RESILIENT MODULUS OF SUBGRADES

BY

Richard P. Long, Professor
Maria Gabriela Delgado, Graduate Assistant

JHR 91-199 Project 88-1

This research was sponsored by the Joint Highway Research Advisory Council (JHRAC) of the University of Connecticut and the Connecticut Department of Transportation and was carried out in the Civil Engineering Department of the University of Connecticut.

SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
	LENGTH			
in	inches	25.4	millimetres	mm
ft	feet	0.305	metres	m
yd	yards	0.914	metres	m
mi	miles	1.61	kilometres	km
	AREA			
in^2	square inches	645.2	millimetres squared	mm^2
ft^2	square feet	0.093	metres squared	m^2
yd^2	square yards	0.836	metres squared	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	kilometres squared	km^2
	VOLUME			
fl oz	fluid ounces	29.57	mililitres	mL
gal	gallons	3.785	Litres	L
ft^3	cubic feet	0.028	metres cubed	m^3
yd^3	cubic yards	0.765	metres cubed	m^3

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

Symbol	When You Know	Multiply By	To Find	Symbol
	MASS			
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams	Mg
	TEMPERATURE (exact)			
°F	Fahrenheit temperature	5(F-32)/9	Celcius temperature	°C

*SI is the symbol for the International System of Measurement

APPROXIMATE CONVERSIONS TO SI UNITS

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

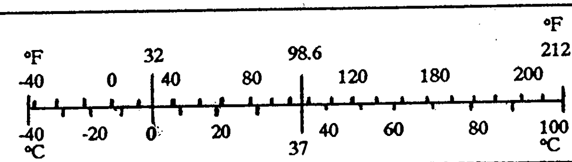


Table of Contents

List of Figures

List of Tables

I. Introduction

The designer of bituminous pavement selects a cross-section of pavement and foundation to control rutting and cracking (1). Proper bituminous pavement design requires knowledge of the stress-strain properties of all of the materials below the top of the pavement. Research, including field tests, has shown that the quasi-elastic properties of the granular material in the foundation are very important. In the past, flexible pavements were often designed with empirical parameters, such as CBR and R values for the foundation soils. In recent years, however, the American Association of State Highway and Transportation Officials (AASHTO) has adopted an approach guided by the theoretical results based on the elastic behavior of layered media (7). The definitive material property for characterizing roadbed soil for pavement design in the current (1986) AASHTO Design Guide is the Resilient Modulus (M_R). It is a measure of the elastic response of soil to stress and determined by AASHTO Test Method T274-82. The resilient modulus is the ratio of stress to recoverable strain on the 200th load repetition and used directly for the design of flexible pavements. It is converted to modulus of subgrade reaction for rigid or composite pavements.

The 1986 AASHTO Design Guide lists several reasons for replacing soil support values with resilient modulus including:

1. That it indicates a basic material property that can be used in the mechanistic analysis of multilayerd systems for predicting roughness cracking, rutting, faulting, etc.
2. It has been recognized internationally as a method for charact-erzing materials for use in pavement design and evaluation.

The design is based on the average resilient modulus of the roadbed soils.

II. Concept of Resilient Modulus

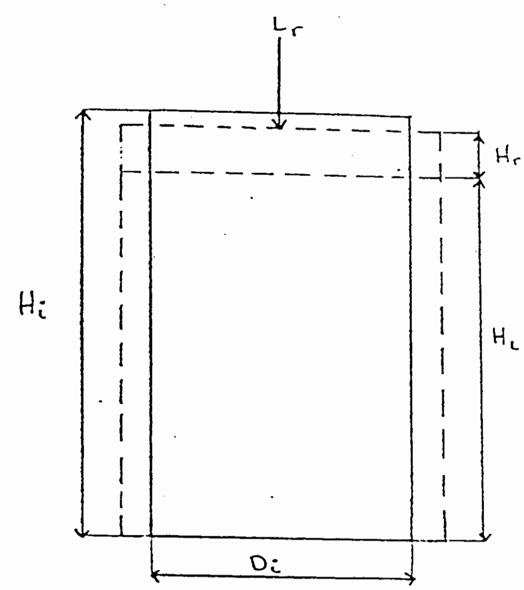
The resilient modulus, the ratio of the repeated deviator stress to the recovered strain, characterizes the elastic stiffness of the pavement and foundation layers. In the laboratory this stress-strain relationship of the foundation material is estimated by a dynamic triaxial test. The Standard Method of Test for Resilient Modulus of Subgrade Soils is presently covered under AASHTO Designation: T 274-82 (1986). The Strategic Highway Research Program has developed a procedure that modifies the ASSHTO standard. (4) The test procedure requires an apparatus that can apply loads at a programed duration and frequency. After the soil specimen has been mounted in the triaxial chamber, a conditioning sequence of loads is applied as shown in Table 1 of Appendix A. The conditioning sequence consists of applying 200 repetitions of each deviator stress. The sequence of loading to measure the resilient modulus also consists of applying each selected deviator stress shown in Table 2 of Appendix A, 200 repetitions with the recoverable strain being measured on the 200th repetition. A recent protocol from the Strategic Highway Research Program recommends averaging the strains over the five applications of the deviator (4).

The measured values used in the computation of resilient modulus are illustrated in Fig. 1.

The resilient modulus is calculated from the Equation:

$$M_R = \frac{\sigma_R}{\epsilon_R} \qquad 1$$

where: M_R = resilient modulus; σ_r = applied stress and ϵ_r = recoverable strain = $\dfrac{H_r}{H_r + H_\ell}$



H_i = Initial Height

H_r = Recoverable Height

H_L = Loaded Height

L_r = Repeated Load

Ai = Initial Diam.

Dimensions of Sample Used in Calculating Resilient Modulus

Fig. No. 1

Several aspects of the procedure for measuring resilient modulus are under review. The primary focus has been on the time required to complete a test (4). Factors under consideration are the reduction of the number of cycles, etc., that can be made while still obtaining essentially the same resilient modulus.

III. Scope of the Present Project

Test equipment capable of the loading sequences to fulfill the requirement of AASHTO T 274-82 (1986) could not be purchased in 1988 under the JHRAC budget. The cost of the equipment was too great. The AASHTO Design Manuals contain methods of estimating M_R for the interim but state that the actual values should be measured. The resilient modulus of Connecticut soils is sufficiently important that it was decided to progress toward making measurements as soon as possible. It was decided, therefore, to conduct a literature search and attempt to adapt equipment that was scheduled for purchase and installation in late 1989 for one of the undergraduate laboratories in the Civil Engineering Department at U. Conn. This apparatus, an Instron 1331 test machine, is more than capable of meeting the requirements of the AASHTO Standard Test.

The installation of the test apparatus was delayed by the requirement for additional equipment, such as a water chiller to cool the pump, which was not anticipated when the apparatus was ordered. While the apparatus was being installed, soil samples presently being used in pavement foundations in District 2 were collected, classified and used to develop some specimen preparation procedures.

Conducting accurate measurements of the modulus of some Connecticut foundation soil presents a significant challenge. In preparing the laboratory specimen for testing, large particles that are included in the foundation in the field must be eliminated because of the limits of specimen size. Various techniques of correcting for the eliminated particle sizes are being investigated.

The AASHTO Standard Method (T274-82) provides for using soil specimens 2.8 inches in diameter and 5.6 inches long or 4 inches in diameter and 8 inches long. The largest particle that can be included has a diameter one-sixth the diameter of the prepared specimen (1). The SHRP Protocol P46 (Interim) has a significant difference in approach in that it hopes to include all particles up to the diameter that represents the 95% finer by weight size. SHRP allows particles that are one-fifth the diameter of the specimens to be included, and provides for specimens 6 inches in diameter and 12 inches long in addition to the two included in AASHTO. This 6 inch diameter sample can include particles up to 1.2 inches in diameter which is not really large enough for Connecticut's processed base and subbase material. The SHRP Protocol does not describe the procedure for these cases. It is planned to determine if there is a measurable difference in modulus from the inclusion of larger particle sizes by testing the same soils in 2.8 and 4.0 inch diameter samples including particles up to the maximum size. The 2.8 inch diameter samples will include particles that pass the 1/2 inch sieve; the 4.0 inch samples will include all particles passing the 3/4 inch sieve. Additional procedures will be developed to address the effect of particle size.

These specimen sizes (2.8 and 4.0) are not standard for the usual compaction equipment. To compare the results of the resilient modulus tests with samples in the field requires a density of the samples that compares with the Standard (13)(15) or Modified Proctor

Test (14)(16). The compaction machines in U. Conn's Soils Laboratory were modified so that the soil could be compacted in special molds fabricated to the exact dimension of two sizes of samples for the resilient modulus triaxial tests.

IV. Previous Work

1. General

In the past, researchers have noted two methods of failure in bituminous pavements: rutting and cracking. Rutting can occur in the foundation or the pavement material. The cause of soil rutting was traced to stress levels capable of causing permanent plastic deformations in the pavement foundation. Increasing the thickness of the asphaltic concrete reduces the stresses in the foundation and prevents rutting in the foundation material but does not always prevent failure by cracking. Cracking continues to occur and becomes a major failure mechanism in pavements that are considered otherwise well designed and show no permanent deformations. Several highway agencies conducted field measurements of deflection and rebound of pavements and found a close correlation between the occurrence of cracking and the magnitude of transient pavement deflections.

Researchers have named these transient, recoverable deflections resilient. These deflections are elastic in the sense that they are recoverable but are not necessarily recovered instantaneously. The proper design of asphaltic pavements requires the ability to predict the stresses and the resilient deflections of pavements in advance of construction, based on measureable characteristics of component materials. The deflections can be predicted reasonably well with the elastic theories, since the strains are recoverable.

Laboratory tests were made with several apparatuses before developing the AASHTO standard method using the triaxial test. Several investigations showed the influence of testing conditions on the measured resilient modulus of granular soils (10). Included among these conditions were:

a. Duration of stress application. Decreasing duration of load application may yield greater resilient moduli by 18%.
b. Rate of deformation. Increasing rate of deformation may increase the measured modulus by about 20%.
c. Frequency of load application. Measured increases of resilient modulus with increasing frequency were as great as 50 to 100% depending on water content and dry density.
d. Type of aggregate and percentage of material passing the No. 200 sieve. This effect is not readily quantified.
e. Void Ratio. Moduli of loose and dense material may vary by about 50%. A limited number of tests indicate that two samples of the same granular soil at different void ratios at the beginning of the test will approach the same void ratio after several hundred load repetitions.
f. Degree of Saturation. Increased degree of saturation decreases the resilient modulus.
g. Confining pressure. This test condition has a great effect on the measured modulus. The greater effective confining stress produces a greater the resilient modulus in the soil.
h. Stress Level. Behavior of particulate materials is correlated with the confining stress and the shear stress often called the deviator stress. Beginning at low confining stress levels, the resilient modulus first decreases with increasing applied shear stresses, then becomes essentially constant.

The major difficulty in testing materials is to define the stress conditions under which the resilient modulus should be measured.

2. Observed Trends in Resilient Modulus Behavior Reported in the Literature

The measured resilient modulus is sensitive to moisture content, level of the deviator stress and level of confining stress.

a. Moisture Content

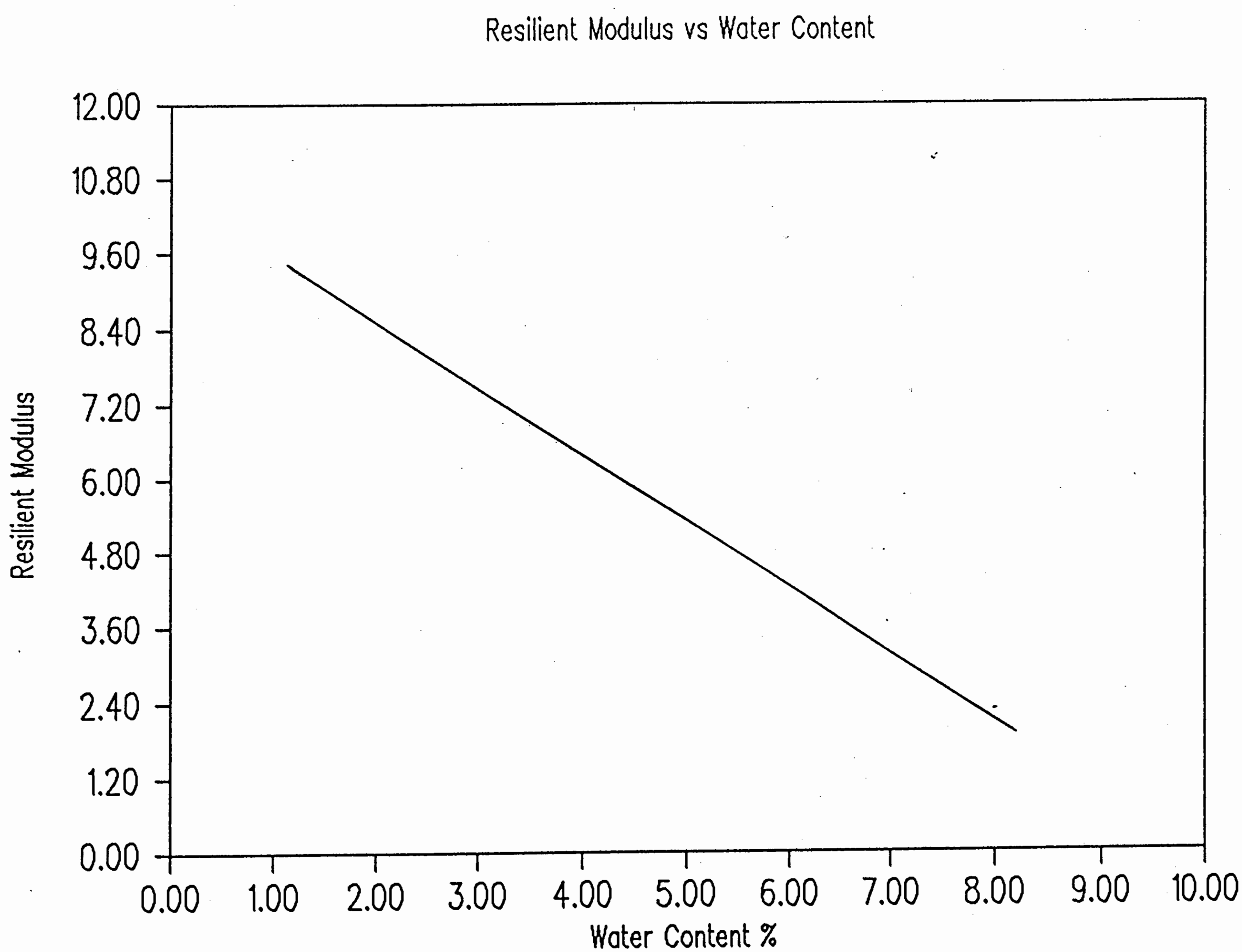
An increase in the moisture content decreases the resilient modulus. This effect can be significant in cohesionless soils. A reduction of 50% of the value of the resilient modulus has been reported for an increase in water content from 5 to 11%, representing a change in degree of saturation from 35% to 72% (11). Several investigators have found that the relation between M_R and moisture content w can be represented by a straight line as shown schematically in Fig. 2.

The trend shown in Fig. 2 is an important consideration for flexible pavements. The moisture content of the soils beneath the pavements changes with the seasons of the year (7)(8). The M_R decreases with increasing moisture content. The AASHTO design procedure provides for a weighted serviceability factor and an estimated change of the M_R throughout the year (7)(8).

b. Stress Level

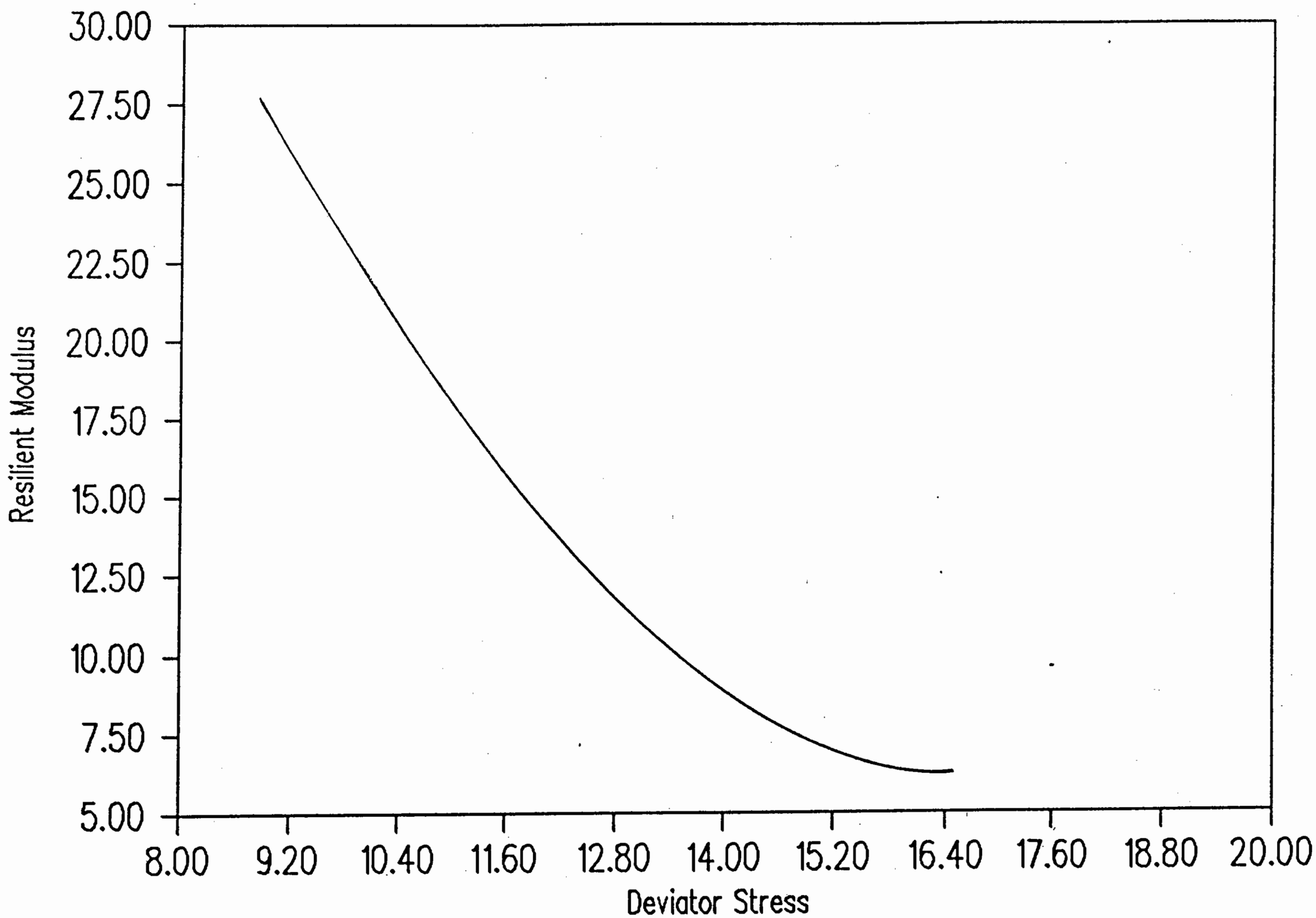
1) Effect of deviator stress

Beginning at a low level of deviator stress, the resilient modulus decreases rapidly with increasing deviator stress as shown in Fig. 3. At some level of the deviator stress a relatively constant value of the M_R is reached in that further increases of the deviator do not cause significant change in the modulus.



General behavior of the resilent modulus with increasing moisture content
Figure No. 2

Resilient Modulus vs Deviator Stress



Schematic Plot of the Relation Between Resilient Modulus and Deviator Stress

Figure No. 3

The behavior shown in Fig. 3 may be important for the design of pavement foundations. The deviator stresses vary with depth beneath the pavement. Fig. 3 indicates that since the resilient modulus varies with the deviator stress, it too may vary with depth beneath the pavement.

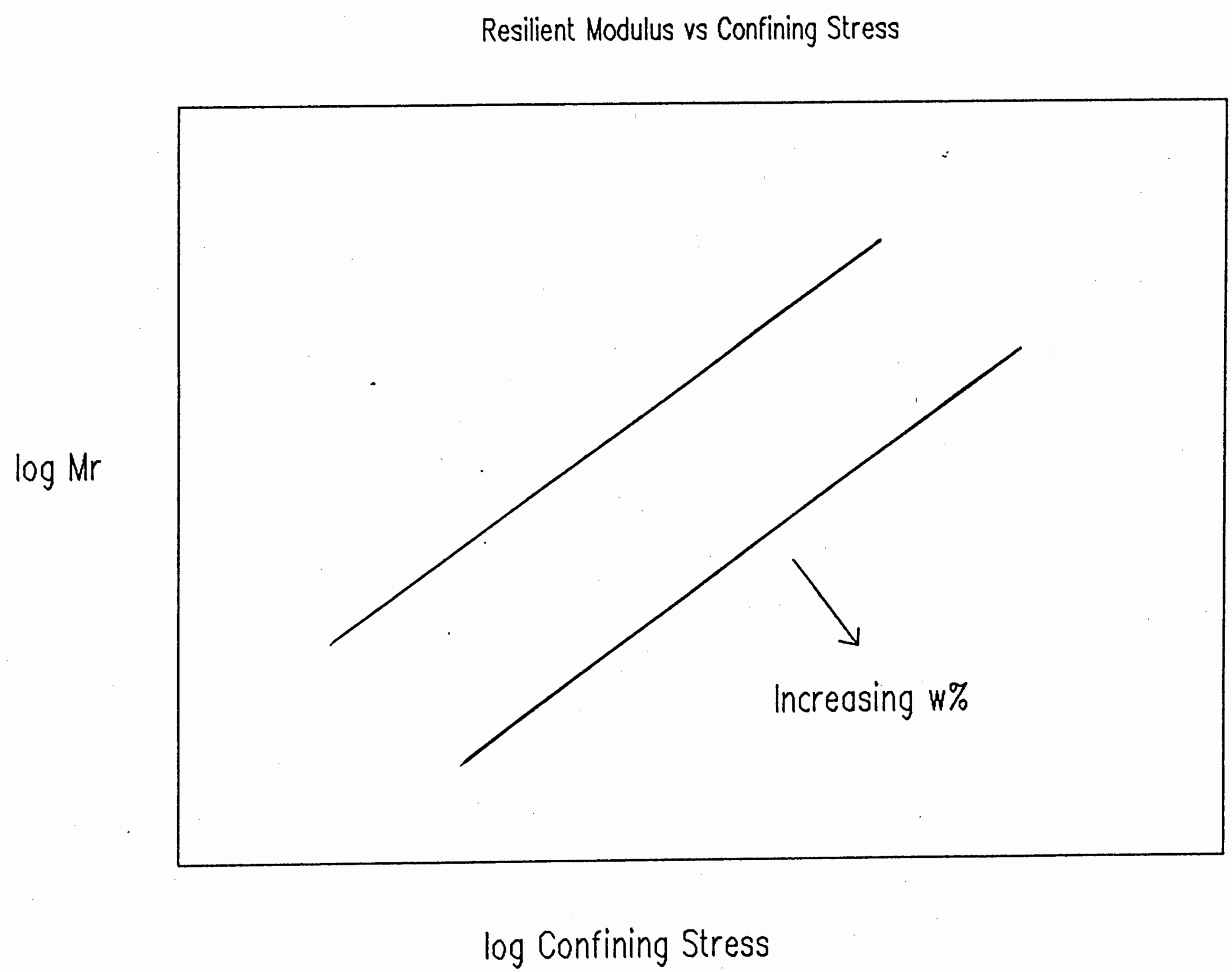
2) Effect of Confining Stress

A linear relation between confining stress and resilient modulus on a logarithmic plot has been established by several investigators (9)(10)(11). This plot is shown schematically in Fig. 4. This relationship depends on the moisture content of the specimen. When the soil is compacted wet of optimum indicated by the standard density tests (13)(14)(15)(16), the degree of saturation will increase, and an increase in confining pressure will not produce a great effect in the resilient modulus. If the soil is compacted dry of optimum, the confining stress will produce noticeable changes in the values of resilient modulus (Fig. No. 4).

Fig. 4 indicates the influence of the confining stress σ_3 and the moisture content on the resilient modulus.

V. Test Methods

Early approaches to the measurement of an appropriate dynamic modulus used apparatuses such as the Hveem Resiliometer and rigid hollow cylinders. A standard for using repeated compression load tests in the triaxial cell eventually evolved (10). Although a standard method for measuring the resilient modulus of subgrade soils has been adopted by AASHTO (1), the test procedure is under continual review by practitioners to determine methods of making the procedures more efficient for various classes of soils(2)(4)(6)(11). The standard method covers: apparatus, specimen preparation,



Schematic Plot of the Relation Between Resilient Modulus and Confining Stress

Figure No. 4

mounting the specimen in the triaxial chamber and the testing procedure itself. The testing procedure includes a process of specimen conditioning and repeated loading before the actual measurements of the recoverable strains.

1. Apparatus

The triaxial pressure chamber is similar in shape and capabilities to other chambers used for testing soils. The basic functions of the chamber are to contain the specimen and the pressure fluid. The present AASHTO procedures, for specimens having a resilient modulus of 15,000 psi or less, allow mounting of the linear variable differential transformer (LVDT) externally at the top of the cell but require internal mounting of the LVDT's for a resilient modulus greater than 15,000 psi. The internal mountings have proved troublesome in previous tests in that the errors using the internal mounts were greater than the compression of the loading ram and top cap that this technique attempted to eliminate (13). It is reasonably certain that the requirement for this type strain measurement internal to the cell will be eliminated. All displacement measurements will be made with two (2) externally mounted LVDT, which will be wired so that the average signal from the pair is recorded.

The AASHTO method allows an external loading device capable of providing a repeated loading in fixed cycles. A load duration of 0.1 second and a cycle duration of 1 to 3 seconds. A haversine, sine, rectangular or triangular shaped stress pulse may be used. The SHRP Protocol recommends the haversine. The tests will be conducted with an INSTRON model 1331 test machine capable of delivering loads within these specifications.

The load may be measured with a load cell internal or external to the test chamber. The internal axial load measuring device is an electronic load cell placed between the cap and the plunger of the triaxial cell. This load cell can also be mounted externally but correction of piston friction must then be made. Test chamber pressures are monitored with conventional pressure gauges of suitable sensitivity.

2. Preparation of Test Specimens

The specimens used in laboratory tests should have, as close as possible, the same soil matrix as the foundation layer in the field. The greatest obstacle to achieving this is the size limitation of the laboratory specimens. The standard method limits the largest size particle in the specimen to one-sixth of the diameter. For a specimen four (4) inches in diameter, the largest size particle is two-thirds of an inch. The samples will have to eliminate all particles retained on the 1/2 inch sieve. This may remove about 20 to 25% by weight of larger particles from many specimens, making the measured resilient modulus somewhat conservative. There is some indication that a recommendation for using six (6) inch diameter by 12 inch long samples may be incorporated into a future specification (4).

Setting aside, for the moment, the question of the larger particles, the most important aspect of the specimen is the dry density. Static or kneading methods are allowed under the specification (1) for compacting specimens. The standard is the maximum dry density from the Proctor Tests (Standard or Modified), (13)(14)-(15)(16). The mold for the standard tests is four (4) inches in diameter by 4.6 inches long, far below a length that is twice the diameter. Special molds are required for the compaction of specimens used in these tests. For each of the different size molds, trial and error adjustments are needed to determine the number of layers and the number of blows per layer, to produce densities comparable to those in the Proctor Tests. All specimens will be compacted according to the established procedure for the mold dimensions used. The compaction requires control of moisture, number of blows, and hammer weight. After compaction the specimen's height and diameter will be measured to the nearest 0.02 in. (0.05 mm).

The specimen will be removed from the mold immediately after compaction and placed in a rubber membrane that will eventually be used to surround the specimen during testing. A vacuum membrane expander has been fabricated to assist in placing the membrane around the sample without disturbance. The specimen inside the membrane will be placed in a plastic bag and stored in an atmosphere of at least 75% relative humidity for a period not less than 24 hours to ensure uniform moisture distribution in the specimen. The membrane will be checked for leakage when the vacuum is applied to the sample during the chamber assembly. The membranes will be sealed with "O" rings around the top and bottom platens for testing.

3. Specimen Conditioning - Granular Samples

The purpose of conditioning is to ensure that the specimen and end caps are seated properly and that the strains measured in the laboratory test more closely compare to those experienced by the compacted soil in the field. In the AASHTO Standard, the specimen is conditioned by applying six deviator stresses at three different confining pressures, two hundred times each. The conditioning is conducted with the drainage valves open and can be accomplished with or without saturation. The loads used in the conditioning phase for granular soils are listed in Table 1 of Appendix A.

4. Resilient Modulus Measurement

Testing for resilient modulus begins with a confining pressure of 20 psi and a deviator stress of 1 psi. The deviator stress is applied for 200 repetitions and the recoverable strain on the 200th repetition is recorded for use in Eq. 1.

The procedure, i.e. 200 repetitions of the deviator, is followed for confining stresses of 5, 10, 15 and 20 psi. The recoverable strain is always measured on the 200th repetition and the modulus computed from Eq. 1. A complete list of the confining pressures and deviator stresses for the testing of granular soils are listed in Table 2 of Appendix A.

VI. Attempts to Modify Testing Procedures

Measuring the resilient modulus of a soil is time consuming. There are thirty-three combinations of stress used in the conditioning and testing sequences. Each of these combinations requires 200 loadings and unloadings. The load cycle is one to three seconds. Combined with specimen preparation, each set of measurements of the resilient modulus requires a substantial time investment. In addition, the AASHTO design procedures require an average resilient modulus computed from the values of the modulus for every one-half month throughout the year (7)(8). The weighting of the resilient modulus by this method requires knowledge of the variation of modulus with moisture content and the manner in which moisture content varies beneath the pavement throughout the year. To provide this information requires resilient modulus measurements at several moisture contents.

1. Modifications of AASHTO T274 Suggested by Others

Several investigators have found that the sophistication of this standard test is not required to yield reliable values of the resilient modulus. A primary focus for simplification has been the number of cycles and the manner in which they affect the measured modulus. Elliott and Thornton (11), testing Illinois soils, found that using 50 cycles of loading-unloading, instead of 200 cycles, resulted in a resilient modulus that differed by only 6 percent. Based, on their tests, Elliot and Thornton concluded that the soils in their test program should be tested at a deviator stress of 6 psi for subgrades.

Sweere and Galjaard (12) investigated the measurement of resilient modulus of sands after applying repeated static loadings. Each load was kept on the sample for two (2) five (5) minute intervals followed by five (5) minute unloading periods after which the samples were statically loaded for thirty (30) minutes and the modulus measured. A plot of the $M_{r,s}$ (30) against M_r in the SI units of MPa yielded a straight line that is described by the equation:

$$M_{r,s}\ (30) = -3.54 + 0.965\ M_r \qquad 2$$

where: $M_{r,s}$ (30) = modulus measured after the static load had been applied to the specimen for 30 minutes and M_r = resilient modulus measured by the standard cyclical procedures.

Drumm, et al (2) have made interesting observations on the use of the hyperbolic stress-strain plot to predict the resilient modulus of cohesive subgrades. In this approach, the authors have shown a correlation between the resilient modulus predicted from the hyperbolic plot of a stress-strain and the strength from an unconfined compression test, the plasticity index of the soil, dry unit weight and percent of particles by weight passing the No. 200 sieve. The hyperbolic stress-strain equation is:

$$\frac{\epsilon}{\sigma} = a + b\epsilon \qquad 3$$

where: ϵ = strain; σ = stress; b = slope of the resulting straight line and a = intercept of the straight line on the vertical axis.

2. Strategic Highway Research Program (SHRP) (4)

The fundamental purpose of SHRP is to improve highways through research. As part of this program SHRP Protocol, P46, has been developed. Suggested modifications to property measurements such as resilient modulus are, therefore, anticipated. An interim protocol was issued in November 1989 for SHRP Test Designation: UG07, SS07, Resilient Modulus of Unbound Granular Base/Subbase Materials and Subgrade Soils. Although this protocol has not been finalized, it gives an indication of several significant changes that will probably be strongly suggested. The modifications attempt to provide test procedures that are less complicated but more repeatable.

The soils are divided into two categories. Soil Type 1 is designed to include unbound granular base and subbase materials. The criteria for this category are: less than 70% passing the No. 10 sieve, and 20 percent or less passing the No. 200 sieve. Soil Type 2 includes all unbound soil not meeting the criteria for Soil Type 1. The intent is that Soil Type 2 soils will be used in the subgrade. The conditioning sequence for both soil types consists of applying 200 repetitions of a deviator stress of 4 psi to the specimen under 6 psi of confining pressure and there are suggested modifications to the testing sequences. The low deviator stresses have been eliminated because they produce high variability of results. The high deviator stresses have been eliminated because they often produce sample failure (3). The testing sequence for each soil type is different. The sequence for Soil Type 1 is shown in Table 3 and that for Soil Type 2 is shown in Table 4 in Appendix A. Note that the number of repetitions for each deviator stress has been reduced to 100, allowing the time of testing to be shortened. The differences in loading sequence are designed to match the anticipated loads of base, subbase and subgrade. A strain failure criteria is also included to eliminate samples whose permanent deformations exceed 10 percent. The resilient modulus is calculated from the deviator stress and resilient deformation averaged over the last five load cycles.

The SHRP testing program experienced great variability when LVDT's were attached internally, directly to the soil specimen as required by the ASSHTO Method for specimens having an M_R greater than 15,000 psi. The shifting of the attachment points through the rubber membrane produced substantial variability. The recommendation is, therefore, to measure displacements for all specimens with LVDT's mounted external to the triaxial cell. The external loading source for the P-46 protocol is a closed-loop electro-hydraulic system. The chamber fluid is air. If the resilient deformation is not very large, a closed-loop air system can be used in some cases. A haversine stress pulse was chosen as representing the shape of a truck load on a pavement. The recommended load cells requirements are shown in Table 5 of Appendix A.

The analysis of the resilient modulus should include a simple linear regression predicting M_R as a function of stress(3). For Soil Type 1 the M_R is expressed as a function of bulk stress, defined as $\theta = \sigma_1 + 2\sigma_3$. Thus:

$$M_R = K_1 \theta^{n1} \qquad 4$$

For Soil Type 2 the M_R is expressed as a function of the deviator stress; $\sigma_d = \sigma_1 - \sigma_3$. Thus:

$$M_R = K_2 \sigma_d^{\,n2} \qquad 5$$

The coefficient of determination (R^2) is reported and can be used to judge the quality of the test.

VII. Equipment and Procedures to be used in Resilient Modulus Testing at UConn

The procedures discussed in this section are found in AASHTO T274-86 or SHRP Protocol P-46 (Interim). There has been some revisions to the present AASHTO procedures that will be incorporated into the next revision of T274.

The procedures that appear to be most reasonable and likely to be adopted in the near future will be used in the UConn testing. In cases where there is some question as to the best approach to take, results from the same soil tested by different procedures will be compared to determine the best method. Examples of this are the different methods of conditioning and the number of repetitions of loading before the recoverable deformations are measured.

1. Sample Compaction

Both methods require a specimen length that is at least twice the diameter. There are differences with respect to the other requirements some of which are listed in Table 1 below:

Table 1

Comparison of Particle Size Limits ASSTHO and P-46

	AASHTO	P-46 (Interim)
Maximum Particle Size	1/6 specimen diam.	1/5 specimen diam.
Specimen Diam.	2.8" and 4"	2.8", 4" and 6"
Nominal Particle Size	--	95% finer by weight

The SHRP definition of nominal particle size raises a question about testing Connecticut bases. According to the interim SHRP procedures, the sample size should be selected to include all particles up to, and including, the nominal particle size. As can be seen from Table 1, the nominal particle size includes 95% of the sample. For a soil having a nominal particle size of 2 inches, for instance, the SHRP protocol is unclear; it discusses specimen size to six (6) inches in diameter having nominal sizes up to 1-1/4 inches, but states that a SHRP Regional Engineer must be contacted for soils having larger nominal sizes. More important than the procedures themselves are the effects of including, or excluding, particles above a certain size. An investigation of the effect of larger particles on the resilient modulus of the specimen will be included in the testing.

2. Special Molds

The molds for the standard compaction tests are too short for preparation of specimens for resilient modulus testing. Two molds were fabricated from steel tubing: one is used in preparing a sample 2.8 inches in diameter x 5.6 inches long and the other in preparing a sample 4.0 inches in diameter by 8 inches long, as illustrated in Fig. 5. Each mold holds a sample having a length of

SPECIAL COMPACTION MOLD

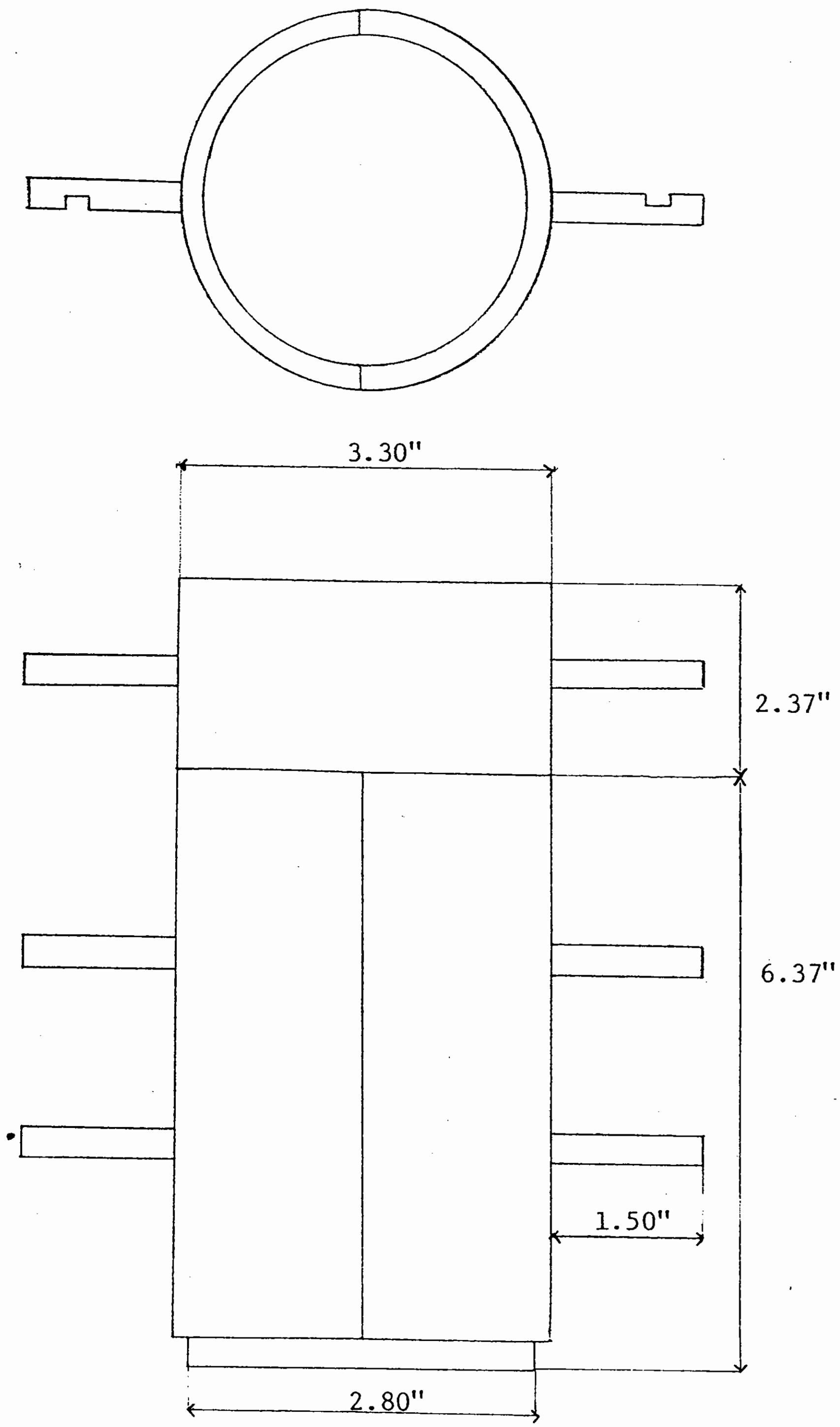


Fig. 5 Diagram of Sample Mold

twice the diameter and is split so that the prepared specimen can be removed easily. During compaction, bolts hold the two halves together to ensure that a specimen of the proper dimensions is prepared. The mold is shown in Fig. 5 with the collar in place. The collar is removed after compaction and the excess soil removed to the top of the mold so that a good end surface is produced.

3. Compaction Machines

Two different compaction machines were used to compact the soil specimens. The Humboldt MFG, 7300w Agatite, which has an automatic control to monitor the number of blows per layer but it can only be used for the 4" diameter mold.

The compaction machine, Rainhart MFT Model 662, was used in the compaction of the 2.8" diameter specimen. This compactor can be easily modified to work with mold sizes other than the standard mold (4" diameter). This machine was modified by fabricating a new hammer. This hammer has the same weight as the original but the geometry was changed in order to keep an area of contact proportional to the diameter of the mold. The new hammer is shown in Fig. 6.

4. Membrane Expander

These cylinders are designed to assist in placing the rubber membrane over the specimen without disturbing the compacted soil. They were fabricated from steel tubing. The tubing has a diameter larger than the specimen with a membrane around it. Vacuum expands the membrane inside the tubing and keeps it in place while apparatus is placed over the specimen.

HAMMER FOR 2.8" COMPACTION MOLD

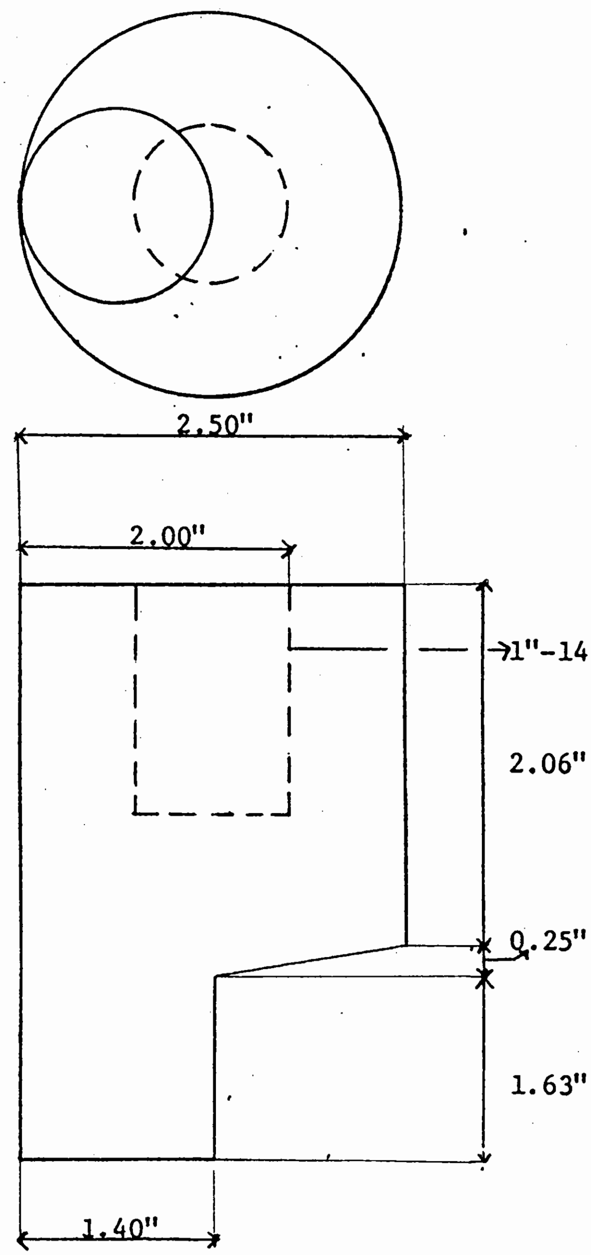


Fig. 6 Special Compaction Hammer for 2.8" Mold

5. Loading Apparatus

Cyclical loading will be accomplished with an Instron Model 1331. This machine uses an electro-hydraulic system for the load application selected as a percentage of the capacity of the load cell (20000 lb). The stress pulses can have different shapes: haversine, rectangular, or triangular. A schematic of the Triaxial Cell in the load frame is shown in Fig. 7. A special collar was designed to avoid any bending moment that would damage the triaxial cell. This collar is shown in Fig. 8.

There are two types of load cells. Large capacity cells are part of the loading frame and support the triaxial cell beneath a platen that was made of steel, thick enough to avoid any deflection. This is shown in Fig. 7. The range of load to be measured is small compared to the capacity of the load cell on the Instron frame. A second load cell will be installed in the interior of the triaxial cell, on top of the specimen between the cap and the plunger. This load cell will measure the force coming directly onto the specimen.

The model chosen for this purpose is a Wagner TH-UM with a range 0 - 600 lbs; this cell has the shape of a disk with a height of 0.81" high and 2" diameter with one threaded stud at each face of the disk to attach it to the cap and the plunger. The cell will send the analog input into the data acquisition system. A proving ring will be used for calibration.

6. Triaxial Cells

Two types of triaxial cell will be used for the two different specimen sizes. The models are Geotest S5026 Cyclic Triaxial Cell but with different sized pedestals. This model is designed to have free access to the cap to attach the plunger for the cyclic loading.

DYNAMIC LOADING FRAME AND TRIAXIAL CELL

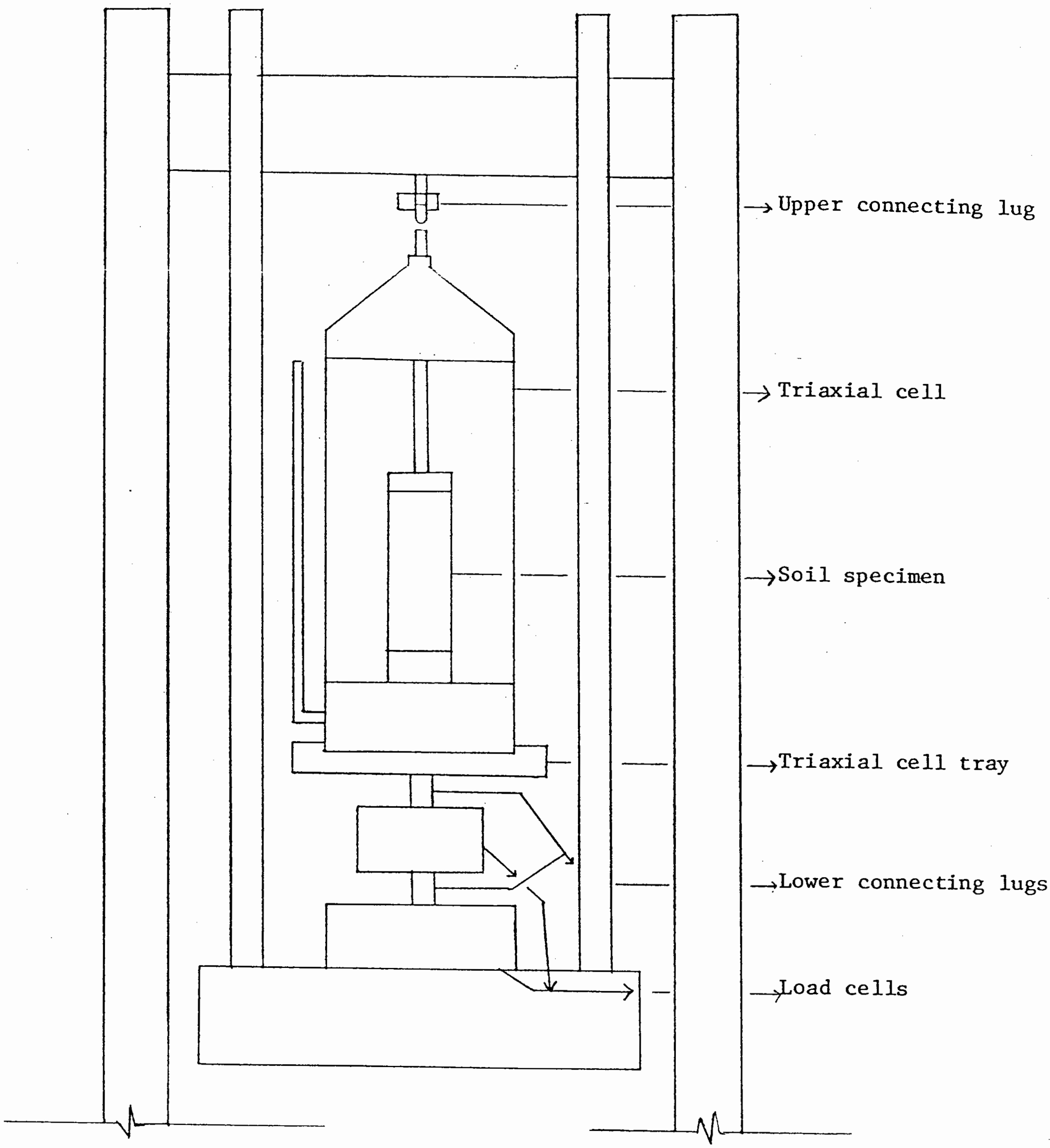
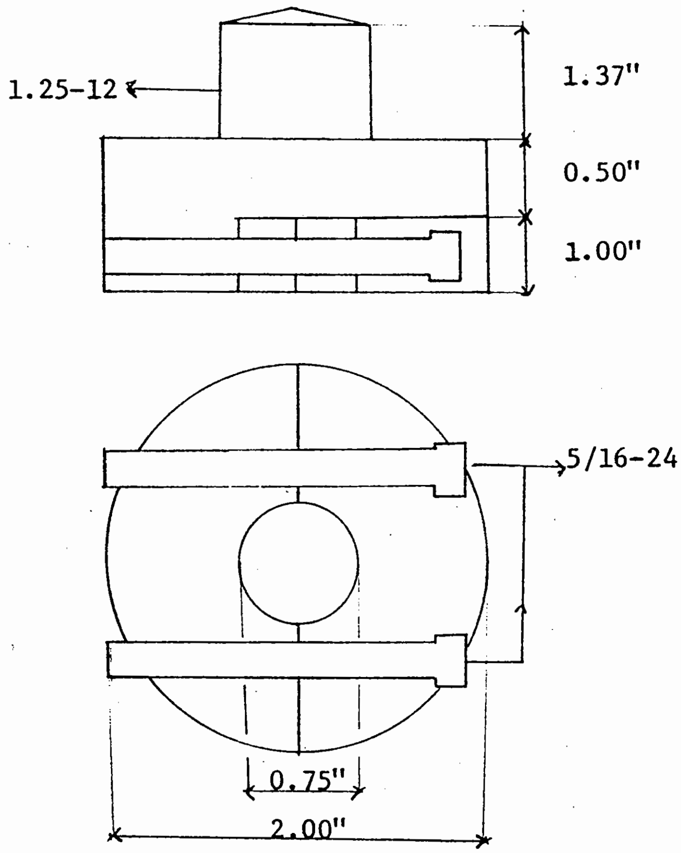


Fig. 7 Triaxial Setup

UPPER CONNECTING LUG



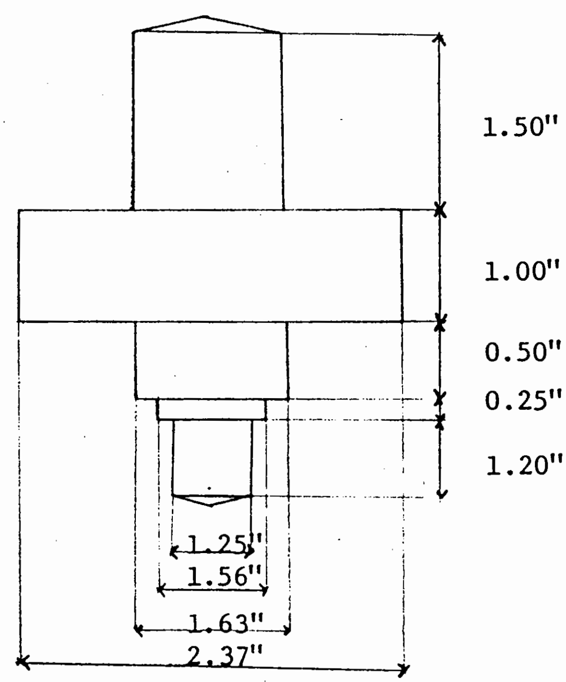


Fig. 8

Connecting Lugs
Instron 1331

LOWER CONNECTING LUG

The plunger is sealed by a teflon bushing and it moves at its own weight with negligible friction. At the base of the specimen valves for cell water, pore water and its purges are mounted and these are connected to the control panel. The acrylic wall of the triaxial chamber is designed to hold 300 psi with no reinforcement.

7. Data Acquisition System

All data pertaining to loads and deformations from the transducers installed in the triaxial cell will be collected by a computer, allowing the opportunity of gathering more accurate data and flexibility in the analysis of the data. The Keithley is a data logging instrument incorporated into a PS2/60 that receives the analog input from the transducers and converts it to the digital signal that the computer requires.

8. LVDT's

Two linear variable distance transducers (LVDT) will be installed outside of the triaxial cell. They will be excited with a DC current. One is a RDP-ELECTROSENCE series D2 with a +/- 0.2" range. The other transducer is a TRANS-TEK- SERIES 243 with a +/- 0.5" RANGE.

9. Control Panel

Geotest Model S5423 was designed to run the controls of the triaxial cell. It has the advantage of putting all the operating valves together for cell pressure, back pressure, vacuum generator, cap saturation, pedestal saturation and pore pressure measurements.

10. Software

The LABTECH NOTEBOOK is software controlling the collection of lab measurements. It reads the data from the interface boards of the Keithley instrument. It can present the data in various graphs and provides the opportunity for making mathematical computation with the data.

11. Calibration

Synthetic specimens made from urethane elastomer will be used to calibrate the equipment of resilient modulus and to verify the procedure. A way to evaluate the performance of the Resilient Modulus equipment is to use a test specimen with known characteristics. These specimens are being developed at the University of Texas at Austin by researchers Kenneth Stokoe, Dong-Soo Kimm, and Ronald Andrus (3). The urethane can be considered a linear viscoelastic material with stiffness characteristics independent of confining pressure, strain amplitude or stress history. They are only dependent on temperature and loading frequency. The values of the modulus of elasticity can be used as a comparison with the resilient modulus at the same temperature and same loading frequency. These cylindrical specimens can be made with stiffnesses ranging from a very soft subgrade to stiff uncemented base.

The specimen for calibrating our equipment was given by the investigators at the University of Texas.

VIII. Sample Preparation

The present AASHTO standard method provides for sample preparation by kneading or static compaction, the objective being to reproduce soil densities as they exist in the field. A method of densifying soil in the laboratory with a gyratory compactor has been gaining favor in some agencies. This method was developed by the U.S. Army Corps of Engineers and is believed by some to duplicate the action of field compactors more faithfully than other methods.

In addition there has been some debate over the merits of the present resilient modulus standard methods (4). A gyratory compaction apparatus is available in the Civil Engineering Department. During the delay in acquiring and installing the Instron 1331 some preliminary tests were conducted with the gyratory compactor as part of the development of sample preparation procedures. The densities from the gyratory compactor were compared with the densities from the standard proctor. The compaction using the special molds for sample preparation were also compared to densities by standard and modified proctor methods.

In all tests, particles larger than 3/4 inch were removed from the sample before compaction. Accounting for the effect of these larger particles will be part of future resilient modulus investigations.

1. Proctor Methods

These methods are covered under AASHTO Standards (15)(16) and ASTM Standards (13)(14). Moisture content was varied until the maximum dry density can be measured. A plot of dry density versus molding water content results in a curve as shown in Fig. 9.

2. Gyratory Compaction Test

This method was developed at the U.S. Army Engineer Waterway Experiment Station. In this test, the soil is loaded with a constant stress in the vertical direction inside a rigid metal cylinder while a cyclical shear stress is applied by rotating the metal cylinder at an angle to the vertical. The voids within the soil decrease with each rotation. The density of interest can be considered as occurring after a predetermined number of revolutions, or at a predetermined rate of density increase per revolution (17).

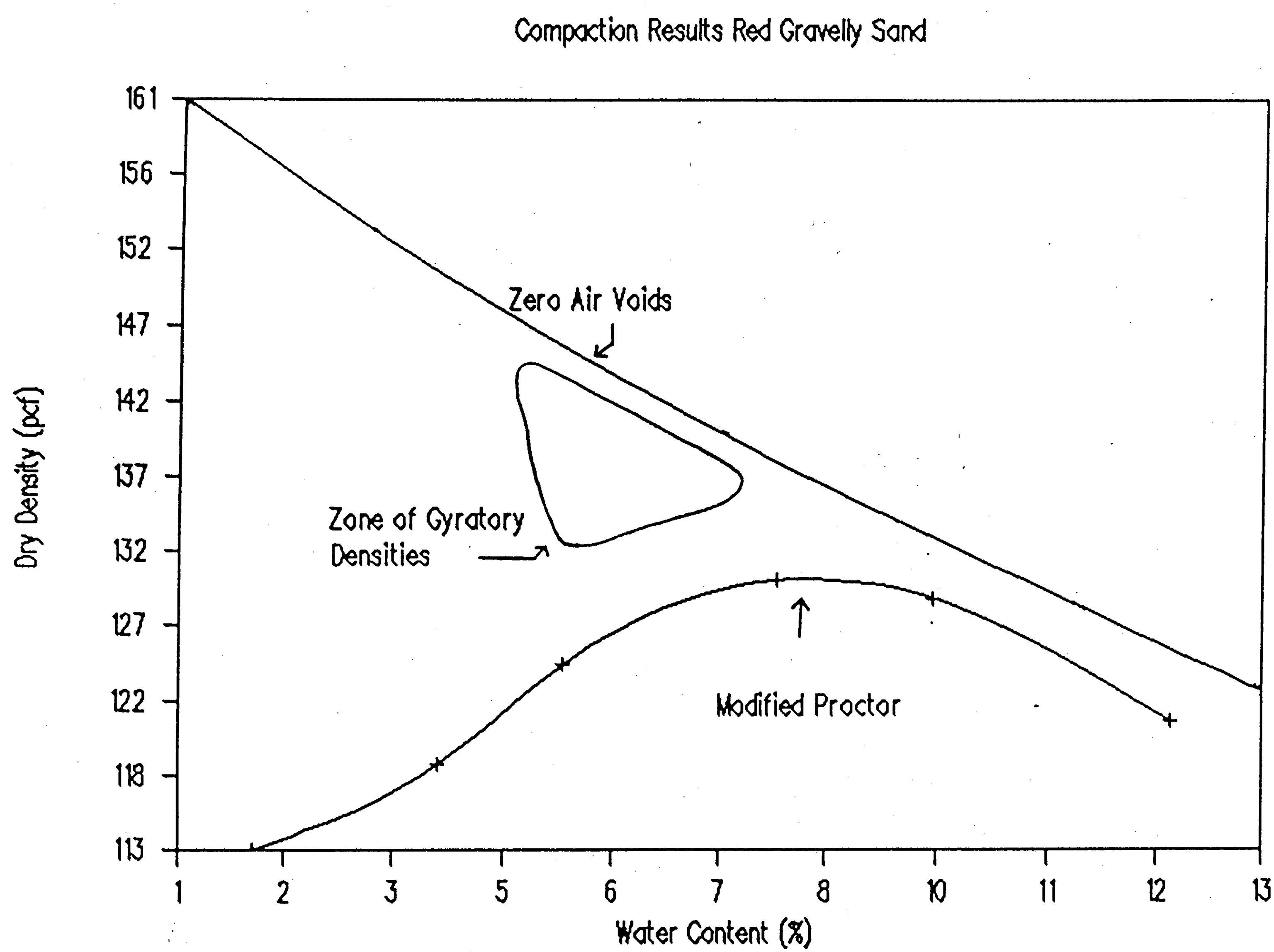


Fig. 9

Compaction
Red Gravel

Using a standard density increase of one pound per cubic foot per one hundred revolutions, the data shown in Fig. 9 were developed for a red gravelly sand. The shaded area in Fig. 9 encompasses the region of dry densities achieved with the gyratory compaction apparatus depending on vertical stress used in the test. The gyratory compaction was performed under vertical stresses of 56, 86, 120, 160, 240 and 320 psi. The samples' density and water content could not be controlled very well during the compaction process. The density migrated toward the zero air voids line and water seeped out of the sample container although "O" rings were used in an attempt to contain the moisture. As a result, the dry densities obtained are shown in a region. The dry densities obtained with the gyratory, even at the lowest values of the vertical stresses, were greater than those obtained by the modified proctor test.

With some additional modification to the gyratory compaction apparatus, the recoverable strain could be measured.

3. Vibration Table

Specimens of granular soils can be made more dense by using either compaction or vibration techniques. In the case of using the latter, soil specimens were densified using a Soil Test Vibration Table Model CN-166. For this purpose, a steel platen was fabricated to fix the mold on to the table.

IX. Comparison of Preparation Techniques Using Connecticut Pavement Foundation Soils

Two samples were obtained with the assistance of Conn DOT District 2. The samples came from two projects, one in Niantic and one from Route 85.

1. Soil Identification

Particle size analysis showed the samples to be granular soils with a small percentage of fines. Atterberg Limits were not necessary. The soils were classified with the Unified Soil Classification System and AASHTO classification of soils as listed in Table 2, below.

Table No. 2

Classification of Soils

Location	% of fines	AASHTO	UCS	Description
Niantic subb	2.6	A-1-b	SW	gravelly sands
Niantic subg	3.8	A-1-b	SP	poorly graded sands
Route 85 subb	5.3	A-1-b	SP	poorly graded sands

2. Determination of Densities

a) Modified Proctor. (14)(16)

This test was performed to determine the optimum water content and the maximum density of the soils as a point of reference for densities measured with other methods. Standard AASHTO procedures were followed. The results are shown in Table 3, below.

Table No. 3

Results from the Modified Proctor Test

	OWC (%)	Maximum Density (pcf)
Niantic subbase	10	118.0
Niantic subgrade	9.4	124.2
Route 85 subbase	8.0	138.6

b) Gyratory Compaction Test

These tests were similar to those on the red gravelly sand but the vertical stress was selected at 285 psi based on previous results. This test was performed at various water contents, with the sample passing the No. 4 sieve. The densities obtained are shown in Table 4 shown below and were higher than the maximum density obtained in the modified proctor test for the Niantic subbase but lower than the same for the Route 85 subbase. The water contents after the compaction was found to be between 7% and 8%, and the granular soil was drained.

Table No. 4

Densities Obtained with Gyratory Compaction

Location	Stress	OWC (%)	Max. Density (pcf)
Niantic subbase	285	8	130.8
Niantic subgrade	285	7.3	134.9
Route 85 subbase	285	8.1	128.0

c) Compaction with Non Standard Molds

The specimens to be tested for resilience are of two different sizes: 4" in diameter and 8" high and 2.8" in diameter 5.6 high. The portion of of the Niantic subgrade soil passing the No. 4 sieve was used to make these specimens. Both specimen sizes were prepared with the modified proctor method but the number of layers were changed to obtain the same compaction energy per volume as in the modified proctor test (2710 kg/m^3). For the 4" diameter mold, 9 layers were used and for the 2.8" mold, 5 layers. The number of blows per layer was kept constant at 25 and the vertical distance of hammer drop was 18".

d) Compaction by Vibrations

There are no specifications available to run a vibration test for maximum densities and optimum water content. The fabrication of the specimen with this method was tested in the 4" diameter mold. The soil was placed inside the mold in layers of 2" with a vibration time of 8 minutes per layer. Maximum density is 4% higher and optimum water content is 11% lower than the modified proctor.

e) Comparison of Results

The results from these four methods of compaction are shown in Fig. 10. As can be seen from Fig. 10, densities with the 2.8" diameter mold were 7% greater than the densities obtained with the standard mold. The density of the sample in the 2.8" mold can be decreased by decreasing the number of compaction layers.

Figure 10 also shows densities achieved by vibration. These densities are also greater than the modified proctor but can be adjusted by vibrating the specimen a shorter time or using a lighter weight. The maximum dry density is 4% greater and the optimum moisture content is 11% lower than the modified proctor values.

Compaction of the specimen in the 4" diameter mold 8" high can yield the same results as those from the modified proctor test.

X. Summary

This project procured, assembled and modified equipment to carry out resilient modulus testing of soils. The tests will be run in a triaxial chamber with air as the confining fluid. The testing procedures will observe the salient aspects of both the AASHTO standard method as well as SHRP Protocol 46.

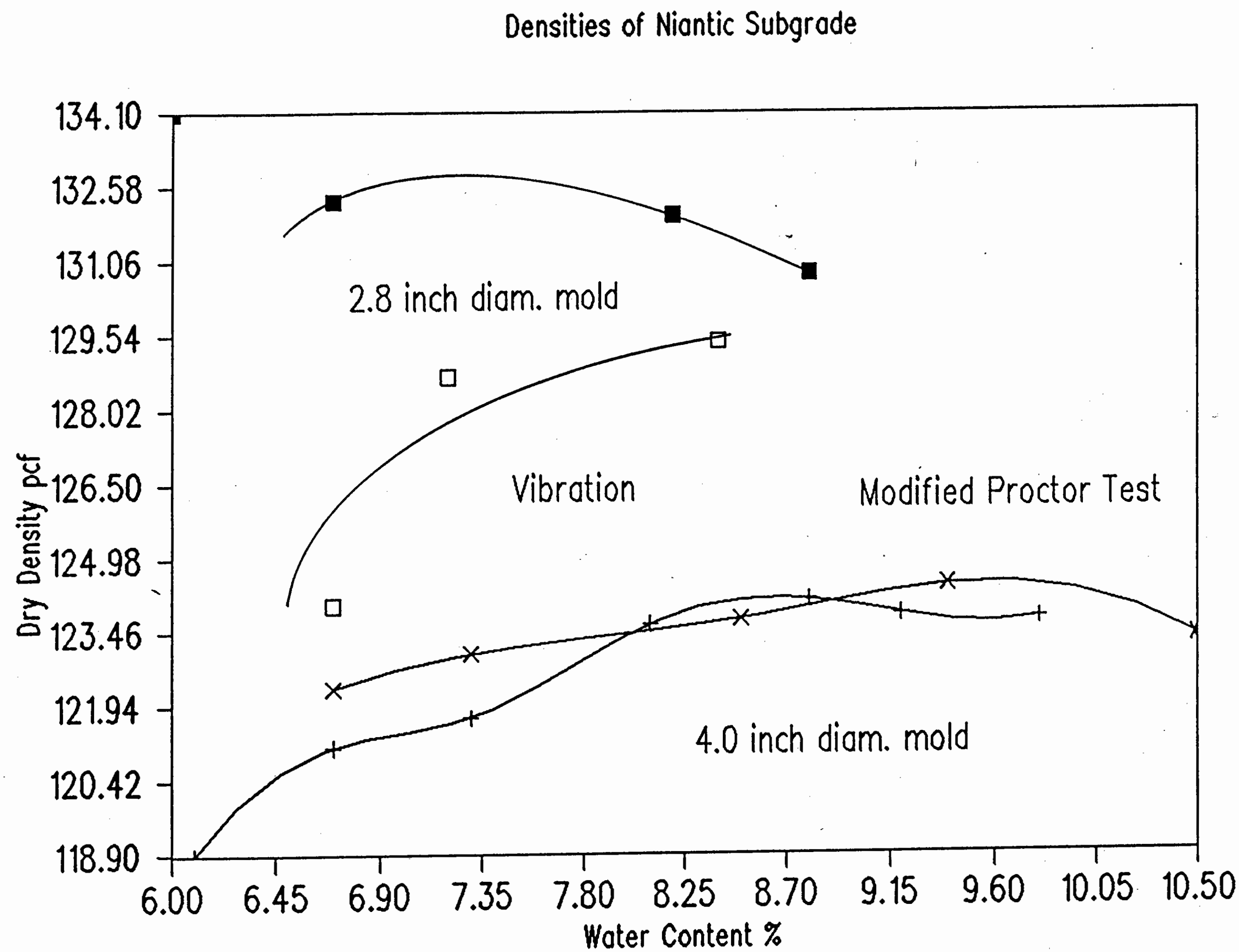


Fig. 10

Gyratory Compaction Results

Special compaction molds were fabricated and the compaction machine modified to prepare specimens 2.8" by 5.6" and 4" by 8" for testing. The soils were compacted several ways and the results compared well.

XI. Conclusions

1. The techniques of compaction in the specially fabricated molds can produce soil densities comparable to standard proctor methods by varing the number of blows per layer.
2. Testing of samples having a significant amount of particles retained on the 3/4 inch sieve will require special consideration.

BIBLIOGRAPHY

1. AASHTO T274-82 (1986), Standard Method for Testing Resilient Modulus, American Association of State Highway and Transportation Officials, Washington, D.C. 20001, 1982.

2. Drumm, E.C., Y. Boateng-Poku, T. Johnson Pierce, "Estimation of Subgrade Resilient Modulus from Standard Test," Journal of Geotechnical Engineering, Vol. 116, 1990.

3. Stokoe, Kenneth H., Kimm D. Soo, R.D. Andrus, "Development of Synthetic Specimens for Calibration and Evaluation of Mr Equipment," Transportation Research Board 69th Annual Meeting, January 7-11, 1990, Washington, D.C.

4. SHRP Protocol P46, Simplification of Testing Resilient Modulus.

5. Yoder, E.J., "Principles of Pavement Design," John Wiley and Sons, Inc., New York, London, Sydney.

6. Wilson, B.E., S.M. Sargand, G.A. Hazen, Roger Green, "Multiaxial Testing of Subgrade," Transportation Research Board 69th Annual Meeting, January 7-11, 1190, Washington, D.C.

7. AASHTO, Guide for Design of Pavement Structures, Volume 1, American Association of State Highway and Transportation Officials, Washington, D.C. 20001, 1986.

8. AASHTO, Guide for Design of Pavement Structures, Volume 2, American Association of State Highway and Transportation Officials, Washington, D.C. 20001, 1986.

9. Wilson, B.E., S.M. Sargard, G.A. Hazen and R. Green, "Multiaxial Testing of Subgrades," Paper presented at the 69th Annual Meeting of the Transportation Research Board, Jan. 7-11, 1990, Washington, D.C.

10. Seed, H.B., F.G. Mitry, C.L. Moresmith and C.K. Chan, "Prediction of Flexible Pavement Deflections from Laboratory Repeated-Load Tests," NAS-NRC Highway Research Board, National Cooperative Highway Research Program, 1967.

11. Elliott, R.P. and S.I. Thornton, "Simplification of Subgrade Resilient Modulus Testing," NAS-NRC, Transportation Research Board, Transportation Research Record 1192, 1988.

12. Sweere, G.T.H. and P.J. Galpard, "Repeated Static Loading Triaxial Tests for Determination of Resilient Properties of Sands," NAS-NRL, Transportation Research Board, Transportation Research Record, 1192, 1988, pp. 8-15.

13. ASTM D-698-78, Standard Test Methods for Moisture-Density Relations of Soils and Soil-Aggregate Mixtures Using 5.5-lb (2.49-Kg) Rammer and 12-in. (305 mm.) DROP, American Society for Testing and Materials, Philadelphia, PA., 1990, pp 160-164.

14. ASTM D-1557-78, Moisture-Density Relations of Soils and Soil Aggregate Mixtures Using 10-lb (4.54-Kg) Rammer and 18-in. (457 mm.) DROP, 1990 Annual Book of Standards Vol. 408 American Society for Testing Materials, Philadelphia, PA.

15. AASHTO T99-86, Standards Methods of Test for The Moisture-Density Relations of Soils Using a 5.5-lb (2.5-Kg) Rammer and a 12-in. (305 mm.) DROP, Standard Specifications for Transportation Materials and Methods of Sampling and Testing. Part II, American Association of State Highway and Transportation Officials, Washington, D.C., 1986.

16. AASHTO T180-86, Standard Methods for the Moisture-Density Relations of Soils Using a 10 lb. (4.54-Kg) Rammer and an 18-in. (456 mm.) DROP, Standard Specifications for Transportation Materials and Methods of Sampling and Testing Part II, American Association of State Highway and Transportation Officials, Washington, D.C., 1986.

17. McRae, J. L., Private communication, 1990.

APPENDIX A

APPENDIX A

Table 5

Applied Loads for Conditioning of Granular Specimen

AASHTO T274-82

Confining Pressure (psi)	Deviator Stress (psi)	Repetitions
5	5	200
5	10	200
10	10	200
10	15	200
15	15	200
15	20	200

APPENDIX A

Table 6

Applied Loads for Resilient Modulus Testing

(Granular Specimens)

AASHTO T274-82

Confining Pressure (psi)	Deviator Stress (psi)	Repetitions
20	1	200
20	2	200
20	5	200
20	10	200
20	15	200
20	20	200
15	1	200
15	2	200
15	5	200
15	10	200
15	15	200
15	20	200
10	1	200
10	2	200
10	5	200
10	10	200
10	15	200
5	1	200
5	2	200
5	5	200
5	10	200
5	15	200
1	1	200
1	2	200
1	5	200
1	7.5	200
1	10	200

APPENDIX A

Table No. 7

Testing Sequence for Soil Type 1 Materials

SHRP Protocol P-46 (Interim)

Sequence No	Confining Pressure S3 in psi	Deviator Stress Sd in psi	# Cycles
1	3	3	100
2	3	6	100
3	3	9	100
4	5	5	100
5	5	10	100
6	5	15	100
7	10	10	100
8	10	20	100
9	10	30	100
10	15	10	100
11	15	15	100
12	15	30	100
13	20	15	100
14	20	20	100
15	20	40	100

APPENDIX A

Table 8
Soil Type 2 Testing Sequence

SHRP Protocol P-46 (Interim)

Sequence No	Confining Pressure S3 in psi	Deviator Stress Sd in psi	# Cycles
1	6	2	100
2	6	4	100
3	6	6	100
4	6	8	100
5	6	10	100
6	4	2	100
7	4	4	100
8	4	6	100
9	4	8	100
10	4	10	100
11	2	2	100
12	2	4	100
13	2	6	100
14	2	8	100
15	2	10	100

APPENDIX A

Table 9

Recommended Load Cells and LVDTs for M_R Testing

SHRP Protocol P-46 (Interim)

Sample Diameter (inches)	Load Cell Capacity (lb)	LVDT Range (inches)
2.8	100	±0.05
4.0	600	±0.10
6.0	1,400	±0.25