc        | 1  | 0.18089 |
clay per  | 1  | 0.00006 |

By trials, using logarithm value for response will get higher
coefficient of determination (R-sq value). From this model, \( \rho \) (maximum dry density) and \( \alpha \) (clay percentage) are insignificant. So the following trials will try to build models eliminating one or both of these two insignificant predictors.

Model (2):

\[
\ln(M_r) = \beta_0 + \beta_1 \omega + \beta_2 (C_u) + \beta_3 (C_c)
\]

(6-3)

The regression equation is

\[
\ln(E(ksi)) = 3.24 - 0.0418 \text{ moisture content(\%)} + 0.0202 \text{ Cu} - 0.0968 \text{ Cc}
\]

<table>
<thead>
<tr>
<th>Predictor</th>
<th>Coef</th>
<th>SE Coef</th>
<th>T</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td>Constant</td>
<td>3.2400</td>
<td>0.1330</td>
<td>24.37</td>
<td>0.000</td>
</tr>
<tr>
<td>moisture</td>
<td>-0.0418</td>
<td>0.01227</td>
<td>-3.40</td>
<td>0.002</td>
</tr>
<tr>
<td>Cu</td>
<td>0.0202</td>
<td>0.01074</td>
<td>1.88</td>
<td>0.070</td>
</tr>
<tr>
<td>Cc</td>
<td>-0.0968</td>
<td>0.05419</td>
<td>-1.79</td>
<td>0.084</td>
</tr>
</tbody>
</table>

\( S = 0.2024 \quad \text{R-Sq = 51.0\%} \quad \text{R-Sq(adj) = 46.0\%} \)

Analysis of Variance

<table>
<thead>
<tr>
<th>Source</th>
<th>DF</th>
<th>SS</th>
<th>MS</th>
<th>F</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td>Regression</td>
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<td>1.23884</td>
<td>0.41295</td>
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<td>0.000</td>
</tr>
<tr>
<td>Residual Error</td>
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<td>1.18795</td>
<td>0.04096</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>32</td>
<td>2.42679</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Source</th>
<th>DF</th>
<th>Seq SS</th>
</tr>
</thead>
<tbody>
<tr>
<td>moisture</td>
<td>1</td>
<td>0.65991</td>
</tr>
<tr>
<td>Cu</td>
<td>1</td>
<td>0.44810</td>
</tr>
<tr>
<td>Cc</td>
<td>1</td>
<td>0.13084</td>
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</table>

Comparing Model (2) with Model (1), the coefficient of determination dropped from 54.2\% to 51.0\%. It means that deleting both of \( \rho \) (maximum dry density) and \( \alpha \) (clay percentage) is not a good choice.
Model (3):

\[
\ln(M_r) = \beta_0 + \beta_1 \cdot \omega + \beta_2 \cdot \rho + \beta_3 \cdot (C_u) + \beta_4 \cdot (C_c)
\]  
(6-4)

The regression equation is

\[
\ln(E(ksi)) = 2.01 - 0.0410 \text{ moisture content(\%)} + 0.0108 \text{ Max Dry Density} \\
+ 0.0243 \text{ Cu} - 0.119 \text{ Cc}
\]

<table>
<thead>
<tr>
<th>Predictor</th>
<th>Coef</th>
<th>SE Coef</th>
<th>T</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td>Constant</td>
<td>2.0080</td>
<td>0.8959</td>
<td>2.24</td>
<td>0.033</td>
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<tr>
<td>moisture</td>
<td>-0.04097</td>
<td>0.01209</td>
<td>-3.39</td>
<td>0.002</td>
</tr>
<tr>
<td>Max Dry</td>
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<td>0.007753</td>
<td>1.39</td>
<td>0.175</td>
</tr>
<tr>
<td>Cu</td>
<td>0.02428</td>
<td>0.01097</td>
<td>2.21</td>
<td>0.035</td>
</tr>
<tr>
<td>Cc</td>
<td>-0.11872</td>
<td>0.05561</td>
<td>-2.13</td>
<td>0.042</td>
</tr>
</tbody>
</table>

\[S = 0.1992 \quad \text{R-Sq} = 54.2\% \quad \text{R-Sq(adj)} = 47.7\%\]

Analysis of Variance

<table>
<thead>
<tr>
<th>Source</th>
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<th>SS</th>
<th>MS</th>
<th>F</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td>Regression</td>
<td>4</td>
<td>1.31553</td>
<td>0.32888</td>
<td>8.29</td>
<td>0.000</td>
</tr>
<tr>
<td>Residual Error</td>
<td>28</td>
<td>1.11126</td>
<td>0.03969</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>32</td>
<td>2.42679</td>
<td></td>
<td></td>
<td></td>
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</table>

<table>
<thead>
<tr>
<th>Source</th>
<th>DF</th>
<th>Seq SS</th>
</tr>
</thead>
<tbody>
<tr>
<td>moisture</td>
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<td>0.65991</td>
</tr>
<tr>
<td>Max Dry</td>
<td>1</td>
<td>0.22191</td>
</tr>
<tr>
<td>Cu</td>
<td>1</td>
<td>0.25283</td>
</tr>
<tr>
<td>Cc</td>
<td>1</td>
<td>0.18089</td>
</tr>
</tbody>
</table>

The prediction Model (3) will get the same coefficient of determination (R-sq value = 54.2\%) with Model (1) if only eliminating the \( \alpha \) (clay percentage) as a predictor.
Model (4):

\[ \ln(M_r) = \beta_0 + \beta_1 * \omega + \beta_2 * \alpha + \beta_3 * (C_u) + \beta_4 * (C_c) \]  

(6-5)

The regression equation is

\[ \ln(E(ksi)) = 3.05 - 0.0396 \text{ moisture content(\%)} + 0.0291 \text{ clay percent} + 0.0175 \text{ Cu} - 0.0853 \text{ Cc} \]

<table>
<thead>
<tr>
<th>Predictor</th>
<th>Coef</th>
<th>SE Coef</th>
<th>T</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td>Constant</td>
<td>3.0497</td>
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<td>15.23</td>
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</tr>
<tr>
<td>moisture</td>
<td>-0.03962</td>
<td>0.01227</td>
<td>-3.23</td>
<td>0.003</td>
</tr>
<tr>
<td>clay per</td>
<td>0.02912</td>
<td>0.02309</td>
<td>-1.26</td>
<td>0.218</td>
</tr>
<tr>
<td>Cu</td>
<td>0.01746</td>
<td>0.02309</td>
<td>1.26</td>
<td>0.218</td>
</tr>
<tr>
<td>Cc</td>
<td>-0.08528</td>
<td>0.05442</td>
<td>-1.57</td>
<td>0.128</td>
</tr>
</tbody>
</table>

S = 0.2004

R-Sq = 53.7% R-Sq(adj) = 47.1%

Analysis of Variance

<table>
<thead>
<tr>
<th>Source</th>
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<th>F</th>
<th>P</th>
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</thead>
<tbody>
<tr>
<td>Regression</td>
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<td>8.11</td>
<td>0.000</td>
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<td>Residual Error</td>
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<td>Total</td>
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<td>2.42679</td>
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<table>
<thead>
<tr>
<th>Source</th>
<th>DF</th>
<th>Seq SS</th>
</tr>
</thead>
<tbody>
<tr>
<td>moisture</td>
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<tr>
<td>clay per</td>
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<tr>
<td>Cu</td>
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<tr>
<td>Cc</td>
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<td>0.09859</td>
</tr>
</tbody>
</table>

Model (4) has a lower R-sq value if deleting \( \rho \) (maximum dry density) as predictor in Model (1). So the final laboratory resilient modulus multiple regression model is:

\[ \ln(M_r) = 2.01 - 0.0410 * \omega + 0.0108 * \rho + 0.0243*(C_u) - 0.119*(C_c) \]  

(6-6)

Again, the units in above equations are very important. The \( M_r \) (resilient modulus) is in ‘kip per square inch’ at 2 psi confining pressure, \( \omega \) (gravimetric moisture content) is in percentage scaling from 0 to 100, \( \rho \) (maximum dry density) is in ‘pound per cubic foot’, and \( C_u \) and \( C_c \) have no units.

Table 6.14 summarizes the regression model trial results.
6.2.5 Overall Utility of the Model

As described in Appendix M, the overall utility of the multiple regression model should be checked before doing prediction by F-test.

<table>
<thead>
<tr>
<th>Testing Global Usefulness of the Model: The Analysis of Variance F-Test</th>
</tr>
</thead>
<tbody>
<tr>
<td>$H_0 : \beta_0 = \beta_1 = \beta_2 = 0$</td>
</tr>
<tr>
<td>$H_a : $ At least one $\beta_i \neq 0$</td>
</tr>
</tbody>
</table>

Test Statistic:

$$ F = \frac{(SS_{\text{mod}} - SSE) / k}{SSE / (n-(k+1))} = \frac{R^2 / k}{(1-R^2) / (n-(k+1))} = \frac{\text{Mean Square (Model)}}{\text{Mean Square (Error)}} $$

Where $n$ is the sample size and $k$ is the number of terms in the model.

Rejection region: $F > F_\alpha$, with $k$ numerator degrees of freedom and $(n-(k+1))$ denominator degrees of freedom.

The calculation of F-value is:

$$ F = \frac{\text{Sum of Squares (Model) / df (Model)}}{\text{Sum of Squares (Error) / df (Error)}} = \frac{\text{Mean Square (Model)}}{\text{Mean Square (Error)}} = \frac{1.31553}{1.11126} = 1.1811 \approx 1.18 $$

If $\alpha = 0.05$, $F = 8.29 > F_{0.05}(4, 28) \approx 2.71$, the null hypothesis should be rejected. Thus, this resilient modulus prediction Model (4) (Eq. 6-6) is statistically useful.

Figure 6.55 shows the comparison of predicted values of above model with the laboratory resilient modulus test results. Figure 6.56 shows the ratio of predicted values of the above model over the lab resilient modulus test results. Figures 6.55 and 6.56 show the variation and accuracy of the above regression model. From Figure 6.56, most of
the ratios of predicted values over the lab results are in the range of 0.8 to 1.2. It means that the usage of the above regression model will obtain a reasonably predicted resilient modulus value within ±20% error.

### 6.2.6 Discussions

Again, the final resilient modulus prediction model is:

$$M_r = e^{(2.01-0.0410\%\omega+0.0108\%(\rho)+0.0243\%(C_r)-0.119\%(C_s))}$$  \hspace{1cm} (6-8)

where, $M_r$=Resilient modulus in ksi, at 2 psi confining pressure

Equation (6-8) is just another transformation of Equation (6-6). As previously discussed, the multiple regression model can be used to predict resilient modulus values without doing an actual laboratory MR test. However, actual tests are required to obtain the values of the predictors. So the accuracy of the test of predictors is very important.

Only five of the eight soils are available with gradation curve data. If all the gradation curve data are available, the regression model could be more refined. Adding more data points will definitely affect the regression coefficient values in front of each predictor.

It should also be noted that all the laboratory resilient modulus data are for granular Florida subgrade soils at 2 psi confining pressure. If the resilient modulus prediction model is to be used for clayey soils, special care should be taken.

The units in the regression model are also very important. Different units will result in different parameters in the equation. For the multiple regression models, $M_r$ (resilient modulus) is in ‘ksi’,
ρ (maximum dry density) is in 'pcf', ω (gravimetric moisture content) is in percentage of 100 (scale from 0 to 100), α (clay percentage) is in percentage of 100 (scale from 0 to 100), \( C_u \) and \( C_c \) have no units.

In addition, if the direct method, i.e., laboratory triaxial test, is available to obtain the resilient modulus, it is always recommended to use laboratory resilient modulus values in lieu of the prediction models.
Table 6.1 $M_r$ vs. Moisture Content, Levy County A-3 Soil

<table>
<thead>
<tr>
<th>Moisture %</th>
<th>Confining Pressure (kPa)</th>
<th>Axial Load (kN)</th>
<th>Dev. Stress (kPa)</th>
<th>Bulk Stress (kPa)</th>
<th>Middle Modulus (MPa)</th>
<th>Full Length Modulus (Mpa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.3</td>
<td>13.79</td>
<td>0.37</td>
<td>46.12</td>
<td>87.49</td>
<td>178.28</td>
<td>122.89</td>
</tr>
<tr>
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<td>13.79</td>
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<td>46.12</td>
<td>87.49</td>
<td>186.34</td>
<td>137.12</td>
</tr>
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<td>46.12</td>
<td>87.49</td>
<td>186.34</td>
<td>137.12</td>
</tr>
<tr>
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<td>13.79</td>
<td>0.38</td>
<td>47.06</td>
<td>88.43</td>
<td>153.33</td>
<td>124.78</td>
</tr>
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<td>46.10</td>
<td>87.47</td>
<td>162.00</td>
<td>109.67</td>
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<td>0.38</td>
<td>46.20</td>
<td>87.57</td>
<td>132.11</td>
<td>89.53</td>
</tr>
<tr>
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<td>13.79</td>
<td>0.38</td>
<td>46.26</td>
<td>87.63</td>
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<td>86.58</td>
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Table 6.2 $M_r$ vs. Moisture Content, SR-70 A-3 Soil

<table>
<thead>
<tr>
<th>Moisture %</th>
<th>Confining Pressure (kPa)</th>
<th>Axial Load (kN)</th>
<th>Dev. Stress (kPa)</th>
<th>Bulk Stress (kPa)</th>
<th>Middle Modulus (MPa)</th>
<th>Full Length Modulus (Mpa)</th>
</tr>
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<tbody>
<tr>
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<td>0.37</td>
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Table 6.3 $M_r$ vs. Moisture Content, A-2-4 12% Soil

<table>
<thead>
<tr>
<th>Moisture Content %</th>
<th>Confining Pressure (kPa)</th>
<th>Axial Load (kN)</th>
<th>Dev. Stress (kPa)</th>
<th>Bulk Stress (kPa)</th>
<th>Middle Modulus (MPa)</th>
<th>Full Length Modulus (Mpa)</th>
</tr>
</thead>
<tbody>
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<td>87.46</td>
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<td>89.86</td>
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<td>46.12</td>
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### Table 6.4 $M_f$ vs. Moisture Content, SR-70 A-2-4 14% Soil

<table>
<thead>
<tr>
<th>Moisture Content</th>
<th>Confining Pressure</th>
<th>Axial Load</th>
<th>Dev. Stress</th>
<th>Bulk Stress</th>
<th>Middle Modulus</th>
<th>Full Length Modulus</th>
</tr>
</thead>
<tbody>
<tr>
<td>%</td>
<td>kPa</td>
<td>kN</td>
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<td>MPa</td>
<td>Mpa</td>
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### Table 6.5 $M_f$ vs. Moisture Content, A-2-4 20% Soil

<table>
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<th>Axial Load</th>
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<th>Bulk Stress</th>
<th>Middle Modulus</th>
<th>Full Length Modulus</th>
</tr>
</thead>
<tbody>
<tr>
<td>%</td>
<td>kPa</td>
<td>kN</td>
<td>kPa</td>
<td>kPa</td>
<td>MPa</td>
<td>Mpa</td>
</tr>
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<td>87.44</td>
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</tr>
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<td>13.79</td>
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<td>98.38</td>
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<td>0.37</td>
<td>46.19</td>
<td>87.56</td>
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### Table 6.6 $M_f$ vs. Moisture Content, A-2-4 24% Soil

<table>
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<th>Moisture Content</th>
<th>Confining Pressure</th>
<th>Axial Load</th>
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<th>Bulk Stress</th>
<th>Middle Modulus</th>
<th>Full Length Modulus</th>
</tr>
</thead>
<tbody>
<tr>
<td>%</td>
<td>kPa</td>
<td>kN</td>
<td>kPa</td>
<td>kPa</td>
<td>MPa</td>
<td>Mpa</td>
</tr>
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<td>87.47</td>
<td>120.75</td>
<td>107.63</td>
</tr>
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<td>116.98</td>
<td>97.96</td>
</tr>
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Table 6.7 $M_r$ vs. Moisture Content, A-2-4 30% Soil

<table>
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<th>Axial Load</th>
<th>Dev. Stress</th>
<th>Bulk Stress</th>
<th>Middle Modulus</th>
<th>Full Length Modulus</th>
</tr>
</thead>
<tbody>
<tr>
<td>%</td>
<td>kPa</td>
<td>kN</td>
<td>kPa</td>
<td>kPa</td>
<td>Mpa</td>
<td>Mpa</td>
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Table 6.8 $M_r$ vs. Moisture Content, Miami Oolite Soil

<table>
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<tr>
<th>Moisture Content</th>
<th>Confining Pressure</th>
<th>Axial Load</th>
<th>Dev. Stress</th>
<th>Bulk Stress</th>
<th>Middle Modulus</th>
<th>Full Length Modulus</th>
</tr>
</thead>
<tbody>
<tr>
<td>%</td>
<td>kPa</td>
<td>kN</td>
<td>kPa</td>
<td>kPa</td>
<td>Mpa</td>
<td>Mpa</td>
</tr>
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<td>46.05</td>
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</tr>
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<td>87.51</td>
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<td>124.87</td>
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<td>46.05</td>
<td>87.42</td>
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<td>95.21</td>
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<td>0.37</td>
<td>46.09</td>
<td>87.46</td>
<td>95.84</td>
<td>77.11</td>
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Table 6.9 Summary of Reduction in $M_r$

<table>
<thead>
<tr>
<th>Soil Type</th>
<th>Properties</th>
<th>Before Soaking</th>
<th>After Soaking</th>
<th>Change in Value</th>
<th>% Reduction in $M_r$</th>
</tr>
</thead>
<tbody>
<tr>
<td>A-3 4%, Levy County</td>
<td>Moisture Content</td>
<td>9.60%</td>
<td>15.15%</td>
<td>+5.6%</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$M_r$ (MPa)</td>
<td>157.7</td>
<td>149</td>
<td>-8.70</td>
<td>-5.5%</td>
</tr>
<tr>
<td>A-3 8%, SR-70</td>
<td>Moisture Content</td>
<td>11.4%</td>
<td>13.7%</td>
<td>2.3%</td>
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</tr>
<tr>
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<td>$M_r$ (MPa)</td>
<td>166.8</td>
<td>146.5</td>
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<td>-12.2%</td>
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<td>+2.5%</td>
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</tr>
<tr>
<td></td>
<td>$M_r$ (MPa)</td>
<td>120.6</td>
<td>110.7</td>
<td>-9.90</td>
<td>-8.2%</td>
</tr>
<tr>
<td>A-2-4 14%, SR70</td>
<td>Moisture Content</td>
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<td>11.8%</td>
<td>+1.0%</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$M_r$ (MPa)</td>
<td>239.36</td>
<td>149</td>
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<td>-37.8%</td>
</tr>
<tr>
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<td>11.9%</td>
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<td></td>
<td>$M_r$ (MPa)</td>
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</tr>
<tr>
<td></td>
<td>$M_r$ (MPa)</td>
<td>152.12</td>
<td>104.03</td>
<td>-48.09</td>
<td>-31.6%</td>
</tr>
</tbody>
</table>
Table 6.10 Classification of Moisture Effect by Rate of Reduction

<table>
<thead>
<tr>
<th>Reduction Rate</th>
<th>Moisture Effect</th>
<th>Soil Type</th>
<th>Max Dry Density (pcf)</th>
<th>LBR</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt;5%</td>
<td>Very Minor</td>
<td>A-3 Soil with 4% fines</td>
<td>106.5</td>
<td>22</td>
</tr>
<tr>
<td></td>
<td></td>
<td>A-2-4 soil with 20% fines</td>
<td>124.4</td>
<td>146</td>
</tr>
<tr>
<td>5-15%</td>
<td>Minor</td>
<td>A-3 soil with 8% fines</td>
<td>112.0</td>
<td>45</td>
</tr>
<tr>
<td></td>
<td></td>
<td>A-2-4 Soil with 12% fines</td>
<td>110.6</td>
<td>30</td>
</tr>
<tr>
<td>15-30%</td>
<td>Severe</td>
<td>A-2-4 Soil with 24% fines</td>
<td>116.3</td>
<td>69</td>
</tr>
<tr>
<td></td>
<td></td>
<td>A-2-4 soil with 30% fines</td>
<td>116.0</td>
<td>72</td>
</tr>
<tr>
<td>&gt;30%</td>
<td>Very Severe</td>
<td>SR 70 A-2-4 soil with 14% fines</td>
<td>122.0</td>
<td>124</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Miami Oolite A-1 soil</td>
<td>132.6</td>
<td>194</td>
</tr>
</tbody>
</table>

Table 6.11 Summary of Laboratory Resilient Moduli

| Soil          | OPTIMUM CONDITION | | | SOAKED CONDITION | | |
|---------------|------------------|-----------------|-----------------|-----------------|-----------------|
|               | Mr (MPa) | Moisture Content (%) | Degree of Saturation (%) | Mr (MPa) | Moisture Content (%) | Degree of Saturation (%) |
| Levy A-3      | 158 | 9.6 | 44.5 | 149 | 15.2 | 70.4 |
| (4%)          |      |   |    |     |     |     |
| SR 70 A-3     | 167 | 11.4 | 61.0 | 147 | 13.7 | 73.3 |
| (8%)          |      |   |    |     |     |     |
| A-2-4         | 121 | 12.1 | 62.3 | 111 | 14.6 | 75.2 |
| (12%)         |      |   |    |     |     |     |
| SR 70 A-2-4   | 239 | 10.8 | 76.4 | 149 | 11.8 | 83.5 |
| (14%)         |      |   |    |     |     |     |
| A-2-4         | 138 | 10.0 | 76.1 | 132 | 11.9 | 90.5 |
| (20%)         |      |   |    |     |     |     |
| A-2-4         | 118 | 10.0 | 60.1 | 92  | 11.9 | 71.5 |
| (24%)         |      |   |    |     |     |     |
| A-2-4         | 112 | 12.0 | 71.5 | 72  | 14.1 | 84.0 |
| (30%)         |      |   |    |     |     |     |
| Oolite        | 152 | 7.8 | 77.7 | 96  | 8.2  | 81.6 |

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### Table 6.12 Summary of tested materials characteristics

<table>
<thead>
<tr>
<th>Soil Properties</th>
<th>SR-70 A-3 (8%)</th>
<th>A-2-4 (12%)</th>
<th>SR-70 A-2-4 (14%)</th>
<th>A-2-4 (20%)</th>
<th>A-2-4 (24%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Passing 200 Sieves, %</td>
<td>8</td>
<td>12</td>
<td>14</td>
<td>20</td>
<td>24</td>
</tr>
<tr>
<td>Clay, %</td>
<td>6</td>
<td>3</td>
<td>10</td>
<td>8</td>
<td>5</td>
</tr>
<tr>
<td>Maximum Dry Density (pcf)</td>
<td>112.0</td>
<td>110.6</td>
<td>122.0</td>
<td>124.4</td>
<td>116.3</td>
</tr>
<tr>
<td>Optimum Moisture Content, %</td>
<td>11.5</td>
<td>12.1</td>
<td>10.5</td>
<td>10.0</td>
<td>10.7</td>
</tr>
<tr>
<td>LBR</td>
<td>45</td>
<td>30</td>
<td>124</td>
<td>146</td>
<td>69</td>
</tr>
<tr>
<td>Permeability (cm/sec)</td>
<td>$2.06 \times 10^{-3}$</td>
<td>$3.05 \times 10^{-4}$</td>
<td>$2.50 \times 10^{-4}$</td>
<td>$1.04 \times 10^{-4}$</td>
<td>$6.50 \times 10^{-5}$</td>
</tr>
<tr>
<td>Suction at OMC$^2$ (kPa)</td>
<td>22.8</td>
<td>441.6</td>
<td>74.0</td>
<td>329.6</td>
<td>378.4</td>
</tr>
</tbody>
</table>

### Table 6.13 Gradation Curve Properties

<table>
<thead>
<tr>
<th>Soil Properties</th>
<th>SR-70 A-3 (8%)</th>
<th>A-2-4 (12%)</th>
<th>SR-70 A-2-4 (14%)</th>
<th>A-2-4 (20%)</th>
<th>A-2-4 (24%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$D_{10}$ (mm)</td>
<td>0.081</td>
<td>0.05</td>
<td>0.001</td>
<td>0.037</td>
<td>0.0095</td>
</tr>
<tr>
<td>$D_{30}$ (mm)</td>
<td>0.15</td>
<td>0.099</td>
<td>0.13</td>
<td>0.091</td>
<td>0.082</td>
</tr>
<tr>
<td>$D_{60}$ (mm)</td>
<td>0.31</td>
<td>0.15</td>
<td>0.29</td>
<td>0.14</td>
<td>0.14</td>
</tr>
<tr>
<td>$C_u$</td>
<td>3.83</td>
<td>3.00</td>
<td>290.00</td>
<td>3.78</td>
<td>14.74</td>
</tr>
<tr>
<td>$C_c$</td>
<td>0.90</td>
<td>1.31</td>
<td>58.28</td>
<td>1.60</td>
<td>5.06</td>
</tr>
</tbody>
</table>

$^2$ Average suction value around OMC.
Table 6.14 Summary of Multiple Regression Model Trials

<table>
<thead>
<tr>
<th>Model Number</th>
<th>Equation</th>
<th>$R^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>(1)</td>
<td>$\ln(M_r) = 2.07 - 0.0409\omega + 0.0102\rho + 0.0239C_u - 0.117C_c + 0.0020\alpha$</td>
<td>54.2%</td>
</tr>
<tr>
<td>(2)</td>
<td>$\ln(M_r) = 3.24 - 0.0418\omega + 0.0202C_u - 0.0968C_c$</td>
<td>51.0%</td>
</tr>
<tr>
<td>(3)</td>
<td>$\ln(M_r) = 2.01 - 0.0410\omega + 0.0108\rho + 0.0243C_u - 0.119C_c$</td>
<td>54.2%</td>
</tr>
<tr>
<td>(4)</td>
<td>$\ln(M_r) = 3.05 - 0.0396\omega + 0.0291\rho + 0.0175C_u - 0.0853C_c$</td>
<td>53.7%</td>
</tr>
</tbody>
</table>

* Model (3) is the final chosen model.
** The meaning and unit of each symbol can be found in text body in this chapter.
Figure 6.1 $k_1$, $k_3$ vs. Moisture Content of Levy County A-3 Soil

Figure 6.2 $k_2$, $k_4$ vs. Moisture Content of Levy County A-3 Soil
Figure 6.3 Mr vs. Moisture Content at Different Confining Pressures for Levy County A-3 Soil

Figure 6.4 Mr vs. Moisture Content at Different Dev. Stresses of A-3 Levy County
Figure 6.5 Mr vs. Moisture Content, Levy County A-3 Soil

Figure 6.6 Mr vs. Moisture Content at Optimum and Soaked Conditions, Levy County A-3 Soil
Figure 6.7 $k_1$, $k_3$ vs. Moisture Content of SR-70 A-3 8% Soil

Figure 6.8 $k_2$, $k_4$ vs. Moisture Content of SR-70 A-3 8% Soil
Figure 6.9 Mr vs Moisture Content for SR-70 A-3 8% Soil at Different Confining Pressures

Figure 6.10 Mr vs Moisture Content for SR-70 A-3 8% Soil at Different Deviator Stresses
Figure 6.11 $M_r$ vs. Moisture Content, SR-70 A-3 8% Soil

Figure 6.12 $M_r$ vs. Moisture Content at Optimum and Soaked Conditions, SR-70 A-3 8% Soil
Figure 6.13 $k_1, k_3$ vs. Moisture Content of A-2-4 12% Soil

Figure 6.14 $k_2, k_4$ vs. Moisture Content of A-2-4 12% Soil
Figure 6.15 Mr vs. Moisture Content for A-2-4 12% Soil at Different Confining Pressures

Figure 6.16 Mr vs. Moisture Content for A-2-4 12% Soil at Different Deviator Stresses
confining pressure 13.79 kPa, Dev. Stress 46 kPa

Figure 6.17 Mr vs. Moisture Content, A-2-4 12% Soil

Confining Pressure 13.8 kPa, Dev. Stress 46.2 kPa

Figure 6.18 Mr vs. Moisture content at Optimum and Soaked Conditions, A-2-4 12% Soil
Figure 6.19 $k_1$, $k_3$ vs. Moisture Content of SR-70 A-2-4 14% Soil

Figure 6.20 $k_2$, $k_4$ vs. Moisture Content of SR-70 A-2-4 14% Soil
Figure 6.21 Mr vs. Moisture Content for SR-70 A-2-4 14% Soil at Different Confining Pressures

Figure 6.22 Mr vs. Moisture Content for SR-70 A-2-4 14% Soil at Different Deviator Stresses
Figure 6.23 Mr vs. Moisture Content, SR-70 A-2-4 14% Soil

Figure 6.24 Mr vs. Moisture Content at Optimum and Soaked Conditions, SR-70 A-2-4 14% Soil
Figure 6.25 $k_1, k_3$ vs. Moisture Content of A-2-4 20% Soil

Figure 6.26 $k_2, k_4$ vs. Moisture Content of A-2-4 20% Soil
Figure 6.27 Mr vs. Moisture Content for A-2-4 20% Soil at Different Confining Pressures

Figure 6.28 Mr vs. Moisture Content for A-2-4 20% Soil at Different Deviator Stresses
Figure 6.29 Mr vs. Moisture Content of A-2-4 20% Soil

Figure 6.30 Mr vs. Moisture Content at Optimum and Soaked conditions for A-2-4 20% Soil
Figure 6.31 $k_1$, $k_3$ vs. Moisture Content of A-2-4 24% Soil

Figure 6.32 $k_2$, $k_4$ vs. Moisture Content of A-2-4 24% Soil
Figure 6.33 $M_r$ vs. Moisture Content for A-2-4 24% Soil at Different Confining Pressures

Figure 6.34 $M_r$ vs. Moisture Content for A-2-4 24% Soil at Different Deviator Stresses
Figure 6.35 Mr vs. Moisture Content of A-2-4 24% Soil

Figure 6.36 Mr vs. Moisture Content at Optimum and Soaked Conditions, A-2-4 24% Soil
Figure 6.37 k1, k3 vs. Moisture Content of A-2-4 30% Soil

Figure 6.38 k2, k4 vs. Moisture Content of A-2-4 30% Soil
Figure 6.39 Mr vs. Moisture Content for A-2-4 30% Soil at Different Confining Pressures

Figure 6.40 Mr vs. Moisture Content for A-2-4 30% Soil at Different Deviator Stresses
Figure 6.41 Mr vs. Moisture Content, A-2-4 30% Soil

Figure 6.42 Mr vs. Moisture Content at Optimum and Soaked conditions, A-2-4 30% Soil
Figure 6.43 k1, k3 vs. Moisture Content of Crushed Miami Oolite (A-1)

Figure 6.44 k2, k4 vs. Moisture Content of Crushed Miami Oolite (A-1)
Figure 6.45 Mr vs. Moisture Content for Crushed Miami Oolite (A-1) at Different Confining Pressures

Figure 6.46 Mr vs. Moisture Content for Crushed Miami Oolite (A-1) at Different Deviator Stresses
Figure 6.47 Mr vs. Moisture Content of Crushed Miami Oolite (A-1)

Figure 6.48 Mr vs. Moisture Content at Optimum and Soaked Conditions, Crushed Miami Oolite (A-1)
Figure 6.49 Mr vs. Moisture Content for 8 Soils
Figure 6.50 Lab Resilient Moduli Summary (Average Values)

Figure 6.51 Mr vs. Dry Unit Weight at Optimum Moisture
Figure 6.52 Reduction Rate of Mr vs. Soil Type
(Note: A-2-4(30%) deduction rate was calculated by the regress equation of resilient modulus vs. moisture)

Figure 6.53 LBR vs. Soil Type
Figure 6.54 Gradation Curves for Five Subgrades

Figure 6.55 Model Prediction versus Lab Mr Results
Figure 6.56 Model Variation versus Moisture Content
CHAPTER 7 ANALYSIS OF TEST-PIT EXPERIMENTAL RESULTS

7.1 Test-pit Test
The test-pit test results are separated into two main parts: a) the moisture profile of tested subgrades as a result of ground water table variation; b) the resilient modulus of subgrade materials under designated plate loads as a result of those water table adjustments and moisture changes. The analysis of moisture profiles includes the drainage effect and capillary rise study. The analysis of the moisture effect resulting from the groundwater table changes for different subgrade materials is presented in this chapter.

7.2 Moisture Study
In this study, short term and long term moisture variations after drainage were evaluated for subgrade materials bearing different permeability values.

7.2.1 Drainage Analysis
The moisture variations after drainage are summarized in Table 7.1 & Table 7.2 for the eight subgrade materials. The short-term rate of moisture dissipation for Levy County A-3 soil is shown in Figure 7.1. The short-term rate of moisture dissipation for SR-70 A-3 Soil is shown in Figure 7.2. The long-term rate of moisture dissipation for SR-70 A-3 and A-2-4 soils are shown in Figures 7.3 and 7.4, respectively. The long-term rate of moisture dissipation for
A-2-4(12%), A-2-4(20%), A-2-4(24%), A-2-4(30%) and Oolite are shown in Figures 7.5, 7.6, 7.7, 7.8 and 7.9, respectively.

The difference in the absolute rate of drainage for the tested subgrades was attributed to the difference in coefficient of permeability and suction value, which were related to their void ratio (gradation and grain size). Here with the passing No.200 fines increased (from 4% for Levy County A-3 to 30% for A-2-4 30% soil), the coefficient of permeability decreased (from the order of magnitude $10^{-3}$ to $10^{-5}$ cm/sec, refer to Table 4.19 and Figure 4.22) and the suction value increased (refer to Figure 4.21). The result was a more time-consuming moisture dissipation process before the final equilibrium was established (Liu, 2001).

### 7.2.2 Discussion

The rate of drainage was directly related to the permeability of the soil. Under a saturated (or nearly saturated) state, the permeability for a specific soil was a function of the void ratio. As the draining process continued, the soil became partially saturated. In this case, the permeability was significantly affected by the combined change in void ratio and degree of saturation. Since water flowed through the pore space occupied also by water, the percentage of the voids filled with water was an important factor. Because the water dissipated first from the large pores under drainage (from flooded condition), the air took its place afterwards. Water had to flow through smaller pores filled with water, which provided a more narrow passage for downward seepage. On the other hand, with the increase of soil suction (because of a decrease in moisture) as drainage
continued, the air-soil interface (capillary meniscus) was drawn closer to the soil particles, which led to a further decrease in the volume of void filled with water. As a result, the permeability of soil (or the rate of drainage) rapidly decreased after a short-term drainage.

The moisture reduction according to drainage for Levy A-3, SR-70 A-3, SR-70 A-2-4, A-2-4(12%), A-2-4(20%), A-2-4(24%), A-2-4(30%) and Oolite are shown in Figures 7.10, 7.11, 7.12, 7.13, 7.14, 7.15, 7.16 and 7.17, respectively. Generally, the closer to the top of subgrade, the more moisture reduction occurred due to drainage. For A-2-4(30%) and Oolite, there is no big moisture change for all the sensors (Liu, 2001).

7.3 Test-pit Equivalent Modulus Study

The equivalent modulus values for the eight subgrade materials under different ground water tables are described and analyzed here using the experimental results presented in Chapter 5. The test results will be the topic of further discussion in Chapter 8 as a case study.

7.3.1 Observation of experimental Results

Phase I: Levy County A-3 Soil

Since the moisture differences within top soil under the water table levels at -20 in., 0.0 in., +12 in. were quite limited (Figure 5.1), they led to no considerable changes in resilient modulus for the A-3 sandy soil. Also they showed that the moisture increase in the middle and lower part of the soil bulk had only a limited influence on the decrease of the soil modulus.
In general, the equivalent modulus for this soil was less sensitive to the variation of moisture content (Figures 5.12, 5.13, and 5.14), especially in a situation when the moisture content of the subgrade near the loading point was below optimum moisture (non-flooded situation).

Phase II: SR-70 A-3 Soil

No significant difference existed for the equivalent modulus when moisture differences within the top of the subgrade soil were quite limited for low ground water table (Figure 5.15). Although a significant difference existed in the equivalent modulus between the drained condition and water table at 12 in. above the embankment (Figures 5.16 and 5.17), generally the equivalent modulus increased slightly with the decrease of moisture content in A-3 soil. In flooded conditions (Figure 5.18), when moisture contents reached to a certain extent, the differences in soil modulus could be insignificant. In the 9/29/99 plate load test (Test No. 2-4), no significant equivalent modulus change was detected when the water level was adjusted from +12 in. to +36 in. above embankment, even though there was quite a difference for moisture contents and degrees of saturation. The converted degree of saturation under test conditions can be found from Table 7.5 to Table 7.12 for all the eight phases.

Since the loading location remained the same in all previous tests for this soil before Test No. 2-6, it might be suspected that the test results would not be too satisfactory due to preloading of the site. However, the relocated test (Test No. 2-5 conducted on 10/5/99
under the same +36 in. water table), revealed a temporary decrease for the value of equivalent modulus between 50 and 10,000 load cycles, but eventually achieved the same result for higher repetitions of load.

**Phase III: SR-70 A-2-4 Soil**

No obvious moisture difference existed within the topsoil (Figure 5.3). The decrease of modulus was caused mainly by the increase of moisture content within the middle and bottom layers of soil. Thus, raised water table from 0.0 to 12 in. did make a difference for the equivalent modulus of this A-2-4 soil.

For the A-2-4 soil, the resilient modulus was more sensitive to the moisture change (and ground water level) in the subgrade as illustrated in Figures 5.19, 5.20, 5.21 and 5.22.

**Phase IV: A-2-4(12%) Soil**

From Figures 5.23A and 5.23B, when the water table was raised from 0 in. to +12 in., the moisture had little difference in each layer of the subgrade. The modulus did not change much either. However, when the water table was raised again from +12 in. to +36 in., the modulus had a significant decrease as shown in Figure 5.24. So, the A-2-4 (12%) soil is sensitive to the change of high groundwater levels.

**Phase V: A-2-4(20%) Soil**

From Figures 5.25 and 5.26, when the water table was raised from 0 in. to +12 in. and again from +12 in. to +36 in., there was a noticeable decrease of the resilient modulus at each stage. The A-2-4(20%) soil
is also sensitive to the moisture change in terms of equivalent modulus.

**Phase VI: A-2-4(24%) Soil**

From Figures 5.27 and 5.28, there was a noticeable decrease of the resilient modulus when the water level was raised from 0 in. to +12 in. and again when the water level was raised from +12 in. to +36 in. The A-2-4(24%) is also little sensitive to the moisture change.

**Phase VII: A-2-4(30%) Soil**

The equivalent modulus and moisture profile data were summarized in Figures 5.29 and 5.30. When the water table was raised from 0 in. to +12 in., the moisture had no change in the soil, but the modulus had an obvious decrease. When the water table was raised from +12 in. to +36 in., the modulus was significantly reduced to about 35%. This soil type, A-2-4(30%), is very sensitive to the moisture change in response to the high groundwater levels. It was abnormal to observe that the moisture profiles did not change due to the change in groundwater levels. Explanation was that the TDR probes were damaged during compaction and installation.

**Phase VIII: Oolite**

Because the Oolite is very stiff, only modulus data under 50 psi plate load test were measured with a lime rock base layer. The modulus was almost reduced to 30% when the water table was raised from +12 in. to +36 in. However, no significant change of moisture profile was shown in Figure 5.31B.
7.3.2 Analysis of Experimental Results

The plate load test results are summarized in Table 7.13, Table 7.14 and are presented in Figures 7.18, 7.19, 7.20, 7.21 and 7.22. The resilient modulus values of different types of soil were affected to a different extent under various levels of groundwater table. For the change of water table level from 0 in. to +12 in. above embankment, there were not much change for equivalent modulus values of most soils except for A-2-4 (24%) soil and Oolite. The A-2-4 (24%) soil had a modulus reduction about 35% as shown in Figure 7.21. Oolite had a modulus reduction about 29% (Figure 7.21). For the change of water table level from +12 in. to +36 in., there were significant changes of modulus values for all the seven soils except for A-2-4 (20%). The most sensitive soils are SR-70 A-2-4, A-2-4 (30%), and Oolite, they had reduction rates of 73%, 67% and 69% in modulus values, respectively (see Figure 7.22).

There was no simple relationship between the resilient modulus reductions and the percent of fines in soils. From the study data, there were two sandy soils, i.e., Levy A-3 and SR-70 A-3. However, they were not sensitive to the water table adjustments (moisture change in the soil). But for the A-2-4 soils with fines, some are very sensitive (SR-70 A-2-4 and A-2-4 (30%)), and some are not (A-2-4 (12%), A-2-4 (20%)).

The fluctuation of resilient modulus values as a result of the change in levels of groundwater table illustrated that the mere soil structure itself was not the controlling factor for the elastic deformation. But the presence of water did not necessarily mean a
decrease in resilient modulus of soils. For example, no significant difference occurred for the resilient modulus of extremely coarse gravel whether it was flooded or completely drained.

7.3.3 Discussion
In the literature, the suggestion has been raised that correlating the resilient behavior of soil with the suction value it assumed, may be more appropriate than using moisture content or degree of saturation as indicators for the analysis of subgrade resilient behavior. For a specific subgrade soil, the resilient modulus is more or less dependent on the capillary moisture developed from the ground water table. However, for different subgrade materials, the resilient modulus is more dependent on the capillary potential of each individual soil (suction value) rather than capillary moisture accumulated within a capillary zone (Liu, 2001).

So many properties of soils can affect resilient modulus value directly or indirectly such as clay content, permeability, suction value, gradation, etc. This research study was focused more on the moisture effect to the resilient modulus of pavement subgrades. Compared the modulus changes due to moisture effect in the test-pit with that of the laboratory resilient modulus tests, the results were correlative. Both the test-pit and laboratory tests showed the same soils (SR-70 A-2-4, A-2-4 30%, and Oolite) were very sensitive to water content change though at different reduction rates (see Figure 7.22). In test-pit tests, the equivalent modulus values were dependent on the effect of the bottom embankment layer as well as the top limerock layer. Therefore, the equivalent modulus obtained from plate load
test was not exactly the resilient modulus for the subgrade soil.

7.3.4 Other Findings with Respect to Plate Load Test

One of the concerns for an experimental program of test-pit test was to find out whether the cyclic loading has any effect on the moisture content of the subgrade materials in the test-pit. For all of the plate load tests conducted in the test-pit, moisture readings from the TDR probes 3 in. to 33 in. below the plate loading area showed that there were no changes of moisture content before and after the implementation of cyclic loading.

For the TDR probes deployed within the test-pit, they had well served their function as moisture detecting sensors. For a precise measurement of moisture content, it would be better to calibrate TDR probes with each individual soil before that soil was compacted into the test-pit for investigation.

From Figure 7.20, the beneficial effect of adding a base layer with limerock is clearly demonstrated. When a 5 in. thick layer of limerock was added and the load was increased from 20 psi to 50 psi, the equivalent modulus values were almost doubled under the same level of water table at +12 in. the modulus value for limerock layer may be estimated from this simple comparison. If the modulus value for embankment may also be obtained from previous tests, then the subgrade layer modulus under various levels of high groundwater table can be computed from simulation computer programs. In next section, layered system will be established and ELSYM5 and KENLAYER program will be used to estimate resilient modulus of subgrade for each soil type.
7.4 Layered System for Test-pit

7.4.1 Purpose
In reality, the pavement has several layers. For a general pavement profile, there are asphalt concrete layer, base layer, subgrade layer and embankment layer from the top to the bottom. For a more complicated layer system, there maybe other layers such as asphalt crack relief layer, drainage layer, and so on. In test-pit tests, there were at least two layers, embankment and subgrade layers. For some tests, the third layer, 5-in. limerock layer was added on the top. Because the water table had some different levels in different periods, the subgrade layer should be divided into several layers. For simplifying the problem, we just make all the subgrade as one layer. The purpose for setting up a layer system for test-pit test is to get the modulus for each layer (actually for the 36 in. thick subgrade layer for each soil type) instead of the equivalent modulus for all the layers. Then the layer modulus for each subgrade can be compared with the results coming from the lab tests.

7.4.2 Layered System Calculations and Analysis
The procedures of calculation for layer moduli are same for ELSYM5 and KENLAYER. The flow chart of the calculation is as follows:
The limerock layer modulus was calculated at first. When the water table was stabled at +12 in. above the embankment, the equivalent modulus was gotten in both with and without limerock layer condition. So using two-layer system, the limerock layer modulus for different subgrade material can be achieved. The limerock layer modulus was summarized in Table 7.15. From the results, the limerock had a variance. The mean value for limerock layer modulus is around 204286 psi (1409 MPa) by ELSYM5 and 326571 psi (2252 Mpa) by KENLAYER. Based on two-layer system, the subgrade layer modulus could be calculated for different soil types when water table at 0 in. and +12 in. above embankment (Table 7.16 and Table 7.17). Based on three-layer system, the subgrade layer modulus could be calculated for different soils types when water table at +36 in. above embankment (Table 7.18). Table 7.19 and Figure 7.23 summarized the results for total seven soils. From the results, when water table increased from 0 in. to +12 in., the layer modulus for subgrade decreased in a degree. For

When the water table continued to increase from +12 in. to +36 in. above embankment, the subgrade layer would be totally emerged in water. The layer modulus for each subgrade had a big drop especially for SR-70 A-2-4 and A-2-4 (30%) soils. These results also proved the theory that water can make a great effect to the modulus for the pavement. At least 24 in. (2 ft) base clearance for each subgrade soil type is recommended.

From Table 7.19 and Figure 7.23, comparing the results from ELSYM5 and KENLAYER, the layer moduli from KENLAYER is around 30% bigger than those from ELSYM5 when water table is at 0 in. and +12 in. above the embankment. There is no much difference for the layer moduli from both programs when water table is at +36 in. Figure 7.24 shows the reduction rates for the eight subgrade soils from water table at +12 inch to water table at +36 inch. It is well known that granular materials and subgrade soils are nonlinear with and elastic modulus varying with the level of stresses. The nonlinear material properties have been incorporated in KENLAYER. According to the theoretical development of KENLAYER, KENLAYER is adequate to estimate the layer modulus in the study (theory in ELSYM5 is not so clear at this point due to material availability) (see Appendix N). In further discussion, only KENLAYER results of the layer modulus were used. The comparison between the layer modulus with the laboratory resilient modulus will be discussed in Chapter 8 to show that there is correlation between those two results.
Table 7.1 Moisture Profile after Drainage for Subgrade Materials in Test-pit (1)

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<tr>
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| A-2-4 (24%)     |     |     |     |     |     |     |             |

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| A-2-4 (30%)     |     |     |     |     |     |     |             |

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| Oolite          |     |     |     |     |     |     |             |

Table 7.2 Moisture Profile after Drainage for Subgrade Materials in Test-pit (2)
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<td>7 days</td>
<td>35 days</td>
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<td>14.92</td>
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<td>16.31</td>
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<td>11.42</td>
<td>8.62</td>
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</tr>
<tr>
<td>Elapse Time</td>
<td>0 hour</td>
<td>1 day</td>
<td>7 days</td>
<td>35 days</td>
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<td></td>
</tr>
<tr>
<td>Oolite</td>
<td>3.18</td>
<td>3.25</td>
<td>3.79</td>
<td>6.53</td>
<td>4.57</td>
<td>4.37</td>
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<td>3.18</td>
<td>3.25</td>
<td>3.79</td>
<td>6.54</td>
<td>4.57</td>
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<td>3.18</td>
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<td>6.61</td>
<td>4.56</td>
<td>4.44</td>
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<tr>
<td>Elapse Time</td>
<td>0 hour</td>
<td>1 day</td>
<td>7 days</td>
<td>35 days</td>
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</table>
Table 7.4 Summary of Capillary Rise for Subgrade Materials in Test-pit Test

<table>
<thead>
<tr>
<th>Soil Type</th>
<th>Water Table (inches)</th>
<th>Capillary Rise (inches)</th>
<th>Moisture Stabilized at each Level</th>
<th>Moisture Data recorded from</th>
<th>Time Period (days)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Levy County A-3 Soil (4%)</td>
<td>-20 to 0.0</td>
<td>26</td>
<td>Yes</td>
<td>1/5/99 to 2/3/99</td>
<td>29</td>
</tr>
<tr>
<td></td>
<td>0.0 to +12</td>
<td>&gt;24</td>
<td>Yes</td>
<td>2/5/99 to 2/23/99</td>
<td>19</td>
</tr>
<tr>
<td>SR-70 A-3 Soil (8%)</td>
<td>-24 to -12</td>
<td>13+12 *</td>
<td>Yes</td>
<td>5/17/99 to 5/31/99</td>
<td>14</td>
</tr>
<tr>
<td></td>
<td>-12 to 0.0</td>
<td>21</td>
<td>Yes</td>
<td>6/10/99 to 6/27/99</td>
<td>17</td>
</tr>
<tr>
<td></td>
<td>0.0 to +12</td>
<td>21</td>
<td>Yes</td>
<td>7/22/99 to 8/20/99</td>
<td>28</td>
</tr>
<tr>
<td>SR-70 A-2-4 Soil (14%)</td>
<td>-24 to -12</td>
<td>15+12 **</td>
<td>Yes</td>
<td>5/17/99 to 6/10/99</td>
<td>24</td>
</tr>
<tr>
<td></td>
<td>-12 to 0.0</td>
<td>&gt;33</td>
<td>No</td>
<td>6/10/99 to 7/22/99</td>
<td>42</td>
</tr>
<tr>
<td></td>
<td>0.0 to +12</td>
<td>15</td>
<td>No</td>
<td>7/22/99 to 9/1/99</td>
<td>40</td>
</tr>
<tr>
<td>A-2-4 (12%)</td>
<td>-24 to 0.0</td>
<td>33</td>
<td>Yes</td>
<td>8/3/00 to 9/25/00</td>
<td>53</td>
</tr>
<tr>
<td>A-2-4 (20%)</td>
<td>-24 to 0.0</td>
<td>0</td>
<td>Yes</td>
<td>8/3/00 to 9/25/00</td>
<td>53</td>
</tr>
<tr>
<td>A-2-4 (24%)</td>
<td>-24 to 0.0</td>
<td>33</td>
<td>Yes</td>
<td>8/3/00 to 9/25/00</td>
<td>53</td>
</tr>
<tr>
<td>A-2-4 (30%)</td>
<td>-24 to 0.0</td>
<td>27</td>
<td>Yes</td>
<td>7/6/00 to 8/14/00</td>
<td>39</td>
</tr>
<tr>
<td>Oolite</td>
<td>-24 to 0.0</td>
<td>15</td>
<td>Yes</td>
<td>7/6/00 to 8/14/00</td>
<td>39</td>
</tr>
</tbody>
</table>

* Capillary rise passes through 12 in. standard A-3 sand within embankment
** Capillary rise passes through 12 in. standard A-3 sand within embankment
### Table 7.5 Levy County A-3 Soil, Degree of Saturation under Plate Load Test

<table>
<thead>
<tr>
<th>Elevation above Embankment (inch)</th>
<th>Dry Density ($\gamma_{pd}$)</th>
<th>Water Content (W %) &amp; Degree of Saturation (S %) under Different Water Table of Plate Load Test (( S% = W \times G_s \times \gamma_{pd} / (\gamma_w \times G_s - \gamma_{pd}) ))</th>
</tr>
</thead>
<tbody>
<tr>
<td>33</td>
<td>107.6 16.91</td>
<td>5.2 24.8 4.5 21.4 5.5 26.2 6.2 29.5 6.2 29.5 15.0 71.5 15.0 71.5</td>
</tr>
<tr>
<td>27</td>
<td>106.9 16.80</td>
<td>7.2 33.7 6.8 31.8 9.1 42.6 9.5 44.5 9.5 44.5 14.7 68.8 14.7 68.8</td>
</tr>
<tr>
<td>21</td>
<td>107.5 16.89</td>
<td>7.4 35.2 8.0 38.0 13.2 62.7 14.0 66.6 14.0 66.6 14.8 70.4 14.8 70.4</td>
</tr>
<tr>
<td>15</td>
<td>107.1 16.83</td>
<td>8.6 40.5 10.9 51.3 14.9 70.1 15.7 73.9 15.7 73.9 16.3 76.7 16.4 77.2</td>
</tr>
<tr>
<td>9</td>
<td>107.2 16.85</td>
<td>9.9 46.7 14.5 68.4 15.2 71.7 15.7 74.1 15.7 74.1 16.3 76.9 16.4 77.4</td>
</tr>
<tr>
<td>3</td>
<td>107.7 16.92</td>
<td>12.9 61.6 15.1 72.2 15.8 75.5 16.3 77.9 16.3 77.9 16.7 79.8 16.7 79.8</td>
</tr>
<tr>
<td>Test Number</td>
<td>1-1 1-2 1-3 1-4 1-5 1-6 1-7</td>
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</tr>
</tbody>
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### Table 7.6 SR-70 A-3 Soil, Degree of Saturation under Plate Load Test

<table>
<thead>
<tr>
<th>Elevation above Embankment (inch)</th>
<th>Dry Density ($\gamma_{pd}$)</th>
<th>Water Content (W %) &amp; Degree of Saturation (S %) under Different Water Table of Plate Load Test (( S% = W \times G_s \times \gamma_{pd} / (\gamma_w \times G_s - \gamma_{pd}) ))</th>
</tr>
</thead>
<tbody>
<tr>
<td>33</td>
<td>112.4 17.66</td>
<td>6.2 33.5 6.1 33.0 6.7 36.2 6.8 36.7 8.0 43.2 17.1 92.4 14.5 78.4</td>
</tr>
<tr>
<td>27</td>
<td>110.2 17.32</td>
<td>8.4 42.8 8.3 42.3 8.9 45.4 9.7 49.5 10.7 54.6 19.8 100.0 15.4 78.5</td>
</tr>
<tr>
<td>21</td>
<td>110.6 17.38</td>
<td>10.1 52.0 10.0 51.5 10.6 54.6 13.4 69.0 13.8 71.1 21.6 100.0 16.1 83.0</td>
</tr>
<tr>
<td>15</td>
<td>109.8 17.25</td>
<td>10.7 54.0 10.6 53.5 11.2 56.5 18.8 94.9 19.3 97.4 20.6 100.0 15.6 78.7</td>
</tr>
<tr>
<td>9</td>
<td>110.4 17.35</td>
<td>10.6 54.3 10.5 53.8 13.4 68.7 20.6 100.0 20.4 100.0 20.2 100.0 17.9 91.7</td>
</tr>
<tr>
<td>3</td>
<td>109.9 17.27</td>
<td>8.6 43.5 8.6 43.5 17.2 87.0 16.7 84.5 16.7 84.5 16.9 85.5 15.4 77.9</td>
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<td>2-1 2-2 2-3 2-4 2-5 2-6 2-7</td>
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Table 7.7 SR-70 A-2-4 Soil, Degree of Saturation under Plate Load Test

<table>
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<tr>
<th>Elevation above Embank-ment (inch)</th>
<th>Dry Density ($\gamma_{soi}$)</th>
<th>Water Content (W %) &amp; Degree of Saturation (S %) under Different Water Table of Plate Load Test (S% = WxGs/($\gamma_{soi}$ - $\gamma_{w}$))</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>US lb/ft$^3$</td>
<td>SI kN/m$^3$</td>
</tr>
<tr>
<td>33</td>
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<td>110.6</td>
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<td>3-2</td>
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Table 7.8 A-2-4 (12%), Degree of Saturation under Plate Load Test

<table>
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<th>Elevation above Embank-ment (inch)</th>
<th>Dry Density ($\gamma_{soi}$)</th>
<th>Water Content (W %) &amp; Degree of Saturation (S %) under Different Water Table of Plate Load Test (S% = WxGs/($\gamma_{soi}$ - $\gamma_{w}$))</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>US lb/ft$^3$</td>
<td>SI kN/m$^3$</td>
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<tr>
<td>33</td>
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<td>4-2</td>
</tr>
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Table 7.9 A-2-4 (20%), Degree of Saturation under Plate Load Test

<table>
<thead>
<tr>
<th>Elevation above Embankment (inch)</th>
<th>Dry Density ($\gamma_{pd}$)</th>
<th>Water Content (W %) &amp; Degree of Saturation (S %) under Different Water Table of Plate Load Test ($S% = W \times G_s \times \gamma_{pd} / (\gamma_w \times G_s - \gamma_{pd})$)</th>
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<tbody>
<tr>
<td></td>
<td>US</td>
<td>SI</td>
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<td>19.55</td>
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Test Number 5-1 5-2 5-3 5-4 5-5 5-6

Table 7.10 A-2-4 (24%), Degree of Saturation under Plate Load Test

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<tr>
<th>Elevation above Embankment (inch)</th>
<th>Dry Density ($\gamma_{pd}$)</th>
<th>Water Content (W %) &amp; Degree of Saturation (S %) under Different Water Table of Plate Load Test ($S% = W \times G_s \times \gamma_{pd} / (\gamma_w \times G_s - \gamma_{pd})$)</th>
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<tr>
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<td>SI</td>
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<td>18.28</td>
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<td>116.3</td>
<td>18.28</td>
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<td>116.3</td>
<td>18.28</td>
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<td>116.3</td>
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<td>18.28</td>
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Test Number 6-1 6-2 6-3 6-4 6-5 6-6
Table 7.11 A-2-4 (30%), Degree of Saturation under Plate Load Test

<table>
<thead>
<tr>
<th>Elevation above Embankment (inch)</th>
<th>Dry Density ($\gamma_{pd}$)</th>
<th>Water Content (W %) &amp; Degree of Saturation (S %) under Different Water Table of Plate Load Test ($S% = W \times G_s \times \gamma_{pd} / (\gamma_{wm} \times G_s - \gamma_{pd})$)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>US lb/ft$^3$</td>
<td>SI kN/m$^3$</td>
</tr>
<tr>
<td>33</td>
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<td>18.23</td>
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<td>3</td>
<td>116</td>
<td>18.23</td>
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Table 7.12 Oolite, Degree of Saturation under Plate Load Test

<table>
<thead>
<tr>
<th>Elevation above Embankment (inch)</th>
<th>Dry Density ($\gamma_{pd}$)</th>
<th>Water Content (W %) &amp; Degree of Saturation (S %) under Different Water Table of Plate Load Test ($S% = W \times G_s \times \gamma_{pd} / (\gamma_{wm} \times G_s - \gamma_{pd})$)</th>
</tr>
</thead>
<tbody>
<tr>
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<td>US lb/ft$^3$</td>
<td>SI kN/m$^3$</td>
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<tr>
<td>33</td>
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<td>20.84</td>
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<td>20.84</td>
</tr>
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<td>3</td>
<td>132.6</td>
<td>20.84</td>
</tr>
<tr>
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</table>
Table 7.13 Summary of Plate Load Test for Subgrade Materials

<table>
<thead>
<tr>
<th>Water Table (in.)</th>
<th>Test No.</th>
<th>Limerock</th>
<th>Plate Load (psi)</th>
<th>Moisture Range (from bottom to top) (%)</th>
<th>Average EQ. Modulus after 10000 Cycles (MPa)</th>
<th>EQ Modulus Range after 100 Cycles (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>-20.0</td>
<td>1-1</td>
<td>NO</td>
<td>20</td>
<td>12.9---5.2</td>
<td>178.02</td>
<td>127.53 -- 149.76</td>
</tr>
<tr>
<td>0.0</td>
<td>1-2</td>
<td>NO</td>
<td>20</td>
<td>15.1---4.5</td>
<td>144.7</td>
<td></td>
</tr>
<tr>
<td>+12.0</td>
<td>1-3</td>
<td>NO</td>
<td>20</td>
<td>15.8---5.5</td>
<td>131.57</td>
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</tr>
<tr>
<td>+12.0</td>
<td>1-4</td>
<td>YES</td>
<td>20</td>
<td>16.3---6.2</td>
<td>226.37</td>
<td>141.57 -- 229.32</td>
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<td>+36.0</td>
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<td>20</td>
<td>16.7---14.7</td>
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<td>50</td>
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<td>50</td>
<td>16.7---14.7</td>
<td></td>
<td></td>
</tr>
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</table>

<table>
<thead>
<tr>
<th>Water Table (in.)</th>
<th>Test No.</th>
<th>Limerock</th>
<th>Plate Load (psi)</th>
<th>Moisture Range (from bottom to top) (%)</th>
<th>Average EQ. Modulus after 10000 Cycles (MPa)</th>
<th>EQ Modulus Range after 10000 Cycles (MPa)</th>
</tr>
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<tbody>
<tr>
<td>0.0</td>
<td>2-1</td>
<td>NO</td>
<td>20</td>
<td>17.2---6.7</td>
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<td>157.95 -- 216.45</td>
</tr>
<tr>
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<td>NO</td>
<td>20</td>
<td>20.6---6.8</td>
<td>174.49</td>
<td></td>
</tr>
<tr>
<td>-24.0</td>
<td>2-3</td>
<td>YES</td>
<td>50</td>
<td>10.7---6.2</td>
<td>499.05</td>
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<td>-24.0</td>
<td>2-4</td>
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<td>50</td>
<td>21.6---17.1</td>
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<td>50</td>
<td>21.5---17.2</td>
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<td>17.9---14.5</td>
<td>207.95</td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>Water Table (in.)</th>
<th>Test No.</th>
<th>Limerock</th>
<th>Plate Load (psi)</th>
<th>Moisture Range (from bottom to top) (%)</th>
<th>Average EQ. Modulus after 10000 Cycles (MPa)</th>
<th>EQ Modulus Range after 10000 Cycles (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0</td>
<td>3-1</td>
<td>NO</td>
<td>20</td>
<td>14.4---8.1</td>
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<td>150.93 -- 188.37</td>
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<tr>
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<td>3-2</td>
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<td>18.3---8.1</td>
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<td>233.04</td>
<td>231.32 -- 401.41</td>
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<tr>
<td>+12.0</td>
<td>3-5</td>
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<td>50</td>
<td>18.3---9.7---11.4</td>
<td>226.57</td>
<td>52.56 -- 251.55</td>
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<td>+36.0</td>
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<td>105.73</td>
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<tr>
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<td>14.0---10.0---22.7</td>
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Table 7.13-continued

<table>
<thead>
<tr>
<th>Water Table (in.)</th>
<th>Test No.</th>
<th>Limerock</th>
<th>Plate Load (psi)</th>
<th>Moisture Range (from bottom to top) (%)</th>
<th>Average EQ. Modulus after 10000 Cycles (MPa)</th>
<th>EQ Modulus Range for Comparison (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0</td>
<td>4-1</td>
<td>NO</td>
<td>20</td>
<td>10.38---4.75</td>
<td>109.44</td>
<td>105.92---111.77</td>
</tr>
<tr>
<td>+12.0</td>
<td>4-2</td>
<td>NO</td>
<td>20</td>
<td>10.77---6.39</td>
<td>107.01</td>
<td>105.72---108.35</td>
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<tr>
<td>+12.0</td>
<td>4-3</td>
<td>YES</td>
<td>50</td>
<td>11.11---7.69</td>
<td>217.11</td>
<td>189.65---223.81</td>
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<tr>
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<td>4-4</td>
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<td>50</td>
<td>11.15---7.68</td>
<td>195.54</td>
<td></td>
</tr>
<tr>
<td>+36.0</td>
<td>4-5</td>
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<td>50</td>
<td>11.3---11.05</td>
<td>148.18</td>
<td>145.75---151.36</td>
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A-2-4(12%) Soil #200 12% Passing

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<th>Water Table (in.)</th>
<th>Test No.</th>
<th>Limerock</th>
<th>Plate Load (psi)</th>
<th>Moisture Range (from bottom to top) (%)</th>
<th>Average EQ. Modulus after 10000 Cycles (MPa)</th>
<th>EQ Modulus Range for Comparison (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0</td>
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<td>20</td>
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<td>159.9</td>
<td>151.52---167.66</td>
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<tr>
<td>+12.0</td>
<td>5-2</td>
<td>NO</td>
<td>20</td>
<td>9.58---4.64</td>
<td>154.43</td>
<td>138.89---156.98</td>
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<tr>
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<td>9.58---3.28</td>
<td>144.15</td>
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<td>50</td>
<td>9.6---3.73</td>
<td>189.74</td>
<td>185.19---244.26</td>
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<tr>
<td>+36.0</td>
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<td>YES</td>
<td>50</td>
<td>9.61---8.02</td>
<td>210.64</td>
<td>204.14---217.62</td>
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A-2-4(20%) Soil #200 20% Passing

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<th>Water Table (in.)</th>
<th>Test No.</th>
<th>Limerock</th>
<th>Plate Load (psi)</th>
<th>Moisture Range (from bottom to top) (%)</th>
<th>Average EQ. Modulus after 10000 Cycles (MPa)</th>
<th>EQ Modulus Range for Comparison (MPa)</th>
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<td>163.79---172.25</td>
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<td>109.19---122.13</td>
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<td>7.36---6.05</td>
<td>186.14</td>
<td>176.43---191.71</td>
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<td>7.39---6.06</td>
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<td>7.58---13.05</td>
<td>138.31</td>
<td>121.92---146.36</td>
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<td>Limerock</td>
<td>Plate Load (psi)</td>
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<td>EQ Modulus Range for Comparison (Mpa)</td>
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<td>----------------------------------------</td>
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<td>---------------------------------------</td>
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<td>155.69---160.52</td>
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<td>110.46---159.62</td>
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<td>79.94</td>
<td>74.76---84.33</td>
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<td>50</td>
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<td>+36.0</td>
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<td>50</td>
<td>3.18---4.38</td>
<td>168.22</td>
<td>163.43---171.96</td>
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Table 7.13-continued

A-2-4(30%) soil #200 30% Passing

Oolite
Table 7.14 Average Equivalent Modulus for Subgrades under Different Water Table

<table>
<thead>
<tr>
<th>Soil Type</th>
<th>Average EQ Modulus (MPa)</th>
<th>Change in Mr Value</th>
<th>% Reduction in Mr</th>
<th>Adjustment Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Levy County A-3</td>
<td>144.70</td>
<td>131.57</td>
<td>13.13</td>
<td>9.1</td>
</tr>
<tr>
<td>SR-70 A-3</td>
<td>203.71</td>
<td>174.49</td>
<td>29.22</td>
<td>14.3</td>
</tr>
<tr>
<td>SR-70 A-2-4</td>
<td>182.95</td>
<td>153.59</td>
<td>29.36</td>
<td>16.1</td>
</tr>
<tr>
<td>A-2-4 (12%)</td>
<td>109.44</td>
<td>107.01</td>
<td>2.43</td>
<td>2.2</td>
</tr>
<tr>
<td>A-2-4 (20%)</td>
<td>159.90</td>
<td>144.15</td>
<td>15.75</td>
<td>9.9</td>
</tr>
<tr>
<td>A-2-4 (24%)</td>
<td>169.12</td>
<td>110.87</td>
<td>58.25</td>
<td>34.4</td>
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<tr>
<td>A-2-4 (30%)</td>
<td>158.67</td>
<td>113.30</td>
<td>45.37</td>
<td>28.6</td>
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</table>

<table>
<thead>
<tr>
<th>Plate Load Test (50psi with Limerock)</th>
</tr>
</thead>
</table>

<table>
<thead>
<tr>
<th>Soil Type</th>
<th>Average EQ Modulus (MPa)</th>
<th>Change in Mr Value</th>
<th>% Reduction in Mr</th>
<th>Adjustment Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Levy County A-3</td>
<td>264.17</td>
<td>196.36</td>
<td>67.81</td>
<td>25.7</td>
</tr>
<tr>
<td>SR-70 A-3</td>
<td>299.72</td>
<td>207.95</td>
<td>91.77</td>
<td>30.6</td>
</tr>
<tr>
<td>SR-70 A-2-4</td>
<td>226.57</td>
<td>60.70</td>
<td>165.87</td>
<td>73.2</td>
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<tr>
<td>A-2-4 (12%)</td>
<td>195.54</td>
<td>148.18</td>
<td>47.36</td>
<td>24.2</td>
</tr>
<tr>
<td>A-2-4 (20%)</td>
<td>237.16</td>
<td>210.64</td>
<td>26.52</td>
<td>11.2</td>
</tr>
<tr>
<td>A-2-4 (24%)</td>
<td>179.40</td>
<td>138.31</td>
<td>41.09</td>
<td>22.9</td>
</tr>
<tr>
<td>A-2-4 (30%)</td>
<td>240.32</td>
<td>79.94</td>
<td>160.38</td>
<td>66.7</td>
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<tr>
<td>Oolite</td>
<td>538.43</td>
<td>168.22</td>
<td>370.21</td>
<td>68.8</td>
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Table 7.15 Limerock Layer Modulus Results (50psi load w/ Limerock W.T. at +12 in.)

<table>
<thead>
<tr>
<th>Subgrade Soil</th>
<th>Resilient deformation $\Delta_R$ (in.)</th>
<th>$E_{2-3@+12}$ (psi)</th>
<th>$E_{1@+12}$ (ELSYM5) (psi)</th>
<th>$E_{1@+12}$ (KENLAYER) (psi)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>psi</td>
<td>psi</td>
<td>psi</td>
</tr>
<tr>
<td>Levy A-3</td>
<td>0.0108</td>
<td>19077</td>
<td>300000</td>
<td>490000</td>
</tr>
<tr>
<td>SR 70 A-3</td>
<td>0.00953</td>
<td>25301</td>
<td>235000</td>
<td>365000</td>
</tr>
<tr>
<td>SR 70 A-2-4</td>
<td>0.0126</td>
<td>22270</td>
<td>125000</td>
<td>179000</td>
</tr>
<tr>
<td>A-2-4 (12%)</td>
<td>0.0146</td>
<td>15516</td>
<td>176000</td>
<td>290000</td>
</tr>
<tr>
<td>A-2-4 (20%)</td>
<td>0.0120</td>
<td>20902</td>
<td>172000</td>
<td>262000</td>
</tr>
<tr>
<td>A-2-4 (24%)</td>
<td>0.0159</td>
<td>16076</td>
<td>122000</td>
<td>190000</td>
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<tr>
<td>A-2-4 (30%)</td>
<td>0.0119</td>
<td>16429</td>
<td>300000</td>
<td>510000</td>
</tr>
</tbody>
</table>

* Soaked embankment layer modulus was assumed as 11207 psi based on other research tests.
** Bold values in Tables 7.15~7.18 were calculated by ELSYM5 and KENLAYER.
*** $E_{i@y}$ is the x layer (x=1 limerock; x=2 subgrade; x=3 embankment; x=2-3 subgrade+embankment) modulus when water table at y in. level.
Table 7.16 Subgrade Layer Modulus Results (20psi load w/o Limerock W.T. at 0 in.)

<table>
<thead>
<tr>
<th>Subgrade Soil</th>
<th>Resilient deformation $\Delta_R$ (in.)</th>
<th>$E_{300}$ (psi)</th>
<th>$E_{200}$ (ELSYM5)</th>
<th>$E_{200}$ (KENLAYER)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>psi</td>
<td>MPa</td>
<td>psi</td>
</tr>
<tr>
<td>Levy A-3</td>
<td>0.00789</td>
<td>11207</td>
<td>77</td>
<td>26400</td>
</tr>
<tr>
<td>SR 70 A-3</td>
<td>0.00561</td>
<td>11207</td>
<td>77</td>
<td>38200</td>
</tr>
<tr>
<td>SR 70 A-2-4</td>
<td>0.00624</td>
<td>11207</td>
<td>77</td>
<td>34000</td>
</tr>
<tr>
<td>A-2-4 (12%)</td>
<td>0.0104</td>
<td>11207</td>
<td>77</td>
<td>19600</td>
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<tr>
<td>A-2-4 (20%)</td>
<td>0.00714</td>
<td>11207</td>
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<td>A-2-4 (24%)</td>
<td>0.00675</td>
<td>11207</td>
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<td>A-2-4 (30%)</td>
<td>0.00720</td>
<td>11207</td>
<td>77</td>
<td>29150</td>
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</table>
Table 7.17 Subgrade Layer Modulus Results (20psi load w/o Limerock W.T. at +12 in.)

<table>
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<tr>
<th>Schematic View</th>
<th>20 psi</th>
</tr>
</thead>
<tbody>
<tr>
<td>Layer 1</td>
<td></td>
</tr>
<tr>
<td>Subgrade (36 inch)</td>
<td>W.T. +12 inch</td>
</tr>
<tr>
<td>Layer 2</td>
<td></td>
</tr>
<tr>
<td>Embankment (36 inch)</td>
<td></td>
</tr>
</tbody>
</table>

Layer Layout (top to bottom):
- Layer 1 in program (modulus: $E_{2@+12}$): Subgrade Layer (36 in.)
- Layer 2 in program (modulus: $E_{3@+12}$): Embankment Layer (36 in.)

<table>
<thead>
<tr>
<th>Subgrade Soil</th>
<th>Resilient deformation $\Delta_R$ (in.)</th>
<th>$E_{3@+12}$</th>
<th>$E_{2@+12}$ (ELSYM5)</th>
<th>$E_{2@+12}$ (KENLAYER)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>psi</td>
<td>MPa</td>
<td>psi</td>
<td>MPa</td>
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<tr>
<td>Levy A-3</td>
<td>0.00868</td>
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<td>SR 70 A-3</td>
<td>0.00655</td>
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<td>A-2-4 (12%)</td>
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<td>19100</td>
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<tr>
<td>A-2-4 (20%)</td>
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<td>A-2-4 (24%)</td>
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<td>11207</td>
<td>77</td>
<td>19800</td>
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<td>A-2-4 (30%)</td>
<td>0.01008</td>
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<td>77</td>
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Table 7.18 Subgrade Layer Modulus Results (50psi load w/ Limerock W.T. at +36 in.)

<table>
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<th>$E_{1@+36}$</th>
<th>$E_{2@+36}$</th>
<th>$E_{2@+36}$ (ELSYM5)</th>
<th>$E_{2@+36}$ (KENLAYER)</th>
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<td>MPa</td>
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<td></td>
<td></td>
<td>12</td>
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</table>

Legend:
- 50 psi
- W.T. +36 inch
- Level 0.0
- Layer 1
  - Limerock Layer (5 in.)
- Layer 2
  - Subgrade Layer (36 in.)
- Layer 3
  - Embankment Layer (36 in.)
Table 7.19 Subgrade Layer Modulus Summaries By ELSYM5 and KENLAYER

<table>
<thead>
<tr>
<th>Water Table</th>
<th>Layer Modulus (MPa)</th>
<th>0 in.</th>
<th>+12 in.</th>
<th>+36 in.</th>
</tr>
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<tr>
<td>Program</td>
<td>ELSYM5</td>
<td>KENLAYER</td>
<td>ELSYM5</td>
<td>KENLAYER</td>
</tr>
<tr>
<td>Levy A-3</td>
<td>182</td>
<td>235</td>
<td>164</td>
<td>209</td>
</tr>
<tr>
<td>SR 70 A-3</td>
<td>263</td>
<td>362</td>
<td>223</td>
<td>297</td>
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<td>SR 70 A-2-4</td>
<td>234</td>
<td>316</td>
<td>194</td>
<td>253</td>
</tr>
<tr>
<td>A-2-4 (12%)</td>
<td>135</td>
<td>169</td>
<td>132</td>
<td>163</td>
</tr>
<tr>
<td>A-2-4 (20%)</td>
<td>203</td>
<td>266</td>
<td>181</td>
<td>234</td>
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<tr>
<td>A-2-4 (24%)</td>
<td>216</td>
<td>286</td>
<td>137</td>
<td>169</td>
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<td>A-2-4 (30%)</td>
<td>201</td>
<td>263</td>
<td>139</td>
<td>175</td>
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Figure 7.1 Levy County A-3 Soil Moisture Profile after Drainage (short-term) (Water Table from +36 in. to -20 in.)

Figure 7.2 SR-70 A-3 Soil Moisture Profile after Drainage (short-term) (Water Table from +36 in. to -24 in.)
Figure 7.3 SR-70 A-3 Soil Moisture Profile after Drainage (long-term) (Water Table from +36 in. to -24 in.)

Figure 7.4 SR-70 A-2-4 Soil Moisture Profile after Drainage (long-term) (Water Table from +36 in. to -24 in.)
Figure 7.5 A-2-4(12%) Soil Moisture Profile after Drainage (long-term) (Water Table from +36 in. to +12 in.)

Figure 7.6 A-2-4(20%) Soil Moisture Profile after Drainage (long-term) (Water Table from +36 in. to +12 in.)
Figure 7.7 A-2-4(24%) Soil Moisture Profile after Drainage (long-term) (Water Table from +36 in. to +12 in.)

Figure 7.8 A-2-4(30%) Soil Moisture Profile after Drainage (long-term) (Water Table from +36 in. to +12 in.)
Figure 7.9 Oolite Moisture Profile after Drainage (long-term) (Water Table from +36 in. to +12 in.)
Moisture Profile vs. Elapse of Time after Drainage for Levy County A-3 Subgrade (at Each Elevation above the Embankment)

Figure 7.10 Moisture Profile vs. Elapse of Time after Drainage for Levy County A-3 Subgrade (with Each Line Indicates a Specific Elevation above the Embankment)
Figure 7.11(a) Moisture Profile vs. Elapse of Time after Drainage for SR-70 A-3 Subgrade (at Each Elevation above the Embankment)
Figure 7.11(b) Moisture Profile vs. Elapse of Time after Drainage for SR-70 A-3 Subgrade (log Scale Chart) (with Each Line Indicates a Specific Elevation above the Embankment)
Figure 7.12 Moisture Profile vs. Elapse of Time after Drainage for SR-70 A-2-4 Subgrade (log Scale Chart) (with Each Line Indicates a Specific Elevation above the Embankment)
Figure 7.13 Moisture Profile vs. Elapse of Time after Drainage for A-2-4 (12%) Subgrade (log Scale Chart) (with Each Line Indicates a Specific Elevation above the Embankment)
Figure 7.14 Moisture Profile vs. Elapse of Time after Drainage for A-2-4(20%) Subgrade (log Scale Chart) (with Each Line Indicates a Specific Elevation above the Embankment)
Figure 7.15 Moisture Profile vs. Elapse of Time after Drainage for A-2-4(24%) Subgrade (log Scale Chart) (with Each Line Indicates a Specific Elevation above the Embankment)
Figure 7.16 Moisture Profile vs. Elapse of Time after Drainage for A-2-4(30%) Subgrade (log Scale Chart) (with Each Line Indicates a Specific Elevation above the Embankment)
Figure 7.17 Moisture Profile vs. Elapse of Time after Drainage for Oolite Subgrade (log Scale Chart) (with Each Line Indicates a Specific Elevation above the Embankment)
Figure 7.18 EQ Modulus at Different Base Clearance (20 psi without Limerock)

Figure 7.19 EQ Modulus at Different Base Clearance (50 psi with Limerock)
Figure 7.20 EQ Modulus Comparisons at Base Clearance 24 in. (20 psi w/o Limerock vs. 50 psi w/ Limerock)

Figure 7.21 EQ Modulus Adjustment Factor for Base Clearance from 3’ to 2’ (20 psi without Limerock)
Figure 7.22 EQ Modulus Adjustment Factor for Base Clearance from 2’ to 0’ (50 psi with Limerock)

Figure 7.23 Summary of Test-pit Layer Moduli
Layer Modulus Reduction
(from base clearance 24 inch to 0 inch)

<table>
<thead>
<tr>
<th>Material</th>
<th>Reduction Rate for Layer Modulus (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Levy A-3 (4%)</td>
<td>58.9</td>
</tr>
<tr>
<td>SR-70 A-3 (8%)</td>
<td>51.6</td>
</tr>
<tr>
<td>A-2-4 (12%)</td>
<td>46.2</td>
</tr>
<tr>
<td>SR-70 A-2-4 (14%)</td>
<td>89.7</td>
</tr>
<tr>
<td>A-2-4 (20%)</td>
<td>39.7</td>
</tr>
<tr>
<td>A-2-4 (24%)</td>
<td>43.8</td>
</tr>
<tr>
<td>A-2-4 (30%)</td>
<td>87.8</td>
</tr>
</tbody>
</table>

Figure 7.24 Reduction Rates of Test-pit Layer Moduli for Base Clearance from 24-in to 0-in
CHAPTER 8 SUMMARY AND DISCUSSION ON HIGH GROUNDWATER EFFECT

8.1 General

In this chapter, major research findings related to the high groundwater effect from both laboratory and test-pit programs are summarized and discussed. The laboratory and test-pit test results are compared to study the major factors influencing the modulus value of subgrade soils. The effect of high groundwater level on pavement subgrade performance is evaluated in terms of its detrimental effect on the resilient modulus of subgrade materials. Finally, a practical case study is performed to demonstrate the high groundwater effect on the design of a flexible pavement.

8.2 Summary of Laboratory Experimental Results

In the Laboratory Test Program, several tests were conducted to study the properties of each subgrade soil. The most important test was the soil resilient modulus test using soil specimens under different moisture content. Suction values for each subgrade soil were obtained by the suction test using psychrometers. Permeability values for each subgrade soil under saturated condition were obtained by the permeability test using flexible wall permeameter. The resilient modulus of a granular soil was influenced by the moisture content, dry unit weight, coefficient of uniformity, and coefficient of curvature. The relationships among the resilient modulus and moisture
content, the suction value and moisture content, and the permeability
value and percentage of fines are further discussed as follows.

8.2.1 Resilient Modulus versus Moisture Content
The laboratory resilient moduli under optimum and soaked conditions
are summarized in Table 8.1. The resilient modulus versus moisture
content for the eight subgrade soils are shown in Figure 8.1 again
for illustration. The average resilient modulus values of the eight
subgrade soils under dry, optimum and soaked conditions are shown
in Figure 8.2.
From Figure 8.1 and Figure 8.2, it is shown that the resilient modulus
value of each subgrade soil is decreased with an increase in moisture
content. However, the rates of reduction for these soils are not the
same. The SR-70 A-2-4 (14%) and A-2-4 (30%) soils are very sensitive
to the change of moisture content. When these two soils are in dry
condition, they have very high resilient modulus values. But with
a little increase of the moisture content (e.g. 2%), the resilient
modulus value will decrease significantly (about 50%). For the other
soil types, they are not as sensitive to the moisture content change.
Summary of the reduction rates in laboratory resilient modulus due
to the increase of moisture content is presented in Table 8.2. A bar
chart illustration the reduction rates in laboratory resilient
modulus is demonstrated in Figure 8.3. The reduction rates were
calculated from the resilient modulus values under optimum moisture
content and soaked conditions. It is clearly shown in Figure 8.3 that
the SR-70 A-2-4 (14%) and A-2-4 (30%) soils have the most severe
reduction rates. Thus, these two soils are the most sensitive soils
to the moisture content changes. From Figure 8.3, it is also shown that there is no relationship between the reduction rate and the percentage of fines in soil. Therefore, the percentage of fines is not a good indicator to categorize the soils by the sensitivity of moisture effect.

8.2.2 Suction Value versus Moisture Content

Summary of the soil suction values at different moisture content is presented in Figure 8.4. Due to the limitation of accuracy of the psychrometer test method, accurate suction values could not be obtained when the values were very low for sandy soils. The general trend is that the soil suction value decreases with an increase in moisture content of each soil. This is in agreement with the Soil-Water Characteristic Curve (SWCC) for each soil. Because of the accuracy problem with the suction values, they are not included in the future analysis of resilient modulus regression model.

8.2.3 Permeability versus Percentage of Fines

The relationship between the permeability values and percentage of fines is shown in Figure 8.5. The permeability value under saturated condition will decrease with an increase of percentage of fines. This can be explained by the pore size change in the soils. Generally, the more the fines, the smaller the pore radius. The size and connectivity of the pores determine the ability of the water going through the soil. The percentage of fines is a good indicator to predict the permeability property for soils.
8.2.4 Factors Influencing Resilient Modulus

From Figures 8.1 and 8.2, the moisture content in subgrade soil is a major factor affecting the resilient modulus value. In addition, statistics also shows that other factors including dry unit weight, coefficient of uniformity and coefficient of curvature are significantly affecting the resilient modulus.

a) Moisture Content

For each soil, the moisture content will affect the resilient modulus at a different extent. Generally, when the moisture content increases, the resilient modulus value of the soil will decrease. From the statistics analysis in Chapter 6, in each model of the regression analysis, the P value for moisture content is always the smallest one (the smaller the P value, the higher correlation between the predictor and the response) as compared with the P values for other predictors (see statistical results in Chapter 6 main text). The moisture content is the most influential factor of the resilient modulus value.

b) Dry Unit Weight

Including the dry unit weight in the regression model will only improve the model a little. Shown in Figure 8.6 is the resilient modulus values under a constant stress level (confining pressure 13.79 kPa, deviated stress 46 kPa) tabulated with the values of dry unit weight of the soils. No simple relationship is observed between the resilient modulus value and dry unit weight. That is the reason that in the regression models, the P value for dry unit weight is much higher.
than the P values for other predictors (see statistical results in Chapter 6).

C) Gradation Curve Parameters

The gradation curve for each soil can be obtained by conducting sieve analysis and hydrometer tests. The degree of particle gradation (well-graded, not well-graded, or poorly graded, etc.) can be derived from the gradation curve. The gradation curves for five of the seven soils are presented in Figure 8.7. From these curves, the coefficient of uniformity ($C_u$) and the coefficient of curvature ($C_c$) can be calculated and are summarized in Table 8.3. From Table 8.3, the SR-70 A-2-4 (14%) soil has extremely high values of $C_u$ and $C_c$. The A-2-4 (24%) soil also has high values of $C_u$ and $C_c$. That is the main reason why these two soils are much more sensitive to the moisture change than the other soils. For these two soils, they are poorly graded and missing some particles in a certain size range. It will generate larger pores inside the soil structure. They are not very stable with the soil structure when the moisture content increases (water goes in and through those pores). The higher resilient deformation due to the moisture effect causes a lower resilient modulus value. Therefore, $C_u$ and $C_c$ are good indicators to categorize the sensitivity of soil due to the change in moisture content.

8.3 Summary of Test-pit Experimental Results

In the test-pit experimental program, full scale simulation was conducted to evaluate the effect of high groundwater level effect
on the modulus of the subgrade soil. With adjustment of the groundwater level in the subgrade, the dynamic plate load test was performed to measure the flexible deformation, from that the equivalent modulus value was derived for the subgrade. However, these are composite layers of subgrade and embankment under the plate loading, sometimes with an additional base layer (limerock layer). The calculated modulus from the plate load test is the equivalent modulus for the composite layers under the load. In Chapter 7, layer system was setup to estimate the resilient modulus value under for the individual subgrade layer under the high groundwater level. The effects of high groundwater level on the equivalent modulus and layer modulus are discussed in this section.

8.3.1 High Groundwater Effect on Equivalent Modulus

The average equivalent modulus values for subgrade soils at different groundwater levels are summarized in Table 8.4. The equivalent modulus values due to the change of groundwater level are shown in Figures 8.8 and 8.9. When the groundwater level was raised from the interface of subgrade and embankment layers (level 0.0) to 12 inch above the interface (level +12.0), i.e., from base clearance 3 ft to 2 ft, the equivalent modulus values for the subgrade soils were only decreased slightly. But, when the groundwater level was changed from +12.0 to +36.0, i.e., from base clearance 2 ft to 0 ft, the SR-70 A-2-4 (14%) soil, A-2-4 (30%) soil, and Oolite had significant reductions on their equivalent modulus values (Figure 8.9). The results are consistent with the results from laboratory tests. The SR-70 A-2-4 (14%) soil, A-2-4 (30%) soil and Oolite were very sensitive to the groundwater
change when the groundwater level was raised above the +12.0 level (i.e., with base clearance less than 2 ft). The other five soils were not as sensitive as those three soils.

8.3.2 High Groundwater Effect on Layer Modulus of subgrade
Layer system was set up by using computer programs ELSYM5 and KENLAYER. The results from these two programs are not exactly the same. The layer modulus results computed by KENLAYER for eight soil subgrades under different groundwater level conditions are summarized in Table 8.5 and are presented in Figure 8.10 for illustration. The layer modulus reductions are shown in Figures 8.11 and 8.12. From Figures 8.10, 8.11 and 8.12, the SR-70 A-2-4 (14%) and A-2-4 (30%) soils are extremely sensitive to the groundwater level change from +12.0 level to +36.0 level. However, for the Levy A-3 (4%), SR-70 A-3 (8%), A-2-4 (12%) and A-2-4 (24%) soils, the reduction rates are still very significant for the base clearance from 2 ft to 0 ft. The A-2-4 (20%) soil is the least sensitive soil in response to the groundwater level change. These results are also consistent with those from laboratory resilient modulus tests.

8.3.3 Effect of Adding Base Layer
Two similar dynamic load tests were conducted with the groundwater level at +12.0 in. above the interface. The only difference was the first test using 20 psi cyclic loading pressure without a limerock base layer, but the second test using 50 psi cyclic loading pressure with a 5-inch thick limerock base layer (see Figure 8.13). By theory, the resilient modulus value should not be significantly affected by
the load pressure. Therefore, the significant increase in the equivalent modulus values was attributed primarily due to the addition of a limerock base layer. With a 5-inch thick limerock layer as the base layer, the equivalent modulus values were almost doubled (see Figure 8.13). All the subgrade soils had significant increase for their equivalent modulus values due to adding a limerock base layer. The limerock base layer certainly improved the dynamic performance of the pavement.

8.4 Comparison of Laboratory and Test-pit Results

The laboratory and test-pit tests were performed under different conditions. The moisture content was mixed with the specimen in the laboratory, whereas in the test-pit, the groundwater level was raised or lowered to a stabilized condition within the subgrade. The laboratory resilient modulus and equivalent layer modulus generally represented the same kind of engineering property of the subgrade performance. However, the physical conditions were very much different for deriving the resilient modulus and equivalent layer modulus. In addition, the resilient modulus reduction was calculated from the resilient modulus values under optimum moisture and soaked conditions, whereas the layer modulus reduction was calculated from the equivalent modulus values under groundwater level at +12.0 in. and at +36.0 in.

8.4.1 Comparison of Modulus Values

Comparing the resilient modulus results from laboratory (Figure 8.2) with the subgrade layer moduli from test-pit (Figure 8.10), the
modulus values were generally within the same range for the subgrade soil.

The laboratory resilient modulus values at optimum moisture were slightly lower than the equivalent layer modulus values under groundwater level at +12 inch (i.e., base clearance 24 inch, base clearance is the depth from the bottom of base layer to the groundwater surface) except for the SR-70 A-2-4 (14%) soil. Therefore, for most soils, it is on the safe side when the laboratory resilient modulus at optimum condition is used to design a roadway pavement with a base clearance at least 24 inch or more.

The laboratory resilient modulus values at wet condition were higher than the equivalent layer modulus values with base clearance 0 ft. Because the moisture conditions were different between the laboratory soaked specimen and the saturated subgrade layers in a test-pit. In fact, the moisture content of the laboratory soaked specimen was lower than the moisture content of the saturated layer in test-pit.

8.4.2 Comparison of Modulus Reductions

Comparing the laboratory resilient modulus reductions (Figure 8.3) with the layer modulus reductions (Figure 8.12), the reduction rates are much more severe for the test-pit conditions. However, the relative severity of moisture damage is the same for each subgrade soil. The SR-70 A-2-4 (14%) and A-2-4 (30%) soils are the most sensitive soils to moisture damage either at laboratory wet condition or at saturated condition in test-pit. The A-2-4 (20%) soil is the least sensitive soil to moisture damage. The reductions due to moisture damage can be used in pavement design to estimate the
resilient modulus values under various moisture conditions.

8.5 Case Study for High Groundwater Effect

The practical significance of designing pavements with base clearances is to optimize the thickness of the pavement layers above the high groundwater level including a structural asphalt concrete layer satisfying both the economical and safety designs. A case study utilizing the measured resilient modulus data to design the required thickness of flexible pavement layer with respect to different high groundwater levels would help to gain an insight into the economic aspect of importance for such base clearances. The schemes for this case study using the measured equivalent modulus in test-pit tests are illustrated in Figures 8.14 and 8.15.

The AASHTO Guide for Design of Pavement Structures (1986 and 1993) was adopted for this case study relative to the change of ground water table. In this design approach, the effective roadbed soil resilient modulus ($M_r$) to be used in the AASHTO design equation was taken from the equivalent modulus of composite pavement profile in test-pit tests, which is summarized in Table 8.4. The two schemes were studied (Figures 8.14 and 8.15) in the following ways:

1) 20 psi plate loading with the equivalent modulus of the composite section for assumed 5 in. or 10 in. limerock base, 36-inch stabilized subgrade plus embankment

2) 50 psi plate loading with the equivalent modulus of the composite section for 5-inch limerock base, 36-inch stabilized subgrade layer, and embankment

The detailed design source data, assumptions, and procedures are
discussed in the following sections.
In this case study, the pavement design includes seven of the eight soil types (except Oolite) as the subgrade to calculate required asphalt concrete thickness.

8.5.1 Traffic Data
Traffic is one of the most important parameters in pavement design. The Florida Department of Transportation (FDOT) collects and stores a broad range of traffic data to assist highway engineers in designing and maintaining safe, state-of-the-art, and cost effective facilities. Traffic data are collected by the Central Office, districts, local governments, and consultants, and include volume and vehicle classification counts, speed surveys, and truck weight measurements. The traffic data are based upon cumulative expected 18-kip (80 kN) equivalent single-axle load (ESAL). In order to calculate accumulated ESAL, Average Annual Daily Traffic (AADT), truck factor and some other traffic factors were needed for Equation 8-1. The AADT is the estimate of typical daily traffic on a road segment for all the days of the week, over the period of one year. The most critical factor for pavement design is the percentage of trucks using a roadway. The structural design is primarily dependent upon the heavy axle loads generated by commercial truck traffic. The estimated future truck volume is needed for calculating the 18 kip (80 KN) Equivalent Single Axle Loads (ESAL) for pavement design. Design traffic calculations use the factor T, the percentage of trucks for 24 hours (one day).

The 18K ESAL required for pavement design purposes can be computed
using the following equation:

\[ W_{t18} = AADT \times T_{24} \times D \times LF \times E_{18} \times 365 \]  

(8-1)

Where:

\( W_{t18} \) = number of 18-kip (80KN) ESAL in the design lane during a given year

\( AADT \) = average annual daily traffic

\( T_{24} \) = percentage of heavy trucks, 24 hours

\( D \) = directional distribution factor

\( LF \) = lane factor, covert directional truck to design lane trucks

\( E_{18} \) = 18K ESAL equivalency factor, the damage caused by one average heavy truck

Since no data were available for the prediction of traffic growth, an annual growth rate of 2% was assumed for calculation of ESALs, based on the experience of the traffic growth rate for the last ten years.

To evaluate the groundwater level (different moisture content condition) effect on the required thickness of asphalt concrete layer, two traffic levels were used. Refer to Table 8.6 from Asphalt Institute, an ESAL values of \( 1.3 \times 10^7 \) was used to present the traffic condition.

8.5.2 Resilient Modulus Based Design Procedure

The AASHTO Guide for Design of Pavement Structures (AASHTO 1986, 1993) is considered as the standard for pavement design using the resilient modulus. In this case study, AASHTO design equation (Equation 8-2) is introduced to determine the required thickness of asphalt concrete
utilizing the composite soil modulus obtained from the plate load test under different groundwater table levels.

\[
\log(W_{18}) = Z_R \times S_0 + 9.36 \times \log(SN + 1) - 0.20 + \frac{\log[\Delta PSI/(4.2 - 1.5)]}{0.4 + 1094/(SN + 1)^{5.19}} + 2.32 \times \log M_R - 8.07
\]

(8-2)

Where:  
SN = Structural number required  
\(W_{18}\) = Number of 18-kip (80KN) ESAL in the design lane during a given year (smaller than \(W_{18}\) to achieve a higher level of reliability)  
\(Z_R\) = Standard normal deviate  
\(S_0\) = Standard deviation  
\(\Delta PSI\) = Change in serviceability  
\(M_R\) = Effective roadbed soil resilient modulus (psi)

For a design using resilient modulus, 95% reliability and 0.45 standard deviation (Standard Normal Deviation -1.645) were selected according to the AASHTO suggested value. The serviceability of a pavement (PSI) is defined as its ability to serve the type of traffic that uses the facility. PSI is the primary measure of serviceability in current use. In this case, a total PSI loss of 1.7 was assumed, and a terminal serviceability level of 2.5 was selected.

For asphalt concrete layer, the resilient modulus was assumed to be 350 ksi. For the flexible pavement design in the case of 20 psi plate load without limerock, a 5-in. or 10-in. limerock base was assumed above the stabilized subgrade layer, and the resilient modulus was taken as 31 ksi for the limerock layer. The layer coefficients for the asphalt concrete and limerock base were valued as 0.44 and 0.18,
respectively, from their resilient modulus.

In this case study, a good drainage was assumed. The percent of time the pavement structure was exposed to moisture levels approaching saturation was 5-25% and the drainage coefficient was set to 1.0. Based upon the required structural number obtained from Equation 8-2, the required thickness of the asphalt concrete layer was determined.

8.5.3 Design Results and Analysis

The results of the required structural number are summarized in Tables 8.7 and 8.8 for the design layers above the tested condition under different groundwater level variations. The required thicknesses of asphalt concrete layer with 5-in limerock base layer under 20-psi plate loading are summarized in Table 8.9. The required thicknesses of asphalt concrete layer with 10-in limerock base layer under 20-psi plate loading are summarized in Table 8.10. The required thicknesses of asphalt concrete layer with 5-in. limerock base layer under 50-psi plate loading are summarized in Table 8.11.

Under 20-psi plate loading condition (Figure 8.16 and Figure 8.17), the Levy A-3, SR-70 A-3, A-2-4 (12%) and A-2-4 (20%) soils were required very little increase of the asphalt concrete layer when the water table was raised from base clearance 3 ft to 2 ft. For the other three soils, SR-70 A-2-4, A-2-4 (24%) and A-2-4 (30%), the required layer thickness of asphalt concrete was significantly increased when the water table was raised.

Under 50-psi plate loading condition (Figure 8.18), the SR-70 A-2-4 and A-2-4 (30%) soils were required very significant increase of the thickness of the asphalt concrete layer when the groundwater level
was raised from +12 in. to +36 in. (i.e., base clearance 2 ft to 0 ft). These two soils were the most sensitive to the change of water table change.

The results of this case study indicated that for some sensitive soil types as the subgrade, an increase of the groundwater table (12 in. or higher above the embankment) would demand a significant increase of the thickness of asphalt concrete layer in order to have the same quality pavement performance. Thus, the most safe and economical way for the design of pavement is to maintain an adequate base clearance between the groundwater table and the bottom of the base layer, which is essential for fine-grained subgrade materials.

8.6 Discussions of High Groundwater Effect

Based on the laboratory and test-pit test results, the SR-70 A-2-4 (14%) and A-2-4 (30%) soils are most sensitive to the moisture damage. Other soil types are not as sensitive to the change of moisture content. According to the analysis in this chapter about the soil properties related to the modulus reductions for both resilient modulus and layer modulus, the coefficient of uniformity ($C_u$) and coefficient of curvature ($C_c$) are two factors that can be used to predict the moisture sensitivity of granular soils. Generally, a well-graded granular soil is not very sensitive to moisture damage, because it has smaller pores in the soil structure under compacted condition. For a well-graded granular soil, $C_u$ should be over 5 and $C_c$ should be in the range of 1 to 3. From Table 8.3 the gradation properties for the subgrade soils, the SR-70 A-2-4 (14%) and A-2-4 (24%) have large values for $C_c$ at
outside of the range of 1 to 3. Even for A-2-4 (24%) soil, the $C_c$ is 5.06 (higher than 3). Based on this research study, a simple criteria is proposed to classify the soil moisture sensitivity as follows:

<table>
<thead>
<tr>
<th>Moisture Sensitivity</th>
<th>Criteria</th>
</tr>
</thead>
<tbody>
<tr>
<td>High</td>
<td>$C_c &gt; 5$</td>
</tr>
<tr>
<td>Intermediate</td>
<td>$3 \leq C_c \leq 5$</td>
</tr>
<tr>
<td>Low</td>
<td>$C_c &lt; 3$</td>
</tr>
</tbody>
</table>

The proposed criteria will need additional research to further evaluate the moisture sensitivity of granular soils.

Of course, the most direct and reliable way to evaluate the effect of moisture damage on the resilient modulus is to conduct a laboratory resilient modulus test. Based on this research, the test-pit dynamic loading test is also a reliable way to evaluate the layer modulus of the subgrade soils subject to various moisture conditions. However, the test-pit test probably will be more expensive than the laboratory test. Some other methods can be used in the field to get the modulus values for the soil such as back calculation of soil layer modulus from Falling Weight Deflectometer (FWD) test. In areas with high groundwater levels, adequate base clearance should be maintained to minimize the moisture damage and to achieve quality performance of the pavement. Granular subgrade materials with low moisture sensitivity values should be used for high groundwater situation.
<table>
<thead>
<tr>
<th>Soil</th>
<th>OPTIMUM CONDITION</th>
<th>SOAKED CONDITION</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mr (MPa)</td>
<td>Moisture Content (%)</td>
</tr>
<tr>
<td>Levy A-3 (4%)</td>
<td>158</td>
<td>9.6</td>
</tr>
<tr>
<td>SR 70 A-3 (8%)</td>
<td>167</td>
<td>11.4</td>
</tr>
<tr>
<td>A-2-4 (12%)</td>
<td>121</td>
<td>12.1</td>
</tr>
<tr>
<td>SR 70 A-2-4 (14%)</td>
<td>239</td>
<td>10.8</td>
</tr>
<tr>
<td>A-2-4 (20%)</td>
<td>138</td>
<td>10.0</td>
</tr>
<tr>
<td>A-2-4 (24%)</td>
<td>118</td>
<td>10.0</td>
</tr>
<tr>
<td>A-2-4 (30%)</td>
<td>112</td>
<td>12.0</td>
</tr>
<tr>
<td>Oolite</td>
<td>152</td>
<td>7.8</td>
</tr>
</tbody>
</table>
Table 8.2 Summary of Reduction in Lab $M_r$

<table>
<thead>
<tr>
<th>Soil Type</th>
<th>Properties</th>
<th>Before Soaking</th>
<th>After Soaking</th>
<th>Change in Value</th>
<th>% Reduction in $M_r$</th>
</tr>
</thead>
<tbody>
<tr>
<td>A-3 4%, Levy County</td>
<td>Moisture Content</td>
<td>9.60%</td>
<td>15.15%</td>
<td>+5.6%</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$M_r$ (MPa)</td>
<td>157.7</td>
<td>149</td>
<td>-8.70</td>
<td>5.5%</td>
</tr>
<tr>
<td>A-3 8%, SR-70</td>
<td>Moisture Content</td>
<td>11.4%</td>
<td>13.7%</td>
<td>2.3%</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$M_r$ (MPa)</td>
<td>166.8</td>
<td>146.5</td>
<td>-20.30</td>
<td>12.2%</td>
</tr>
<tr>
<td>A-2-4, 12%</td>
<td>Moisture Content</td>
<td>12.1%</td>
<td>14.6%</td>
<td>+2.5%</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$M_r$ (MPa)</td>
<td>120.6</td>
<td>110.7</td>
<td>-9.90</td>
<td>8.2%</td>
</tr>
<tr>
<td>A-2-4 14%, SR70</td>
<td>Moisture Content</td>
<td>10.8%</td>
<td>11.8%</td>
<td>1.0%</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$M_r$ (MPa)</td>
<td>239.36</td>
<td>149</td>
<td>-90.36</td>
<td>37.8%</td>
</tr>
<tr>
<td>A-2-4, 20%</td>
<td>Moisture Content</td>
<td>10.0%</td>
<td>11.9%</td>
<td>+1.9%</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$M_r$ (MPa)</td>
<td>137.6</td>
<td>132.4</td>
<td>-5.20</td>
<td>3.8%</td>
</tr>
<tr>
<td>A-2-4, 24%</td>
<td>Moisture Content</td>
<td>10.0%</td>
<td>11.9%</td>
<td>+1.9%</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$M_r$ (MPa)</td>
<td>117.7</td>
<td>92.3</td>
<td>-25.40</td>
<td>21.6%</td>
</tr>
<tr>
<td>A-2-4, 30%</td>
<td>Moisture Content</td>
<td>12.0%</td>
<td>14.1%</td>
<td>+2.1%</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$M_r$ (MPa)</td>
<td>112.43</td>
<td>72.48</td>
<td>-39.95</td>
<td>35.5%</td>
</tr>
<tr>
<td>Oolite</td>
<td>Moisture Content</td>
<td>7.8%</td>
<td>8.2%</td>
<td>+0.4%</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$M_r$ (MPa)</td>
<td>152.12</td>
<td>95.84</td>
<td>-56.28</td>
<td>37.0%</td>
</tr>
</tbody>
</table>
Table 8.3 Soil Properties of Gradation Curve

<table>
<thead>
<tr>
<th>Soil Properties</th>
<th>SR-70 A-3 (8%)</th>
<th>A-2-4 (12%)</th>
<th>SR-70 A-2-4 (14%)</th>
<th>A-2-4 (20%)</th>
<th>A-2-4 (24%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$D_{10}$ (mm)</td>
<td>0.081</td>
<td>0.05</td>
<td>0.001</td>
<td>0.037</td>
<td>0.0095</td>
</tr>
<tr>
<td>$D_{30}$ (mm)</td>
<td>0.15</td>
<td>0.099</td>
<td>0.13</td>
<td>0.091</td>
<td>0.082</td>
</tr>
<tr>
<td>$D_{60}$ (mm)</td>
<td>0.31</td>
<td>0.15</td>
<td>0.29</td>
<td>0.14</td>
<td>0.14</td>
</tr>
<tr>
<td>$C_u$</td>
<td>3.83</td>
<td>3.00</td>
<td>290.00</td>
<td>3.78</td>
<td>14.74</td>
</tr>
<tr>
<td>$C_c$</td>
<td>0.90</td>
<td>1.31</td>
<td>58.28</td>
<td>1.60</td>
<td>5.06</td>
</tr>
</tbody>
</table>
Table 8.4 Average Equivalent Modulus for Subgrades under Different Water Table

<table>
<thead>
<tr>
<th>Soil Type</th>
<th>Average EQ Modulus (MPa)</th>
<th>Change in Mr Value</th>
<th>% Reduction in Mr</th>
<th>Adjustment Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Levy County A-3</td>
<td>144.70</td>
<td>131.57</td>
<td>13.13</td>
<td>9.1</td>
</tr>
<tr>
<td>SR-70 A-3</td>
<td>203.71</td>
<td>174.49</td>
<td>29.22</td>
<td>14.3</td>
</tr>
<tr>
<td>SR-70 A-2-4</td>
<td>182.95</td>
<td>153.59</td>
<td>29.36</td>
<td>16.1</td>
</tr>
<tr>
<td>A-2-4 (12%)</td>
<td>109.44</td>
<td>107.01</td>
<td>2.43</td>
<td>2.2</td>
</tr>
<tr>
<td>A-2-4 (20%)</td>
<td>159.90</td>
<td>144.15</td>
<td>15.75</td>
<td>9.9</td>
</tr>
<tr>
<td>A-2-4 (24%)</td>
<td>169.12</td>
<td>110.87</td>
<td>58.25</td>
<td>34.4</td>
</tr>
<tr>
<td>A-2-4 (30%)</td>
<td>158.67</td>
<td>113.30</td>
<td>45.37</td>
<td>28.6</td>
</tr>
</tbody>
</table>

Plate Load Test (50psi with Limerock)

<table>
<thead>
<tr>
<th>Soil Type</th>
<th>Average EQ Modulus (MPa)</th>
<th>Change in Mr Value</th>
<th>% Reduction in Mr</th>
<th>Adjustment Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Levy County A-3</td>
<td>264.17</td>
<td>196.36</td>
<td>67.81</td>
<td>25.7</td>
</tr>
<tr>
<td>SR-70 A-3</td>
<td>299.72</td>
<td>207.95</td>
<td>91.77</td>
<td>30.6</td>
</tr>
<tr>
<td>SR-70 A-2-4</td>
<td>226.57</td>
<td>60.70</td>
<td>165.87</td>
<td>73.2</td>
</tr>
<tr>
<td>A-2-4 (12%)</td>
<td>195.54</td>
<td>148.18</td>
<td>47.36</td>
<td>24.2</td>
</tr>
<tr>
<td>A-2-4 (20%)</td>
<td>237.16</td>
<td>210.64</td>
<td>26.52</td>
<td>11.2</td>
</tr>
<tr>
<td>A-2-4 (24%)</td>
<td>179.40</td>
<td>138.31</td>
<td>41.09</td>
<td>22.9</td>
</tr>
<tr>
<td>A-2-4 (30%)</td>
<td>240.32</td>
<td>79.94</td>
<td>160.38</td>
<td>66.7</td>
</tr>
<tr>
<td>Oolite</td>
<td>538.43</td>
<td>168.22</td>
<td>370.21</td>
<td>68.8</td>
</tr>
</tbody>
</table>
Table 8.5 Subgrade Layer Modulus Computed By KENLAYER

<table>
<thead>
<tr>
<th>Soil Type</th>
<th>Layer Modulus (MPa)</th>
<th>Modulus Decrease (MPa) by Increase of W.T. (in.)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>W.T.@0in.</td>
<td>W.T.@+12in.</td>
</tr>
<tr>
<td>Levy A-3</td>
<td>235</td>
<td>209</td>
</tr>
<tr>
<td>SR 70 A-3</td>
<td>362</td>
<td>297</td>
</tr>
<tr>
<td>SR 70 A-2-4</td>
<td>316</td>
<td>253</td>
</tr>
<tr>
<td>A-2-4 (12%)</td>
<td>169</td>
<td>163</td>
</tr>
<tr>
<td>A-2-4 (20%)</td>
<td>266</td>
<td>234</td>
</tr>
<tr>
<td>A-2-4 (24%)</td>
<td>286</td>
<td>169</td>
</tr>
<tr>
<td>A-2-4 (30%)</td>
<td>263</td>
<td>175</td>
</tr>
</tbody>
</table>

Table 8.6 Traffic Classification

<table>
<thead>
<tr>
<th>Traffic class</th>
<th>Type of street or highway</th>
<th>Range of heavy trucks expected in design period</th>
<th>ESAL</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>Parking lots, driveways</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Light traffic residential streets</td>
<td>Less than 7000</td>
<td>$5 \times 10^3$</td>
</tr>
<tr>
<td></td>
<td>Light traffic farm roads</td>
<td></td>
<td></td>
</tr>
<tr>
<td>II</td>
<td>Residential streets</td>
<td>7000 to 15,000</td>
<td>$10^4$</td>
</tr>
<tr>
<td></td>
<td>Rural farm and residential roads</td>
<td></td>
<td></td>
</tr>
<tr>
<td>III</td>
<td>Urban minor collector streets</td>
<td>70,000 to 150,000</td>
<td>$10^5$</td>
</tr>
<tr>
<td></td>
<td>Rural minor collector roads</td>
<td></td>
<td></td>
</tr>
<tr>
<td>IV</td>
<td>Urban minor arterial and light industrial streets</td>
<td>700,000 to 1,500,000</td>
<td>$10^6$</td>
</tr>
<tr>
<td></td>
<td>Rural major collector and minor arterial highways</td>
<td></td>
<td></td>
</tr>
<tr>
<td>V</td>
<td>Urban freeways, expressways, and other principal arterial highways</td>
<td>2,000,000 to 4,500,000</td>
<td>$3 \times 10^6$</td>
</tr>
<tr>
<td></td>
<td>Rural interstate and other principal arterial highways</td>
<td></td>
<td></td>
</tr>
<tr>
<td>VI</td>
<td>Urban interstate highways</td>
<td>7,000,000 to 15,000,000</td>
<td>$10^7$</td>
</tr>
<tr>
<td></td>
<td>Some industrial roads</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Note: Whenever possible, more rigorous traffic analysis should be used for roads and streets in traffic category IV or higher. (Source: Asphalt Institute, 1981b)
### Table 8.7 Required Structural Number for the Layer above Tested Layers (Plate Load 20 psi)

<table>
<thead>
<tr>
<th>Traffic Data (ESAL)</th>
<th>1.30E+07</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water Table (above Embankment)</td>
<td>0 in.</td>
</tr>
<tr>
<td>Levy County A-3 (4%)</td>
<td>3.80</td>
</tr>
<tr>
<td>SR70 A-3 (8%)</td>
<td>3.34</td>
</tr>
<tr>
<td>SR70 A-2-4 (14%)</td>
<td>3.48</td>
</tr>
<tr>
<td>A-2-4 (12%)</td>
<td>4.21</td>
</tr>
<tr>
<td>A-2-4 (20%)</td>
<td>3.66</td>
</tr>
<tr>
<td>A-2-4 (24%)</td>
<td>3.59</td>
</tr>
<tr>
<td>A-2-4 (30%)</td>
<td>3.67</td>
</tr>
</tbody>
</table>

### Table 8.8 Required Structural Number for the Layer above Tested Layers (Plate Load 50 psi)

<table>
<thead>
<tr>
<th>Traffic Data (ESAL)</th>
<th>1.30E+07</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water Table (above Embankment)</td>
<td>12 in.</td>
</tr>
<tr>
<td>Levy County A-3 (4%)</td>
<td>3.02</td>
</tr>
<tr>
<td>SR70 A-3 (8%)</td>
<td>2.88</td>
</tr>
<tr>
<td>SR70 A-2-4 (14%)</td>
<td>3.21</td>
</tr>
<tr>
<td>A-2-4 (12%)</td>
<td>3.39</td>
</tr>
<tr>
<td>A-2-4 (20%)</td>
<td>3.15</td>
</tr>
<tr>
<td>A-2-4 (24%)</td>
<td>3.51</td>
</tr>
<tr>
<td>A-2-4 (30%)</td>
<td>3.14</td>
</tr>
</tbody>
</table>
Table 8.9 Required Thickness of AC Layer with 5 in. Limerock under 20 psi

<table>
<thead>
<tr>
<th>Water Table (above Embankment)</th>
<th>Levy County A-3 (4%)</th>
<th>SR70 A-3 (8%)</th>
<th>SR70 A-2-4 (14%)</th>
<th>A-2-4 (12%)</th>
<th>A-2-4 (20%)</th>
<th>A-2-4 (24%)</th>
<th>A-2-4 (30%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0 in.</td>
<td>12 in.</td>
<td>Difference in AC Thickness</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Levy County A-3 (4%)</td>
<td>6.59</td>
<td>6.91</td>
<td>0.32</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SR70 A-3 (8%)</td>
<td>5.55</td>
<td>6.00</td>
<td>0.45</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SR70 A-2-4 (14%)</td>
<td>5.86</td>
<td>6.41</td>
<td>0.55</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>A-2-4 (12%)</td>
<td>7.52</td>
<td>7.59</td>
<td>0.07</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>A-2-4 (20%)</td>
<td>6.27</td>
<td>6.61</td>
<td>0.34</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>A-2-4 (24%)</td>
<td>6.11</td>
<td>7.48</td>
<td>1.37</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>A-2-4 (30%)</td>
<td>6.30</td>
<td>7.41</td>
<td>1.11</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 8.10 Required Thickness of AC Layer with 10 in. Limerock under 20 psi

<table>
<thead>
<tr>
<th>Water Table (above Embankment)</th>
<th>Levy County A-3 (4%)</th>
<th>SR70 A-3 (8%)</th>
<th>SR70 A-2-4 (14%)</th>
<th>A-2-4 (12%)</th>
<th>A-2-4 (20%)</th>
<th>A-2-4 (24%)</th>
<th>A-2-4 (30%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0 in.</td>
<td>12 in.</td>
<td>Difference in AC Thickness</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Levy County A-3 (4%)</td>
<td>4.55</td>
<td>4.86</td>
<td>0.31</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SR70 A-3 (8%)</td>
<td>3.50</td>
<td>3.95</td>
<td>0.45</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SR70 A-2-4 (14%)</td>
<td>3.82</td>
<td>4.36</td>
<td>0.54</td>
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<td>A-2-4 (12%)</td>
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<td>A-2-4 (20%)</td>
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<td>A-2-4 (24%)</td>
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<tr>
<td>A-2-4 (30%)</td>
<td>4.25</td>
<td>5.36</td>
<td>1.11</td>
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Table 8.11 Required Thickness of AC Layer with 5 in. Limerock under 50 psi

<table>
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<tr>
<th>Water Table (above Embankment)</th>
<th>Required Thickness of AC Layer (in.) (50psi with Assumed Limerock Base 5 in.)</th>
<th>Difference in AC Thickness</th>
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<td>12 in.</td>
<td>36 in.</td>
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<td>Levy County A-3 (4%)</td>
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<td>SR70 A-3 (8%)</td>
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<td>A-2-4 (30%)</td>
<td>7.14</td>
<td>10.68</td>
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</table>
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CHAPTER 9 CONCLUSIONS AND RECOMMENDATIONS

9.1 Conclusions

Based upon the analyses and findings of this experimental study, the conclusions are summarized as follows:

Laboratory Experimental Program

1. Based on laboratory resilient modulus test, the resilient modulus value of each subgrade soil decreased with an increase in moisture content. However, the rates of reduction for these soils were not at the same level. The SR-70 A-2-4 (14%), A-2-4 (30%) soils and Oolite were very sensitive to the change of moisture content from the optimum to soaked conditions. These three soils had the reduction rates in the range of 31% to 38%. The other soil types were not as sensitive to the moisture content change (with reduction rates lower than 22%) as those three soils.

2. The moisture content in subgrade soil was a major factor affecting the resilient modulus. In addition, the statistical model showed that other factors including dry unit weight, coefficient of uniformity and coefficient of curvature were also significantly affecting the resilient modulus.

3. No relationship existed between the reduction rate and the percentage of fines in soil. The percentage of fines was not a good indicator for categorizing the soils in terms of the sensitivity of moisture effect on the resilient modulus. However, the percentage of fines was a good indicator to predict the
permeability properties of soil. The permeability value under saturated condition decreased with an increase in percentage of fines.

4. According to the limited laboratory test results, the $C_u$ and $C_c$ were considered as two good indicators for correlating the moisture sensitivity of granular soils.

5. In accordance with the Soil-Water Characteristic Curve (SWCC), the suction values decreased with an increase in moisture content for each soil.

Test-Pit Experimental Program

6. The test-pit dynamic load test was reliable method to evaluate the layer modulus of subgrade soils subject to various moisture conditions.

7. The A-2-4 (24%) and A-2-4 (30%) soils were very sensitive to the change of high groundwater level. When the groundwater level was raised from the +0.0 level to the +12.0 level (i.e., base clearance from 3 ft to 2 ft), the layer modulus values were reduced in the range of 30% to 40%. The other five soils (with reduction rates lower than 20%) were not as sensitive as those two soils.

8. The SR-70 A-2-4 (14%) and A-2-4 (30%) soils were extremely sensitive to the change of high groundwater level from +12.0 level to +36.0 level (i.e., base clearance from 2 ft to 0 ft). The layer modulus reduction rates were higher than 90%. For the Levy A-3 (4%), SR-70 A-3 (8%), A-2-4 (12%) and A-2-4 (24%) soils, the reduction rates were also very significant for the base clearance from 2 ft to 0 ft with the layer modulus reduction rates in the range of 55%
to 60%. The A-2-4 (20%) soil was the least sensitive soil in response to the change of high groundwater level with the layer modulus reduction rate about 40%.

9. Adding a 5-inch limerock base layer was very beneficial to the pavement resistance, and the equivalent modulus values were almost doubled. The added limerock base layer certainly improved the dynamic performance of the pavement.

10. Comparing the laboratory resilient modulus results with the subgrade layer modulus values from test-pit, the modulus values were generally within the same range for the same type of soil. The laboratory resilient modulus value at optimum condition was about 70% of the layer modulus for the same type of soil tested in the test-pit with a base clearance of two feet (24 inches). For the soils in this study, it should be on the safe side when the laboratory resilient modulus at optimum condition was used to design a roadway pavement with a base clearance of at least 24-inch or more.

Case Study for High Groundwater Effect

11. The results of the case study indicated that for some sensitive soils, such as SR-70 A-2-4 (14%) and A-2-4 (30%) soils, an increase of high groundwater table would demand a significant increase of the required thickness of asphalt concrete layer in order to have the same quality of pavement performance. The most severe condition was for base clearance reduced from two feet to zero foot. The other subgrade soils also required some increase of asphalt concrete layer thickness.
12. In areas with high groundwater levels, adequate base clearance should be maintained to minimize the moisture damage and to achieve quality performance of the pavement.

9.2 Recommendations

1. Further research is needed by adding more soil types to make the resilient modulus prediction model more accurate and useful.
2. In future test-pit tests, TDR sensors should be calibrated against each soil type to have more accurate measurements of moisture content along pavement profile.
3. More sensible soil suction test method (such as the filter paper method) should be used to obtain the suction values for soils with low suction capability. In turn, the suction value might be evaluated to be an indicator in the resilient modulus regression model.
4. Limerock base should be compacted on the top of the stabilized subgrade prior the plate load test so as to have a direct comparison of the effect of the groundwater level on the subgrade modulus under an identical pavement profile.
5. Upon excavation of the test-pit, the density of the embankment layer should be re-evaluated to identify any possible consolidation or densification of the embankment layer due to the plate loading and compaction.
6. Adequate compaction of pavement subgrades under a high groundwater level may not be feasible to achieve the desired density and stability during construction operations. Compaction of typical
roadway subgrades under high groundwater levels should be studied to evaluate the constructability of such pavement materials.

7. A good drainage is very important to a pavement system. Moisture exerts detrimental effects on the roadway base and pavement system. The pavement system should be designed in such a way that water is prevented from entering the places where it can cause damage. An adequate base clearance should be designed to prevent water from entering the pavement system in order to reduce its detrimental effects.
APPENDIX A

BASIC CONCEPT OF TIME DOMAIN REFLECTOMETRY
A.1 Dielectric Constant and Moisture Content

Unbound material used in pavement structures is comprised of a three-phase system: soil solid, air, and water. The dielectric constant for air is 1. For most minerals comprising soil and aggregate system, the dielectric constant typically varies between 3 and 5, while the dielectric constant of water is typically near 80. As water has such a large dielectric constant (compared to the air and solid phases), the amount of water present in a soil-water mixture is the primary determinant of the dielectric constant of the mixture between the conducting surfaces of TDR probe. For a completely dry soil, the composite dielectric constant will be slightly less than the soil solid. As moisture is added to the soil, the composite dielectric constant increases due to the large dielectric constant of water (Aabral et al, 1999) (Campbell Scientific Inc., 1998).

A.2 TDR -- Equipment and its Approach

TDR probe (also named Water Content Reflectometer) consists of two or three stainless steel rod connected to a printed circuit board. A shielded four-conductor cable (coaxial cable) is connected to circuit board to supply power. The probe provides a measure of the volumetric water content of porous media. The water constant information is derived from the effect of changing dielectric constant on the electromagnetic waves propagating along a wave-guide (Stainless steel rod).

To measure soil moisture using the TDR approach, a Tektronix 1502B Cable Tester is used to emit an electromagnetic pulse throughout a coaxial cable connected to the probe. The
electromagnetic wave travels through the center of the cable at approximately the speed of light, factored by the resistance of the cable in the air, and then through the rod of the probe. Once the pulse reaches the end of the probe, a portion of the signal is reflected back through the shielding of the coaxial cable to the Tektronix unit. The reflected voltage versus time is registered on a screen display of the Tektronix unit and/or saved to an ASCII file. The portion of the trace of interest goes from when the signal reaches the beginning of the probe to the point when the signal reaches the end of the probe. A drop in reflected voltage is seen on the display of the Tektronix unit when the signal reaches the beginning of TDR probe, due to the increased resistance of the smaller path in the printed circuit board, and a vast rise in the reflected voltage is noticed when the signal reaches the end of the probe.

The horizontal distance between the initial and final inflection points of the TDR trace response, as measured by an oscilloscope, is the travel time of the signal (as the probe CS615 used in the DHW research). This travel time represents the apparent length ($L_a$) of the TDR response. Knowledge of the actual probe length and signal speed permits a calculation of an "apparent dielectric constant" ($K_a$) of the media into which the TDR probe is inserted. The computed dielectric constant is referred to as the "apparent dielectric constant" ($K_a$) and is defined as follow:

$$K_a = \frac{(L_a)/(L)}{(V_p)} = \frac{(B-A)/(L)}{(V_p)}$$  \hspace{1cm} (A-1)

$K_a$: dielectric constant  
$L_a$: (B-A) = apparent length of the probe (m)  
$B = $ final inflection point  
$A = $ initial inflection point  
$L = $ actual length of probe (m)  
$V_p = $ the ratio of the actual propagation velocity to the speed of light
On TDR cable tester, the phase velocity setting is usually 0.99 for maximum resolution. Once the $K_a$ is computed for a specific soil mixture, a correlation equation is used to predict the volumetric content (Campbell Scientific Inc., 1998).

### A.3 Other Factors Effecting Dielectric Constant

Although volumetric water content exerts a dominant influence upon the dielectric constant, still there are other factors that can affect $K_a$ value. They are:

1) **Soil mineral dielectric constant variability**
   Generally, fine and coarse-grained soils have distinctly different mineral compositions. Fine-grained soils are primarily comprised of magnesium and calcium, while coarse-grained soil predominately contains silica and quartz. With fine-grained soils’ dielectric constant as 4 and coarse-grained soils’ as 8, this generates a relatively large variation in dielectric value.

2) **Water Constant Variability Factor**
   This includes the influence of free versus bound water in soil. In some cases this is important because absorbed water has a low dielectric constant than free water. For example, when volumetric moisture content falls below 5 percent, the dielectric constant is increasingly influenced by the soil type and mineralogy (in this case, bound water constitute a big part of total volumetric water content).

3) **Saline Conditions**
   This is another key factor in establishing the dielectric constant. When a saline solution is added in the area where the TDR probe is located, a short-circuiting occurs to the probe, thus make the final TDR response difficult to interpret.

4) **Temperature Effects**
Some research found that when water content is very high and the electromagnetic wave travels in a higher frequency, the difference in temperature can generate a big difference for the test results (Campbell Scientific Inc., 1998).

**A.4 Apparent Length and its Determination**

Because the dielectric constant $K_a$ is proportional to the square of the apparent length $L_a$ (or the wave travel period through the rod), error or differences in the measurement of $L_a$ will significantly influence the computed (measured) $K_a$ value of the soil mixture. The purpose of the initial phase of this study was to identify the best method for determining the apparent length of the TDR probe when calculating the dielectric constant. Presently, the five known methods for calculating the dielectric constant from the TDR trace are: 1) Method of Tangents; 2) Method of Peaks; 3) The Alternate Method of Tangents approach; 4) Method of Diverging Lines; 5) Campbell Scientific Method. It’s apparent that each method uses a slightly different location to measure the initial and final inflection points of the trace signal. The differences in the measured $L_a$ can influence the predictive model and their associated accuracy (Campbell Scientific Inc., 1998).

**A.5 Three Phase Approach for Modeling**

Two different approaches are used to relate soil volumetric moisture content to the TDR response. (1) The first approach is empirical. It selects functional relationships based on their mathematical flexibility to fit the experimental data points. This modeling approach is used for the
TDR probes equipped in research work of Design Highwater Clearances.

(2) The second approach derives a mechanistic of fundamental equation from the dielectric mixing models. The fundamental equation relates the composite dielectric number of a multiphase mixture to the dielectric numbers and volume fractions of its constituents. In this approach, the soil is considered to be a three-phase mixture of soil, water, and air. Using the volumetric properties of the soil, such as dry density and specific gravity, in addition to the dielectric values of water and air, a mixing model can be derived. The following derivation separates the soil’s elements to assume a mixing/composite model of the form:

\[ k^a_s = \frac{\sum V_i \varepsilon_i^a}{\sum V_i} \]  \hspace{1cm} (A-2)

Where: \( V_i \) = Volume of the \( i^{th} \) Material Phase.
\( \varepsilon_i \) = Dielectric Constant of the \( i^{th} \) Material.

\( a \) = Assumed Power Coefficient.

Letting \( V_t = \Sigma V_i \), \( k^a_s = (V_s/V_t)\varepsilon_s^a + (V_a/V_t)\varepsilon_a^a + (V_w/V_t)\varepsilon_w^a \) (for a soil mixture: 's'=Solid, 'a'=Air, 'w'=Water)

\( V_s/V_t = W_s/G_s\gamma_w V_t = \gamma_d/G_s\gamma_w = V_s(\%) \).

Since, \( \varepsilon_a = 1 \) (Dielectric Constant of Air)

\[ K^a_s = \frac{\gamma_d}{G_s\gamma_w} \varepsilon_s^a + V_a(\%) + V_w(\%)\varepsilon_w^a \]  \hspace{1cm} (A-3)

Where, \( V_a(\%) = V_a/V_t \) (Volumetric Air Content)
\( V_w(\%) = V_w/V_t \) (Volumetric Water Content)
Also,

\[ V_a(\%) = 1 - \left[ V_i(\%) + V_w(\%) \right] \]  \hspace{1cm} (A-4)

\[ K_a^* = \frac{\gamma_d}{G_s\gamma_w} \varepsilon_s^a + 1 - V_i(\%) - V_w(\%) + V_w(\%)\varepsilon_w^a \]  \hspace{1cm} (A-5)

\[ K_a^* = \frac{\gamma_d}{G_s\gamma_w} (\varepsilon_s^a - 1) + V_w(\%)(\varepsilon_w^a - 1) + 1 \]  \hspace{1cm} (A-6)

\[ K_a = \left( \frac{L_a}{L_p V_p} \right)^2 \]  \hspace{1cm} (A-7)

Assume \( \alpha = 0.5 \); Use FHWA standard TDR length \( L_p = 0.203m \)

\( V_p = \) Velocity of Propagation (0.99). Then:

or:

\[ V_w(\%) = \frac{(5L_a - 1) - \left( \sqrt{\varepsilon_s - 1} \right) \frac{\gamma_d}{G_s\gamma_w}}{\left( \sqrt{\varepsilon_w - 1} \right)} \]  \hspace{1cm} (A-8)

\[ V_w(\%) = \frac{\sqrt{K_a} - 1 - \left( \sqrt{\varepsilon_s - 1} \right) \frac{\gamma_d}{G_s\gamma_w}}{\left( \sqrt{\varepsilon_w - 1} \right)} \]  \hspace{1cm} (A-9)

For water and soil, the dielectric constant can be assumed near '4' and '81' respectively, thus:

\[ V_w(\%) = \frac{\sqrt{K_a} - 1 - \left( \sqrt{\varepsilon_s - 1} \right) \frac{\gamma_d}{G_s\gamma_w}}{\left( \sqrt{\varepsilon_w - 1} \right)} \]  \hspace{1cm} (A-10)

Since the contribution of the constant \( \gamma_d/8G_s\gamma_w \) will only between 0.06 to 0.10 percent,

\[ V_w(\%) = 0.125 \sqrt{K_a} - 0.205 \]  \hspace{1cm} (A-11)

The above analysis helps to explain literature model form of \( V_w = \sqrt{K_a} \).

(Note: \( \alpha = 0.5 \) is found through linear regression technique)

(Roth et al., 1990 and Dirksen & Dasberg, 1993)
As long as the FHWA standard TDR probe is followed, the above equation can be used to approximate the volumetric moisture content of most of soils. For refined measurement of specific soil or soils group, hierarchical methodology for estimating volumetric water content can be followed (Aabral et al, 1999) (Campbell Scientific Inc., 1998).

A.6 The Hierarchical Methodology for Estimating Volumetric Moisture Content

According to the 28 soils tested covering most of the groupings of the AASHTO classification, these hierarchical levels were defined by:

1) Each individual soil (level 1);
2) Each soil classification (level 2);
3) Coarse and fine grained group (level 3);
4) All soils group together to develop a universal model for all application (level 4).

Level 4: This approach is recommended as it is suitable for measuring the volumetric moisture content of a soil in just any circumstance. When no information is available to a specific soil calibration, a close approximation is all that is needed in many applications.

Level 3: Approach adopted in this Level could determine the volumetric moisture content when soil can be defined as either coarse or fine grained. For granular soil, this estimation can generate considerable accuracy.

Level 2: is more specific and detailed in that the volumetric moisture content is based on the AASHTO soil classification.

Level 1: The most accurate level. This approach is based on a site-specific calibrated soil. A calibration curve would be
developed using varying moisture levels for each soil for which volumetric moisture is needed. Once the apparent length of TDR response (or travel time on the TDR guide rod in our case) is measured, the predicted volumetric moisture can be calculated. The modeling approach of the granular subgrade soils in design high water clearance research work rests upon Level 3. For those sandy soils in Florida, this can produce enough accuracy (Aabral et al, 1999) (Campbell Scientific Inc., 1998).
APPENDIX B

FIELD MONITORING PROGRAM
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B.1 General

The main purpose for the implementation of a field monitoring test on SR-70 is to evaluate the capillary behavior and moisture variation within SR-70 subgrades (A-3, A-2-4) under actual field geologic strata. Being exposed to the open environment, the environmental factors such as precipitation and atmospheric temperature will be introduced into the moisture data measurement of SR-70 subgrades for the design highwater research.

Two test sites were selected with SR-70 A-2-4 and A-3 subgrade soils present at both (pavement profile) sites. The close proximity of the test sites (300 ft apart) helped achieve an easy deployment of test equipment and communication.

B.2 Field Installation

The field installation began on March 7, 2000, and was accomplished within a three-day period. After the excavation of the field test pit, CS615 TDR probes were inserted into the pit walls in a manner shown in Figure B.1. A plan view of the equipment layout in the test area is illustrated in Figure B.2. The photo view of the TDR probe installation together with the pavement profile is shown in Figure B.3. The pits were back filled and compacted in accordance with its original geologic strata after the TDR probes were put in place. A small amount of porous concrete was mixed into the backfill to ensure the original subgrade compacted-consolidated situation.

Upon completion of field installation, subsoil exploration was conducted near the pit sites. The results of the soil boring adjacent to both pits location are summarized in Table B.1.
The instruments for field monitoring consisted of a Campbell Scientific CS615 water content reflectometer (TDR probe), a Campbell Scientific CR10x datalogger (measurement and control unit), a rain gauge, a SC12R cable, and an in-lab remote control terminal. The Campbell Scientific CS615 water content reflectometer (TDR probe) provides a measure of the volumetric water content for porous media like sandy soil. The output of an on-site installed CS615 reflectometer is a square wave and can be connected to the Campbell Scientific CR10x datalogger. A more detailed description of this equipment can be found in Chapter 3 and Appendix A.

The Campbell Scientific CR10x Datalogger (measurement and control unit) powered by a solar power system, is the major part of the field instrumentation. It consists of a measurement and control module and a detachable wiring panel. Protected in a sealed, stainless steel box, this data logger functioned as a measurement and control unit for the sensor measurement, communication, data reduction, data/program storage and control. The maximum rate for the unit to execute its program is 64 times per second (enough for a 15 minute interval data acquisition period in a field test). The wiring panel consisted of a baseplate, an end bracket and a top panel. The top panel provided screw terminals for the sensor connection.

A rain gauge installed near the test site facilitated the precipitation record for the evaluation of moisture variation within the subgrade. The data acquisition interval was also 15 minutes and activated in synchrony with the data logger. Its photo illustration is shown in Figure B.4.
The SC12R is a rugged, temperature-resistant cable that connects peripherals to the CR10X measurement and control unit. The in-lab remote control terminal installed with PC208W2.3 software has the remote access to the data storage unit on the test site (non-volatile flash memory or battery-backed RAM for CR10X) through a public-telephone communication system. PC208W2.3 software can initiate connection, data transfer, data display, data storage from CR10X on the test site to a remote control computer in the lab. It also facilitates the re-programming of the datalogger (CR10X) from the terminal. The in-lab data acquisition was performed once a week.

### B.4 Data Reduction

Moisture data in each elevation of the pits were acquired weekly from the datalogger (CR10X) on site through a telephone line by activating PC208W2.3 software. The initial moisture data were recorded by the TDR probe in the form of volumetric water content \( \theta \). With the dry density \( \gamma_d \) acquired in corresponding layers through the site exploration, it was converted into gravimetric water content through the following equation:

\[
\begin{align*}
w(\%) &= \frac{M_w}{M_s} = \frac{\gamma_w \times V_w}{\gamma_d \times V} = \frac{\gamma_w \times \theta}{\gamma_d} \\
&= (\text{B-1})
\end{align*}
\]

Where,
- \( M_w \) = Mass of Water
- \( M_s \) = Mass of Soil Solid
- \( \gamma_w \) = Density of Water
- \( \gamma_d \) = Dry Density of Soil

The above moisture result can be converted further into degrees of saturation \( S \) through the equation below:
\[ S(\%) = \frac{wG_s\gamma_d}{\gamma_wG_s - \gamma_d} \]  \hspace{1cm} (B-2)

Where, \( G_s \) = Specific Gravity of Soil Solid
\( W \) = Moisture Content

For the moisture analysis on a daily basis, moisture and precipitation data were recorded every 15 minutes in the field and were then averaged to present data on a 24-hour basis.

The timing of the datalogger is not in the form of a calendar, rather it was demonstrated through a three-digit number. This can be translated into a specific date (Mo./Date/Yr.) by referring to the CR10X manual. The data reduction process of the field test correlated the date of the season and the precipitation with the moisture profile obtained by TDR probes in the pavement of the test sites (Liu, 2001).
### Table B.1 Summary of Soil Boring Results on Field Test Sites

#### SR-70 West Site (Pit No.1)

<table>
<thead>
<tr>
<th>Depth (ft)</th>
<th>SPT Blows (Dry density, pcf)</th>
<th>Material Description</th>
<th>-200% Passing</th>
<th>AASHTO Classification</th>
<th>Remarks</th>
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</thead>
<tbody>
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<td>0.5</td>
<td>3</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.0</td>
<td>4 (87.4)</td>
<td>Gray Sand</td>
<td>8</td>
<td>A-3</td>
<td>0-0.3 Asphalt 0.3-2.7 Gray Sand</td>
</tr>
<tr>
<td>1.5</td>
<td>6 (86.2)</td>
<td>Gray Sand into Hardpan</td>
<td></td>
<td>A-3</td>
<td></td>
</tr>
<tr>
<td>2.0</td>
<td>6 (82.1)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2.5</td>
<td>7 (89.8)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3.0</td>
<td>8 (82.6)</td>
<td></td>
<td></td>
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</tr>
<tr>
<td>3.5</td>
<td>5 (79.3)</td>
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</tr>
<tr>
<td>4.0</td>
<td>4 (89.6)</td>
<td>Hardpan into Tan sand</td>
<td>9</td>
<td>A-3</td>
<td>2.7-4.1 Hardpan &amp; Organic Material</td>
</tr>
<tr>
<td>4.5</td>
<td>5 (94.5)</td>
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#### SR-70 West Site (Pit No.2)

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368
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C.1 Presentation of Field Monitoring Results

The moisture and precipitation data were acquired through the remote control system (PC208) and reprocessed for analysis. The presentation of the test results was separated into four seasonal groups representing moisture variations for the past year. Within each season (from spring 2000 to winter 2000/2001), the test results were then grouped together according to different test sites. Since the moisture profile of the SR-70 subgrade materials was the main concern of the field test, the presentation of the test results from field monitoring program was focused on two main categories:

1) The influence of rainfall upon the moisture within each layer of the subgrade for a specific season. These are illustrated in the figures denoted as “Degree of Saturation versus Date and Precipitation”.

2) A continuous moisture variation below the asphalt concrete pavement for a designated time period. These are presented in the figures denoted as “Degree of Saturation versus Depth”, which is in the form of an envelope encompassing the maximum and minimum degree of saturation along the depth of the subgrade layer for the season in consideration.

All of the test results are presented in the tables and figures at the end of this Appendix C.

C.2 Discussion on Field Monitoring Results

The following observations were made by evaluating the field monitoring results:
1) The moisture change in each soil layer resulted from temperature variation within a 24-hour period was not significant.

2) The A-3 soil with a small percentage of passing #200 fines was more sensitive to change of precipitation. The degree of saturation increased significantly with the rain. It also exhibited faster moisture dissipation after the rain.

3) Light rains (with daily precipitation less than 0.7 in.) had no significant effect on the moisture content of deep soils (i.e., deeper than three feet below the asphalt concrete layer)

4) For the deeper A-3 soil above the ground water table, there would be an appreciable amount of increase in moisture content due to heavy rains (with daily precipitation more than 1.2 in.). The level of moisture increment exceeded all the soil layers above the deep A-3 soil.

5) The response of moisture increase due to precipitation was instant but limited for the topsoil, and slower for deeper soils (with a 24-hour time lag). The accumulation of moisture was observed to be continuing even 10 days after a heavy rain for deep soils (i.e., the A-3 soil, 6 ft. below the asphalt concrete layer) on test site No.2.

6) Precipitation had no significant impact upon the degree of saturation for the A-2-4 soil.

7) The hardpan layer and A-2-4 soil layer could impeded the quick accumulation of moisture for the soil layer within its adjacent area, but could not stop it from gaining moisture after 24 hours.

8) With the exception of heavy rain, the moisture in hardpan layer was kept stable (degree of saturation about 45%) despite of the moisture fluctuation in the adjacent soil layers.
Overall the moisture content within the A-2-4 soil for a given layer was relatively stable under the climatic change. However, the moisture content within the A-3 soil was volatile in response to the climatic change, with a rapid change in moisture variation for the top layer (Liu, 2001).
### Moisture Profile (%) for SR-70 Field Test Site No.1 (Spring, 2000)

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<td>102.39 74.08 55.24 25.99 24.44 16.76 0.00</td>
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Figure C.1 Degree of Saturation vs. Date and Precipitation (Field Test Site No.1 -- Spring 2000)
Figure C.2 Degree of Saturation vs. Depth (Field Test Site No.1 -- Spring 2000)
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Figure C.3 Degree of Saturation vs. Date and Precipitation (Field Test Site No.2 -- Spring 2000)
Figure C.4 Degree of Saturation vs. Depth (Field Test Site No.2 -- Spring 2000)
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* Reading Jumped from 43% to 82% within 15 Min. upon 16:30, July 6th.
Table C.5  Moisture Profile of SR-70 Soils (Field Test Site No.1)

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Figure C.5 Degree of Saturation vs. Date and Precipitation (Field Test Site No.2 -- Summer 2000)
Figure C.6 Degree of Saturation vs. Depth (Field Test Site No.1 -- Summer 2000)
Table C.6 Moisture Profile of SR-70 Soils (Field Test Site No.2)

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Figure C.7 Degree of Saturation vs. Date and Precipitation (Field Test Site No. 2 -- Summer 2000)
Figure C.8 Degree of Saturation vs. Depth (Field Test Site No.2 -- Summer 2000)
### Table C.7 Moisture Profile (%) for SR-70 Field Monitoring (Fall, 2000)

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TDR Probe out of order upon 7/27  Volumetric Moisture Content >1.0 to 6999

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Moisture Profile (%) for SR-70 Field Test Site No. 2 (Fall, 2000)

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Figure C.9 Degree of Saturation vs. Date and Precipitation (Field Test Site No.1 -- Fall 2000)
Figure C.10 Degree of Saturation vs. Depth (Field Test Site No.1, Fall 2000)
Table C.9  Moisture Profile of SR-70 Soils (Field Test Site No.2)

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<th>Rainfall (inch)</th>
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Figure C.11 Degree of Saturation vs. Date and Precipitation (Field Test Site No.2 -- Fall 2000)
Figure C.12 Degree of Saturation vs. Depth (Field Test Site No.2 -- Fall 2000)
### Table C.10 Moisture Profile (%) for SR-70 Field Monitoring (Winter, 2000/2001)

#### Moisture Profile (%) for SR-70 Field Test Site No.1 (Winter, 2000/2001)

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#### Moisture Profile (%) for SR-70 Field Test Site No.2 (Winter, 2000/2001)

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<td>Rainfall (inch)</td>
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Table C.14  Moisture Profile of SR-70 Soils (Field Test Site No.2 Year 2001)

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Table D.5 SR-70 A-3 Soil Plate Load Test (Deformation vs. Number of Cycles)
### Table D.6  SR-70 A-2-4 Soil Plate Load Test (Deformation)

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Figure D.1 Levy County A-3 Soil, Deformation under 20 psi Plate Load (Water Table at -20 in., without Limerock)

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Table E.1 Triaxial test results A-3 Levy County after drying
(Sample # A3LEVYD1)

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Figure E.1.1 Resilient Modulus versus bulk stress for A-3 Levy County after drying (Sample # A3LEVYD1)

Figure E.1.2 Resilient Modulus versus confining stress for A-3 Levy County after drying (Sample # A3LEVYD1)
Table E.2 Triaxial test results of A-3 Levy County after drying (Sample # A3LEVYD2)

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Moisture 4.30%  Opt. Moist. 9.60%
Lab. Den. 105.8 pcf  Opt. Den. 106.2 pcf

Conditioning Information
Load Type: Dynamic
Dev. Stress: 82.74 kPa
Conf. Stress: 103.42 kPa
No. Reps.: 1000

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<th>Confining Pressure</th>
<th>Axial Load</th>
<th>Dev. Stress</th>
<th>Bulk Stress</th>
<th>Middle Strain</th>
<th>Full Length Strain</th>
<th>Middle Modulus</th>
<th>Full Length Modulus</th>
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<tbody>
<tr>
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<td>kN</td>
<td>kPa</td>
<td>kPa</td>
<td>MPa</td>
<td>kPa</td>
<td>MPa</td>
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<td>0.0001629</td>
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<td>231.499</td>
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Figure E.2.1 Resilient Modulus versus bulk stress for A-3 Levy County after drying (Sample # A3LEVYD2)

Figure E.2.2 Resilient Modulus versus confining stress for A-3 Levy County after drying (Sample # A3LEVYD2)
Table E.3 Triaxial test results of A-3 Levy County at optimum condition (A3LEVYO1)

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<th>Summary Resilient Modulus Test Result</th>
<th>Soil Identification</th>
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<td>A-3</td>
</tr>
<tr>
<td>Sample No: A3LEVYO1</td>
<td>levy county</td>
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**Conditioning Information**
- Load Type: Dynamic
- Dev. Stress: 82.74 kPa
- Conf. Stress: 103.42 kPa
- No. Reps.: 1000

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<tr>
<th>Confining Pressure</th>
<th>Axial Load</th>
<th>Dev. Stress</th>
<th>Bulk Stress</th>
<th>Middle Strain</th>
<th>Full Length Strain</th>
<th>Middle Modulus</th>
<th>Full Length Modulus</th>
</tr>
</thead>
<tbody>
<tr>
<td>kPa</td>
<td>kN</td>
<td>kPa</td>
<td>kPa</td>
<td>MPa</td>
<td>MPa</td>
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<td></td>
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<td>0.000178</td>
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Figure E.3.1 Resilient Modulus versus bulk stress for A-3 Levy County at optimum moisture (Sample # A3LEVYO1)

Figure E.3.2 Resilient Modulus vs. confining stress for A-3 Levy County at optimum moisture (Sample # A3LEVYO1)
Table E.4 Triaxial test results of A-3 Levy County at optimum condition (Sample # A3LEVYO2)

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<td><strong>Soil Identification</strong></td>
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<tr>
<td>Optimum Moist. 9.60%</td>
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<tr>
<td>Optimum Density 106.2</td>
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</table>

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<th>Conditioning Information</th>
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<td>Load Type: Dynamic</td>
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<tr>
<td>Dev. Stress: 82.74 kPa</td>
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<tr>
<td>Conf. Stress: 103.42 kPa</td>
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<tr>
<td>No. Reps.: 1000</td>
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</table>

<table>
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<th>Dev. Stress</th>
<th>Bulk Stress</th>
<th>Middle Strain</th>
<th>Full Length Strain</th>
<th>Middle Modulus</th>
<th>Full Length Modulus</th>
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<td>Mpa</td>
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Figure E.4.1 Resilient Modulus versus bulk stress for A-3 Levy County at optimum moisture (Sample # A3LEVYO2)

Figure E.4.2 Resilient Modulus vs. confining stress for A-3 Levy County at optimum moisture (Sample # A3LEVYO2)
Table E.5 Triaxial test results of A-3 Levy County after soaking (Sample # A3LEVYS1)

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<td>Opt. Den. 106.2 pcf</td>
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<th>Conditioning Information</th>
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<td>Load Type: Dynamic</td>
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<td>Dev. Stress: 82.74 kPa</td>
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<td>Conf. Stress: 103.42 kPa</td>
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<tr>
<td>No. Reps.: 1000</td>
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<th>Confining Pressure</th>
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<th>Bulk Stress</th>
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<th>Full Length Strain</th>
<th>Middle Modulus</th>
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<td>MPa</td>
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</table>

Note: soaked one month, 3 times conditioning
Figure E.5.1 Resilient Modulus versus bulk stress for A-3 Levy County after soaking (Sample # A3LEVYS1)

Figure E.5.2 Resilient Modulus versus confining stress for A-3 Levy County after soaking (Sample # A3LEVYS1)
### Table E.6 Triaxial test results of A-3 Levy County after soaking (Sample # A3LEVYS2)

<table>
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<th>Full Length Strain</th>
<th>Middle Modulus</th>
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Figure E.6.1 Resilient Modulus versus bulk stress for A-3 Levy County after soaking (Sample # A3LEVYS2)

Figure E.6.2 Resilient Modulus versus confining stress for A-3 Levy County after soaking (Sample # A3LEVYS2)
Table E.7 Triaxial test results of A-3 Levy County after soaking
(Sample # A3LEVYS3)

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**Conditioning Information**

- Load Type: Dynamic
- Dev. Stress: 82.74 kPa
- Conf. Stress: 103.42 kPa
- No. Reps.: 1000

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Figure E.7.1 Resilient Modulus versus bulk stress for A-3 Levy County after soaking (Sample # A3LEVYS3)

Figure E.7.2 Resilient Modulus versus confining stress for A-3 Levy County after soaking (Sample # A3LEVYS3)
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Table F.1 Triaxial test results of A-3 SR70 after drying (Sample # A3SR70D1)

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Figure F.1.1 Resilient Modulus versus bulk stress for A-3 SR70 after drying (Sample # A3SR70D1)

Figure F.1.2 Resilient Modulus versus confining pressure for A-3 SR70 after drying (Sample # A3SR70D1)
Table F.2 Triaxial test results of A-3 SR70 after drying (Sample # A3SR70D2)

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**Conditioning Information**

- **Load Type:** Dynamic
- **Dev. Stress:** 82.74 kPa
- **Conf. Stress:** 103.42 kPa
- **No. Reps.:** 1000

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<td>0.000156</td>
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<td>13.79</td>
<td>0.261</td>
<td>32.224</td>
<td>73.594</td>
<td>0.0001932</td>
<td>0.0002682</td>
<td>166.774</td>
<td>120.128</td>
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</tr>
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<td>13.79</td>
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<td>127.167</td>
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</tr>
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</table>
Figure F.2.1 Resilient Modulus versus bulk stress for A-3 SR70 after drying (Sample # A3SR70D2)

$y = 13.622x^{0.5195}$

$R^2 = 0.9654$

Figure F.2.2 Resilient Modulus versus confining pressure for A-3 SR70 after drying (Sample # A3SR70D2)

$y = 38.13x^{0.444}$

$R^2 = 0.9998$
Table F.3 Triaxial test results of A-3 SR70 after drying (Sample # A3SR70D3)

<table>
<thead>
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<th>Summary Resilient Modulus Test Result</th>
</tr>
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<tr>
<td><strong>Soil Identification</strong></td>
</tr>
<tr>
<td>Sample No. A3SR70D3</td>
</tr>
<tr>
<td>A-3, SR70</td>
</tr>
</tbody>
</table>

| Lab. Moist. | 4.48% |
| Lab. Den.   | 108.8 pcf |
| Opt. Moist. | 11.40% |
| Opt. Den.   | 112.1 pcf |

**Conditioning Information**

- **Load Type:** Dynamic
- **Dev. Stress:** 82.74 kPa
- **Conf. Stress:** 103.42 kPa
- **No. Reps.:** 1000

<table>
<thead>
<tr>
<th>Confining Pressure</th>
<th>Axial Load</th>
<th>Dev. Stress</th>
<th>Bulk Stress</th>
<th>Middle Strain</th>
<th>Full Length Strain</th>
<th>Middle Modulus</th>
<th>Full Length Modulus</th>
</tr>
</thead>
<tbody>
<tr>
<td>kPa</td>
<td>kN</td>
<td>kPa</td>
<td>kPa</td>
<td>MPa</td>
<td>MPa</td>
<td>MPa</td>
<td>MPa</td>
</tr>
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<td>356.374</td>
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<td>0.0001284</td>
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<td>0.0001859</td>
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<td>0.0001532</td>
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<td>0.0002249</td>
<td>340.459</td>
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<td>101.282</td>
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<td>0.0003344</td>
<td>339.660</td>
<td>302.886</td>
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<td>205.414</td>
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<td>0.000151</td>
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<td>0.0002124</td>
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<td>0.0002995</td>
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<td>222.797</td>
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<td>0.0003066</td>
<td>220.508</td>
<td>105.243</td>
</tr>
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<td>13.79</td>
<td>0.374</td>
<td>46.131</td>
<td>87.501</td>
<td>0.0002104</td>
<td>0.000396</td>
<td>219.204</td>
<td>116.490</td>
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</table>
Figure F.3.1 Resilient Modulus versus bulk stress for A-3 SR70 after drying (Sample # A3SR70D3)

Figure F.3.2 Resilient Modulus versus confining pressure for A-3 SR70 after drying (Sample # A3SR70D3)
Table F.4 Triaxial test results of A-3 Levy County after drying (Sample # A3LEVYD4)

<table>
<thead>
<tr>
<th>Sample No.</th>
<th>A3LEVYD4</th>
<th>A-3</th>
</tr>
</thead>
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<tr>
<td>Moisture</td>
<td>4.00%</td>
<td>Opt. Moist.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>11.40%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>112.1 pcf</td>
</tr>
</tbody>
</table>

### Conditioning Information
- Load Type: Dynamic
- Dev. Stress: 82.74 kPa
- Conf. Stress: 103.42 kPa
- No. Reps.: 1000

<table>
<thead>
<tr>
<th>Confining Pressure</th>
<th>Axial Load</th>
<th>Dev. Stress kPa</th>
<th>Bulk Stress kPa</th>
<th>Middle Strain MPa</th>
<th>Full Length Strain</th>
<th>Middle Modulus Mpa</th>
<th>Full Length Modulus Mpa</th>
</tr>
</thead>
<tbody>
<tr>
<td>103.42</td>
<td>0.373</td>
<td>45.997</td>
<td>356.257</td>
<td>7.084E-05</td>
<td>0.0001461</td>
<td>649.281</td>
<td>314.876</td>
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<tr>
<td>103.42</td>
<td>0.541</td>
<td>66.706</td>
<td>376.966</td>
<td>0.0001305</td>
<td>0.0002124</td>
<td>511.226</td>
<td>313.996</td>
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<td>0.00027</td>
<td>373.796</td>
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Figure F.4.1 Resilient Modulus versus bulk stress for A-3 SR70 after drying (Sample # A3SR70D4)

Figure F.4.2 Resilient Modulus versus confining pressure for A-3 SR70 after drying (Sample # A3SR70D4)
Table F.5 Triaxial test results of A-3 SR70 at optimum condition
(Sample # A3SR70O1)

<table>
<thead>
<tr>
<th>Summary Resilient Modulus Test Result</th>
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<tr>
<td>Sample No.: A3SR70O1</td>
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<tr>
<td>Soil Identification: A-3, SR70</td>
</tr>
<tr>
<td>Lab. Moist. 11.40%</td>
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<tr>
<td>Opt. Moist. 11.40%</td>
</tr>
<tr>
<td>Lab. Den. 111 pcf</td>
</tr>
<tr>
<td>Opt. Den. 112.1 pcf</td>
</tr>
<tr>
<td>Conditioning Information</td>
</tr>
<tr>
<td>Load Type: Dynamic</td>
</tr>
<tr>
<td>Dev. Stress: 82.74 kPa</td>
</tr>
<tr>
<td>Conf. Stress: 103.42 kPa</td>
</tr>
<tr>
<td>No. Reps.: 1000</td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>Confining Pressure</th>
<th>Axial Load</th>
<th>Dev. Stress</th>
<th>Bulk Stress</th>
<th>Middle Strain</th>
<th>Full Length Strain</th>
<th>Middle Modulus</th>
<th>Full Length Modulus</th>
</tr>
</thead>
<tbody>
<tr>
<td>kPa</td>
<td>kN</td>
<td>kPa</td>
<td>kPa</td>
<td>MPa</td>
<td>MPa</td>
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</tr>
<tr>
<td>103.42</td>
<td>0.376</td>
<td>46.353</td>
<td>356.613</td>
<td>0.0001462</td>
<td>0.0001638</td>
<td>317.011</td>
<td>282.956</td>
</tr>
<tr>
<td>103.42</td>
<td>0.545</td>
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<td>0.0002338</td>
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<td>0.0001468</td>
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<td>0.0001776</td>
<td>0.0002105</td>
<td>262.125</td>
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Figure F.5.1 Resilient Modulus versus bulk stress for A-3 SR70 at optimum moisture (Sample # A3SR7001)

Figure F.5.2 Resilient Modulus versus confining pressure for A-3 SR70 at optimum moisture (Sample # A3SR7001)
Table F.6 Triaxial test results at optimum condition for SR70, A-3 (Sample # A3SR70O2)

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<th>Soil Identification</th>
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<tr>
<td>Mold#: 1</td>
<td>SR 70</td>
</tr>
<tr>
<td>Sample#: 2</td>
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<td>Opt. Moist. 11.40%</td>
</tr>
<tr>
<td>Lab. Den. 110.8 pcf</td>
<td>Opt. Den. 112.1 pcf</td>
</tr>
</tbody>
</table>

**Conditioning Information**
- Load Type: Dynamic
- Dev. Stress: 82.74 kPa
- Conf. Stress: 103.42 kPa
- No. Reps.: 1000

<table>
<thead>
<tr>
<th>Confining Pressure</th>
<th>Axial Load</th>
<th>Dev. Stress</th>
<th>Bulk Stress</th>
<th>Middle Strain</th>
<th>Full Length Strain</th>
<th>Middle Modulus</th>
<th>Full Length Modulus</th>
</tr>
</thead>
<tbody>
<tr>
<td>kPa</td>
<td>kN</td>
<td>kPa</td>
<td>kPa</td>
<td>MPa</td>
<td>MPa</td>
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<td>332.841</td>
<td>300.841</td>
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<td>0.263</td>
<td>32.433</td>
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<td>128.340</td>
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</table>
Figure F.6.1 Resilient Modulus versus bulk stress for A-3 SR70 at optimum moisture (Sample # A3SR70O2)

\[ y = 23.86x^{0.4364} \]
\[ R^2 = 0.9785 \]

\[ y = 12.68x^{0.5254} \]
\[ R^2 = 0.9804 \]

Figure F.6.2 Resilient Modulus versus confining pressure for A-3 SR70 at optimum moisture (Sample # A3SR70O2)

\[ y = 58.41x^{0.367} \]
\[ R^2 = 0.9952 \]

\[ y = 37.16x^{0.4406} \]
\[ R^2 = 0.9916 \]
Table F.7 Triaxial test results of A-3 SR70 after soaking
(Sample # A3SR70S1)

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<td><strong>Soil Identification</strong></td>
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<td>SR 70</td>
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<tr>
<td><strong>Lab. Moist.</strong> 13.41%</td>
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<tr>
<td><strong>Opt. Moist.</strong> 11.40%</td>
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<tr>
<td><strong>Lab. Den.</strong> 109.67 pcf</td>
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<tr>
<td><strong>Opt. Den.</strong> 112.1 pcf</td>
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**Conditioning Information**
- **Load Type:** Dynamic
- **Dev. Stress:** 82.74 kPa
- **Conf. Stress:** 103.42 kPa
- **No. Reps.:** 1000

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<th>Dev. Stress</th>
<th>Bulk Stress</th>
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<th>Full Length Strain</th>
<th>Middle Modulus</th>
<th>Full Length Modulus</th>
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<td>MPa</td>
<td>Mpa</td>
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Figure F.7.1 Resilient Modulus versus bulk stress for A-3 SR70 after soaking (Sample # A3SR70S1)

Figure F.7.2 Resilient Modulus versus confining pressure for A-3 SR70 after soaking (Sample # A3SR70S1)
Table F.8 Triaxial test results of A-3 SR70 after soaking (Sample # A3SR70S2)

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<td>Moisture 13.69%</td>
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### Conditioning Information

- **Load Type:** Dynamic
- **Dev. Stress:** 82.74 kPa
- **Conf. Stress:** 103.42 kPa
- **No. Reps.:** 1000

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<th>Full Length Strain</th>
<th>Middle Modulus</th>
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<td>kPa</td>
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Figure F.8.1 Resilient Modulus versus bulk stress for A-3 SR70 after soaking (Sample # A3SR70S2)

Figure F.8.2 Resilient Modulus versus confining pressure for A-3 SR70 after soaking (Sample # A3SR70S2)
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Table G.1 Triaxial test results of A-2-4 12% at optimum (Sample # A2412%O1)

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<td>12.10%</td>
<td>12.10%</td>
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<td>Dev. Stress: 82.74 kPa</td>
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<td>Conf. Stress: 103.42 kPa</td>
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<td>No. Reps.: 1000</td>
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<th>Dev. Stress</th>
<th>Bulk Stress</th>
<th>Middle Strain</th>
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Figure G.1.1 Resilient Modulus versus bulk stress for A-2-4 12% at optimum moisture (Sample # A2412%O1)

Figure G.1.2 Resilient Modulus versus confining pressure for A-2-4 12% at optimum moisture (Sample # A2412%O1)
Table G.2 Triaxial test results of A-2-4 12% at optimum (Sample # A312%O2)

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<td>Dev. Stress: 82.74 kPa</td>
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<td>0.00013171</td>
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<td>172.598</td>
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</table>
Figure G.2.1 Resilient Modulus vs. Bulk Stress of A-2-4 12% at optimum moisture (Sample # A2412%O2)


g = 9.054x^{0.5911} 
R^2 = 0.9407

\[ y = 6.6733x^{0.6202} \]

\[ R^2 = 0.9700 \]

Figure G.2.2 Resilient Modulus vs. Confining Stress of A-2-4 24% at optimum moisture (Sample # A2412%O2)

\[ y = 30.083x^{0.4987} \]

\[ R^2 = 0.9700 \]

\[ y = 21.134x^{0.5271} \]

\[ R^2 = 0.9916 \]
Table G.3 Triaxial test results of A-2-4 12% after drying (Sample # A312%D1)

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<thead>
<tr>
<th>Summary Resilient Modulus Test Result</th>
</tr>
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<tr>
<td>Soil Identification</td>
</tr>
<tr>
<td>Sample No. A2412%D1</td>
</tr>
<tr>
<td>A-2-4, 12%</td>
</tr>
<tr>
<td>SR 70</td>
</tr>
<tr>
<td>Lab. Moist. 12.10%</td>
</tr>
<tr>
<td>Opt. Moist. 12.10%</td>
</tr>
<tr>
<td>Lab. Den. 110.69 pcf</td>
</tr>
<tr>
<td>Opt. Den. 110.6 pcf</td>
</tr>
<tr>
<td>After Drying 7.10%</td>
</tr>
</tbody>
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### Conditioning Information
- Load Type: Dynamic
- Dev. Stress: 82.74 kPa
- Conf. Stress: 103.42 kPa
- No. Reps.: 1000

<table>
<thead>
<tr>
<th>Confining Pressure</th>
<th>Axial Load</th>
<th>Dev. Stress</th>
<th>Bulk Stress</th>
<th>Middle Strain</th>
<th>Full Length Strain</th>
<th>Middle Modulus</th>
<th>Full Length Modulus</th>
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<tbody>
<tr>
<td>kPa</td>
<td>kN</td>
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<td>kPa</td>
<td>MPa</td>
<td>MPa</td>
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<td>MPa</td>
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<td>0.541</td>
<td>66.740</td>
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<td>0.000168273</td>
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<td>0.000231833</td>
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<td>66.815</td>
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<td>0.000319309</td>
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<td>0.000407861</td>
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<td>112.995</td>
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</table>
Figure G.3.1 Resilient Modulus vs. Bulk Stress of A-2-4 12% after drying (Sample # A2412%D1)

Figure G.3.2 Resilient Modulus vs. Confining Pressure of A-2-4 12% after drying (Sample # A2412%D1)
Table G.4 Triaxial test results of A-2-4 12% after drying (Sample # A312%D2)

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<td>Sample No. A2412%D2</td>
</tr>
<tr>
<td>Lab. Moist. 12.10%</td>
</tr>
<tr>
<td>Lab. Den. 110.7 pcf</td>
</tr>
<tr>
<td>After Drying 7.04%</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Conditioning Information</th>
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<tbody>
<tr>
<td>Load Type: Dynamic</td>
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<tr>
<td>Dev. Stress: 82.74 kPa</td>
</tr>
<tr>
<td>Conf. Stress: 103.42 kPa</td>
</tr>
<tr>
<td>No. Reps.: 1000</td>
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</table>

<table>
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<tr>
<th>Confining Pressure</th>
<th>Axial Load</th>
<th>Dev. Stress</th>
<th>Bulk Stress</th>
<th>Middle Modulus</th>
<th>Full Length Modulus</th>
</tr>
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<tbody>
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<td>kPa</td>
<td>kPa</td>
<td>MPa</td>
<td>Mpa</td>
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Figure G.4.1 Resilient Modulus vs. Bulk Stress of A-2-4 12% after drying (Sample # A2412%D2)

Figure G.4.2 Resilient Modulus vs. Confining Pressure of A-2-4 12% after drying (Sample # A2412%D2)
Table G.5 Triaxial test results of A-2-4 12% after soaking (Sample # A312%S1)

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<td><strong>Soil Identification</strong></td>
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<tr>
<td><strong>Lab. Moist.</strong> 12.10%</td>
</tr>
<tr>
<td><strong>Opt. Moist.</strong> 12.10%</td>
</tr>
<tr>
<td><strong>Lab. Den.</strong> 109.6 pcf</td>
</tr>
<tr>
<td><strong>Opt. Den.</strong> 110.6 pcf</td>
</tr>
<tr>
<td><strong>After Soaking</strong> 14.60%</td>
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| Conditioning Information               |
|**Load Type:** Dynamic                  |
| **Dev. Stress:** 82.74 kPa              |
| **Conf. Stress:** 103.42 kPa            |
| **No. Reps.:** 1000                    |

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<th>Confining Pressure</th>
<th>Axial Load</th>
<th>Dev. Stress</th>
<th>Bulk Stress</th>
<th>Middle Strain</th>
<th>Full Length Strain</th>
<th>Middle Modulus</th>
<th>Full Length Modulus</th>
</tr>
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<td>kN</td>
<td>kPa</td>
<td>kPa</td>
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<td>MPa</td>
<td>MPa</td>
<td>MPa</td>
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Figure G.5.1 Resilient Modulus vs. Bulk Stress of A-2-4 12% after soaking (Sample # A2412%S1)

Figure G.5.2 Resilient Modulus vs. Confining Stress of A-2-4 12% after soaking (Sample # A2412%S1)
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<th>Soil Identification</th>
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<td>A-2-4, 12%</td>
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| Lab. Moist. | 12.10% | Opt. Moist. | 12.10% |
| Lab. Den. | 110.3 pcf | Opt. Den. | 110.6 pcf |
| Afer Soaking | 13.60% |

**Conditioning Information**
- Load Type: Dynamic
- Dev. Stress: 82.74 kPa
- Conf. Stress: 103.42 kPa
- No. Reps.: 1000

<table>
<thead>
<tr>
<th>Confining Pressure</th>
<th>Axial Load</th>
<th>Dev. Stress</th>
<th>Bulk Stress</th>
<th>Middle Strain</th>
<th>Full Length Strain</th>
<th>Middle Modulus</th>
<th>Full Length Modulus</th>
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<td>kPa</td>
<td>kPa</td>
<td>MPa</td>
<td>MPa</td>
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<td>245.529</td>
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<td>103.42</td>
<td>0.542</td>
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Figure G.6.1 Resilient Modulus vs. Bulk Stress of A-2-4 12% (Sample # A2412%S2)

$$y = 11.825x^{0.5211} \quad R^2 = 0.9869$$

$$y = 6.701x^{0.6053} \quad R^2 = 0.9961$$

Figure G.6.2 Resilient Modulus vs. Confining Pressure of A-2-4 12% after soaking (Sample # A2412%S2)

$$y = 34.795x^{0.4344} \quad R^2 = 0.9893$$

$$y = 23.699x^{0.5013} \quad R^2 = 0.9949$$
APPENDIX H

LABORATORY TEST RESULTS OF SR70 A-2-4 14%
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Table H.1 Triaxial test results of A-2-4, SR70 after drying
(Sample #A24SR70D1)

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| Lab. Moist. | 8.41% | Opt. Moist. | 10.60% |
| Lab. Den. | 120.3 pcf | Opt. Den. | 122.4 pcf |

**Conditioning Information**
- Load Type: Dynamic
- Dev. Stress: 82.74 kPa
- Conf. Stress: 103.42 kPa
- No. Reps.: 1000

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Figure H.1.1 Resilient Modulus versus bulk stress for A-2-4 SR70 after drying (Sample # A24SR70D1)

Figure H.1.2 Resilient Modulus versus confining stress for A-2-4 SR70 after drying (Sample # A24SR70D1)
Table H.2 Triaxial test results of A-2-4 SR70 after drying
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Conditioning Information

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Figure H.2.1 Resilient Modulus versus bulk stress for A-2-4 SR70 after drying (Sample # A24SR70D2)

Figure H.2.2 Resilient Modulus versus confining stress for A-2-4 SR70 after drying (Sample # A24SR70D2)
Table H.3 Triaxial test results of A-2-4 SR70 at optimum condition (Sample # A24SR7001)

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Figure H.3.1 Resilient Modulus versus bulk stress for A-2-4 SR70 at optimum moisture (Sample # A24SR7001)

Figure H.3.2 Resilient Modulus versus confining stress for A-2-4 SR70 at optimum moisture (Sample # A24SR7001)
Table H.4 Triaxial test results of A-2-4 SR70 at optimum condition (Sample # A24SR7002)

<table>
<thead>
<tr>
<th>Summary Resilient Modulus Test Result</th>
</tr>
</thead>
<tbody>
<tr>
<td>Test Type: T292-91I Soil Identification</td>
</tr>
<tr>
<td>Sample No. A24SR7002 A-2-4 SR 70</td>
</tr>
<tr>
<td>Lab. Moist. 10.39% Opt. Moist. 10.60%</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Conditioning Information</th>
</tr>
</thead>
<tbody>
<tr>
<td>Load Type: Dynamic</td>
</tr>
<tr>
<td>Dev. Stress: 82.74 kPa</td>
</tr>
<tr>
<td>Conf. Stress: 103.42 kPa</td>
</tr>
<tr>
<td>No. Reps.: 1000</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Confining Pressure</th>
<th>Axial Load</th>
<th>Dev. Stress</th>
<th>Bulk Stress</th>
<th>Middle Strain</th>
<th>Full Length Strain</th>
<th>Middle Modulus</th>
<th>Full Length Modulus</th>
</tr>
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<tbody>
<tr>
<td>kPa</td>
<td>kN</td>
<td>kPa</td>
<td>kPa</td>
<td>MPa</td>
<td>MPa</td>
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</tr>
<tr>
<td>103.42</td>
<td>0.376</td>
<td>46.356</td>
<td>356.616</td>
<td>0.000125</td>
<td>0.0001427</td>
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<tr>
<td>103.42</td>
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<td>339.979</td>
<td>300.879</td>
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<td>222.215</td>
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<td>0.0002422</td>
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<td>0.000367</td>
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<td>0.0003324</td>
<td>184.681</td>
<td>140.004</td>
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Figure H.4.1 Resilient Modulus versus bulk stress for A-2-4 SR70 at optimum moisture (Sample # A24SR70O2)

Figure H.4.2 Resilient Modulus versus confining stress for A-2-4 SR70 at optimum moisture (Sample # A24SR70O2)
Table H.5 Triaxial test results of A-2-4 SR70 after soaking (Sample # A24SR70S1)

<table>
<thead>
<tr>
<th>Test Type: T292-91I</th>
<th>Soil Identification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sample No. A24SR70S1</td>
<td>A-2-4 SR 70</td>
</tr>
<tr>
<td>Moisture 11.23%</td>
<td>Opt. Moist. 10.60%</td>
</tr>
<tr>
<td>Lab. Den. 121.4 pcf</td>
<td>Opt. Den. 122.4 pcf</td>
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</table>

**Conditioning Information**

<table>
<thead>
<tr>
<th>Load Type: Dynamic</th>
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<tbody>
<tr>
<td>Dev. Stress: 82.74 kPa</td>
</tr>
<tr>
<td>Conf. Stress: 103.42 kPa</td>
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<tr>
<td>No. Reps.: 1000</td>
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</table>

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<thead>
<tr>
<th>Confining Pressure</th>
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<th>Dev. Stress</th>
<th>Bulk Stress</th>
<th>Middle Strain</th>
<th>Full Length Strain</th>
<th>Middle Modulus</th>
<th>Full Length Modulus</th>
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</thead>
<tbody>
<tr>
<td>kPa</td>
<td>kN</td>
<td>kPa</td>
<td>MPa</td>
<td>kPa</td>
<td></td>
<td></td>
<td></td>
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<td>143.821</td>
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</table>
Figure H.5.1 Resilient Modulus versus bulk stress for A-2-4 SR70 after soaking (Sample # A24SR70S1)

Figure H.5.2 Resilient Modulus versus confining stress for A-2-4 SR70 after soaking (Sample # A24SR70S1)
### Summary Resilient Modulus Test Result

**Test Type:** T292-91I  
**Soil Identification:** A-2-4 SR 70

<table>
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<th>Sample No.</th>
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<tr>
<td>Lab. Den.</td>
<td>120 pcf</td>
<td>Opt. Den. 122.1 pcf</td>
</tr>
</tbody>
</table>

#### Conditioning Information

- **Load Type:** Dynamic
- **Dev. Stress:** 82.74 kPa  
- **Conf. Stress:** 103.42 kPa  
- **No. Reps.:** 1000

<table>
<thead>
<tr>
<th>Confining Pressure</th>
<th>Axial Load</th>
<th>Dev. Stress</th>
<th>Bulk Stress</th>
<th>Middle Strain</th>
<th>Full Length Strain</th>
<th>Middle Modulus</th>
<th>Full Length Modulus</th>
</tr>
</thead>
<tbody>
<tr>
<td>kPa</td>
<td>kN</td>
<td>kPa</td>
<td>kPa</td>
<td>MPa</td>
<td>MPa</td>
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Figure H.6.1 Resilient Modulus versus bulk stress for A-2-4 SR70 after soaking (Sample # A24SR70S2)

Figure H.6.2 Resilient Modulus versus confining stress for A-2-4 SR70 after soaking (Sample # A24SR70S2)
Table H.7 Triaxial test results of A-2-4 SR70 after drying (Sample # A24SR70D3)

<table>
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<td>Sample No. A24SR70D3 (without mold)</td>
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</tr>
<tr>
<td>Load Type: Dynamic</td>
</tr>
<tr>
<td>Dev. Stress: 82.74 kPa</td>
</tr>
<tr>
<td>Conf. Stress: 103.42 kPa</td>
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<tr>
<td>No. Reps.: 1000</td>
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<tr>
<th>Confining Pressure</th>
<th>Axial Load</th>
<th>Dev. Stress</th>
<th>Bulk Stress</th>
<th>Middle Strain</th>
<th>Full Length Strain</th>
<th>Middle Modulus</th>
<th>Full Length Modulus</th>
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<tbody>
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<td>kN</td>
<td>kPa</td>
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<th>521</th>
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<td>Resilient Modulus of A-2-4, 20% at OMC (Sample # A2420%O2)</td>
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<td>525</td>
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<tr>
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<tr>
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<tr>
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<td>531</td>
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<td>Sample # A2420%O1</td>
<td>A-2-4, 20%</td>
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<thead>
<tr>
<th>Lab. Moist.</th>
<th>10%</th>
<th>Opt. Moist.</th>
<th>10%</th>
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<tbody>
<tr>
<td>Lab. Den.</td>
<td>117.9 pcf</td>
<td>Opt. Den.</td>
<td>124.4 pcf</td>
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<th>Conditioning Information</th>
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<tr>
<td>Load Type: Dynamic</td>
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<td>Dev. Stress: 82.74 kPa</td>
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<tr>
<td>Conf. Stress: 103.42 kPa</td>
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<td>No. Reps.: 1000</td>
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<tr>
<th>Confining Pressure</th>
<th>Axial Load</th>
<th>Dev. Stress</th>
<th>Bulk Stress</th>
<th>Middle Strain</th>
<th>Full Length Strain</th>
<th>Middle Modulus</th>
<th>Full Length Modulus</th>
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<tbody>
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<td>kPa</td>
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<td>kPa</td>
<td>kPa</td>
<td>MPa</td>
<td>Mpa</td>
<td>Mpa</td>
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<td>46.065</td>
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<td>291.681</td>
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<td>0.000205</td>
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<td>149.585</td>
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Figure I.1.1 Resilient Modulus vs. Bulk Stress of A-2-4 20% at OMC (Sample # A2420%01)

Figure I.1.2 Resilient Modulus vs. Bulk Stress of A-2-4 20% at OMC (Sample # A2420%01)
Table I.2 Resilient Modulus of A-2-4, 20% at OMC (Sample # A2420%O2)

<table>
<thead>
<tr>
<th>Summary Resilient Modulus Test Result</th>
</tr>
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</table>

**Test Type:** T292-91I  
**Soil Identification**  
Sample # | A2420%O2  
A-2-4, 20%

| Lab. Moist. | 10% | Opt. Moist. | 10% |
| Lab. Den. | 118.9 pcf | Opt. Den. | 124.4 pcf |

**Conditioning Information**

- **Load Type:** Dynamic  
- **Dev. Stress:** 82.74 kPa  
- **Conf. Stress:** 103.42 kPa  
- **No. Reps.:** 1000

<table>
<thead>
<tr>
<th>Containing Pressure</th>
<th>Axial Load</th>
<th>Dev. Stress</th>
<th>Bulk Stress</th>
<th>Middle Strain</th>
<th>Full Length Strain</th>
<th>Middle Modulus</th>
<th>Full Length Modulus</th>
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<tbody>
<tr>
<td>kPa</td>
<td>kN</td>
<td>kPa</td>
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<td>MPa</td>
<td>MPa</td>
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<td>0.196497</td>
<td>0.189687</td>
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<td>0.399458</td>
<td>0.134448</td>
<td>0.115542</td>
</tr>
</tbody>
</table>
Figure I.2.1 Resilient Modulus vs. Bulk Stress of A-2-4 20% at OMC (Sample # A2420%O2)

![Resilient Modulus vs. Bulk Stress](image)

\[ y = 10.387x^{0.55862} \]

\[ r^2 = 0.983 \]

\[ y = 6.5854x^{0.6529} \]

\[ r^2 = 0.9867 \]

Figure I.2.2 Resilient Modulus vs. Confining Stress of A-2-4 20% at OMC (Sample # A2420%O2)

![Resilient Modulus vs. Confining Stress](image)

\[ y = 34.294x^{0.4928} \]

\[ r^2 = 0.9961 \]

\[ y = 25.07x^{0.347} \]

\[ r^2 = 0.9956 \]
Table I.3 Resilient Modulus of A-2-4 20% after drying (Sample # A2420%D1)

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<tr>
<th>Summary Resilient Modulus Test Result</th>
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<tbody>
<tr>
<td>Test Type: T292-91I</td>
</tr>
<tr>
<td>Soil Identification</td>
</tr>
<tr>
<td>Sample # A2420%D1</td>
</tr>
<tr>
<td>A-2-4.20%</td>
</tr>
<tr>
<td>Lab. Moist. 10.00%</td>
</tr>
<tr>
<td>Opt. Moist. 10.00%</td>
</tr>
<tr>
<td>Lab. Den. 117.3 pcf</td>
</tr>
<tr>
<td>Opt. Den. 124.4 pcf</td>
</tr>
<tr>
<td>After drying 8.26%</td>
</tr>
</tbody>
</table>

| Conditioning Information               |
| Load Type: Dynamic                     |
| Dev. Stress: 82.74 kPa                 |
| Conf. Stress: 103.42 kPa               |
| No. Reps.: 1000                        |

<table>
<thead>
<tr>
<th>Confining Pressure</th>
<th>Axial Load</th>
<th>Dev. Stress</th>
<th>Bulk Stress</th>
<th>Middle Strain</th>
<th>Full Length Strain</th>
<th>Middle Modulus</th>
<th>Full Length Modulus</th>
</tr>
</thead>
<tbody>
<tr>
<td>kPa</td>
<td>kN</td>
<td>kPa</td>
<td>kPa</td>
<td>MPa</td>
<td>Mpa</td>
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<td></td>
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Figure I.3.1 Resilient Modulus vs. Bulk Stress of A-2-4 20% after drying (Sample # A2420%D1)

Figure I.3.2 Resilient Modulus vs. Confining Stress of A-2-4 20% after drying (Sample # A2420%D1)
Table I.4 Resilient Modulus of A-2-4 20% after drying (Sample # A2420%D2)

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<td><strong>Sample #</strong></td>
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<td><strong>Soil Identification</strong></td>
</tr>
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<td>A-2-4, 20%</td>
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</tr>
<tr>
<td><strong>Opt. Moist.</strong></td>
</tr>
<tr>
<td>10%</td>
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<td><strong>After drying</strong></td>
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<td>7.32%</td>
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<tr>
<th>Conditioning Information</th>
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</thead>
<tbody>
<tr>
<td><strong>Load Type:</strong> Dynamic</td>
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<tr>
<td><strong>Dev. Stress:</strong> 82.74 kPa</td>
</tr>
<tr>
<td><strong>Conf. Stress:</strong> 103.42 kPa</td>
</tr>
<tr>
<td><strong>No. Reps.:</strong> 1000</td>
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</table>

<table>
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<th>Confining Pressure</th>
<th>Axial Load</th>
<th>Dev. Stress</th>
<th>Bulk Stress</th>
<th>Middle Strain</th>
<th>Full Length Strain</th>
<th>Middle Modulus</th>
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<td>kPa</td>
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Figure I.4.1 Resilient Modulus vs. Bulk Stress of A-2-4 20% after drying (Sample # A2420%D2)

Figure I.4.2 Resilient Modulus vs. Confining Pressure A-2-4 20% after drying (Sample # A2420%D2)
Table I.5 Resilient Modulus of A-2-4 20% after soaking (Sample # A2420%S1)

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### Conditioning Information

- **Load Type:** Dynamic
- **Dev. Stress:** 82.74 kPa
- **Conf. Stress:** 103.42 kPa
- **No. Reps.:** 1000

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<th>Full Length Strain</th>
<th>Middle Modulus</th>
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Figure I.5.1 Resilient Modulus vs. Bulk Stress of A-2-4 20% after soaking (Sample# A2420%S1)

Figure I.5.2 Resilient Modulus vs. Confining Pressure of A-2-4 20% after soaking (Sample # A2420%S1)
Table I.6 Resilient Modulus of A-2-4 20% after soaking (Sample # A2420%S2)

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| Lab. Moist. | 10% | Opt. Moist. | 10% |
| After Soaking | 12.27% |

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Figure I.6.1 Resilient Modulus vs. Bulk Stress of A-2-4 20% after soaking (Sample # A2420%S2)

Figure I.6.2 Resilient Modulus vs. Confining Pressure of A-2-4 20% after soaking (Sample # A2420%S2)
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Figure J.6.2 Resilient Modulus vs. Confining Pressure of A-2-4, 24% (Sample # A2424%S2) 547
Table J.1 Resilient Modulus of A-2-4 24% at OMC (Sample # A2424%O1)

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<td>97.625</td>
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</tbody>
</table>
Figure J.1.1 Resilient Modulus vs. Bulk Stress of A-2-4 24% at OMC (Sample # A2424%01)

Figure J.1.2 Resilient Modulus vs. Confining Pressure of A-2-4 24% at OMC (Sample # A2424%01)
Table J.2 Resilient Modulus of A-2-4 24% at OMC (Sample # A2424%O2)

<table>
<thead>
<tr>
<th>Sample #</th>
<th>A2424%O2</th>
<th>A-2-4, 24%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lab. Moist.</td>
<td>10.70%</td>
<td>Opt. Moist. 10.70%</td>
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</tbody>
</table>

**Conditioning Information**

- Load Type: Dynamic
- Dev. Stress: 82.74 kPa
- Conf. Stress: 103.42 kPa
- No. Reps.: 1000

<table>
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<tr>
<th>Confining Pressure</th>
<th>Axial Load</th>
<th>Dev. Stress</th>
<th>Bulk Stress</th>
<th>Middle Strain</th>
<th>Full Length Strain</th>
<th>Middle Modulus</th>
<th>Full Length Modulus</th>
</tr>
</thead>
<tbody>
<tr>
<td>kPa</td>
<td>kN</td>
<td>kPa</td>
<td>kPa</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
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<td>0.000346</td>
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Figure J.2.1 Resilient Modulus vs. Bulk Stress of A-2-4 24% at OMC (Sample # A2424%O2)

Figure J.2.2 Resilient Modulus vs. Confining Pressure of A-2-4 24% at OMC (Sample # A2424%O2)
Table J.3 Resilient Modulus of A-2-4, 24% after drying (Sample # A2424%D1)

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<td>A-2-4, 24%</td>
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<thead>
<tr>
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<tbody>
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<td>10.70%</td>
<td>10.70%</td>
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<td>Dev. Stress: 82.74 kPa</td>
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<td>No. Reps.: 1000</td>
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<table>
<thead>
<tr>
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<th>Bulk Stress</th>
<th>Middle Strain</th>
<th>Full Length Strain</th>
<th>Middle Modulus</th>
<th>Full Length Modulus</th>
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<tbody>
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<td>kPa</td>
<td>kPa</td>
<td>MPa</td>
<td>MPa</td>
<td>MPa</td>
<td>MPa</td>
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</table>
Figure J.3.1 Resilient Modulus vs. Bulk Stress of A-2-4, 24% after drying (Sample # A2424%D1)

Figure J.3.2 Resilient Modulus vs. Confining Pressure of A-2-4, 24% after drying (Sample # A2424%D1)
### Table J.4 Resilient Modulus of A-2-4, 24% after drying (A2424%D2)

#### Summary Resilient Modulus Test Result

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<th>Soil Identification</th>
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<tbody>
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<th>Condition Information</th>
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<tr>
<td>Dev. Stress: 82.74 kPa</td>
</tr>
<tr>
<td>Conf. Stress: 103.42 kPa</td>
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<tr>
<td>No. Reps.: 1000</td>
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<table>
<thead>
<tr>
<th>Confining Pressure</th>
<th>Axial Load</th>
<th>Dev. Stress</th>
<th>Bulk Stress</th>
<th>Middle Strain</th>
<th>Full Length Strain</th>
<th>Middle Modulus</th>
<th>Full Length Modulus</th>
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<tbody>
<tr>
<td></td>
<td>kPa</td>
<td>kN</td>
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Figure J.4.1 Resilient Modulus vs. Bulk Stress of A-2-4, 24% (Sample # A24224%D2)

Figure J.4.2 Resilient Modulus vs. Confining Pressure of A-2-4, 24% (A2424%D2)
Table J.5 Resilient Modulus of A-2-4, 24% after soaking (Sample # A2424%S1)

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<td>Sample #</td>
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**Conditioning Information**

- **Load Type:** Dynamic
- **Dev. Stress:** 82.74 kPa
- **Conf. Stress:** 103.42 kPa
- **No. Reps.:** 1000

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<tr>
<th>Confining Pressure</th>
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<th>Bulk Stress</th>
<th>Middle Strain</th>
<th>Full Length Strain</th>
<th>Middle Modulus</th>
<th>Full Length Modulus</th>
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<td>Mpa</td>
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Figure J.5.1 Resilient Modulus vs. Bulk Stress of A-2-4, 24% after soaking (A2424%S1)

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Figure J.6.1 Resilient Modulus vs. Bulking Stress of A-2-4, 24% (Sample # A2424%S2)

Figure J.6.2 Resilient Modulus vs. Confining Pressure of A-2-4, 24% (Sample # A2424%S2)
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Table K.1 Triaxial test results of A-2-4 30% fine after drying (A2430%D1)

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**Conditioning Information**

- **Load Type:** Dynamic
- **Dev. Stress:** 82.74 kPa
- **Conf. Stress:** 103.42 kPa
- **No. Reps.:** 1000

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Figure K.1.1 Resilient Modulus versus bulk stress for A-2-4 30% after drying (Sample # A2430%D1)

Figure K.1.2 Resilient Modulus versus confining stress for A-2-4 30% fine after drying (Sample # A2430%D1)
Table K.2 Triaxial test results of A-2-4 30% fine after drying
(Sample # A2430%D2)

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Figure K.2.1 Resilient Modulus versus bulk stress for A-2-4 30% after drying (Sample # A2430%D2)

Figure K.2.2 Resilient Modulus versus confining stress for A-2-4 30% fine after drying (Sample # A2430%D2)
Table K.3 Triaxial test results of A-2-4 30% at optimum condition (Sample # A2430%O1)

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**Conditioning Information**
- **Load Type:** Dynamic
- **Dev. Stress:** 82.74 kPa
- **Conf. Stress:** 103.42 kPa
- **No. Reps.:** 1000

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Figure K.3.1 Resilient Modulus versus bulk stress for A-2-4 30% at optimum moisture (Sample # A2430%O1)

Figure K.3.2 Resilient Modulus versus confining stress for A-2-4 30% at optimum moisture (Sample # A2430%O1)
Table K.4 Triaxial test results of A-2-4 30% at optimum condition (Sample # A2430%O2)

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<td>Dev. Stress: 82.74 kPa</td>
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<tr>
<td>Conf. Stress: 103.42 kPa</td>
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<tr>
<td>No. Reps.: 1000</td>
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<th>Soil Identification</th>
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<td>Sample No A2430%O2</td>
<td>A-2-4, 30% fine</td>
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<th>Bulk Stress</th>
<th>Middle Strain</th>
<th>Full Length Strain</th>
<th>Middle Modulus</th>
<th>Full Length Modulus</th>
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<tbody>
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<td>kN</td>
<td>kPa</td>
<td>kPa</td>
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<td></td>
<td></td>
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<td>8.91E-05</td>
<td>0.000199</td>
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Figure K.4.1 Resilient Modulus versus bulk stress for A-2-4 30% at optimum moisture (Sample # A2430%O2)

Figure K.4.2 Resilient Modulus versus confining stress for A-2-4 30% at optimum moisture (Sample # A2430%O2)
Table K.5 Triaxial test results of A-2-4 30% after soaking (Sample # A2430%S1)

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<th>Summary Resilient Modulus Test Result</th>
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Test Type: T292-91I  
Soil Identification  
Sample N\(\text{A2430%S1}\)  
A-2-4, 30% fine

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<tbody>
<tr>
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Conditioning Information

Load Type: Dynamic  
Dev. Stress: 82.74 kPa  
Conf. Stress: 103.42 kPa  
No. Reps.: 1000

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<th>Confining Pressure</th>
<th>Axial Load</th>
<th>Dev. Stress</th>
<th>Bulk Stress</th>
<th>Middle Strain</th>
<th>Full Length Strain</th>
<th>Full Length Modulus</th>
<th>Middle Modulus</th>
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<td>kPa</td>
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<td>Mpa</td>
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Figure K.5.1 Resilient Modulus versus bulk stress for A-2-4 30% after soaking (Sample # A2430%S1)

Figure K.5.2 Resilient Modulus versus confining stress for A-2-4 30% after soaking (Sample # A2430%S1)
Table K.6 Triaxial test results of A-2-4 30% after soaking (Sample # A2430%S2)

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<th>Soil Identification</th>
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<td>A-2-4, 30% fine</td>
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| Lab. Moist. | 13.20% | Opt. Moist. | 12% |

**Conditioning Information**
- Load Type: Dynamic
- Dev. Stress: 82.74 kPa
- Conf. Stress: 103.42 kPa
- No. Reps.: 1000

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<th>Confining Pressure</th>
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<th>Middle Strain</th>
<th>Full Length Strain</th>
<th>Middle Modulus</th>
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Figure K.6.1 Resilient Modulus versus bulk stress for A-2-4 30% after soaking (Sample # A2430%S2)

Figure K.6.2 Resilient Modulus versus confining stress for A-2-4 30% after soaking (Sample # A2430%S2)
APPENDIX L

LABORATORY TEST RESULTS OF MIAMI OOLITE
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<table>
<thead>
<tr>
<th>Figure L.1.1</th>
<th>Resilient Modulus versus bulk stress for Oolite (crushed) after drying (OOLITED1)</th>
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<tr>
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<tr>
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<th>Bulk Stress</th>
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<th>Full Length Strain</th>
<th>Middle Modulus</th>
<th>Full Length Modulus</th>
</tr>
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<td>kN</td>
<td>kPa</td>
<td>kPa</td>
<td>MPa</td>
<td>Mpa</td>
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Figure L.1.1 Resilient Modulus versus bulk stress for Oolite (crushed) after drying (OOLITED1)

Figure L.1.2 Resilient Modulus versus confining stress for Oolite (crushed) after drying (Sample # OOLITED1)
Table L.2 Triaxial test results of oolite (crushed) after drying (Sample # OOLITED2)

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<th>Conditioning Information</th>
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<tr>
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<tr>
<td>Conf. Stress: 103.42 kPa</td>
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<td>No. Reps.: 1000</td>
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<th>Confining Pressure</th>
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<th>Dev. Stress</th>
<th>Bulk Stress</th>
<th>Middle Strain</th>
<th>Full Length Strain</th>
<th>Full Length Modulus</th>
<th>Middle Modulus</th>
<th>Full Modulus</th>
</tr>
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<tbody>
<tr>
<td>kPa</td>
<td>kN</td>
<td>kPa</td>
<td>kPa</td>
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<td></td>
<td></td>
<td></td>
<td></td>
</tr>
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Figure L.2.1 Resilient Modulus versus bulk stress for Oolite (crushed) after drying (OOLITED2)

Figure L.2.2 Resilient Modulus versus confining stress for Oolite (crushed) after drying (Sample # OOLITED2)
Table L.3 Triaxial test results of Oolite (crushed) at optimum condition (Sample # OOLITE01)

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<td>Soil Identification</td>
</tr>
<tr>
<td>Sample No. OOLITE01</td>
</tr>
<tr>
<td>Oolite (A-1, crushed)</td>
</tr>
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</tr>
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</tr>
<tr>
<td>Conf. Stress: 103.42 kPa</td>
</tr>
<tr>
<td>No. Reps.: 1000</td>
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<th>Bulk Stress</th>
<th>Middle Strain</th>
<th>Full Length Strain</th>
<th>Middle Modulus</th>
<th>Full Length Modulus</th>
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<td>MPa</td>
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<tr>
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Figure L.3.1 Resilient Modulus versus bulk stress for Oolite (crushed) at optimum moisture (Sample # OOLITE01)

Figure L.3.2 Resilient Modulus versus confining stress for Oolite (crushed) after drying (Sample # OOLITE01)
Table L.4 Triaxial test results of Oolite (crushed) at optimum condition (Sample # OOLITEO2)

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<table>
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<th>Optimum Density</th>
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<td></td>
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<td>Dev. Stress: 82.74 kPa</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Conf. Stress: 103.42 kPa</td>
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<td>No. Reps.: 1000</td>
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<th>Full Length Modulus</th>
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<td>Bulk Stress</td>
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<td>kN</td>
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Figure L.4.1 Resilient Modulus versus bulk stress for Oolite (crushed) at optimum moisture (Sample # OOLITEO2)

Figure L.4.2 Resilient Modulus versus confining stress for Oolite (crushed) after drying (Sample # OOLITEO1)
Table L.5 Triaxial test results of oolite (crushed) after soaking (Sample # OOLITES1)

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<td>Sample No. OOLITES1</td>
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</table>

| Lab. Moist. | 8.20% | Opt. Moist. | 7.80% |
| Lab. Den.   | 131.52 pcf | Opt. Den. | 131.3 pcf |

**Conditioning Information**
- Load Type: Dynamic
- Dev. Stress: 82.74 kPa
- Conf. Stress: 103.42 kPa
- No. Reps.: 1000

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Figure L.5.1 Resilient Modulus versus bulk stress for Oolite (crushed) after soaking (Sample # OOLITES1)

Figure L.5.2 Resilient Modulus versus confining stress for Oolite (crushed) after soaking (Sample # OOLITES1)
Table L.6 Triaxial test results of Oolite (crushed) after soaking (Sample # OOLITES2)

<table>
<thead>
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<tr>
<td><strong>Test Type:</strong> T292-91I</td>
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<tr>
<td><strong>Soil Identification</strong></td>
</tr>
<tr>
<td>Sample No. OOLITES2</td>
</tr>
<tr>
<td>Oolite (A-1, crushed)</td>
</tr>
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| Lab. Moist. | 8.09% | Opt. Moist. | 7.80% |
| Lab. Den.   | 131.2 pcf | Opt. Den. | 131.3 pcf |

<table>
<thead>
<tr>
<th>Conditioning Information</th>
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<tbody>
<tr>
<td>Load Type: Dynamic</td>
</tr>
<tr>
<td>Dev. Stress: 82.74 kPa</td>
</tr>
<tr>
<td>Conf. Stress: 103.42 kPa</td>
</tr>
<tr>
<td>No. Reps.: 1000</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Confining Pressure</th>
<th>Axial Load</th>
<th>Dev. Stress</th>
<th>Bulk Stress</th>
<th>Middle Strain</th>
<th>Full Length Strain</th>
<th>Middle Modulus</th>
<th>Full Length Modulus</th>
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<tr>
<td>kPa</td>
<td>kN</td>
<td>kPa</td>
<td>kPa</td>
<td>MPa</td>
<td>Mpa</td>
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</table>
Figure L.6.1 Resilient Modulus versus bulk stress for Oolite (crushed) after soaking (Sample # OOLITES2)

Figure L.6.2 Resilient Modulus versus confining stress for Oolite (crushed) after soaking (Sample # OOLITES2)
APPENDIX M

SOIL RESILIENT MODULUS PREDICTION MODEL
M.1 Multiple Regression Models in Applications

Most practical applications of regression analysis utilize models that are more complex than the simple straight-line model. Probabilistic models that include more than one independent variable are called multiple regression models. The general form of these models is

\[ y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \cdots + \beta_k x_k + \epsilon \]  

(M-1)

The dependent variable \( y \) is now written as a function of \( k \) independent variables, \( x_1, x_2, \ldots, x_k \). The random error term is added to make the model probabilistic rather than deterministic. The value of the coefficient \( \beta_i \) determines the contribution of the independent variable \( x_i \), and \( \beta_0 \) is the \( y \)-intercept. The coefficients \( \beta_0, \beta_1, \ldots, \beta_k \) are usually unknown because they represent population parameters (McClave et al, 2000) (StatSoft, 1984-2003).

The symbols \( x_1, x_2, \ldots, x_k \) may represent higher-order terms for quantitative predictors or terms that represent qualitative predictors.

The steps used to develop the multiple regression model are similar to those used for the simple regression model.

Step 1. Hypothesize the deterministic component of the model. This component relates the mean, \( E(y) \), to the independent variables \( x_1, x_2, \ldots, x_k \). This involves the choice of the independent variables to be included in the model.

Step 2. Use the sample data to estimate the unknown model parameters \( \beta_0, \beta_1, \ldots, \beta_k \) in the model.

Step 3. Specify the probability distribution of the random error term, \( \epsilon \), and estimate the standard deviation of this distribution, \( \sigma \).
Step 4. Check that the assumptions on $\varepsilon$ are satisfied, and make model modifications if necessary.

Step 5. Statistically evaluate the usefulness of the model.

Step 6. When satisfied that the model is useful, use it for prediction, estimation, and other purposes.

**M.2 The first-order model**

A model that includes only terms for quantitative independent variables, called a first-order model, is described in the following. Note that the first-order model does not include any higher-order terms.

$$E(y) = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \ldots + \beta_k x_k$$

where $x_1, x_2, \ldots, x_k$ are all quantitative variables that are not functions of other independent variables.

The method of fitting first-order models—and multiple regression models in general—is identical to that of fitting the simple straight-line model: the method of least squares. That is, we choose the estimated model

$$\hat{y} = \hat{\beta}_0 + \hat{\beta}_1 x_1 + \ldots + \hat{\beta}_k x_k$$

that minimizes

$$SSE = \sum (y - \hat{y})^2$$

As in the case of the simple linear model, the sample estimates $\hat{\beta}_0, \hat{\beta}_1, \ldots, \hat{\beta}_k$ are obtained as a solution to a set of simultaneous linear equations.

First of all, as is evident in the name multiple linear regression, it is assumed that the relationship between variables is linear. In practice this assumption can virtually never be confirmed; fortunately, multiple regression procedures are not greatly affected by minor deviations from this assumption. However, as a rule it is prudent to always look at
bivariate scatterplot of the variables of interest. If curvature in the relationships is evident, one may consider either transforming the variables, or explicitly allowing for nonlinear components (McClave et al., 2000) (StatSoft, 1984-2003).

The primary difference between fitting the simple and multiple regression models is computational difficulty. The \((k+1)\) simultaneous linear equations that must be solved to find the \((k+1)\) estimated coefficients \(\hat{\beta}_0, \hat{\beta}_1, \ldots, \hat{\beta}_k\) are difficult (sometimes nearly impossible) to solve with a calculator. Consequently, we resort to the use of computers software such as Minitab, SAS, SPSS, etc.

**M.3 Assumptions for Random Error \(\varepsilon\)**

1. For any given set of values of \(x_1, x_2, \ldots, x_k\), the random error \(\varepsilon\) has a normal probability distribution with mean equal to 0 and variance equal to \(\sigma^2\).

2. The random errors are independent (in a probabilistic sense).

We will use the estimator of \(\sigma^2\) both to check the utility of the model and to provide a measure of reliability of predictions and estimates when the model is used for those purposes. Thus, we can see that the estimation of \(\sigma^2\) plays an important part in the development of a regression model (McClave et al., 2000) (StatSoft, ????).

Estimator of \(\sigma^2\) for a multiple regression model with \(k\) independent variables is

\[
s^2 = \frac{SSE}{n - \text{Number of estimated } \beta \text{ parameters}} = \frac{SSE}{n - (k + 1)}
\]

**(M-5)**

**M.4 Inferences about the \(\beta\) parameters**

Inferences about the individual \(\beta\) parameters in a model are
obtained using either a confidence interval or a test of hypothesis.

<table>
<thead>
<tr>
<th>Test of an Individual Parameter Coefficient in the Multiple Regression Model</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>One-Tailed Test</strong></td>
</tr>
<tr>
<td>$H_0: \beta_i = 0$</td>
</tr>
<tr>
<td>$H_a: \beta_i &lt; 0$ [or $H_a: \beta_i &gt; 0$]</td>
</tr>
</tbody>
</table>

Test Statistic: $t = \frac{\hat{\beta}_i}{s_{\hat{\beta}_i}}$

Rejection region:
- $t < -t_{\alpha}$
- $t > t_{\alpha}$ when $H_a: \beta_i > 0$

<table>
<thead>
<tr>
<th>Rejection region:</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>$</td>
<td>t</td>
</tr>
</tbody>
</table>

Where $t_{\alpha}$ and $t_{\alpha/2}$ are based on $n-(k+1)$ degrees of freedom and

$n =$ Number of observations

$k+1 =$ Number of $\beta$ parameters in the model

A $100(1-\alpha)\%$ confidence interval for a $\beta$ parameter is

$\hat{\beta}_i \pm t_{\alpha/2} s_{\hat{\beta}_i}$ (McClave et al, 2000).

**M.5 Checking the Overall Utility of a Model**

Conduction t-test on each $\beta$ parameter in a model is not the best way to determine whether the overall model is contributing information for the prediction of y. If we were to conduct a series of t-tests to determine whether the independent variables are contributing to the predictive relationship, we would be very likely to make one or more errors in deciding which terms to retain in the model and which to exclude. In multiple regression models for which a large number of independent variables are being considered, conductung a series of t-tests may include a large number of insignificant variables and
exclude some useful ones. If we want to test the utility of a multiple regression model, we will need a global test (one that encompasses all the $\beta$ parameters). We would also like to find some statistical quantity that measures how well the model fits the data.

We use the multiple regression equivalent of $r^2$, the coefficient of determination for the straight-line model. The multiple coefficient of determination, $R^2$, is defined as

$$R^2 = 1 - \frac{\text{SSE}}{\text{SS}_{yy}} = \frac{\text{SS}_{yy} - \text{SSE}}{\text{SS}_{yy}} = \frac{\text{Explained variability}}{\text{Total variability}}$$ \hspace{1cm} (M-6)

Just as for the simple linear model, $R^2$ represents the fraction of the sample variation of the $y$ values (measured by $\text{SS}_{yy}$) that is explained by the least squares prediction equation. Thus, $R^2 = 0$ implies a complete lack of fit of the model to the data and $R^2 = 1$ implies a perfect fit with the model passing through every data point. In general, the larger the value of $R^2$, the better the model fits the data.

A large value of $R^2$ computed from the sample data does not necessarily mean that the model provides a good fit to all of the data points in the population. We will always obtain a perfect fit ($R^2 = 1$) to a set of $n$ data points if the model contains exactly $n$ parameters. Consequently, if we want to use the value of $R^2$ as a measure of how useful the model will be for prediction $y$, it should be based on a sample that contains substantially more data points than the number of parameters in the model. Most authors recommend that one should have at least 10 to 20 times as many observations (cases, respondents) as one has variables, otherwise the estimates of the regression line are probably very unstable and unlikely to replicate if one were to do the study over.
Despite its utility, $R^2$ is only a sample statistic. Therefore, it is dangerous to judge the global usefulness of the model based solely on these values. A better method is to conduct a test of hypothesis involving all the $\beta$ parameters (except $\beta_0$) in a model.

### Testing Global Usefulness of the Model: The Analysis of Variance F-Test

<table>
<thead>
<tr>
<th>$H_0$</th>
<th>$\beta_1 = \beta_2 = \cdots = \beta_k = 0$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$H_a$</td>
<td>At least one $\beta_i \neq 0$</td>
</tr>
</tbody>
</table>

**Test Statistic:**

$$F = \frac{(SS_y - SSE) / k}{SSE / [n - (k + 1)]} = \frac{R^2 / k}{(1 - R^2) / [n - (k + 1)]} = \frac{\text{Mean Square (Model)}}{\text{Mean Square (Error)}}$$

Where $n$ is the sample size and $k$ is the number of terms in the model.

**Rejection region:** $F > F_\alpha$, with $k$ numerator degrees of freedom and $[n - (k + 1)]$ denominator degrees of freedom.

A rejection of the null hypothesis $H_0: \beta_1 = \beta_2 = \cdots = \beta_k = 0$ in the global F-test leads to the conclusion [with $100(1-\alpha)$% confidence] that the model is statistically useful. However, statistically “useful” does not necessarily mean “best”. Another model may prove even more useful in terms of providing more reliable estimates and predictions. This global F-test is usually regarded as a test that the model must pass to merit further consideration (McClave et al, 2000).
APPENDIX N

LAYERED SYSTEM THEORY
LIST OF FIGURES

Figure N.1 Two-layer System 597
Figure N.2 An n-layer System in Cylindrical Coordinates 597
N.1 Layered System

Flexible pavements are layered systems with better materials on top and cannot be represented by a homogeneous mass, so the use of Burmister's layered theory is more appropriate. Burmister (1943) (7) first developed solutions for a two-layer system and then extended them to a three-layer system. The theory of stresses and displacements in a two-layer system was developed in accordance with the methods of the mathematical theory of elasticity and is presented in order to reveal some of the fundamental relations existing between the physical factors, which control the load-settlement relations, and in order to provide a practical method of analysis for the design of pavement. The theory reveals the controlling influence of two important ratios on the load-settlement characteristics of the "two-layer system", namely: (1) the ratio \( r/h_1 \) of the radius bearing area to the thickness of the reinforcing or pavement layer; and (2) the ratio \( E_2/E_1 \) of the modulus of the subgrade to that of the pavement. For practical design purposes, the theoretical results have been evaluated numerically and expressed in Basic Influence Curves, giving values of the settlement coefficient \( F_w \) in terms of these basic ratios. The settlement coefficient is applied as a simple multiplying or correction factor to the familiar Boussinesq Equation for surface settlement at the center of a circular flexible bearing area. The layer system theory was adopted to calculate subgrade layer in test-pit.

N.1.1 Two-layer System Theory Assumptions and Conditions

Boussinesq solved the problem of stresses and displacements in a uniform deposit for concentrated load applied at the surface.
The scientific approach in the present problem of stresses and displacements in the more general case of a “two-layer system” by the methods of the mathematical theory of elasticity, which is believed to be correct. The general solution of the “two-layer” problem required that the necessary assumptions of the theory of elasticity be made, and that certain essential boundary and continuity conditions be satisfied, but did not require any radical simplifying assumptions beforehand as to the nature of the distribution of stresses on the subgrade or of their relation to displacements (Burmister, 1943) (Huang, 1993).

The “two-layer system”, illustrated in Figure N.1, consists of a surface or pavement layer 1 of a certain thickness \( h_1 \), which rests continuously upon and reinforces a weaker subgrade layer 2. A surface load is applied, uniformly distributed over a flexible bearing area of radius \( r \). The application of the theory of elasticity to the solution of the problem required the following assumptions and conditions:

1. The necessary assumptions of the theory of elasticity were made that the soils of each of the two layers are homogeneous, isotropic, elastic materials, for which Hooke’s law is valid. While these assumptions are only imperfectly satisfied in natural soil deposits, the evaluation of full-scale load tests should yield average strength properties of the soils, which are fairly representative within the range of permissible settlements.

2. The surface reinforcing layer 1 is assumed to be weightless and to be infinite in extent in the horizontal direction, but of finite thickness \( h_1 \). The subgrade layer 2 is assumed to be infinite in extent both horizontally and vertically downward.
(3) The solution of the problem must satisfy certain necessary boundary conditions, namely, that the surface of layer 1 must be free of normal and shearing stresses outside the limits of the loaded area, and that at infinite depth the stresses and displacements in the subgrade layer 2 must be equal to zero.

(4) Most important of all, the solution for the “two-layer” problem must satisfy certain essential continuity conditions of stress for layer 1 and layer 2. It is assumed that the two layers are continuously in contact and act together as an elastic medium of composite nature. Furthermore, it is assumed that the subgrade provides initially a continuous uniform support for the pavement layer, which is really the primary condition to be achieved in good construction practice. Continuity requires that the normal and shearing stresses and the vertical and horizontal displacements must be equal in the two layers at the interface. Only in the horizontal radial stress $\sigma_r$ will there be a discontinuity across the interface. This follows from the fact that, since the horizontal displacements $u_1$ and $u_2$ must be equal, the radial stress $\sigma_{r1}$ and $\sigma_{r2}$ either side of the interface will be different and must be determined by the modulii $E_1$ and $E_2$, respectively.

(5) In order to obtain a practical solution of the problem and to reduce the complications, it was necessary to assume that Poisson’s ratio was 0.35 in both layers. The value of 0.35 was used, because it was considered to be somewhat more representative of the actual conditions in Florida pavement conditions (Burmister, 1943) (Huang, 1993).
N.1.2 Mathematical Theory of Elasticity

The following are equations of elasticity for the three-dimensional problem of axial symmetry.

(a) Equations of Equilibrium.

\[
\frac{\partial \sigma_r}{\partial r} + \frac{\partial \tau_{rz}}{\partial z} + \frac{\sigma_r - \sigma_\theta}{r} = 0 \quad (N-1a)
\]

\[
\frac{\partial \tau_{rz}}{\partial r} + \frac{\partial \sigma_z}{\partial z} + \frac{\tau_r}{r} = 0 \quad (N-1b)
\]

(b) Equations of Compatibility.

\[
\nabla^4 = 0 \quad (N-2a)
\]

\[
\nabla^2 = \left[ \frac{\partial^2}{\partial r^2} + \frac{1}{r} \frac{\partial}{\partial r} + \frac{\partial^2}{\partial z^2} \right] \quad (N-2b)
\]

(c) Equations of Elasticity.

(1) Stress

\[
\sigma_z = \frac{\partial}{\partial z} \left[ (2 - \mu) \nabla^2 \phi - \frac{\partial^2 \phi}{\partial z^2} \right] \quad (N-3a)
\]

\[
\sigma_r = \frac{\partial}{\partial z} \left[ \mu \nabla^2 \phi - \frac{\partial^2 \phi}{\partial r^2} \right] \quad (N-3b)
\]

\[
\sigma_\theta = \frac{\partial}{\partial z} \left[ \mu \nabla^2 \phi - \frac{1}{r} \frac{\partial \phi}{\partial r} \right] \quad (N-3c)
\]

\[
\tau_{rz} = \frac{\partial}{\partial r} \left[ (1 - \mu) \nabla^2 \phi - \frac{\partial^2 \phi}{\partial z^2} \right] \quad (N-3d)
\]

(2) Displacement

\[
W = \frac{1 + \mu}{E} \left[ (1 - 2\mu) \nabla^2 \phi + \frac{\partial^2 \phi}{\partial r^2} + \frac{1}{r} \frac{\partial \phi}{\partial r} \right] \quad (N-4a)
\]

\[
u = \frac{1 + \mu}{E} \left[ \frac{\partial^2 \phi}{\partial r^2} \right] \quad (N-4b)
\]

After equation solving, there are two simple equations for calculate vertical surface deflections.
(a) Flexible bearing area

\[ W = \frac{2(1-\mu^2)}{E_2} \cdot p r F_2 \]  
\[ \text{(N-5)} \]

(b) Rigid bearing area

\[ W = \frac{\pi(1-\mu^2)}{E_2} \cdot p r F_2 \]  
\[ \text{(N-6)} \]

- \( W \) -- Resilient deflection of surface
- \( \mu \) -- Poisson ratio
- \( p \) -- Uniform pressure on the top layer
- \( r \) -- Radius of uniform circular pressure on the top
- \( F_2 \) -- Deflection factor decided by \( E_1/E_2 \)
- \( E_1 \) -- Resilient modulus for first layer
- \( E_2 \) -- Resilient modulus for second layer

In test-pit, we use Poisson ratio \( \mu \) as 0.35, and the rigid circular plate was adopted, so the Equation (N-6) would be applied and simplified into following equation.

\[ W = \frac{1.38}{E_2} \cdot p r F_2 \]  
\[ \text{(N-7)} \]

According to Equation (N-7), \( F_2 \) can be solved for the test-pit data. From the chart of \( F_2 \), the resilient modulus for the upper layer can be gotten. This is a method to calculate the upper layer resilient modulus if knowing the lower layer modulus or lower layers equivalent modulus. By hand calculate will cost inaccuracy for the chart reading of \( F_2 \). So ELSYM5 and KENLAYER programs were adopted to finish this calculation (Burmister, 1943) (Huang, 1993).

### N.1.3 Three-layer System

When there is a limerock layer on the top, the profile of test-pit can be divided into three different layers. From the top to
bottom, they are limerock layer (layer 1), subgrade layer (layer 2) and embankment layer (layer 3). Because the three-layer system is very complex and cannot be calculated by hand, ELSYM5 and KENLAYER programs were adopted to calculate the subgrade layer modulus. The embankment layer modulus was assumed as 11207psi (77Mpa) in soaked condition.

N.2 KENLAYER Program Theoretical Development

N.2.1 Elastic Multilayer System

Figure 6.2 shows an n-layer system in cylindrical coordinates, the nth layer being of infinite thickness. The modulus of elasticity and the Poisson ratio of the ith layer are $E_i$ and $\mu_i$, respectively (Huang, 1993). For axisymmetric problems in elasticity, a convenient method is to assume a stress function that satisfies the governing differential equation and the boundary and continuity conditions. After the stress function is found, the stresses and displacements can be determined (Timoshenko and Goodier, 1951). The governing differential equation to be satisfied is a fourth-order differential equation. The stress function for each layer has four constants of integration in Eq. (N-2), $A_i, B_i, C_i$ and $D_i$, where the subscript $i$ is the layer number. Because the stress function must vanish at an infinite depth, the constants $A_n$ and $C_n$ should be equal to zero, i.e., the bottom most layer has only two constants. For a n-layer system, the total number of constants or unknowns is $4n-2$, which must be evaluated by two boundary conditions and $4(n-1)$ continuity conditions. The two boundary conditions are that the vertical stress under the circular loaded area is equal to $q$ and that the surface is free of shear stress. The four conditions at each of the n-1 interfaces are the continuity of vertical stress, vertical
displacement, shear stress, and radial displacement. If the interface is frictionless, the continuity of shear stress and radial displacement replaced by the vanish of shear stress both above and below the interface. The equations to be used in KENLAYER for computing the stresses and displacements in a multilayer system under a circular loaded area are presented later (Huang, 1993).

N.2.2 Nonlinear Layers
It is well known that granular materials and subgrade soils are nonlinear with an elastic modulus varying with the level of stresses. The elastic modulus to be used with the layered systems is the resilient modulus obtained from repeated unconfined or triaxial compression tests. The resilient modulus of granular materials increases with the increase in stress intensity, while that of fine-grained soils decreases with the increase in stress intensity. If the relationship between the resilient modulus and the state of stresses is given, a method of successive approximations can be used. The nonlinear material properties, which have been incorporated in KENLAYER, are described below (Huang, 1993).

N.2.3 Granular Materials
The resilient modulus of granular materials increases with the increase in the first stress invariant. However, KENLAYER employs a more popular relationship which is described below. A simple relationship between resilient modulus and the first stress invariant can be expressed as

\[ E = K_1 \theta^{K_2} \]  

(N-8)

in which \( K_1 \) and \( K_2 \) are experimentally derived constants and \( \theta \) is the stress invariant, which can be either the sum of three
normal stresses, \( \sigma_x, \sigma_y, \) and \( \sigma_z, \) or the sum of three principal stresses, \( \sigma_1, \sigma_2, \) and \( \sigma_3; \)

\[
\theta = \sigma_1 + \sigma_2 + \sigma_3 = \sigma_x + \sigma_y + \sigma_z \tag{N-9}
\]

Including the weight of a layered system gives

\[
\theta = \sigma_x + \sigma_y + \sigma_z + \gamma (1 + 2K_0) \tag{N-10}
\]

in which \( \gamma \) is the average unit weight, \( z \) is the distance below surface at which the modulus is to be determined, and \( K_0 \) is the coefficient of earth pressure at rest. The reason \( \sigma_1, \sigma_2, \) and \( \sigma_3 \) are not used in Equation (N-10) is that they may not be in the same direction as the geostatic stresses. In contrast to other computer programs, KENLAYER uses the soil mechanics sign convention for stresses and strains. Therefore, \( \theta \) is positive when in compression and negative when in tension.

It should be noted that the use of layered system for nonlinear analysis is an approximate approach. It is desirable to have more exact solutions so that the results of KENLAYER can be compared. Theoretically, the finite element method should provide the best solutions for such nonlinear problems. Unfortunately, the finite element computer programs currently available have serious defects and cannot be used to check the accuracy of a solution (Huang, 1993).

**N.2.4 Fine-Grained Soils**

The resilient modulus of fine-grained soils decreases with the increase in deviator stress \( \sigma_d \). In laboratory triaxial tests, \( \sigma_2 = \sigma_3, \) so the deviator stress is defined as

\[
\sigma_d = \sigma_1 - \sigma_3 \tag{N-11}
\]
In a layered system, $\sigma_2$ may not be equal to $\sigma_3$, so the average of $\sigma_2$ and $\sigma_3$ is considered as $\sigma_3$. Including the weight of layered system yields

$$\sigma_d = \sigma_1 - 0.5(\sigma_2 + \sigma_3) + \gamma(1-K_0)$$

Equation (N-12) is not theoretically correct because the principal loading stresses may not be in the same direction as the geostatic stresses. Since the loading stresses in the subgrade are usually small and do not have significant effect on the computed modulus, KENLAYER uses the three normal stresses, $\sigma_1, \sigma_2,$ and $\sigma_3$ in Equation (N-12). If the point selected for computing the modulus is on the axis of symmetry for a single tire or on the plane of symmetry between two dual tires, the three normal stresses and the three principal stresses are identical (Huang, 1993).

**N.3 KENLAYER Program Subroutines**

KENLAYER consists of one main program and 18 subroutines. All variables are transferred from the main program to the subroutines through arguments and no common statements are used. Therefore, the program can be easily modified if needed (Huang, 1993).

The main program is relatively short because its main purpose is to call the various subroutines and conduct a damage analysis, if desired. The subroutines can be divided into six groups: data input, layered system, superposition and principal stresses, nonlinear analysis, viscoelastic analysis, and output. For linear elastic systems, the flowchart of KENLAYER program is simple as following:
**ELAINP** reads and writes input data for an elastic layered system under single or multiple wheels. For multiple wheels, the distance and direction cosines from each specified point to each of the wheels are also computed for later use. If a layer is nonlinear, the elastic modulus is the assumed elastic modulus to be used for the first iteration. If a layer is viscoelastic, the elastic modulus maybe assigned 0 or any value.

**LAYERS** computes the vertical displacement, four components of stress, and four components of strains at different radial and vertical distances under a single wheel.

**SINOUT** prints the vertical displacement, vertical stress, radial stress, tangential stress, shear stress, vertical strain, radial strain, tangential strain, and shear strain under a single-wheel load and determines the most critical strains for damage analysis. The stresses and strains are positives when in compression and negative in tension.
Figure N.1 Two-layer System

Figure N.2 An n-layer System in Cylindrical Coordinates
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