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# Dynamic Properties of Fine Grained Soils

## Les Propriétés Dynamiques de Terres Granulées Fines

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**SYNOPSIS** Three fine-grained soils, varying in clay content between 20% and 70%, were tested in a unique repetitive loading apparatus to determine how soil suction, temperature, and stress state affect the resilient modulus and residual strains expected under highway and railroad loadings. In developing equations to predict these dynamic properties, three values of soil suction, stress intensity, and temperature were used in tests of each of the three soils in a statistically designed experiment. A fundamental change in the behavior of the tested soils from "effectively saturated" to "effectively unsaturated" occurs at a soil suction corresponding to two percent dry of the optimum moisture content. The critical soil suction is directly related to the clay content of the soils. This relation has important implications for the climatic design and stabilization of highway pavements and railroads.

### INTRODUCTION

The design of highway pavements and railroads requires the use of the dynamic properties of the materials as they are affected by climatic conditions. The dynamic properties used to define the subgrade soils are the resilient modulus and the residual strain, both of which are determined from repetitive load testing.

Two important climatic factors are the available water and the temperature range. The amounts of rainfall, evaporation, and transpiration are related to a climatic moisture index, while the availability of water in the soil is related to the soil suction. The climatic index used was the Thornthwaite Moisture Index, which is related to soil suction by K. Russam and J.D. Coleman (1961) as shown in Figure 1.

Previous research by B. Shackel (1973) has shown that it should be possible to predict the resilient modulus and residual strain by knowing the soil suction and stress condition in the soil. In this paper, in addition to using soil suction and stress state, temperature and phase relationships will be used in predicting the resilient modulus and residual strain of three typical fine-grained soils with Unified Soil Classifications of ML, CL, and CH. By relating these dynamic properties to soil properties which are determined through simpler tests than the repeated loading test, they will be available for use in the design of better pavements.

### Definitions

Several terms used in this paper are defined here:

Resilient deformation or recoverable deformation is that portion of the total deformation that is

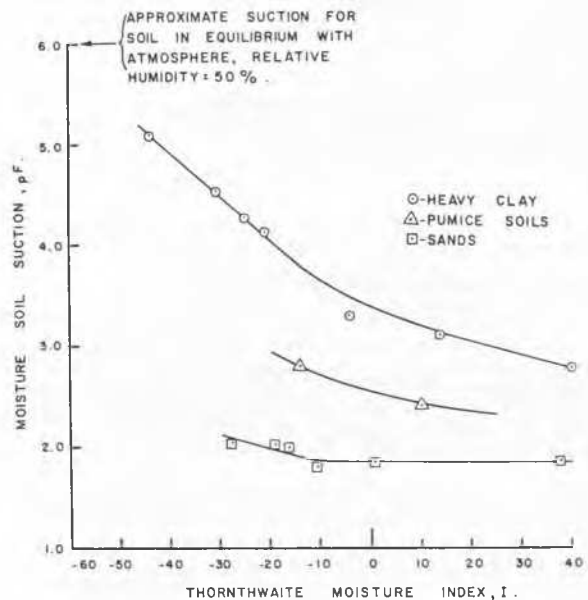


Figure 1 Subgrade Soil Suction as a Function of the Thornthwaite Moisture Index, After K. Russam and J.D. Coleman (1961)

recovered after the load is removed. (See Figure 2.)

Residual deformation or plastic deformation is that portion of the total deformation that is not recovered before the next load application. (See Figure 2.)

Resilient strain or elastic strain ( $\epsilon_r$ ) is the ratio of the resilient deformation to the sample length.

Residual strain or plastic strain ( $\epsilon_p$ ) is the ratio of the residual deformation to the sample length.

Resilient modulus ( $M_R$ ) is the ratio of the deviator stress to resilient strain. The resilient modulus is analogous to the elastic modulus in static testing.

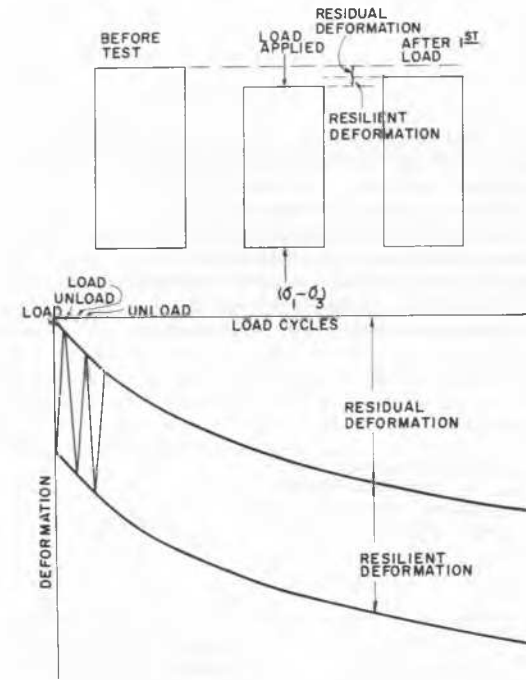


Figure 2 Residual and Resilient Deformations

Soil suction is the energy with which water is attracted to soil and is measured by the work required to move this water from its existing state to a pressure free, distilled state.

The total suction can be determined by measuring the vapor pressure in equilibrium with the soil water. The total suction can be quantitatively defined by the Kelvin equation, which expresses the total suction ( $h$ ) in grams-centimeters/gram of water vapor (centimeters of water):

$$h = \frac{RT}{gm} \log_e (P/P_0) \quad \dots (1)$$

where

- R = gas constant,  $8.314 \times 10^7$  ergs/ $^{\circ}$ C mole
  - T = absolute temperature,  $^{\circ}$ C
  - g = gravitational force, 981 cm/sec<sup>2</sup>
  - m = molecular weight of water, 18.02
  - P = vapor pressure of soil water
  - P<sub>0</sub> = vapor pressure of free water
  - P/P<sub>0</sub> is the relative humidity and is also described as the relative vapor pressure.
- Thus, the total suction is directly

related to the relative humidity of the soil. Since the relative humidity is always 1.0 or less, its logarithm is always 0 or negative and thus  $h$  is always negative. Consequently, the higher the relative humidity, the more moisture the sample contains and the smaller the absolute value of the suction will be.

Besides being expressed in grams-centimeters/gram of water vapor, total suction is expressed in terms of inch-pounds/cubic inch (pounds/square inch).

Although soil suction is defined as a negative quantity, its absolute value or positive magnitude is normally used for ease of discussion. Thus, a soil suction of -142 psi (-979.8 kN/m<sup>2</sup>) is referred to as a suction of 142 psi (979.8 kN/m<sup>2</sup>).

**MATERIALS AND TEST EQUIPMENT**

**Materials**

The three soils used in this test program are classified as CH, CL, and ML. For ease in identifying the different soils, each soil is named for the town near which it was obtained. The CH soil was obtained from Moscow, Texas. This soil consists of dark gray plastic clay that has a high shrink-swell potential. The permeability is very low and the water retention capacity is high. The CL soil was obtained from Floydada, Texas. This soil consists of brown fine textured clay with alkaline sediments from the High Plains. The permeability is very low and the water retention capacity is high. The ML soil was obtained from Allenfarm, Texas. This soil consists of reddish calcareous soils which make up the flood plains of the Brazos River, therefore a small percentage of clay is mixed with a large amount of silt. Due to the silt and larger particles, the water retention capacity is low. The physical properties of the three soils are listed in Table I.

TABLE I. PHYSICAL PROPERTIES

Property	Moscow	Floydada	Allenfarm
Liquid Limit	83%	30%	27%
Plastic Index	55%	13%	0%
Shrinkage Limit	14%	14%	23%
Optimum Moisture Content (Harvard Miniature, 20 psi)	31.5%	18%	16%
AASHTO Soil Classification	A-7-6(20)	A-6(8)	A-4(8)
Unified Soil Classification	CH	CL	ML
Specific Gravity	2.69	2.70	2.72
Thornthwaite Index	+21	-17	0
% Passing #200 Sieve	91%	71%	72%
% Clay (2 $\mu$ )	70%	39%	20%

The distribution of the soil less than 0.2 millimeters was determined by using a hydrometer analysis in accordance with ASTM test D422-61T (1961). The Moscow soil has more clay than the Floydada soil which has more clay than the Allenfarm soil, the percentages

of clay are 70%, 39%, and 20% respectively. In summary, the Moscow soil is an active clay, while the Floydada soil is an average clay, and the Allenfarm soil is an average silt. Although the soil density and soil structure are important factors in determining the dynamic properties of soils, they were not controlled in this study. Johnson and Sallberg (1960) reports that the kneading compactive method best represents the soil structure obtained in the field. For this reason, Harvard miniature samples were made using this compactive method with a compressive force of 20 psi (138 kN/m<sup>2</sup>) which approximates the compactive effort which produces 97% of AASHTO T-180 density.

### Test Equipment

The repetitive loading apparatus is a pneumatic operated testing machine that applies an axial load to a standard triaxial cell. The confining pressure is controlled by a pressure regulator, and measured with a pressure gage. The axial load is controlled and measured the same way as the confining pressure. The pressure pulse is controlled by two 2-way solenoid valves operated such that when one valve is open the other valve is closed. The timing of the solenoid valves is controlled by motor driven cams. Once the regulators and the cams are set, the triaxial pulses are applied in a regular cycle.

Air is used to activate the loading piston because the pressure pulse is sharper and more like the actual condition than if some other medium is used. The pressure pulse used in this program consists of 0.2 seconds with the load applied and 1.8 seconds with the load off. This frequency corresponds to one vehicle traveling at 45 miles per hour (72.4 km/hr) every 2 seconds.

For this program, the following were to be measured: 1) the soil suction before, during and after the test; 2) the vertical deformation, both permanent and recoverable, at any time during the test; 3) the magnitude of the applied vertical load.

The suction of the soil samples was measured with a psychrometer. The psychrometer was chosen because it has a large range, and it could be incorporated into an end cap, thus measuring the soil suction during the test. By using the dew point method of measurement, the temperature corrections could be made easily, and the results are accurate to within  $\pm 5\%$ . A psychrometer was installed in each end cap, as shown in Figure 3 to measure the soil suction at both ends of the sample.

Besides the soil suction, the axial deflections were measured. This was accomplished by a pair of induction coils mounted as shown in Figure 3. These coils measure the change in the magnetic field caused by a change in the spacing of the coils. The magnetic signal is converted into a direct current signal which in turn is compared with a reference signal, set at the beginning of the test. The difference between the direct current signal and the reference signal was recorded on an X-Y-Y plotter as the residual and resilient deformations. The signal is as accurate as the instrument used to transform the

magnetic signal into a usable electrical signal. For this program the accuracy of the deflection measurements is  $\pm 0.0005$  in. (0.0127 mm). Thus for an average sample length of 2.750 (6.985 cm), the error would be  $\pm 0.02\%$ . Since the magnetic signal is not linear, a calibration curve was established for each test with a screw micrometer which measured the distance between the coils within  $\pm 0.0005$  in (0.0127 mm).

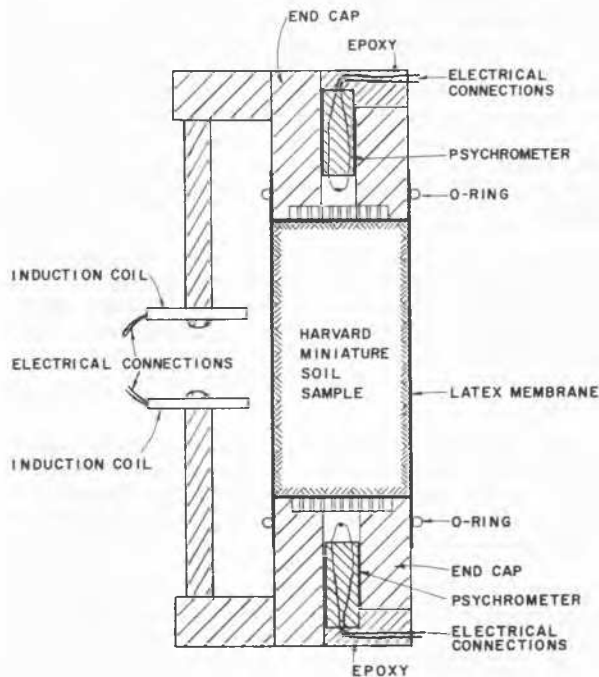


Figure 3 Cross Section of the Sample Set-up, Showing Endcaps With the Induction Coils and Psychrometers

The vertical load was measured with a pressure transducer located immediately before the load piston. The transducer or pressure potentiometer has a range of 0 - 250 psi (0 - 1725 kN/m<sup>2</sup>) and was used to make sure that the pressure at the regulator is the same pressure reaching the sample.

### DATA OBTAINED

The data collected from the repetitive load tests can be divided into four groups:

1. Resilient modulus
2. Residual strain
3. Temperature
4. Soil suction.

Besides the moisture content and the dry density, the following basic properties are calculated for each sample:

1. Porosity,  $n$
2. Degree of saturation,  $S$
3. Volumetric moisture content,  $nS$
4. Volumetric soil content,  $(1-n)$ .

## Resilient Modulus

The samples exhibited two creep movements, one took place when the load was applied and the other creep recovery occurred after the load was removed. The creep movement demonstrates that the soils tested behave in a viscoelastic manner instead of an elastic manner.

The soil suction was chosen as the best single variable to describe the resilient modulus. Small variations of the dry density did not have an effect on this dynamic property. The soil suction readings were broken down into three groups. The initial soil suction, the test suction, which is the suction measured during the test, with the minimum measurements taken at 1000, 10000, and 40000 load cycles and the final suction which is measured after the test has stopped.

**Moscow Soil (CH).** As the soil suction increased past the suction corresponding to the optimum moisture content, the resilient modulus decreased as the deviator stress increased. Before that suction level, there is a rapid change in the resilient modulus for a small change in the suction.

**Floydada Soil (CL).** The curves for this soil are flatter than the curves of the Moscow soil. These curves flatten out at a suction corresponding to a moisture content that is two percent dry of the optimum moisture content.

**Allenfarm Soil (ML).** Generally the resilient modulus versus soil suction curves have a steep slope up to a suction corresponding to two percent dry of optimum, then the curves change to a flatter slope at a suction of 25 psi (172.5 kN/m<sup>2</sup>). The slope of the flat portion of the curve is dependent upon the deviator stress.

The effect of the soil type on the resilient modulus - soil suction relationship is shown in Figure 4. The resilient modulus seems to reach a peak at a clay content of 40 percent, then it decreases. Most of the curves increase rapidly to a soil suction that corresponds to a moisture content that is about two to three percent dry of the optimum moisture content, then they decrease gradually. E.K. Sauer and C.L. Monismith (1968) showed the same general results for a glacial till material.

## Residual Strain

The residual strain continually increases during the test. This increase is not linear; more residual strain is developed per load cycle in the beginning of the test than as the number of cycles increases. Because the samples were not pre-loaded, there was a large seating error. To compensate for this, the residual strain was set to zero at the one hundredth load repetition, and the differences in the strains are due to differences in the samples.

Comparing the residual strain with different soil properties, more residual strain is caused by stress conditions with higher ratios of

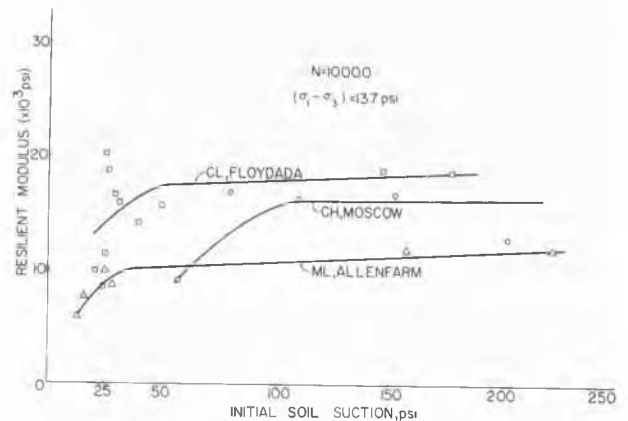


Figure 4 Resilient Modulus of the Three Soils at 10,000 Load Cycles As A Function of the Initial Soil Suction

deviator stress to mean stress. The middle deviator stress (13.7 psi) has the largest ratio; 1.7, while the largest deviator stress (15.0 psi) has a ratio of 0.6. The smallest deviator stress (10.0 psi) has a ratio of 0.55.

As with the resilient modulus, the soil suction was the best single moisture variable to describe the residual strain.

**Moscow Soil (CH).** There is a gradual increase in the residual strain as the soil suction gets lower. The point where the curves change from a high slope to a low slope is a suction level that corresponds to a moisture content that is two percent dry of the optimum moisture content. From this point, as the suction increases, the residual strain is directly related to the ratio of deviator stress to mean stress.

**Floydada Soil (CL).** There is a rapid increase in the residual strain as the soil suction decreases below the level that corresponds to a moisture content that is about two percent dry of the optimum moisture content. Again as the soil suction increases past the dividing point, the deviator-mean stress ratio dictates how much residual strain will be developed.

**Allenfarm Soil (ML).** Has a very rapid increase in the residual strain for a small change in the soil suction below 25 psi (103.5 kN/m<sup>2</sup>), which corresponds to about two percent dry of the optimum moisture content. Beyond this point, the curves become very flat with a very low slope. Overall, there is more strain developed in this soil than in any of the other soils.

The effect of the different soils on the residual strain - soil suction relationship is shown in Figure 5. Here it can be seen that the amount of residual strain that will develop at low suction levels is dependent upon the clay

content of the soil. On the other hand, at high suction levels, the ratio of deviator stress to mean stress is important in determining the residual strain. As shown in Figure 5, in the high suction range, as the clay content increases to 40%, the residual strain decreases to a minimum and then begins to increase again.

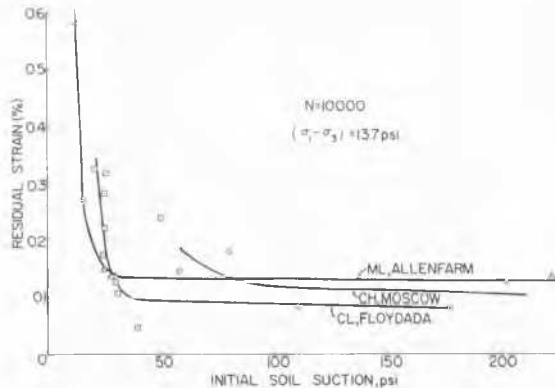


Figure 5 Residual Strain of the Three Soils at 10,000 Load Cycles As A Function of the Initial Soil Suction

#### Temperature Effects on the Resilient Modulus

The resilient modulus is dependent upon the temperature, increasing when the temperature decreases and vice versa. Generally, the sensitivity of the resilient modulus to a temperature change is more than doubled when the temperature is increased than when it is decreased.

The stress level and number of load cycles do not have a significant effect of the change of the resilient modulus with temperature.

The percent change in resilient modulus is strongly related to clay content. When the temperature increases, the resilient modulus decreases but the percentage change of resilient modulus decreases as the clay content increases. When the temperature decreases, the resilient modulus increases but the percentage change of resilient modulus increases with a greater clay content.

#### Temperature Effects on the Residual Strain

As with the resilient modulus, the residual strain varies with changes in the temperature. Generally when the temperature increases, the residual strain increases and vice versa. The residual strain is about 4.5 times as sensitive to an increase of temperature as it is to a decrease of temperature. The variation in the residual strain is over twice the variation of the resilient modulus.

As before, the clay content is related to the change in the residual strain when the temperature is below room temperature. However, unlike the resilient modulus, changes in the mean stress are best related to residual strain changes.

#### Summary

The relation of several soil properties and load variables to the resilient modulus have been shown. As the number of load cycles, the soil suction and the mean stress increase the resilient modulus increases. But as the saturation and the volumetric moisture content decrease the resilient modulus increases.

There are several variables that have been shown to be related to the residual strain. As the number of load cycles, saturation, and volumetric moisture content increase, the residual strain increases. But as the mean stress and soil suction increase, the residual strain decreases.

#### PREDICTIVE RELATIONSHIP

To develop a relationship that will describe the resilient modulus and the residual strain, it is necessary to determine the important independent variables. These terms can be divided into three groups of variables; moisture distribution, stress intensity, and loading history. The soil suction, saturation, volumetric moisture content, and volumetric soil content comprise the terms that make up the moisture distribution group. The deviator stress, mean stress, and confining stress are the terms included in the stress intensity group. The number of load cycles comprises the load history group.

The soil suction group is divided into three parts, initial suction, test suction, and final suction.

#### Resilient Modulus

The equation determining the resilient modulus ( $M_R$ ) is:

$$M_R(\text{psi}) = a_0 + a_1 \left[ \left( \frac{h_f}{h_i} \right)^{0.20} N^b \right] \{ [1 + a_2(1-n)^c] \{ 1 + a_3(\sigma_1 - \sigma_3)^d \} + a_4(S)^e \{ 1 + a_5(\sigma_1 - \sigma_3)^d + a_6 \sigma_m^f \} + a_7(nS)^g \{ 1 + a_8(\sigma_1 - \sigma_3)^d \} \} \quad \dots (2)$$

where:

- $h_i$  = initial suction, psi
- $h_f$  = final suction, psi
- $(1-n)$  = volumetric soil content, decimal form
- $nS$  = volumetric moisture content, decimal form
- $S$  = saturation, %
- $(\sigma_1 - \sigma_3)$  = deviator stress, psi
- $\sigma_m$  = mean stress, psi.

The values of the constants are given in Table II.

Table II. Resilient Modulus Constants

Constant	Moscow (CH)	Floydada (CL)	Allenfarm (ML)
b	0.084	0.145	0.081
c	3.6	3.3	1.4
d	-0.60	-0.60	-0.16
e	3.6	2.0	-0.26
f	-0.27	-0.23	0.063
g	-3.3	-2.25	-0.30
a <sub>0</sub>	-4791.99	7980.89	-1827.72
a <sub>1</sub>	-27272.4	2981.64	171705.
a <sub>2</sub>	-45.0169	64.397	0.6566
a <sub>3</sub>	-3.733	-4.2008	-4.4849
a <sub>4</sub>	1.706x10 <sup>-7</sup>	-2.002x10 <sup>-3</sup>	64.6522
a <sub>5</sub>	-5.0763	-3.7228	-1.6108
a <sub>6</sub>	-0.1288	-0.1639	-0.001155
a <sub>7</sub>	0.05999	-0.1974	-14.8816
a <sub>8</sub>	-5.8416	-4.2766	-1.5899

where:  $h_t$  = test suction, psi  
 $\sigma_3$  = confining stress, psi.  
 $c_1 = 1 - c_2$   
 $c_2 = \frac{1}{1 + e^{46[\text{clay} - 0.3]}}$

The values of the constants are given in Table III.

Table III. Residual Strain Constants

Constant	Moscow (CH)	Floydada (CL)	Allenfarm (ML)
b	0.45	0.63	0.395
c	0.61	0.50	0.17
d	0.25	0.38	0.10
e	0.24	1.58	0.30
f	0.24	0.54	0.17
g	0.40	0.60	0.15
a <sub>0</sub>	-0.000186	0.01519	0.07915
a <sub>1</sub>	-0.000443	-0.000254	0.01995
a <sub>2</sub>	-63.0264	-24.62205	-10.44812
a <sub>3</sub>	-0.09398	-0.01297	-0.35852
a <sub>4</sub>	123.8399	61.1811	15.9875
a <sub>5</sub>	-5.9323	-0.52205	-4.7268

The final suction and the number of load cycles are directly related with the resilient modulus while the deviator stress is inversely related. The power of the suction ratio is 0.20 while the power of the number of load cycles varies between 0.081 and 0.145. The power of the deviator stress is negative and becomes smaller as the percent clay is decreased.

The coefficients of determination for this equation are 0.534, 0.453, and 0.766 for the CH, CL, and ML soils, respectively. The final suction and the number of load cycles have a larger influence on the resilient modulus than does the deviator stress.

There are several general observations that can be made from this equation. The single most important term in the equation is the number of load cycles. As the clay content decreases, the equations are less dependent upon the soil suction and more dependent on the volumetric moisture properties. By comparing the coefficients of determination, it appears that the resilient modulus becomes more predictable with lower clay contents.

Residual Strain

The equation determining the residual strain ( $\epsilon_p$ ) is:

$$\epsilon_p (\%) = c_1 \{ a_0 + a_1 N^b [ 1 + a_2 (\frac{h_t}{h_f})^{c_1} (\frac{1}{\sigma_3 h_f})^d + a_3 (\sigma_1 - \sigma_3)^e (\frac{1}{h_f})^f ] + a_4 (\frac{1}{\sigma_m h_f})^g + a_5 (\sigma_1 - \sigma_3)^e (\frac{1}{h_f})^f \} + c_2$$

$$[ -1.2679 (\frac{1}{h_t})^{0.65} N^{0.395} ] [ 1 - 1.2067 \times 10^{-15} \{ (\frac{S}{NS})^{5.35} (\frac{1}{1-n})^{10.4} \} ] + 0.04076 \} \dots (3)$$

Of the three stress terms, the deviator stress is directly proportional while the mean stress and confining stress are inversely proportional to the residual strain. The number of load cycles is directly related and the final suction is inversely related to the residual strain. The coefficients of determination for this equation are 0.830, 0.802, and 0.900 for the CH, CL, and ML soils, respectively.

There are several general observations to be made concerning the residual strain equation. The number of load cycles is the single most important term in the equation. As the clay content increases, the residual strain is more dependent on the stress conditions and the soil suction rather than on the volumetric soil properties. The coefficients of determination are better for the soil with the low clay content and they are higher for the residual strain equation than they were for the resilient modulus equations. Thus the residual strain is more predictable than the resilient modulus.

Method of Predicting the Resilient Modulus and the Residual Strain

Using the developed equations, it is possible to predict the dynamic properties of any soil with a clay content between 20 and 70 percent.

In arriving at design quantities, the terms needed for the equations are developed in several ways. The stress terms along with the number of load cycles are obtained from the design load criteria. The clay content is determined by either a hydrometer analysis or by clay mineralogy fractionation. The soil moisture properties are determined by compacting a laboratory sample as close to field conditions as possible. The initial soil suction can be determined by using Figure 1 knowing the climatic index and the percent passing the #200 sieve. The final suction is best found by making

field observations. However, the ratio of final suction to initial suction can be estimated from Figure 6 which shows the ratio of final suction to the initial suction as a function of clay content. It can be seen that high clay content soils have ratios near one, and as the clay content decreases the curve reaches a peak around 40%. The ratio of test suction to final suction increases as a function of the number of load cycles and the largest rate of increase was measured on the CL soil. In all cases, the ratio remains very nearly one. Thus, the predictive equations presented herein allow dynamic soil properties to be predicted once a set of simple laboratory identification tests have been performed.

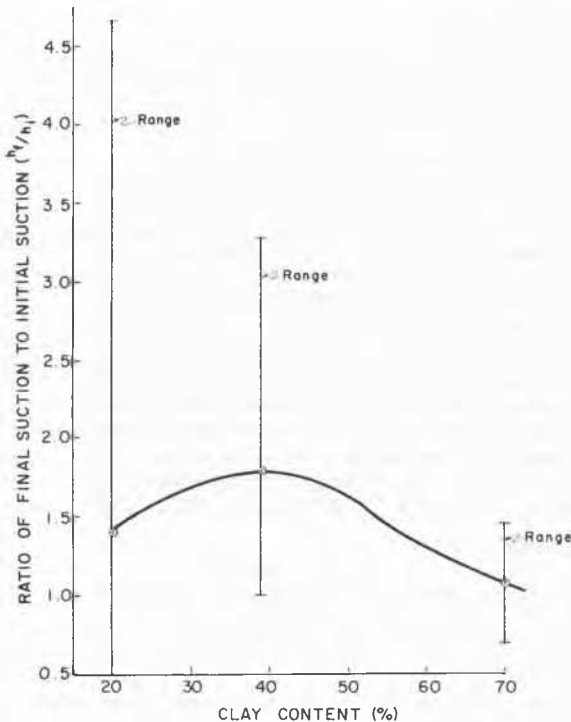


Figure 6 The Ratio of the Final Suction to the Initial Suction As A Function of the Clay Content

### Predicting the Effect of Temperature

When trying to predict the effect of a temperature change, there are several factors other than the temperature that must be considered. The number of load cycles influences the soil behavior differently at different temperature levels. The soil suction will generally change inversely as the temperature changes and as the temperature increases there is more deformation developed with the same stress levels. Thus the change in all these variables must be included when predicting the effect temperature changes have on the dynamic properties.

To determine the temperature effect, all of the above terms are referenced to a single state: 72°F (22.2°C) temperature, 13.7 psi (94.5 kN/m<sup>2</sup>)

deviator stress, 10000 load cycles and the soil suction that occurred when the moisture content was two percent dry of the optimum moisture content. In addition, the resilient modulus and residual strain that corresponded to this state was used as the reference.

### Resilient Modulus

The equation developed for the temperature correction factor for the resilient modulus is:

$$f_{M_R} = a_0 - a_1 \left(\frac{D}{D_0}\right)^b + a_2 \left(\frac{h}{h_0}\right)^c + a_3 \left(\frac{T}{T_0}\right)^d \left[1 - a_4 \left(\frac{h}{h_0}\right)^c \left(\frac{D}{D_0}\right)^b + a_5 \left(\frac{N}{N_0}\right)^e \left[1 - a_6 \left(\frac{h}{h_0}\right)^c + a_8 \left(\frac{h}{h_0}\right)^c \left(\frac{D}{D_0}\right)^b - a_7 \left(\frac{D}{D_0}\right)^b\right]\right] \quad \dots (4)$$

where:  $\left(\frac{D}{D_0}\right)$  = deviator stress ratio

$\left(\frac{h}{h_0}\right)$  = soil suction ratio

$\left(\frac{T}{T_0}\right)$  = temperature ratio

$\left(\frac{N}{N_0}\right)$  = number of load cycle ratio

$b = -1.7013 + 6.2014 (PL)$

$c = 0.0271 - 0.2873 \log(\text{clay})$

$d = 0.0697 - 0.9846 (\text{clay})$

$e = 0.0582 - 0.00226 (1/\text{clay})$

$a_0 = -125.574(SL) - 2764.13(PL) + 21234.1 (SL \times PL)$

$a_1 = -465.052(SL) - 2890.01 (PL) + 23642.5 (SL \times PL)$

$a_2 = -37.6644 + 279.813 (SL + PL)^2$

$a_3 = -15.0184 + 13786.434 (SL \times PL)^2$

$a_4 = 0.8088 + 0.3006 (\text{clay})$

$a_5 = 30.8763 - 306.7167 (LL)^2$

$a_6 = 7.5058(SL) - 6.0135(PL) + 41.1548(SL \times PL)$

$a_7 = 3.6476(PL) + 2.0336(LL) - 7.3402(PL \times LL)$

$a_8 = 4.370(SL) - 6.1516(PL) + 53.4137(SL \times PL)$

clay = clay fraction of soil in decimal form

LL = liquid limit

PL = plastic limit

SL = shrinkage limit.

The powers of the ratios have excellent relations with soil properties. All except the deviator stress ratio are related to the clay content of the soil. The coefficients of determination for the power relationships are all above 0.90. As with the deviator stress ratio, the soil suction and number of load cycle ratio changes are directly related to the resilient modulus changes.

Whereas the powers were generally related to the clay content, the coefficients are generally related to the Atterberg limits. The coefficients of determination for the coefficient relationships are all above 0.90.

### Residual Strain

The equation to determine the temperature correction factor for the residual strain is:

$$f_{e_p} = a_0 + a_1 \left(\frac{h}{h_0}\right)^c + a_2 \left(\frac{T}{T_0}\right)^d \left(\frac{N}{N_0}\right)^e \left\{ 1 - a_3 \left(\frac{h}{h_0}\right)^c + a_4 \left(\frac{h}{h_0}\right)^c \left(\frac{D}{D_0}\right)^b - a_5 \left(\frac{D}{D_0}\right)^b \right\} \dots (5)$$

where:

$$\begin{aligned} b &= 0.6761 - 0.2384 (1/\text{clay}) \\ c &= -1.7043 + 1.9130 (200 \text{ sieve}) \\ d &= 2.3620 - 0.4128 (1/\text{clay}) \\ e &= 0.3716 + 0.1700 (\text{clay}) \\ a_0 &= -114.111 + 159.212 (200 \text{ sieve}) \\ a_1 &= 119.823 - 166.053 (200 \text{ sieve}) \\ a_2 &= -81.345 - 41.866 (1/\log \text{ clay}) \\ a_3 &= 0.7882 + 1.4700 (\text{SL}) \\ a_4 &= -0.0663 + 1.5214 (200 \text{ sieve}) \\ a_5 &= -0.2791 + 1.7426 (200 \text{ sieve}) \end{aligned}$$

200 sieve = the amount of soil that passed the #200 sieve in decimal form.

The powers of the ratios have good relations with the grain sizes of the soil. All the powers of the ratios except the soil suction ratio, which is related with the percent of the soil passing the #200 sieve, are related to the clay content. All the coefficients of determination of the power relationships are all above 0.90. The temperature, deviator stress and number of load cycle ratios are directly related to the residual strain while the soil suction ratio is inversely related. As with the powers, the coefficients are generally related to part of the soil grain size distribution. The coefficients of determination for the coefficient relationships are all above 0.90.

The equations to determine the change in the resilient modulus and the residual strain caused by temperature variations are multiplied by the respective property calculated at room temperature. In order to be able to use the equations for all soils, the powers and coefficients have been related to soil properties. Generally the resilient modulus is dependent upon the plasticity of the soil and the clay content while the residual strain is dependent upon the grain size distribution of the soil in the fine-grained region.

#### CONCLUSIONS AND RECOMMENDATIONS

**Conclusions** - A study of the relationship between the resilient modulus, residual strain, and the soil properties of fine-grained soil has been made by repetitive load testing of the soil samples. The following conclusions can be made:

1) There is an important change in behavior of the soils when the moisture content is about two percent dry of optimum moisture content. Wetter than this point, a small change in a soil moisture property would cause a large change in the dynamic behavior. Drier than this point, a small change in a soil moisture property has little effect on the dynamic behavior. The soil suction that corresponds to this point is related to the clay content by the following equations:

$$\begin{aligned} h &= 21.5 + 181. (\text{clay}) \text{ and} \\ pF &= 3.07 + 1.18 (\text{clay}) \end{aligned} \dots (6)$$

where:

$$\begin{aligned} \text{clay} &= \text{clay fraction of soil in decimal form} \\ h &= \text{soil suction in psi (1 psi} = 6.9 \text{ kN/m}^2) \\ pF &= \text{soil suction expressed as the log} \\ &\quad (\text{cm. of water}). \end{aligned}$$

By knowing the soil suction in pF at the point where the soil behavior changes, the Thornthwaite Moisture Index where such behavior changes can be determined for each soil using Figure 1. Figure 7 shows the map of the United States where the Thornthwaite Index that corresponds to the change in behavior of

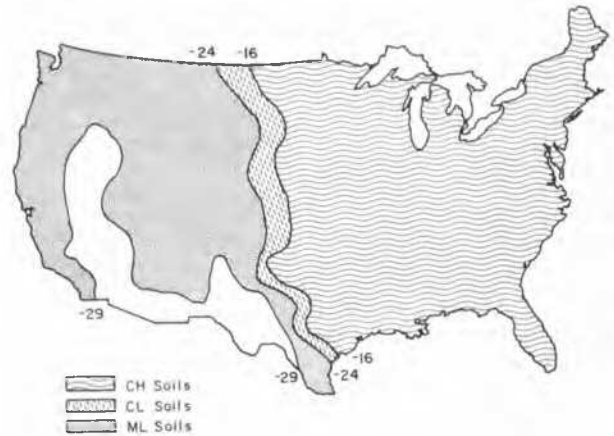


Figure 7 The Critical Thornthwaite Moisture Index Where CH, CL, and ML Soils Change Behavior

each soil is shown. Generally, anywhere the index is larger and thus wetter (shaded area), soil stabilization needs to be considered in the design of any structure or pavement where dynamic loads are important. The necessity of stabilization will depend upon local conditions such as drainage and temperature variation.

2) The most important term for all the equations is the number of load cycles. The changes in the dynamic properties as a function of this term are presented. For the resilient modulus, the power of the number of load cycles is 0.08 and 0.15. For the residual strain, the power of this term is between 0.30 and 0.63.

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